Mapping the Nearshore Substrates and Hydrodynamics in Lakes

A Thesis Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF ARTS

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MAPPING THE NEARSHORE SUBSTRATES AND HYDRODYNAMICS IN LAKES

by

PAUL M. COOLEY

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
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1. Abstract

This study sought to better understand the spatial distribution of substrates in the nearshore area within and among six small lakes in the Precambrian Shield. For this task a new nearshore classification system (NSCS) and wave energy programs were developed. A GIS database containing detailed substrate, slope, and depth data, was compiled for 6 lakes. This multi-lake database containing 16 km of detailed substrate distribution data was used to describe and contrast the habitat structure of the lakes using a hierarchical classification system. Sediment dynamics were investigated in one lake by integrating GIS maps of substrate, slope, and predicted wave properties.

Using the NSCS where three material types can occupy a single substrate area, 20 of the possible 221 substrate combinations described greater than 80% of the combined nearshore area among all the lakes. Three substrate classes, detritus, boulder/cobble, and bedrock, were common to all six lakes and described 25% of the combined nearshore area.

Substrate diversity, as indicated by the number of substrate classes and polygons, decreased with an increase with water depth. Substrate diversity was correlated with the shoreline development index which indicates the shape of shorelines are good indicators of aqueous habitat. Substrate material composition is homogenous only in low (<= 6 degrees) or high slope (> 40 degrees) areas.

Inter-lake statistical comparisons of the NSCS substrate data were prevented by the high inter-lake habitat diversity which has resulted from the erratic nature of glacial action and deposition in the region. However, by aggregating substrate classes, comparisons were possible at higher levels of the classification hierarchy. The six lakes were divided into two groups based on summed habitat characteristics; two in one group, four in the other. A more general classification method is proposed for inter-lake comparisons based on the dominant shore types documented from the detailed substrate data. These Shore Type Associations (STA) compile data at about the middle of the classification hierarchy which is suitable for inter-lake comparisons. Ten classes of shore types describe the study lakes.

Spatial sediment dynamics were investigated in one lake by comparing the lower limit of the sub-surface wave base predicted from a maximum fetch model and the zone of offshore deposition from a detailed substrate map. In small lakes, maximum fetch is a good predictor of substrate redistribution in most areas of

low slope. Sediments are also redistributed by gravity in areas below the sub surface wave base where the slope exceeds about 10 degrees.

2. Acknowledgments

This work was funded by the Canadian Department of Fisheries and Oceans. It was developed from preliminary studies on nearshore fish habitat by William G. Franzin at the Freshwater Institute in Winnipeg. W. G. Franzin participated in field activites in five of the study lakes. Jeff Dunham assisted in the collection of field data on Lake 226. Everett Fee and Ken Mills provided Figures of ELA and northwest Ontario. Greg McCullough provided hard copy bathymetric maps of Lake 226 and data on previous lake levels on Lake 226. Mark Shymanski of CEOS, and Prairie Farm Rehabilitation Administration, offered assistance in early concepts of AutoCAD, C programming language, and instruction to encode topology into the substrate polygons using ArcInfo GIS. Use of ArcView and ArcInfo GIS software was provided by Andreas Blouw and the Environmental Assessment Review Group of the Fish Habitat Management Division at the Freshwater Institute.

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5. Introduction

The nearshore areas of freshwater lakes are the complex products of geomorphology and the redistribution of the native materials by the hydraulic forces of water. Lacustrine nearshore areas form habitats that are critical to the survival of many species of plants, invertebrates and fishes, including younger life stages of important sport and commercial fish. As such, this narrow band of habitats is important in both the biodiversity and metabolism of lake ecosystems. Biodiversity of the nearshore area is probably the most sensitive indicator of environmental change within lakes from anthropogenic activities because the margins of lakes and the terrestrial environment are contiguous. This proximity means that the nearshore areas of lakes are first to exhibit degradative effects of physical habitat change from, for example, local activities like shoreline development, or from changes which are much more widespread, such as water level regulation.

The substrates of the nearshore area (NSA) in temperate lakes are known to have the highest rates of primary and secondary production, the highest diversity, biomass, and turnover of benthos, macrophytes, and zoobenthic biodiversity (Winberg 1972, Rasmussen 1988, Wetzel 1983). Most lacustrine fish species spawn on the substrates of the nearshore area. Despite the importance of nearshore substrates to freshwater ecosystem structure and function, this complex interface region between the terrestrial drainage basin and the offshore zone of lakes remains the least understood lake ecosystem component (Wetzel 1983) due to its spatial, temporal, and three dimensional heterogeneity (Rasmussen 1988). This gap in our understanding of nearshore biological production is not surprising when the diverse myriad of physical processes which influence the form of substrates are considered.

Substrate materials on lake shorelines are redistributed horizontally and vertically by size into areas of erosion, transport, and deposition by hydraulic sheer stress combined with gravity and slope. The composition of substrates within theses areas is highly variable. In the hydraulically active zone of erosion, sorting of materials by size occurs which produces material gradients. The redistribution of fine materials occurs both along shore and in offshore directions. Deposition occurs in energetically quiescent areas like secluded back bays of low slope or in deeper areas below the depth that surface waves can mix. Although many of the variables which influence substrate redistribution in lakes have been studied extensively using large scale point data (see Hakanson and Jansson 1983, Rasmussen 1988, Rowan et al. 1992), the spatial aspects of surficial material composition and redistribution in the NSA of lakes remains unexplored.

Physical habitat management has become a focus of many fisheries management strategies (Macleod 1992). Canadian government policy and the contention of many managers of fisheries is that physical habitats are directly or indirectly responsible for fish production, and that management of fish populations in a period of declining fish habitat quality is futile and not cost effective. Nearshore habitat management and protection has become a higher priority in recent years (Macleod et al. 1992) because fisheries managers recognize that some species of fish spend their entire lives in NSA's, and that large scale and incremental loss of nearshore habitat can reduce natural fish production (Macleod et al. 1993).

In an effort to improve on or sustain current levels of fish production, the Government of Canada promulgated a fish habitat policy aimed at improving the management of fish habitat. Underpinning such policy is the premise that sustainable development could take place within the "no net loss" concept. However, the implementation of such policy has had limited application because the relationships between physical habitat and fish production have yet to be learned. Indeed, the concept of productive capacity is based on the general recognition that certain areas of lake basins offer physical features or hydraulic conditions essential to fish production. However, the habitat management policies were simpler to develop than was the scientific data which should have been the foundation for the policy. At present, what constitutes a loss or gain of habitat is not clear because methods are lacking to measure productive capacity

(Macleod et al. 1993). Only recently have protocols been developed for the implementation of no net loss policy (e.g. Minns et al. 1995). While such precursor frameworks provide methods for the implementation of no net loss policy, some rigorous assumptions are required regarding physical habitat/productive capacity relationships which are not known. The implementation of this policy, through Environmental Impact Assessments, therefore must continue to operate on a case by case basis.

Recent advances in digital computing technology, namely Computer Aided Design (CAD) and Geographic Information Systems (GIS), have provided a means for reconstructing and storing detailed spatial inventories on desktop computers. These systems offer an analytical functionality that previously was not possible. Habitat managers are beginning to develop methods and systems for classification of NSA's - now that a technological infrastructure exists that can support such goals. GIS offers strong modeling capability which has been under utilized in Environmental Assessment (Joao and Fonseca 1996).

Information on the spatial distribution of aquatic habitats in the NSA of lakes is lacking (Macleod et al. 92). The understanding of the relationships between fish and the many habitat types of the NSA has been slow to develop because methods used to gather data are few and unstandardized. Most techniques are designed only to inventory shoreline habitat and do not delineate habitat boundaries adequately. Such linear habitat maps do not indicate the cause and effect relationships which were formative in the development and maintenance of the physical habitat. To better understand NSA process, therefore, methods for habitat inventory should be designed to accommodate and show the effects of wave and slope process on habitat form.

Large amounts of spatial data collected over many spatial scales will be needed to develop fish habitat models. The interpretation and management of such data requires standardization and development of classification structures which collate and organize spatial data. While the uses for habitat data are many, all studies must align methods to suit objectives. Recently, Busch and Sly (1992) developed an Aquatic Habitat Classification System (AHC) for lakes to provide a common framework for classification systems. Although the AHC is available, the lack of NSA mapping techniques has prevented databases from being developed to demonstrate the interpretation and management of mapped habitat information.

Multi-lake GIS databases are a necessary first step in the development of methods for inventory/modeling of lake dynamics so fish and habitat relationships can be elucidated. The integration of data on substrate, slope, wave energy, and depth, in a GIS can provide insight into the distribution of physical processes which form and maintain the quality of habitats. Process models in a GIS can be used as a tool by EIA panels to predict in general the form of habitats in lakes that are too large, remote, or numerous to assess using manual techniques.

The purpose of this study was to improve the understanding of the distribution of habitat types in the NSA, the dynamics of sediment redistribution, and the management and interpretation of spatial habitat data. To do this, a GIS database containing detailed substrate, slope, and depth information was compiled for six small lakes in the Precambrian Shield. This information was produced using the proposed nearshore classification system (NSCS). The NSCS data appends to the hierarchical Aquatic Habitat Classification System (AHC of Busch and Sly 1992) which does not accommodate detailed data. Two approaches were used to describe and compare the habitat structure in the study lakes: 1) The detailed NSCS data classes located in the lowest levels of the AHC are summed for each lake and the dominant classes are described. 2) the NSCS data are aggregated into more general classes found near the highest levels of the AHC and compared among basins. I show that data archived in low levels of the AHC are best suited to site specific inventory, and that the aggregation of detailed data into more general classes can allow the habitats for entire lakes to be compared directly. However, pooled habitat characteristics lose the distribution and scale features that are vital in habitat assessments. In order to perform inter-lake comparisons of habitat that retain these qualities, another classification technique is proposed which resides at about the middle of the AHC at a moderate level of detail.

To demonstrate the application of GIS in modeling lake dynamics the sixth lake in this study, Experimental Lake 226, was used as a case study. To estimate wave properties custom GIS fetch distance programs were constructed. The processes of erosion and transport due to surface wave action and slope were compared to the detailed substrate NSCS map using thematic maps of slope and fetch distance.

Thesis Structure

This document follows the format of standard scientific papers. In each major section that follows the three main areas of research are separated into three parts: 1) physical habitat classification and mapping, 2) wave energy mapping, and 3) the integration of these two in the form of GIS process models.

6. Literature Review

Organization

Part 1 of this chapter introduces concepts regarding habitat and the general character of nearshore area geomorphology, and hydrodynamics, and how these processes can be perceived at 3 spatial scales in which they operate. Part 2 reviews lake classification and classification systems. Part 3 reviews recent literature on the study of bottom dynamics of lakes, and the methods for modeling wave energy.

6.1 What is habitat?

Although a widely used term, habitat can mean many things to many people. For example, wildlife management has been practiced for many decades, and probably encountered many of the problems that now face the relatively young discipline of aquatic habitat management. At the Wildlife 2000 workshop Salwasser (1986) stated: "It is unsettling that 50 years into the business of wildlife management, people still argue about what habitat is". From this it is clear that without general consensus on such principles, it is unquestionably difficult to aggregate or separate the components of habitat for a full understanding of their functional relationships.

6.1.1 What is a Fish Habitat?

NSA's are composed of physical features and hydraulic conditions and water quality to which fish species have adapted over long periods of time. The definition of fish habitat must encompass the variety of aquatic systems and their structural elements and conditions. Consequently, the Canadian Fisheries Act defines fish habitat as:

> "Spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life

processes." (Canadian Fisheries Act, Section 34(1), Department of Fisheries and Oceans, 1986).

This definition contends that not only are the physical and hydraulic characteristics of aquatic systems are included as fish habitat, but the quality of the waters and the "total surroundings" in which plants, invertebrates, and vertebrates, interact to produce fish life.

Although such broad and encompassing definitions are suitable for development of policy, this generality poses problems for the definition of habitats for individual species, or groups of species. What may be critical habitat to one species is not necessarily vital for another. Developers of Environmental Impact Assessments therefore are faced with the task of identifying all the species expected to be affected by development, and also to understand what integration of aquatic habitat variables are relevant to maintain the level of biological production for that species. This level of information escapes generality. It requires detailed knowledge about the form and function of the aquatic system, and how the different species inhabiting that system partition resources throughout their ontological development.

6.1.2 What is Physical Habitat?

Physical habitat is a subset of fish habitat characteristics, and is defined here as the structural or hydraulic surroundings from which measurements can be obtained directly. This includes lake basin morphology, substrates, macrophytes, woody debris, and lake hydrodynamics. As lake substrates comprise the vast majority of physical structure in the lacustrine NSA, the structure and distribution of substrates and the formative lake hydrodynamics are the focus of physical habitat assessment here.

6.2 The Nearshore Substrates of Lakes

The vast majority of lakes in Canada are found in the central and eastern regions of the country in the Precambrian Shield. In this region, past glacial movements have scoured away surficial deposits down to bedrock, leaving countless water filled depressions amongst abundant exposed bedrock and heterogeneously distributed glacial deposits like till, and boulder lag. Consequently, the nearshore areas of lakes are a spatially diverse and structurally complex interface which form rings of surficial habitat located between land and open water. This rim of substrate which surrounds the perimeter of a lake basin is hydraulically active and offers diverse physical habitats through a suite of slope and substrate material combinations along the lake shore.

The spatial extent, composition, and shape of this ring of habitat can vary from expansive low gradient areas with fine substrate materials and smooth crescent shaped shorelines, to cusped shorelines which have variable gradients of slope and substrate material sizes, to areas which are narrow and of high slope with large materials or bedrock.

The types of substrates found in nearshore areas can vary from predominantly mineral to organic and have a heterogeneous or homogeneous composition. The surficial materials in Shield lakes are mostly geological materials (e.g. boulder, gravel, sand), bedrock, colloidal materials like clays and silt), and dead organic materials (e.g. vegetation), derived from either autochthonous (within lake) or allochthonous (outside lake) sources.

The colloidal materials in lake basins can originate from pockets of material deposited from past glacial events, from processes during recession of glacial lakes, or can be transported to the lake from tributaries. These materials tend to be deposited in areas of lakes where rivers inflow and wave energy is insufficient to mobilize the bottom sediments.

The dead organic materials which have been in the shallow areas of basins a relatively short time are known as detritus. Much of the detrital materials, like leaf litter, remains in areas of the lake which are shallow and energetically quiescent, or in the shallows in most areas of lakes that are not large enough to produce wave energy sufficient to break down the organic material to facilitate redistribution. Organic materials that have been present in the basin for a longer period have been reworked by wave action to a very small and flocculent particle size, and are referred to as flocc. (G. McCullough Department of Fisheries and Oceans, pers comm.),. Flocc. usually is re-suspended in the water column in nearshore areas by wave action, or at a much slower rate by microbial decomposition (Hakansson 1983). Much of the resuspended flocc. subsequently is deposited into deeper areas of the profundal zone (i.e. zone of perennial deposition) where wave action can not mobilize bottom materials.

Substrate diversity usually is highest nearshore due to the effects of wave energy on erosion and sorting of lake bed materials. Gradients of sediment types and sizes occur with increasing depth due to the constant refocusing of sediments to the lake centre by wave and slope processes.

The specific composition of a substrate is dependent on a complex set of physical processes which operate at several spatial and temporal scales. To understand the spatial heterogeneity of substrate form and the processes which produce and maintain these characteristics, the fundamental elements of wave form and shoreline process will be reviewed. Subsequently, the factors which control the form, availability, and the maintenance of nearshore area habitat over time are reviewed at three spatial scales. The first is a basin-wide scale, the second is at increased resolution where the lake is divided into contiguous sections, referred to here as reaches, and the third contains specific information at a site scale.

6.3 Hydrodynamics

Hydrodynamics are important in the study of lake processes, and surface waves are important physical modifiers of nearshore substrates Wetzel (1983). Wave action in shallow water areas releases kinetic energy, both at the surface and at depth, which causes shoreline erosion (Reading 1986), sorts substrate materials by size (Busch and Sly 1992), and re-suspends and deposits reworked materials into more energetically quiescent areas of the lake (Hakanson 1981). An understanding of the physical properties of waves and the variables which control wave form is essential, therefore, to fully appreciate the physical processes that affect the development and maintenance of nearshore substrates.

Detailed understanding of hydrodynamics in lakes is a complex problem, one that is ultimately a problem of fluid mechanics, a detailed discussion of which is well beyond the scope of this work. The relationships that describe surface wave form in lakes, however, are well understood.

The form of surface waves has been studied since the late 1880's (Hutchinson 1957). Surface waves are formed by the transfer of energy from the wind to the water. The shear stress created by the wind breaks the surface tension of the water and sets the surface into oscillation. Initially, capillary waves, or ripples, develop on the water surface. As the wind blows over a single ripple, an eddy of low atmospheric pressure is produced on the lee side. The effect of this eddy is to deflect the main wind momentarily upward. Beyond this disturbance the wind will fall with a downward component of momentum. This increases the atmospheric pressure on the side of the next wave exposed to the wind. As a result, the water will be rising where the pressure is falling, and falling where the air pressure is rising. This causes the wave to grow in height as long as the wave velocity is less than that of the wind.

6.3.1 Surface Wave Development and Form

A wave traveling across the water surface not only sets the surface into oscillation, but also causes oscillatory and wave-drift currents (Elliot 1986). Oscillatory water movements show a rotation of water molecules which attenuate with increasing depth (Figure 1). At the surface the diameter of the orbital path is equivalent to the height of the wave. The diameter of the orbital paths decreases with increasing depth until there is no motion, which is about one-half the wavelength (Hutchinson 1957). Some movement, however, can occur at a depth equal to the wave length (Selby 1990). The water molecules that travel in these cycloid paths do not travel with the wave, they are only translocated along the orbital path as the surface wave travels.

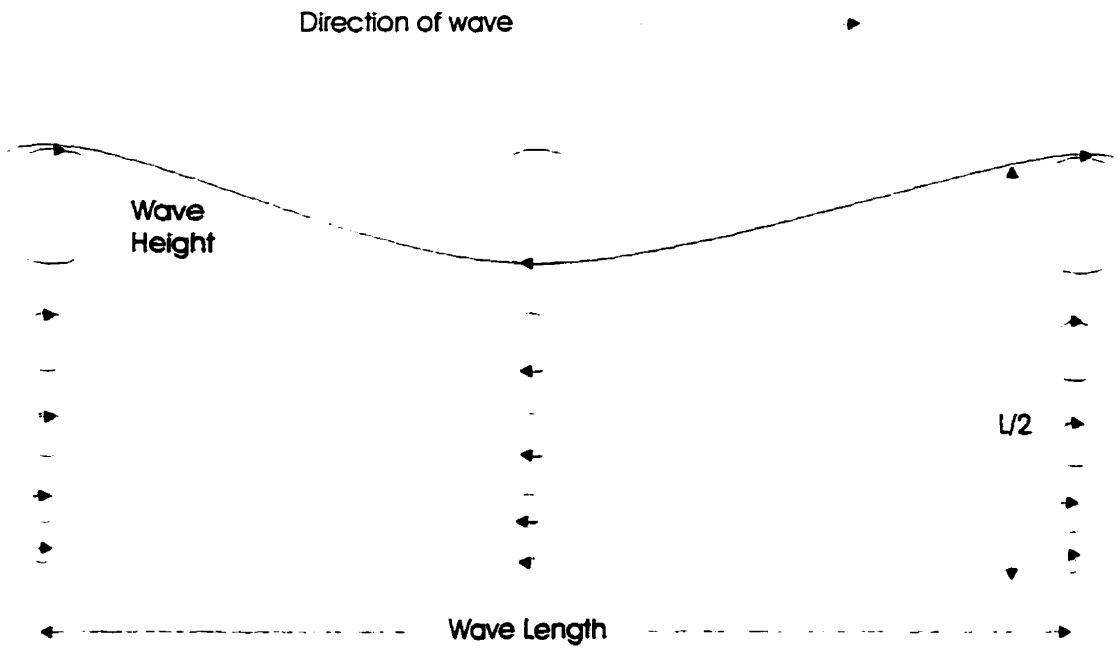


Figure 1. Simplified deep water wave form. The wave length and height determine the depth to the wave base where the sub-surface orbital motion of water molecules ceases. Redrawn from Davis 1985.

Water depth is important in the physical form of surface waves. When a wave contacts the bottom, the orbital movements of the water molecules near the substrate experience friction, which deforms the wave shape and causes it to crest, or collapse. Two types of surface waves can be considered depending on their size relative to water depth; deep water waves and shallow water waves (Davis 1986). Deep water waves occur in areas of lakes where the water depth is greater than one-quarter the wavelength. Deep water waves exhibit a sinusoidal form on the surface because the orbital motion of the water molecules is unaffected by friction on the lake bottom. Deep water waves may become steeper until they reach a height equal to 1/7 the wavelength, where the wave becomes unstable and collapses.

As a shallow water wave moves towards a shoreline the water depth decreases and the drag induced from the bottom causes the orbital motion of the water molecules to elongate into an elliptical form because the base of the wave moves slower than does the crest (Figure 2). This causes the wave height to increase until the wave front becomes too steep for continued stability. At this point, the wave breaks and the wave crest is thrown forward into the shoreline. At the substrate, the elliptical motion is replaced by a straight line to-and-fro motions called wave-drift currents (Selby 1990). From this a unidirectional flow causing directional water transport results (Selby 1990, Wetzel 1983).

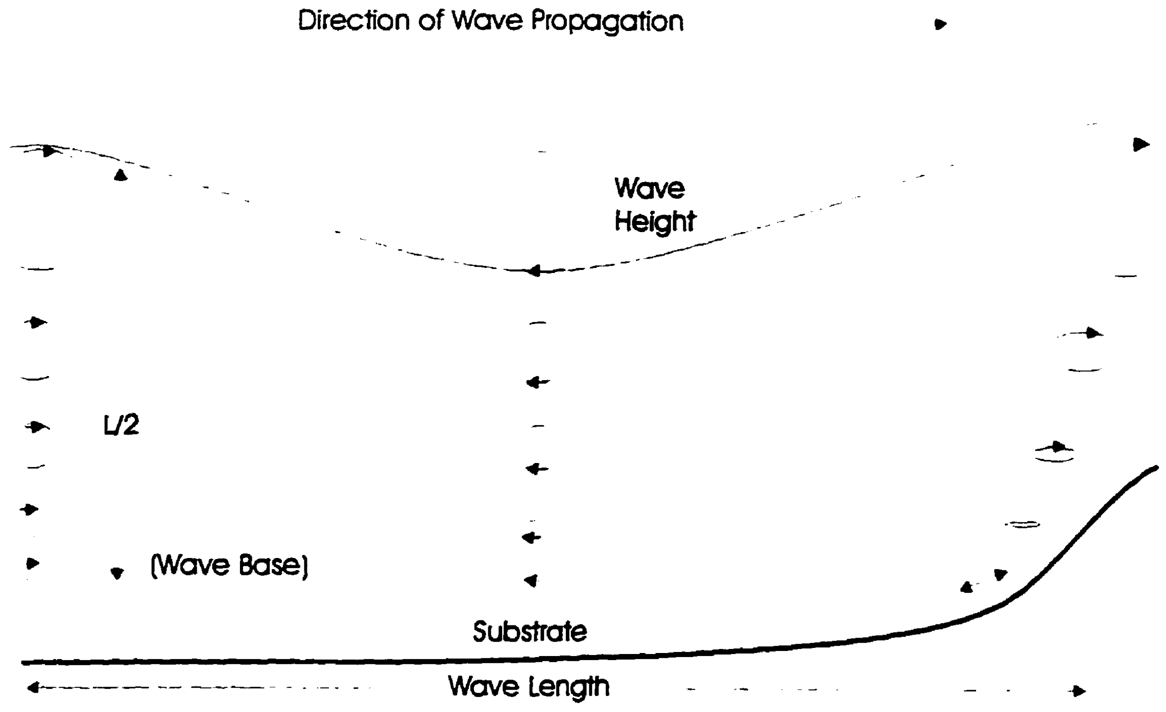


Figure 2. The change in wave form due to drag induced from wave/substrate interaction.

The physical form of waves determines how their kinetic energy is released. The variables which influence the form of waves are complex, but are well understood.

6.3.2 Physical Variables which Influence Surface Wave Form

The height and period of surface waves depend mainly on the wind velocity and duration (Selby 1990), and the shape and size of the basin (Hutchinson 1957). The strength of the wind and the length of time the wind blows is a fundamental control on the amount of energy that is transferred from the wind to the lake. The morphology of the basin controls the orientation of the lake to the predominant wind direction (Hakanson 1977). In small lakes, wave height appears to be nearly independent of the depth. In large lakes, the wave height and length increase with increasing lake depth (Hutchinson 1957). The estimation of wave properties has centered around the measurement of fetch distance, which is defined as the linear distance over which a wind travels uninterrupted by land. The estimation of wave properties has been most accomplished most frequently by using Airy deep water wave theory (Airy 1845).

6.3.3 Estimating Surface Wave Properties

Airy deep water wave theory provides estimates of wave properties including wave length, height, and depth to the sub surface wave base, for sites with an error of < 5% where depth (h) > 0.25 deep water wavelength (L) (Komar 1976). Airy deep water wave theory has been simplified by Rowan et al. (1992) to:

(1) $h > L/4$.

To determine the applicability of deep water wave theory, estimates of wave length are necessary because measurements are unavailable for most lakes. Deep water wavelength is approximately 20 times the wave height (H) in lakes (Wetzel 1983):

(2) $L = 20\ H$

Maximum wave height data also is lacking for most lakes. However, maximum wave height is related to maximum fetch (Wetzel 1983). Maximum deep water wave height (H_{max}, metres) can be estimated by the empirical relationship:

(3) $H_{max} = 0.332F^{0.5}$

where F = maximum fetch (kilometers) (Wetzel 1983). Substituting equation 3 for wave height in equation 2, deep water wavelength is obtained as a function of maximum fetch:

(4) $L = 6.640F^{0.5}$

Substituting equation 4 for wavelength in equation 1, and simplifying, one obtains the limit of applicability of Airy deep water wave theory in terms of site depth (m) and maximum fetch (kilometres):

(5) $h > 1.660F^{0.5}$

Equation 5 indicates the depth to the wave base for waves in water greater than 0.25 the wave length. As the wave progresses towards the shore past this point, the orbital motion of the wave changes due to the friction induced by the bottom and Airy wave theory no longer applies.

6.3.4 Nearshore Wave form

Shallow water waves are commonly described in three groups; they are spilling, plunging, and surging breakers. Each of these types of breaker is associated with a particular nearshore slope. Spilling breakers tend to occur on beaches with very low slopes but have steep waves; plunging waves develop on steeper shorelines above a steeply shoaling bottom; surging usually occurs on shorelines with steep slopes.

The breaking wave sends its turbulent swash up the shoreline slope near the lake margin; the energy from the swash is rapidly dissipated as it collides with materials too heavy to move, and carries smaller material up-slope. In some shorelines like beaches, some water from the swash percolates into the porous shoreline before the remainder of the water then returns to the lake as backwash. The backwash often has a smaller volume than the swash. For waves of a particular height and steepness, the work done by the swash/backwash (i.e. the sorting of geological shoreline materials by size as an inverse function of depth) adjusts the beach slope until it is in equilibrium with the forces acting on it (Selby 1990).

The physical form of shallow water surface waves are not well understood due to the heterogeneity of nearshore slopes and materials which modify wave form.

6.4 Processes of Shoreline Development:

Because waves often meet shorelines at an oblique angle, the swash ascends the beach along the same axis and moves shoreline materials with it. The retreat of the backwash with gravity then causes the materials to move down slope towards the water line. Hence, a net transport of materials, called beach drift (Strahler and Strahler 1978), can occur along the shore in a zig-zag fashion.

Longshore drift (Strahler and Strahler 1978) is another mechanism for transport of materials parallel to the shoreline. Unlike beach drift, longshore drift occurs only during strong winds. The net transport of water which slowly moves towards the beach raises the water level. As the lake's surface is set into oscillation, the excess water on the shoreline will move along the path of least resistance, along the shore away from the direction of source winds. Both beach and longshore drift move materials in the same direction for a given wind angle. The combined effect of both processes is called littoral drift and produces shoreline forms, including spits and tombolos.

6.4.1 Wave Refraction - the interception of waves by shorelines

A wave which moves towards a shoreline with prominent headlands and bays first experiences friction from the bottom at depth in front of the headland. This slows the velocity of that part of the wave. As a result, the shape of the wave front becomes refracted because most of the same wave crest is in front of the beach and continues to travel at the speed of a deep water wave. Thus, shape of the wave front changes from parallel to the shore in deep water, to a curved shape which is concentrated on the headland (Figure 3).

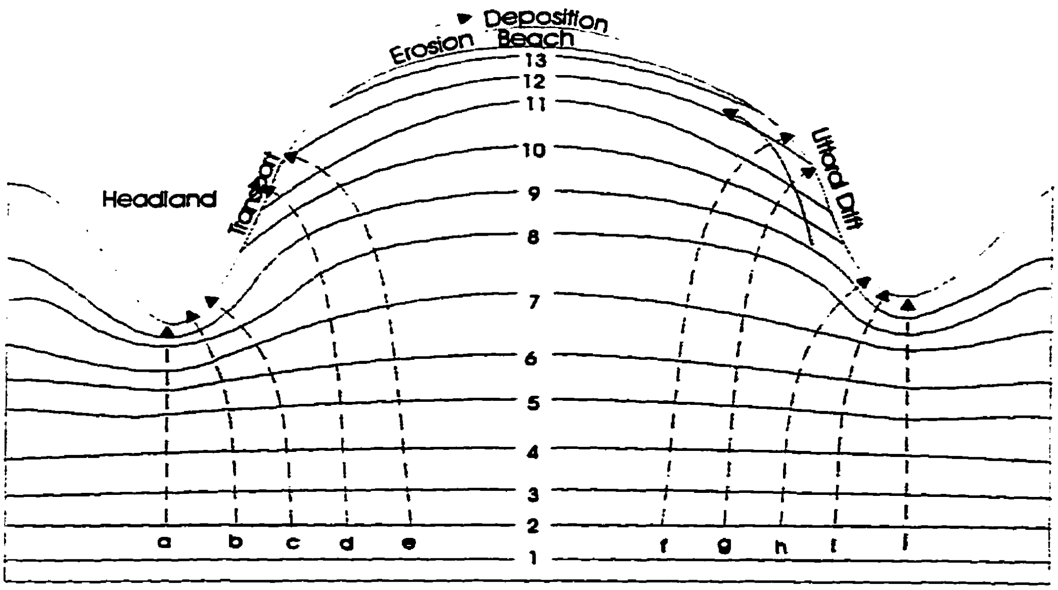


Figure 3. Wave refraction (dashed lines, a-j) of wave crests (numbered 1-13) on an embayed shoreline, and the resultant erosion-transport-deposition of materials from littoral drift. Modified from Strahler and Strahler, 1978.

The change in the form of a wave and how the wave interacts with the bottom, or the shoreline, changes the manner in which the wave expends kinetic energy. The distribution of wave energy on an embayed shoreline changes from a concentrated high energy-erosive wave at the headland, to a much weaker and dispersed deposition wave in the bay. The redistribution of materials in embayed nearshore areas due to this gradient of wave energy is known as littoral drift (Strahler and Strahler 1978). Littoral drift moves shoreline materials mostly in two directions: offshore, and along the shore.

The decrease of hydraulic energy in offshore and longshore directions forces gradients of response in the form of substrate material size distribution. Typically, headlands have the highest nearshore slope and largest substrate materials of the embayment. As the bed materials move, an equilibrium is established between material size, the incident wave energy, and the resultant slope. Material size and slope decrease in the direction towards the centre of the embayment.

6.4.2 Slope of NSA's: the effects of geomorphology:

Bottom slope is an important factor in determining the size of materials on the lake bed (Hakanson and Jansson 1983), and also for distribution of many sedentary fish species. Slope can explain the presence of sediments in offshore areas which are coarser than expected (Rowan et al. 1992), is central to the distribution of macrophytes (Jensen et al. 1992), and is also an important predictor of littoral zoobenthic biomass (Rasmussen and Kalff 1987, Rasmussen 1988). Duarte and Kalff (1986) found less macrophyte biomass on slopes greater than 2.2- 5.3 % and hypothesized that the distribution of macrophytes is due to substrate type.

The specific composition of a substrate is determined by an integration of factors including, material availability, geomorphology, slope, wave energy, and the substrate's three dimensional characteristics. The separation of these variables into cause and effect is difficult due to the erratic nature of material availability, and the cross-linked effects of wave energy, substrate form, and resultant slope.

The slope of NSA substrates is a consequence of one of two mechanisms: the first, in gradational environments, an equilibrium is established between sorted bed materials and the hydraulic energy from waves (Selby 1990). Geomorphology is another slope factor (Busch and Sly 1992), that is evident usually in NSA's which are not gradational. The specific form of reaches of immobile shoreline may be due to ancient processes like lithogenisis, glacial scouring and/or deposition, or from talus deposits, which are commonly found below slopes of steep gradient.

6.5 Hydraulic Habitats

The distribution and magnitude of hydraulic energy incident on a substrate is dependent on the available wave energy, the slope of the bottom, and the type and size of materials which form the substrate (Selby 1990). Gradients of wave energy or slope can redistribute materials into patterns by size, but this applies only to the materials which are transportable. The availability of materials larger than can be reworked by the lake can increase the diversity of material sizes in gradational environments. The diversity of materials which comprise a substrate also will affect the magnitude and distribution of hydraulic energy at the water/substrate interface.

The distribution of wave energy incident on a substrate will be more uniform on smooth planar substrates than on others with materials of various sizes. The largest materials on the lake bed at that site will dampen the hydraulic sheer stress from waves higher in the water column. Consequently, a substrate with a large range in material sizes can offer interstitial spaces which have hydraulic conditions which may differ considerably from those of the overlying waters.

Thus physical forcing variables like geomorphology and glacial action control the availability, size, and distribution of materials. The three dimensional characteristics of nearshore environments and how they vary spatially result from the interaction of regional geomorphology, hydraulic energy, and slope.

6.6 Nearshore Area Structure and Shoreline Processes at Three Spatial Scales

Basin Scale

The geomorphology of a watershed sets the large scale framework which determines the availability and distribution of the parent material. In much of the Precambrian Shield the parent material is insoluble bedrock.

The lakes of the Precambrian Shield are called glacial lakes because their shapes are controlled mostly from glacial action on the landscape. The glacial scouring of overburden materials (e.g. sand, gravel, boulder) from the bedrock, and the subsequent deposition of that material in the form of moraines, eskers, and other localized forms determines the distribution and availability of bedrock and geological materials in an area. Consequently, the distribution of insoluble parent material and its shape strongly control the size and shape of lakes in the Precambrian Shield.

The lake size and shape set limits to the maximum amount of energy produced by wind on the lake and consequently the waves erode and sort the bed materials on non-bedrock shorelines. This maximum energy limit determines what size of materials can form a stable shoreline, and will vary along the perimeter of the lake due to variable fetch. Unstable shorelines will develop new shapes and profiles depending on the availability of geological materials and incident energy from surface waves.

Reach Scale

At a within-lake scale, the shape of the parent geomorphology and the distribution of material and wave energy segment the lake's shoreline into sections, here called reaches. A reach is a scale independent shoreline feature based on the parent geomorphology, overburden material availability, and wave energy. As the shape of the shoreline is the product of these integrated processes, the shoreline configuration is the primary means for segmenting the lake shore into sections. For example, a reach can be tens of kilometres in length for a homogenous shoreline composed of boulder, or small beach with a smooth and crescent shaped shore formed from wave action.

The regional geology at the basin scale interrupts shorelines laden with overburden materials. The reaches of shoreline between such parent features, and their formative wave and slope processes also become compartmentalized. This physical segmentation changes the scale at which the processes which form and maintain substrates operate. The reworking of overburden materials between parent features by waves affects the shape of the lake's shoreline and profile. The form of reach scale aquatic habitats, then, are controlled by the relative dominance of bedrock and overburden materials, and the redistribution of materials by wave and slope processes.

Lake form also determines how a lake's waves develop and controls how the energy provided by waves is expended along its shorelines to form and maintain substrate by sorting and cleansing bed materials. Wave energy incident on a shoreline reach depends on the size of the wave, and the orientation of the shoreline to the direction of wave propagation.

Site Scale

The form of substrates at a site scale is dependent on the physical variables at the basin and reach scale. The materials on the lake bed may grade in size due to redistribution by wave energy with a resultant moderate slope, or the remaining material is not transportable by existing energy and the angle of repose is stable. Other non-gradational substrates in areas of high slope are due to parent geomorphology. Secluded areas may have depositional characteristics due to lack of wave energy. The specific three dimensional form and pattern of substrates develop from a complex interaction of variables which operate at all three spatial scales and from short to long temporal scales.

Part 1:

6.7 Lake Classification and Classification Taxonomies

Habitat description and classification are common tasks of most ecological inventories. Habitat classification provides a convenient mechanism for reducing the complexity of habitat variables to a small number of more homogenous groups. This reductionist perspective enables understanding of generalized relationships from detailed spatial data.

Classification systems provide standardized frameworks that contribute to the systematic analysis and more effective and sustainable management of habitat resources. They are required for the direct and equitable comparison of data gathered from geographically disparate locations. Without such systems, classifications are influenced by their intended use and the classifier's background, which often limits their usefulness to others. The structure of a classification system typically consists of pre-defined numbers and types of categories for use in classification. Because data can be collected at many different scales of resolution, classification taxonomies provide an ordered framework for the compiling of classified data.

6.7.1 Lake Habitat Classification

Methods for habitat classification in lakes fall far behind those for terrestrial and riverine habitats counterparts. Most lake classifications have been developed to indicate lake trophic status or productivity.

A review of lake classification was presented by Leach and Herron (1993). Lakes have been classified by a host of variables like, shape, location, and by properties that are physical, chemical, and optical, among a suite of others. Of the 32 categories reviewed, 24 were trophic classifications.

Remote sensing has been used for lake classification to limit manual work. Boland (1976), Boland and Blackwell (1977) used Multispectral Scanner Indices, acquired from LANDSAT and aerial platforms, to estimate the trophic status of lakes. As is clear however, most methods classify lake trophic status, not the physical structure of habitats within lakes which is the focus here.

Most substrate mapping projects have been produced from a limited number of point stations in only the offshore areas of large lakes, like Lake Winnipeg (Brunskill and Graham 1979).

Remote sensing studies have played a valuable role in some aquatic habitat applications, but the use the use of remote sensing methods has lead to a disproportionate emphasis of study to entities that are directly identifiable from aerial platforms, like floating and emergent macrophytes (Jensen et al. 1992, Marshall 1993, Cowardin et al. 1979, Hua Runkui and Li Yuquin 1992).

Remote sensing of substrate types has been assessed using multi-spectral scanner data by Macleod (1992), Lyon et al. (1979), and Mellor (1981) to detect general sediment types. However, the limitation of remote sensing is the high sensitivity to water quality parameters, like water turbidity. Other limitations include an image resolution which is only sufficient for general mapping, and inter-lake comparisons of substrate data from satellite imagery or airborne platforms rarely are equitable because clearer lakes can be sensed to greater depths than are other more turbid lakes. The use of present remote sensing methods provides a level of detail more suitable for shallow water inventory; they do not provide for learning the form and function of physical habitat through the production of detailed basin maps (which must often sample areas below the photic zone) to capture the effects of lake process. Thus, because substrates rarely are discerned at depth from remote platforms, and are spatially heterogeneous, methods for mapping NSA substrates are lacking.

Three of the more widely used and recent physical classifications used for aquatic habitat assessment are the evaluation system used for the wetlands of Ontario (OMNR/CWS 1984), the classification of wetlands and deep water habitats of the U.S (Cowardin et al. 1979), and the proposed system for great lakes habitat assessment (Busch and Sly 1992 ; see next section).

These systems have been developed for different purposes but all have adopted hierarchical structures. Hierarchical classifications allow aggregation and disaggregation of data, and can provide the level of detail needed at several geographic scales (McKee et al. 1992). The system used by the Ontario Ministry of Natural Resources (OMNR) requires the entire systems information to be complete and is purpose specific, which limits its value in other applications. The method used by Busch and Sly (1992) is superior because their system also uses nested biogeographic zones as a basis for information collation. Jaworski and Raphael (1979) developed a geomorphic wetland habitat classification on the Laurentian Great Lakes, but the structural context was large and was limited to morphological description only.

Habitat mapping was conducted at the Experimental Lakes Area, northwest Ontario, in 1991 and 1992 by Franzin (unpublished data, Department of Fisheries and Oceans, Freshwater Institute, Wpg. MB). The nominal classification system for material size was based on existing stream substrate assessment classifications. The field method involved manual measurement and assessment of the shoreline materials. On site generalization of the often heterogeneous shoreline materials was reduced to one homogeneous class.

Using Franzin's technique, qualitative notes and alongshore measurements were gathered on shoreline materials. These data adequately assessed the patterns of substrate materials along the shoreline, and allowed the contribution of each material class to be compared relative to the total perimeter of the lake. However, qualitative notes are difficult to collect systematically and as a result gaps of information occurred. A problem with such methods is that the simplification of an area of structurally heterogeneous materials to a single nominal class can over generalize the habitat structure. This method captured only the readily visible shoreline materials which are intermittently exposed during drier hydrologic cycles, and are probably less important biologically.

Saskatchewan Environment and Resources Management conducted a spatial fish habitat survey which extended to 2m depth on Emma Lake (Liaw 1995). Using vector GIS the inventory included collection of macrophyte information with site surveys. Information on substrate and shoreline types and slope also were collected at selected sites. For the entire lakes perimeter, data was gathered at 5 points at 0.5m depth intervals to the 2.0 m contour. The sampling frequency along the shoreline length was variable.

Macleod et al. (1992) conducted a comparison of manual shoreline survey techniques and coincident airborne spectral sensors for the Bay of Quinte area, Lake Ontario, to learn the applicability of remote sensing methods to aquatic habitat inventory. Manual substrate classification accommodated up to two material types within substrate areas. Substrate classes included muck, silt, gravel, cobble, boulders. The highest correspondence was found between vegetation in both data sets; most areas classified as vegetation in the imagery were coincident with soft bottom types collected from the field data.

Fish habitat GIS models have been developed as a tool to assess pre-and post development change in the Great Lakes (Minns et al. 1995). In the development of this protocol to assess compliance to Government policy regarding the "no net loss" of habitat, their initial implementation using SPANS GIS integrated substrate, macrophyte, and wave energy maps to assess changes in habitat due to shoreline development., The development of an offshore structure in the

Hamilton Harbor area of. Lake Ontario decreased wave energy in the area such that a 43% increase in macrophyte cover would occur, and also quantified losses of substrate types due to development.

Summary

The literature available regarding the use of GIS for fish habitat assessment is limited compared to the use of GIS in other disciplines. This is more a function of the length of time GIS has been widely available than the applicability of GIS to assess fish habitat. GIS fish habitat/lake dynamic models are early in development; most work is still being conducted at the inventory level. Most of this research is reported in government reports and scientific symposia which are not widely available. The use of GIS for fish habitat modeling is rare, which also indicates the youth of GIS as a fisheries management tool.

All studies cited here have had a diversity of objectives and scales of data resolution. To standardize and organize the collation of heterogeneous habitat data, Busch and Sly (1992) developed an aquatic habitat classification system for lakes.

6.7.2 The Aquatic Habitat Classification System (AHC) for Lakes

A symposium on the Classification and Inventory of Great Lakes Aquatic Habitats (CIGLAH) was held February 1988 at Barrie, Ontario, to promote the development of an aquatic habitat classification techniques for lakes. A goal of CIGLAH was to provide an AHC system for both fishery and water quality agencies for management and public discussions. The symposium was published (Busch and Sly 1992) and provided a review which addressed the problems and direction of lake aquatic habitat classification. The thrust of the work was directed to describing and organizing the functional relationships performed by various components of aquatic habitat, reviewing existing classification methods, and production of a classification system that provides a framework to standardize information collection. It also applies a hierarchical order to the data which can integrate data collected at different spatial scales but the AHC focused mostly on offshore habitats. Busch and Sly (1992) recognized that information is needed for specific areas of lakes based on critical habitat features.

The hierarchy of the AHC is a five level system consisting of system, sub-system, division, sub-division, and class (Figure 4). Bush and Sly indicate that each level of the hierarchy is related to confining factors, and functions of force and response, to express the structure of habitat. The AHC's hierarchy is tied to spatial and temporal scales of resolution of scale which are otherwise excluded from most classification systems.

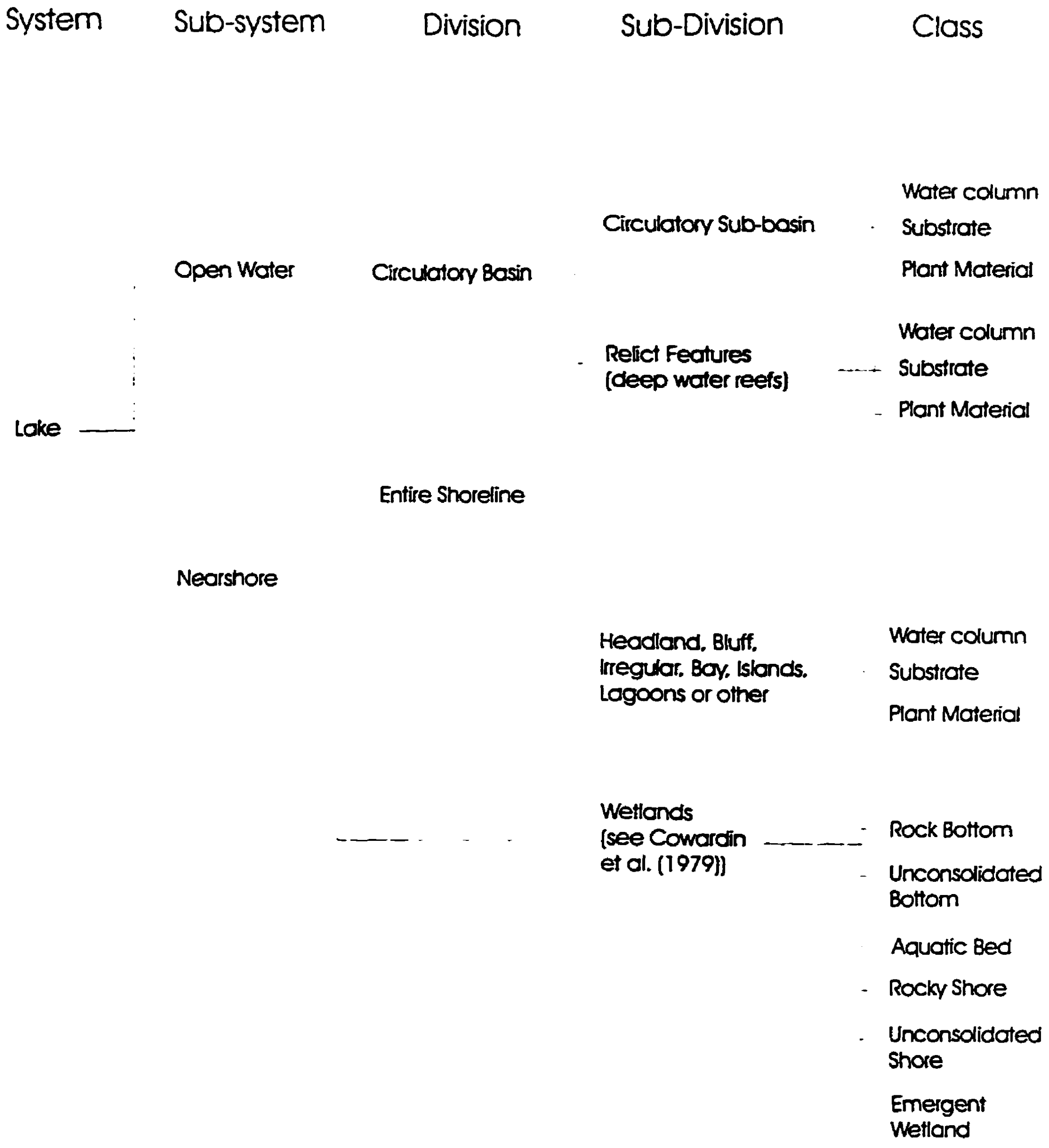


Figure 4.The Aquatic Habitat Classification System for Lakes (Busch and Sly 1992) showing system, sub-system, division and class levels which interfaces with the Wetland Classification System for the United States (Cowardin et al. 1979).

Levels of the AHC

System

The system level of the AHC is determined by the principle characteristics of the system to be classified (e.g. lake).

Sub - System

At the sub-system level, lakes are divided into areas based on the extent to which the shoreline and lake bottom characteristics influence aquatic habitat. Typically, the lake is partitioned into "open water" and "shoreline" or "nearshore" zones, but other classes like littoral and profundal may be designated.

Division and Sub - Division

At the division and sub-division levels, aquatic habitats are classified based on the size and physical complexity of physical features. Sly and Busch (1992) suggest that an extensive length of shoreline that has only minor changes in shape in the form of indentation and headland (point) development, would be classified at the division level. A more convoluted shoreline with prominent indentations and headlands would be classified at the sub-division level.

Class

Information about each major component of the habitat is compiled at the class level, such as water column, substrate, and plant material. Classes provide the most detailed information collated in the AHC system. Sly and Busch (1992) emphasize that each component responds to forcing functions and each component is examined separately in terms of its response.

AHC Functional Relationships:

One of the underlying goals of the CIGLAH was to better understand the interactions among components of habitat and to use this to aid in habitat classification. The AHC's use of expressions, like response function, describes the relationship between one or two or a set of variables which simplifies the interpretation of data. Confining factor, another AHC term, limits the number and types of habitat attributes available, such as for example, lake location on available geology. Forcing functions are variables which produce responses in other variables. Substrate sorting and the critical depth where the offshore zone of perennial deposition begins are just two examples of responses to physical forcing functions, like wave energy.

Hierarchical Scales

To minimize costs and level of effort during data collection, habitat inventories typically adopt a scale of data resolution sufficient to solve project objectives. Consequently, studies with different objectives probably would use data of different resolution. Bush and Sly describe that scale usually imposes a temporal stability to the habitat data where large scale but low resolution data (type "L") are stable over longer periods than are small scale and high resolution (site specific, type "S") data. Watershed scale geology, a type L form of data, and detrital input, type S, to nearshore areas are two examples which show that some forms of data have a spatial and temporal stability which are inherently more noisy than are others.

Type S data are essential tools for site specific habitat management. Detailed data can be used to determine availability of habitat, or net gains of habitat. Type

L data more commonly are used for regional planning. Although type L and S data can be very different, they are complementary.

The use of AHC data is not limited to a level by level analysis. Data from different levels of the hierarchy can be hybridized. For example, the summation of habitat from several sites at the AHC class level can be used to determine total habitat availability at the system level. This aggregation of detailed data into lower resolution classes higher in the AHC is known as synthesis. The reverse, where low resolution analyses pass through several stages of data integration, each using data of higher resolution than the previous step, may be used to determine cause and effect. Busch and Sly acknowledge that analysis by reduction is easier than is the corresponding path using synthesis. The latter requires much more data at the onset of the analysis than does reduction. Consequently, analysis by reduction is the method of investigation used most frequently.

It is due to the prevalence of methods adopting analyses by reduction that nearshore aquatic habitat assessment is lacking methods and data. Although the systematic elimination of variables using reduction may be the most efficient, and least costly method of investigation, it is not well suited to learning the dynamics of heterogeneous pattern distributions found in many NSA's of lakes. The inventory of substrates in lakes is clearly a method using synthesis.

The need for a Geographic Information System

The development and implementation of the AHC was seen by Busch and Sly to pose several problems in terms of data complexity; in particular its scale, display, and the integration of data from low and high levels of hierarchy. Habitat inventories, by their very nature, require managment of large volumes of data, and effectively methods to query and displaying the data. The integration of data with different spatial scales also raises issues of data reconstruction at a common scale; each reconstructed layer would have different probabilities for error and for all of these tasks a GIS was seen to offer many advantages over traditional methods.

Part 2:

6.8 On the Bottom Dynamics of Lakes

Many factors govern the distribution of modern lake sediments (Hakanson 1981). These include climate, geography, hydrology, sedimentology, and morphology. Although the spatial patterns of contemporary substrates in lakes are a net result from the interaction of these variables, the diversity of lake types in regards to each of these parameters is so large that it is not only desirable, but is necessary to reduce the number of variables down to those which are of central importance and readily quantifiable in most lakes. From Norrman (1964), Hakanson (1977, 1981), Sly (1978), Busch and Sly (1992) it is clear that wave energy, water depth, substrate type, and slope are the key elements which control the distribution of sediment in lakes.

6.8.1 Sediment Redistribution Models

Many of the models relating the variables central to sediment dynamics have been constructed by L. Hakanson. His initial work on Lake Vanern in Sweden in the late 1970's to delineate the areas of lakes which erode, transport, or deposit sediment has led to detailed studies of littoral process and form by Rasmussen (1988), and Rowan et al. (1992). Hakanson developed two point models to describe lake dynamics. The first, in 1977, illustrated the relationships between a fetch estimate (described below), and water depth, to determine an erosion-transportation- accumulation diagram (Figure 5).

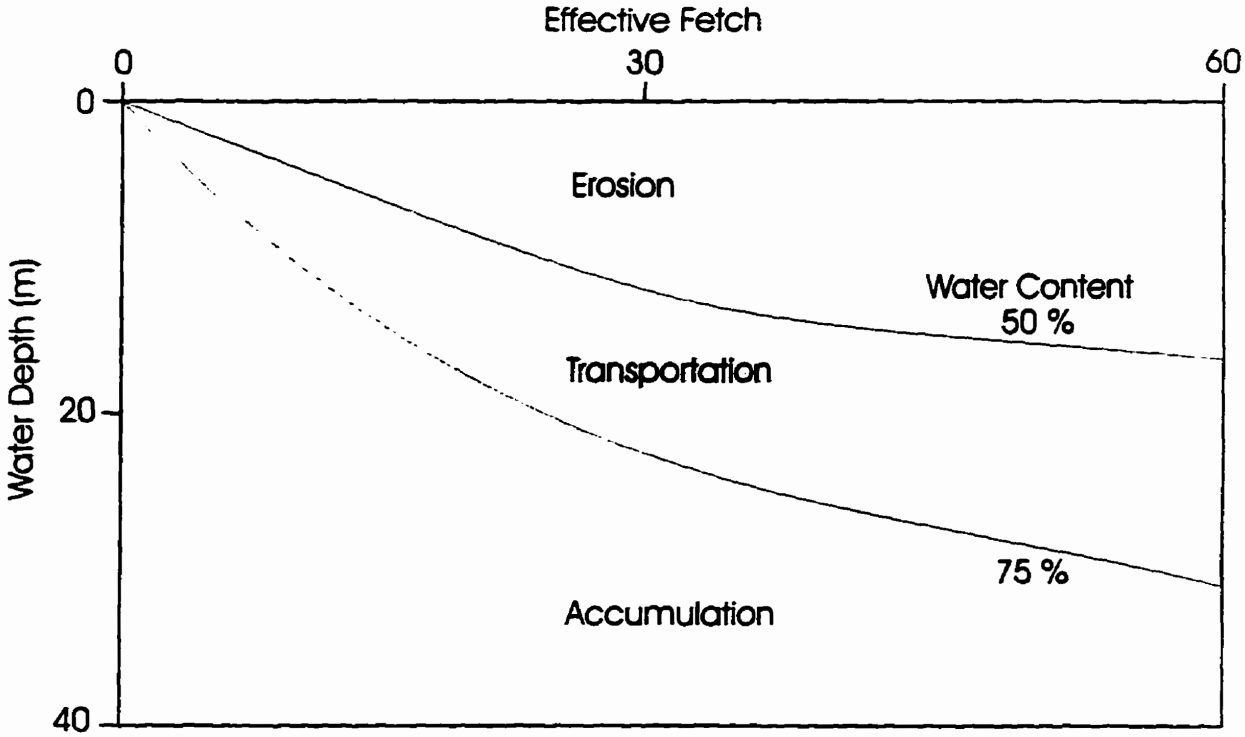
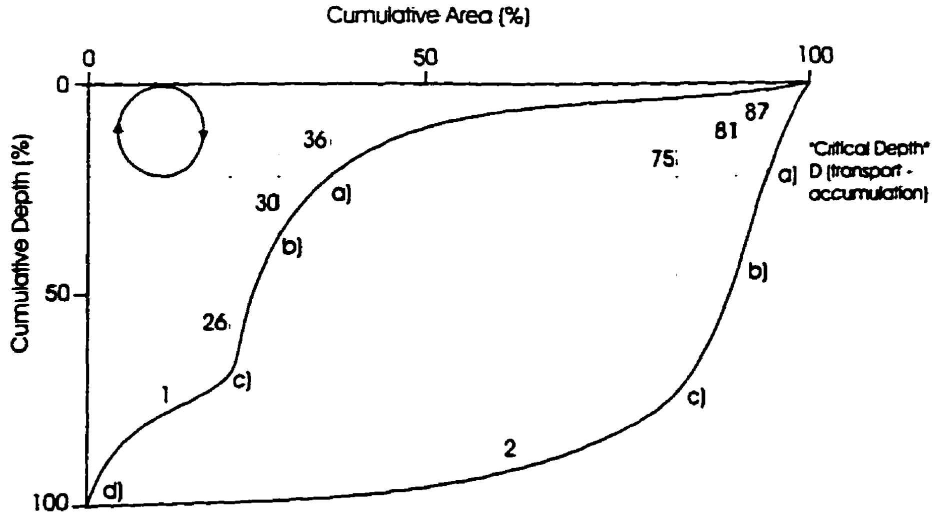


Figure 5. The energy-transport-accumulation diagram (Hakanson 1981).

Hakanson (1981) recognized the spatial implications for this sediment redistribution model, but because this involved extensive manual work, he developed a more simple morphometric, the energy-topography factor. This model provided a means to determine the percentage of a given lake area that is dominated by processes that produce either erosion, transportation, or accumulation from only three easy to obtain morphometric parameters; an energy factor, a slope factor, and a form factor (for details of model see Hakanson 1981 pg. 899).

The components of the model are: 1) a wave energy estimate from which the sub-surface wave base can be estimated, 2) a form factor (related to the lakes hypsographic curve - see Hakanson 1981) which indicates how the basin morphology controls the influences of waves on bottom dynamics, and 3) a slope factor; sediments are rarely stable on slopes > 4-5%. Figure 6 shows this model for a shallow and a deep lake, which have convex and concave hypsographic curves, respectively.



Lake 1

a) Transportation (and erosion): 100-36=64

b) Accumulation : 36-30=6

c) Transportation (slopes > 5%): 30-26=4

d) Accumulation : 26-0=26

A = 32%
E+T = 68%

Lake 2

a) Transportation (and erosion): 100-87=13

b) Accumulation : 87-81=6

c) Transportation (slopes > 5%): 81-75=6

d) Accumulation : 75-0=75

A = 81%
E+T = 19%

Figure 6. Illustration of the impact of the energy factor on the position of the wave base and how the form of the lake and the slope conditions influence the distribution of erosion, transportation, and accumulation zones (Hakanson 1982)

This model describes the area of a basin subject to erosion, transport, or accumulation, but due to the generalized hypsographic data these areas can not be delineated spatially.

6.8.1.1 Estimation of the Mud Deposition Boundary Depth in Lakes

Rowan et al. (1992) derived a point model from the theory of waves and sediment threshold velocities that predicts the upper limit of fine grained sediments in lakes of any size. They describe the mud energy boundary depth (mud EBD) and the mud deposition boundary depth (mud DBD) in lakes as the depth at which the orbital motion of the sub-surface wave base ceases, and the boundary between high-energy erosive environments (coarse-grained non-cohesive sediments) and low energy zones of deposition where fine-grained cohesive sediments accumulate, respectively. Their analysis involved the simplification of wave theory to equations which used only depth and wave height surrogate models of maximum fetch and exposure (described below).

Rowan at al. (1992) also showed that the maximum wave height over-estimates the bottom dynamic conditions, and that "critical" wave heights, i.e. the size of waves which most closely determine sediment patterns, are responsible for sediment distribution. From observed sediment distributions, Rowan et al. (1992) determined the critical wave height to be approximately 77% of the maximum wave height. This implies that contemporary bottom dynamics are controlled not by the large magnitude (infrequent) storm events, but by the less intense storms which occur several times each year. Both of the models produced by Hakanson and Rasmussen required an energy estimate of surface wave activity.

Part 3:

6.9 Models of Fetch Distance

Hakanson (1981) proposed to map areal the areas of basins where the sub-surface base of the surface wave contacted the lake bed. To delineate this area Hakanson recommended using the ratio between the maximum potential effective fetch and the water depth for a number of site locations. According to Hakanson's proposed method, the lakes' wave energy would be mapped by hand drawing isopleths for the whole lake from a number of selected sites. Hakanson did not do this procedure because it was a time consuming and demanding task (but which is ideally suited to a GIS). I found no published examples of analysis of spatial substrate dynamics using GIS.

6.9.1 Fetch Distance Estimation using GIS

Fetch distance models have been widely recognized for their utility in learning substrate dynamics, but their use has been limited to point models using estimates of maximum, mean, or effective fetch. GIS programs for estimating fetch distance have been implemented in a raster data structure by Jensen et al. (1992) for predicting areal macrophyte growth in reservoirs in southern Carolina. Bartlett (1989) implemented a fetch program written in Fortran which was merged with ARC/INFO, a proprietary vector GIS, to generate maps of wave energy distribution. Crean et al. (1996) also developed a vector fetch model for ArcInfo using C programming language. I found no published examples of GIS models that integrate fetch, substrate, and slope information.

A maximum fetch estimate is produced by making several to many fetch measurements from a single location; the largest fetch value is extracted from the selection set of measurements and is used to derive hydraulic conditions (Figure 7).

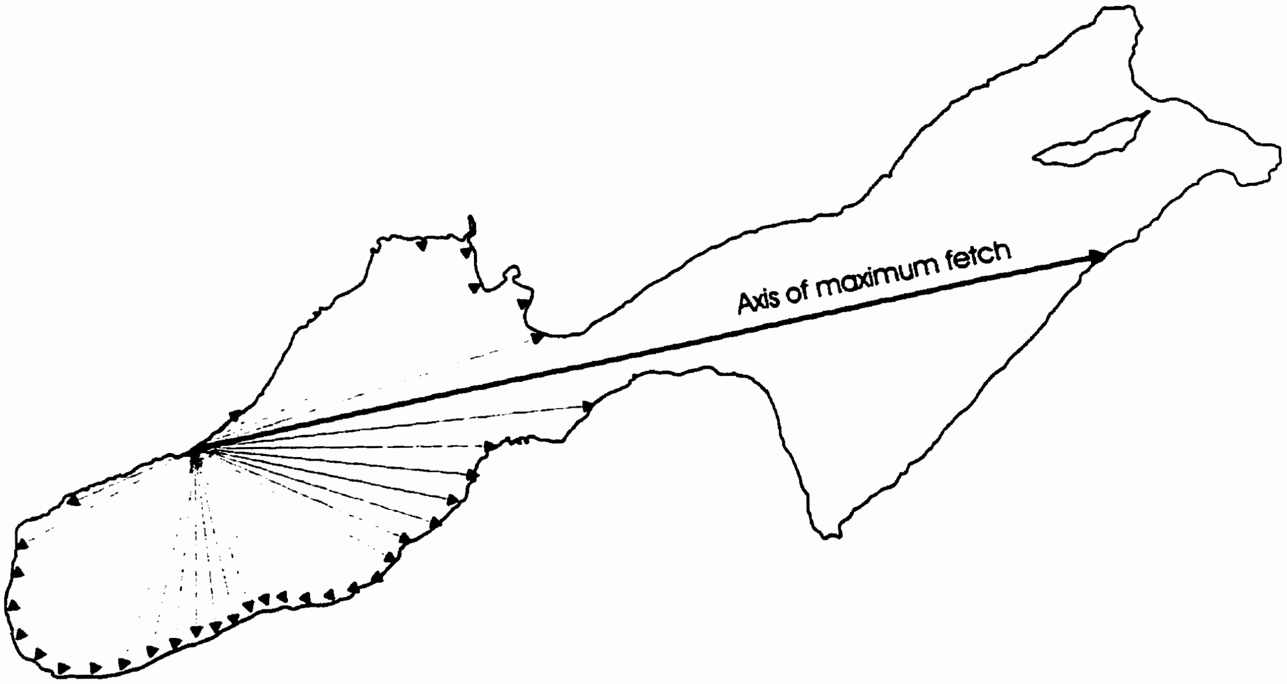
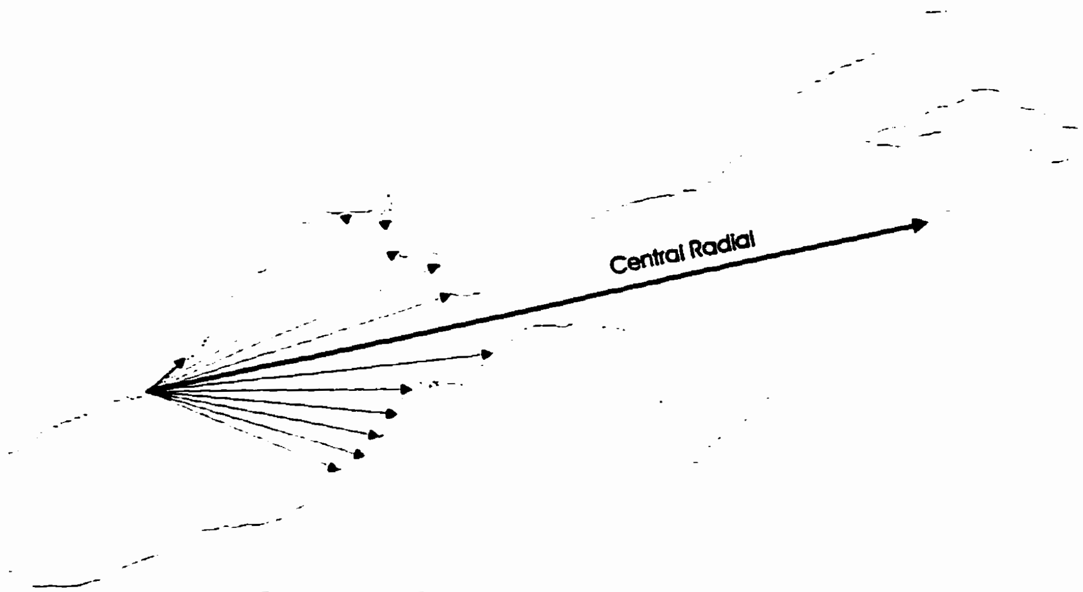
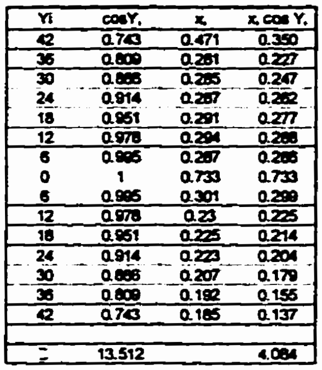


Figure 7. Estimation of maximum fetch distance from 60 axes made at 6 degree intervals.

Mean fetch distance was used by Jensen et al (1992) to provide an index of exposure for prediction of macrophyte distribution. They demonstrated that previous methods for fetch estimation were insufficient to adequately describe macrophyte distribution. They developed a raster fetch model which made 360 fetch distance measurements at one degree intervals, from which the mean was calculated. They stated that earlier fetch models (e.g. Harvey et al. 1989) which used one or a mean of 8 measurements, (one for each of the major compass bearings and another for the closest point in each quadrant), was insufficient for their purposes. Jensen et al. did not explain or rationalize the increased sampling frequency from 8 to 360, but they did describe the utility of weighting individual measurements according to specific wind direction data. None was applied.

Effective fetch has been adopted more widely as point models (e.g. Hakanson 1981, Rasmussen 1988, Rowan et al. 1992). Hakanson compared effective fetch to maximum fetch for 44 stations in irregularly shaped Lake Vanern in Sweden. He found effective fetch to produce better results than maximum fetch because it integrates the cosine of 15 axes (a selection set of 15 fetch estimates) as a sum at 6 degree angles for each site (Figure 8). Rowan (1992) also concluded the same with maximum fetch and exposure. Exposure, an estimate which is mathematically similar to effective fetch, describes the area of the lake visible from a site as it estimates the circular integral of fetch. Unlike maximum or mean fetch, effective fetch models require a direction for the central fetch axis to be specified because it samples mainly in one direction.





Y_i	$\cos Y_i$	x_i	$x_i \cos Y_i$
42	0.743	0.471	0.350
36	0.809	0.281	0.227
30	0.866	0.285	0.247
24	0.914	0.287	0.262
18	0.951	0.291	0.277
12	0.978	0.294	0.288
6	0.995	0.267	0.266
0	1	0.733	0.733
6	0.995	0.301	0.299
12	0.978	0.23	0.225
18	0.951	0.225	0.214
24	0.914	0.223	0.204
30	0.866	0.207	0.179
36	0.809	0.192	0.155
42	0.743	0.185	0.137
Σ	13.512		4.084

Figure 8. Estimation of effective fetch (Lf) distance using 15 axes measured at 6 degree intervals for an arbitrary point along a lakes shoreline.

An effective fetch GIS model was produced by Minns et al. (1995) to assess the change in wave energy due to the development of offshore structures, i.e. breakwalls, which seclude marinas from offshore wave action.

6.10 Summary

Fetch models remain in the developmental phase. Although the GIS programs developed thus far have demonstrated some aspects of shoreline or coastal processes, they have disadvantages. Custom applications have limited distribution, they require specific computing and display platforms, and also have specific output capabilities, which makes them less flexible. The effective linkage between observed sediment patterns to fetch estimates requires the selection of the appropriate fetch estimate and the number of measurements used to collect the estimate. The use of fetch estimates has been devoted mostly to their use as point models. Although Hakanson's effective fetch has been adopted most often in other studies, Rowan et al. (1992) found in their multi-lake database that Hakanson's effective fetch model did not adequately describe sediment distribution in other lakes, and therefore was applicable only on lake Vanern, the lake from which the model was developed.

6.10.1 Characteristics of Nearshore Substrates:

The variables which influence substrate form and distribution can be viewed in the successive levels of scale in which they operate. The scales range from basin wide to site locations; the latter scales operate at levels lower than the present AHC system accommodates. At the largest scale, the specific location and confinement of lakes controls the types of materials available. At the next increasing level of scale, i.e. the watershed level, the lake basin's parent geomorphology sets fundamental controls on the shape and orientation of the basin. This sets maximum limits to the expenditure of energy on shorelines by waves. The potential for waves to modify substrates is dependent both on the availability of materials of various sizes for transport, and also the expression of the dominant climatological regime in the form of surface waves. The variables of wind direction, periodicity, and magnitude must work within the constraints of the lake to form the dominant hydraulic regime. The redistribution of available substrate materials from offshore sorting and littoral drift is co-dependent on the wave energy available, and the availability, form, and distribution, of landforms that are stable relative to the present hydraulic conditions. The integration of each of these variables produces the configuration of a lake's shoreline and the patterns of substrates in their NSA's

6.10.2 Status of Current Models on Bottom Dynamics

The knowledge of hydraulic and sediment dynamics in lakes can now be integrated together as GIS process models. However, the initial studies of sediment dynamics have exposed methodological concerns which require further investigation, particularly for fetch estimation. The foundation studies have, by necessity, focused on large scale distribution patterns like erosion, transport, and deposition, or at a higher level of detail, predicted the mud DBD from point models, and have concentrated on the transport and depositional areas. The prediction of mud DBD locations is needed to delineate the areas of lakes within which nearshore variables, like the material sorting along lake edges, can be studied. Although more standardized classification systems like the AHC have been developed recently, its youth means that most classifications of NSA's are unsuitable for learning the bottom dynamics because field methods did not capture the effects of process. A necessary first step in this area of research is the development of field methods to document nearshore substrates. The documentation and understanding of nearshore processes for habitat management requires the standardization and development of techniques including: classifications, base-line information studies, GIS models of substrates and wave energy, and evaluations of their implementation.

7. Methods

Part 1

7.1 Study area

The Experimental Lakes Area (ELA) is a research area designated by the Canada Department of Fisheries and Oceans (DFO) and the province of Ontario for aquatic study. The location of ELA in northwestern Ontario is shown in Figure 9. All lakes south of the Trans-Canada highway in the region of 93 15'-94 15' and 49 30'-49 51' N were numbered for identification in the survey of 1967 by Cleugh and Hauser (1971). All of the six lakes in this study, i.e. Lakes 164, 165, 226, 442, 373, 377 are located between 93 44'-93 52' and 49 37'-49 50'; the lakes are contained in a circular area with a diameter of 17 km. The six study lakes are shown in Figure 10.

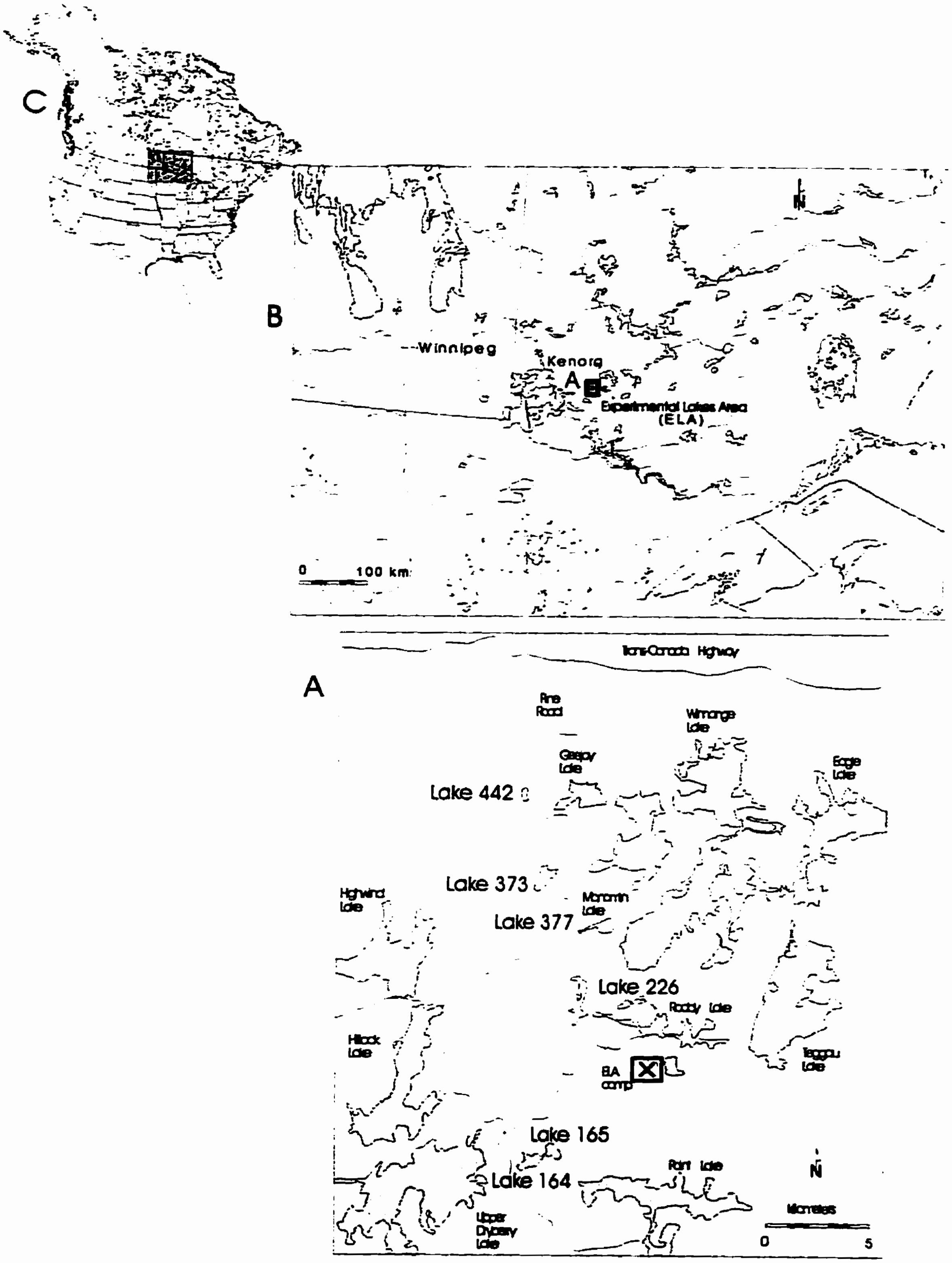


Figure 9. A) The Experimental Lakes Area (ELA), B) the location of ELA in Northwest Ontario, and C) location of inset B in North America.

Figure 10. The six study lakes in the Experimental Lakes Area.

These lakes present a range of geomorphological conditions through which to test the utility of the nearshore substrate classification system, and also to document the variability in nearshore habitat availability among lakes. The first lake selection criterion was to select small lakes in this one area of relatively homogenous geomorphology. This criterion facilitates data completeness and improves the likelihood of equitable comparisons of substrates among lakes. The second criterion was to select lakes with varying depths to ensure that a broad spectrum of nearshore slope environments would be sampled. Five of the six lakes chosen for this study were included in the lake variation and climate change program (McCullough and Campbell 1993) by the DFO. These lakes fulfilled these above criteria and also morphometric data on the lakes was available.

The set of lakes was completed with the addition of Experimental Lake 226. Other concurrent work by the DFO on this system provided an ideal opportunity to pursue other corollary objectives on this system; in particular, to map the substrates of the entire basin, and to compare the observed and predicted zones of deposition and erosion, respectively. The controlled draw-down of lake level to 3.1 m below its natural level over two years exposed much of the nearshore substrates. The lower water level provided the opportunity to conduct a complete lake substrate survey, and also to evaluate the precision of classifications made at the natural lake stage.

7.2 Geology and Geological History

The geology and geological history of the Experimental Lakes Area was described in detail by Brunskill and Schindler (1971), and summarized by McCullough and Campbell (1993). The ELA is located in a region of the Precambrian Shield on an extensive exposed batholith mostly of pink granodiorite, with localized zones of grey (biotite-rich) granodiorite. The area was subjected to several ice movements during the Pleistocene. The last retreat, which progressed in a north-northeast direction, left abundant glacial striae along this axis.

Generalized maps (Clayton 1983, figs. 4,5, Teller 1985) suggest that the Pleistocene ice sheet would have retreated north of ELA about 11500-11000 years ago. At that time ELA would have been partially inundated under eastern Lake Agassiz, with the shoreline in the ELA area resembling that of contemporary Lake of the Woods; a very irregular shoreline and abundant islands. By 10800 BP the ice sheet had retreated sufficiently far north to allow drainage to the east, at an elevation of about 390-400 m ASL today. During the changing glacial lake levels, ELA was an archipelago where numerous beach ridges (sub aqueous sorted sands) developed. Over the next 1000 years, the level of Lake Agassiz decreased to less than 300 m ASL, before a final glacial advance again blocked the drainage to the east (about 9900 BP). With the last retreat, circa 9500 BP, Lake Agassiz fell below the level of the study lakes, which range in elevation from 369-424 m ASL. This history suggests that all of the study lakes were incorporated in Lake Agassiz. Lakes 373 and 442 would have become separated about 10800 BP, whereas lakes 377, 226, 164, 165 would not have become discrete lakes until about 9500 years ago (McCullough and Campbell 1993).

Granodiorite predominates in ELA due to the its high resistance to glacial scouring. The batholith underlying ELA now forms a regional height of land which forms a divide between drainage into the north via the English River system, and to the south and west by the Rainy River-Lake of the Woods systems. Lakes 442, 373, 377, and 226 drain northwest via Winnange Lake to the English River, whereas lakes 164 and 165 drain south into Dryberry Lake before emptying into Lake of the Woods. The maximum range of relief in the ELA exceeds 100m, from 369m to 495m. ELA has become a region of abundant bedrock-rimmed lakes infilling the glacially scoured depressions. The shorelines of lakes not controlled by bedrock are mostly sorted glacial till or fragmented talus deposits, or fen peat in energetically quiescent back bays. About one-quarter of ELA surface area is water.

McCullough and Campbell (1993) noted that advancing glacial events in the area scoured most of the higher land areas clear of overburden, but that the retreat left scattered deposits of glacial drift in the form of ridges and depression-infillings of boulder and sandy tills, and pro-glacial outwash sand and gravel. Less frequently, local lacustrine deposits (of historic or present)-silts and more rarely clays-can be found in low-lying areas.

7.3 Morphology of the Study Lakes

Morphometric data for the study lakes are found in Table 1. The study lakes are small, varying in area from 16 - 27.3 ha. with simple shoreline development (Kent and Wong 1982). The maximum SLD is about 2.0. The lakes can be placed into two morphometric groups by depth and volume (McCullough and Campbell 1993). Lakes 164 and 165 are shallow and do not thermally stratify, whereas lakes 442, 226, 377, 373 are much deeper and exhibit annual thermal stratification.

Table 1.Selected morphometric data for the study lakes. All data taken from McCullough and Campbell (1993) except Lake 226 which were produced in this study. AL= lake surface area, V = lake volume, SLD = shoreline development, L = length of shoreline including islands, Z_m = maximum depth, Z = mean depth. Maximum map scale used for estimates was 1:2500.

Lake	A_L (ha.)	V (m^3x 10^5)	SLD	L (m)	Z (m)	Z_m (m)
442	16.0	14.40	1.74	2470	9.0	17.8
226	16.2	9.6	2.08	2986	10	15.7
165	18.4	6.19	1.51	2290	3.4	4.6
164	20.3	10.02	1.50	2390	4.9	7.1
377	26.9	24.66	1.72	3170	9.2	17.9
373	27.3	30.09	1.51	2790	11.0	20.8

7.4 Cultural and Biogenic Effects on the Study Lakes

Clear-cut forestry, fire, and road building have been the major sources of physical change to lakes in ELA in the recent past. The west shoreline of Lake 377 has been modified for a road crossing over the lakes' inflow. Other small and localized changes have occurred from rock removal from shorelines for dock building, as occurred at about the mid-point of the east shoreline of Lake 373.

The water levels of Lakes 164, 165, 226, and 442 at the time of sampling were controlled by beaver dams at their outlets and, with the exception of Lake 226, appear to have maintained relatively consistent water levels over the past several decades. Lakes 226, 377, and 442 have had variable water levels due to intermittent beaver activity. In 1994, Lake 226 experienced its highest recent water level indicated by erosion of Sphagnum sp. on the lake's western-most shoreline. Three longer-term lower water levels were visible on a smooth bedrock face on the north side of the lakes' only Island. The lowest visible water level was about 1 m below the August 1994 level. Lake 377 and 442 have experienced water levels higher than present; this was evidenced by sorted materials and dead and fallen timber in epilittoral areas. The lake level of Lake 377 at the time of sampling was lower by about 0.5 m, and for Lake 442 approximately 1 m. The latter water level was much older and more difficult to discern. The water level of Lake 377 presently is controlled by natural geology at its outlet.

Beavers occur in all the lakes presently dammed, and affect the quality of fish habitat. The effects of beaver activity on nearshore habitats, i.e. abundant bark and woody matter with excavated channels, is pronounced and can extend 15 - 20 m on either side of the beaver den. Materials redistributed by beavers were not mapped - they are best collected as a supplementary "woody" thematic layer to augment the database later.

7.5 Nearshore Area Substrate Mapping

7.5.1 Data Collection

All data were collected from the study lakes during the open-water period (May - October), 1993-1995. Low altitude aerial photographs were taken to delineate contemporary shorelines. Substrate information was collected with on-lake surveys. Transect data containing substrate information was reconstructed from the photography in digital form to shoreline vector files using Autocad software.

7.5.1.1 Aerial Reconnaissance

Aerial Surveys were conducted a total of four times during the study period by Airquest Resource Surveys Ltd. using panchromatic film (AGFA 200). To ensure a precise and spatially consistent scale on the photography, targets were placed on the shoreline at opposite ends of each lake in two groups of three. The linear distance between the targets was recorded (to nearest 0.1m). Lakes 164,165, 373, 377 and 442 were photographed on September 10, 1993 between 0630 and 0830 local time, with an average scale of 1:5000. Lake 226 was photographed twice at the same scale, before and after draw down, at October 21 1994, and May 14 1995 by Norwest Geomatics Inc.

7.5.1.2 Field Survey:

The Nearshore Classification System (NSCS) was designed to inventory substrates with mixed compositions and to capture the patterns of substrates that form from mechanical sorting and slope processes. The NSCS substrate material sizes are based on a nominal interval classification (Burrough 1986) using a modified version of geological materials by size from Platts (1983). Table 2 shows the nominal classification and the numbers by which classes were named. Substrate patterns were documented using line-intercept transects (Hamilton and Bergersen 1984) which were oriented along the lakes' perimeter and also perpendicular to it. Two crew members classified substrates, kept records, and handled a 12 ft. aluminum boat.

Table 2. Interval system used for classification of nearshore substrates in the study lakes at the ELA.

	Substrate Material	
Class Name	Class	Size (mm)
Silt/Clay	1.0	Texture
Bedrock	2.0	Solid Rock
Sand	3.0	0.06 - 4
Gravel		
- fine	4.1	4 - 8
- coarse	4.2	8 - 64
Cobble		
- small	5.1	64 - 128
- large	5.2	128 - 256
Boulder		
- small	6.1	256 - 1024
- large	6.2	1024 - 496
Detritus	71	
Flocculent Material	72	

Two types of transects were used to detect the change in size of substrate materials using 2-100 m surveyors' tapes. The first measured the perimeter of the lake along the high watermark. This long-shore transect served as a base line to reference the location of the second type of transect which was oriented perpendicular to the shore to detect the material size changes as water depth increased. These off-shore transects were located systematically every 50 m along the base line transect, and also where changes in material size occurred along the shoreline. The off-shore transects extended through the nearshore zone to a depth of 3m. All offshore transects were marked with fluorescent marking tape that indicated the metre number of the longshore transect (+/- 0.25

m). The horizontal distance (+/-0.10 m) to each material class change, and the distance from shore at intervals of 1 m depth were recorded.

Unlike many classifications, the NSCS accounts for potential heterogeneity of materials within a given polygon, and allows class memberships to overlap across polygons. The maximum number of material classes that can be included in a single polygon is three. For example, the classification: 51/42/30 is a polygon that is comprised of small cobble, coarse gravel, and sand; each class occupies 33.3% of the substrate area of the polygon. Comparatively, 62/71, indicates that the polygon of interest contains 66.6 % large boulder with 33.3 % of the substrate area comprised of detritus. A class number of 30 represents an area of homogeneous sand. The nested classification structure assumes there is no discernible pattern of materials by size within a polygon. The NSCS accommodates and satisfies all of the criteria described by Laurini and Thompson (1992) for building classification taxonomies.

The nearshore area was classified in 100 m segments along the baseline transect. An arbitrary point on the lake shoreline was designated metre number 0, then the classification proceeded in a clockwise direction. The beginning of the baseline transect was flagged and marked with fluorescent marking tape where the first 100 m tape was affixed. The person classifying the substrates walked/waded along the high-water mark on the shoreline with the tape and noted material characteristics immediately visible along and just below the high water mark. Stations which indicated the location of offshore transects were flagged systematically at each 50 m interval on the baseline transect, and also where the size of materials changed along the shoreline. The material classifications and the location (i.e. metre number) for offshore transects along the baseline transect were called to the boat operator to record. When the 100 m baseline segment was completed, the classifier flagged the terminal station, then returned to the beginning of the baseline transect in the boat.

Offshore transects were completed at each flagged station as follows: The surveyor, from the bow of the boat, attached the second tape measure to an object on the shoreline at the high water mark. The boat operator slowly reversed the boat away from the shoreline in a perpendicular direction. The surveyor then noted substrate characteristics as water depth increased. A 5 m aluminum pole with surveyors rod facing attached, was used to measure the water depth and acted also as a tool for interpreting the size of materials (measured relative to the level water surface) and the textural composition in areas where the substrate was not visible. During each transect the surveyor relayed information regarding substrate, depth and the horizontal distance from shore to the boat operator.

With the exception of Lake 226, classification and distance measurements of offshore materials stopped at the 3m depth contour. When all offshore transects were complete for that 100 m reach of shoreline, the transect data were inspected. The NSCS data sheet is shown in Appendix A.

Discrepancies of classification among adjacent offshore transects indicated: 1) additional offshore transects were required to detect ends of material class changes missed previously, 2) ends of polygons must be interpolated when the distance between offshore transects was small (about 5 m).

Schematic polygons were formed in the field to ensure the substrate patterns were adequately documented. One of two methods of interpolation were used to close polygons. Substrate types which were immediately adjacent to the high water mark were bounded by transect information on three of the four sides. The offshore boundary for these polygons were sketched as straight lines between the same material class on each of the offshore transects. The other substrate polygons located offshore had direct observations for one or two sides of the polygon. If one offshore transect had a unique class (compared to each adjacent offshore transect), the unique polygon's outer boundary was interpolated to the boundary with a shorter distance to shore. The second type of interpolation was used only when the distance between adjacent offshore transects was short (approximately 5m). Each of these interpolations assumes the change in distance from the shoreline to the offshore boundary is linear.

7.5.2 Vector Data Storage and Manipulation

7.5.2.1 Lake Perimeter files

Digital files of lake shorelines were produced from the aerial photography. Georectification and corrections for scale distortion were exercised in vector format with Microstation, Idrisi, and Autocad (CAD) software using the scale ratio technique and ground control point models, and known distances from the scale targets placed on the lake shores. Universal Transverse Mercator (UTM) map products were produced at 1:1000 scale. Offshore stations were located on the CAD polyline which delimited the lake perimeter (i.e. baseline transect) as a CAD block reference which included the meter number of the shoreline. Data relevant to these files was archived in a separate CAD layer.

7.5.2.2 Map Construction Techniques

For each lake surveyed, a tabular database was constructed in MS Excel which included the substrate and depth data by shoreline station number. The horizontal distance from shore to 1m depth intervals and substrate boundaries and the angle of the transect in the offshore direction, in degrees, were recorded.

7.5.2.2.1 Reconstruction of transect data

Offshore transects were reconstructed in Autocad by placing from one to many vertices on a polyline which was perpendicular to the shoreline. Each node indicated the horizontal distance from the shore to a substrate boundary. Each offshore polyline, then, had one or more nodes at specific distances along the digital form of the transect, depending on substrate complexity.

The large number of offshore transects required for reconstruction in the six lakes suggested that an automated way to map the offshore transects was needed. Excel was used as a server to send command line instructions to AutoCAD using a Dynamic Data Exchange (DDE).

Prior to the DDE, an attribute data extraction was performed in AutoCAD to identify the UTM coordinates of shoreline stations where offshore transects were inititated. This was done by creating block references (compound entities), each with an attribute which indicated station number. The blocks were inserted into the shore polyline at the desired locations. An ASCII template file was constructed and was used to extract the geographical coordinates of the shoreline station, the station number, and other entity information from the Autocad database. The extraction was accomplished with the ATTEXT (attribute extract) command.

An Excel workbook, which contained the field data and a macro, was formatted to accept attribute extraction data from AutoCAD. In addition, the spreadsheet was programmed to convert the offshore horizontal distance data into AutoCAD polar coordinate (i.e. distance at angle) format. To reconstruct the offshore data in AutoCAD, the spreadsheet produced command line requests from concatenations of the data from several spreadsheet fields into a single one. Each record in the database produced a command line sequence for a single offshore transect. The Excel macro created a direct channel to AutoCAD and sent the command lines to AutoCAD in a record by record fashion.

In AutoCAD, offshore polygon boundaries were interpolated visually between offshore transect nodes. The interpolation assumed that the change in horizontal distance of the offshore boundary to the shoreline was linear between the two offshore transects. This interpolation captures the longshore and offshore material gradients, especially in transition reaches where longshore material gradients occur between headlands and embayments.

7.5.2.2.2 Encoding Vector Polygon Topology

Polygon topology was added to the source AutoCAD drawings of substrate and depth using PC ArcInfo (version 3.4.2), after file translation to shape file format using ArcView (version 2.1). In ArcInfo, polygons were encoded topology using the ArcInfo clean utility. Spatial accuracy of arc nodes was reduced to 0.1 m.

A spreadsheet was used to determine all possible substrate combinations and was used to assign substrate classes to the sequentially numbered polygons. All substrate polygons were assigned integer codes within the byte data range in the polygon and arc attribute tables in ArcInfo. This Table is archived in Appendix B.

All polygon and arc data were translated into Idrisi GIS format using USGS DLGN (optional digital line graph) format files.

7.5.2.2.3 Raster Data and Attribute Table Data

Raster maps were produced for each of the study lakes with the following themes for the nearshore area: 1) digital elevation model, 2) slope model, 3) substrate, and 4) depth. All maps were produced with 0.5 m cell resolution at a scale of 1:1000 using Universal Transverse Mercator Projection (UTM) and North American Datum (NAD 83). Attribute tables for the substrate polygon data were converted from ArcInfo format to dBase 4.0 format files before import to Idrisi as MS Access tables.

7.6 GIS Methods and Analyses

Methods for Sub-System Results

The number and areal coverage of substrate polygons for each depth stratum and lake NSA, was determined by image to image crosstabulation between the substrate and depth maps. From these tables the following information was compiled: 1) the number of substrate classes used per depth stratum and lake, 2) the area of NSA that each class occupied, 3) the number of mono, bi, or tri-typic substrate classes per depth stratum and lake.

The total areal coverage of each of the 11 substrate classes for each of the six NSA's was determined as follows, each attribute table was coded values in a field which indicated if the class was homogenous (i.e. mono-typic), or was a nested classification with two (bi-typic) or three (tri-typic) classes. SQL queries were constructed to fill one of eleven new fields with area data. For example, a classification of 61/52 with an area of 1 hectare would fill two fields with data, the first for field 61 would contain 0.66 Ha., the second field for 52 sized materials would be 0.33 Ha.

Part 2:

7.7 Mapping Fetch Distance

Because detailed information on wave properties on all types and sizes of lakes is lacking, fetch distance estimation is needed to estimate the physical properties of surface waves. Although the application of fetch information can have many end uses, the necessary prerequisite for all applications is a full understanding of fetch distance modeling and the choice of a fetch model which is best suited to the specific application. The purpose of this section is to introduce and describe some fundamental techniques used to acheive satisfactory fetch distance mapping.

7.7.1 Estimating Fetch Distance

Three fetch distance models, maximum, mean, and effective fetch, were developed as ANSI C 16 bit DOS applications compatible with IDRISI GIS to map the distribution of fetch distance in the study lakes.

Using the maximum and mean fetch programs, the number of measurements used in the estimate of fetch (i.e. the sampling frequency) for each raster cell may be selected from one of eight different sampling frequencies (i.e.1, 4, 8, 20, 40, 60, 180, 360 axes) made at equal intervals in degrees.

To calculate fetch distance at a specific angle the program searches for the first shoreline or land cell using an offset in x and y directions which correspond to a specific angle in degrees. When the location of the shoreline cell is known, the Pythagorean theorem is used to determine the straight line distance from the lake cell to the land cell.

However, 352 of the 360 measurement angles must use checks for cell identity which are not contiguous. This can cause the fetch distance to"overshoot" a lake's shoreline. Such measurement axes, therefore, have a unit distance for measurement that is larger than is the cell size of the image (Figure 11). This unit distance error (UDE) is what cuases over estimates of fetch measurements. Only the measurement axes which include 0, 45, 90, 135, 180, 225, 270, and 315 degrees do not have a UDE.

For all measurements which have identified a land cell (measurements to shoreline cells do not require corrections) the effects of UDE are corrected by making three measurements that do not have a UDE from the last lake cell encountered to the shoreline (Figure 12). Three measurements were made using angles which correspond to horizontal, vertical, and diagonal in each quadrant of the image which is divided into a Cartesian coordinate system. After Pythagorean corrections, the minimum of the three distance estimates is added to the original fetch estimate.

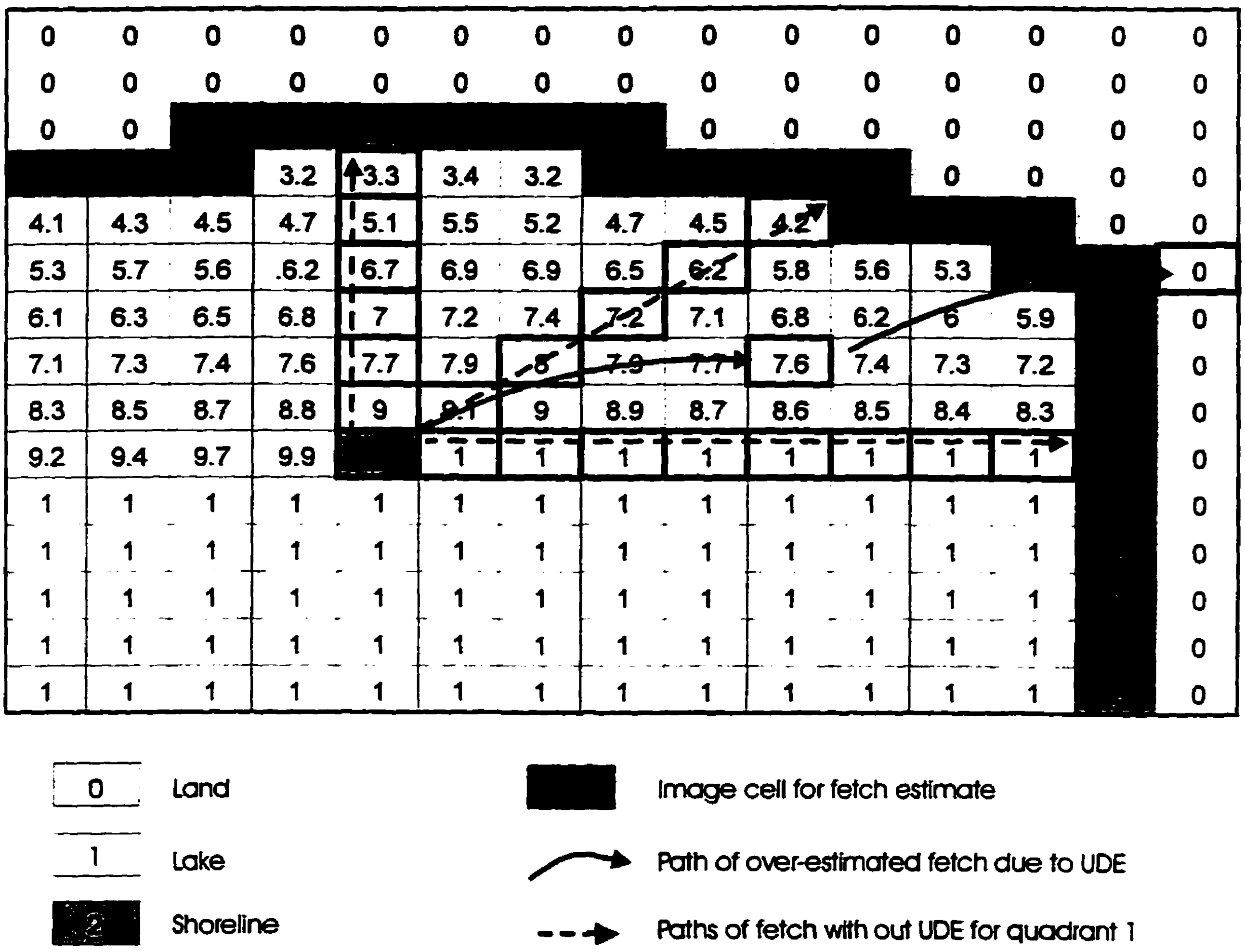
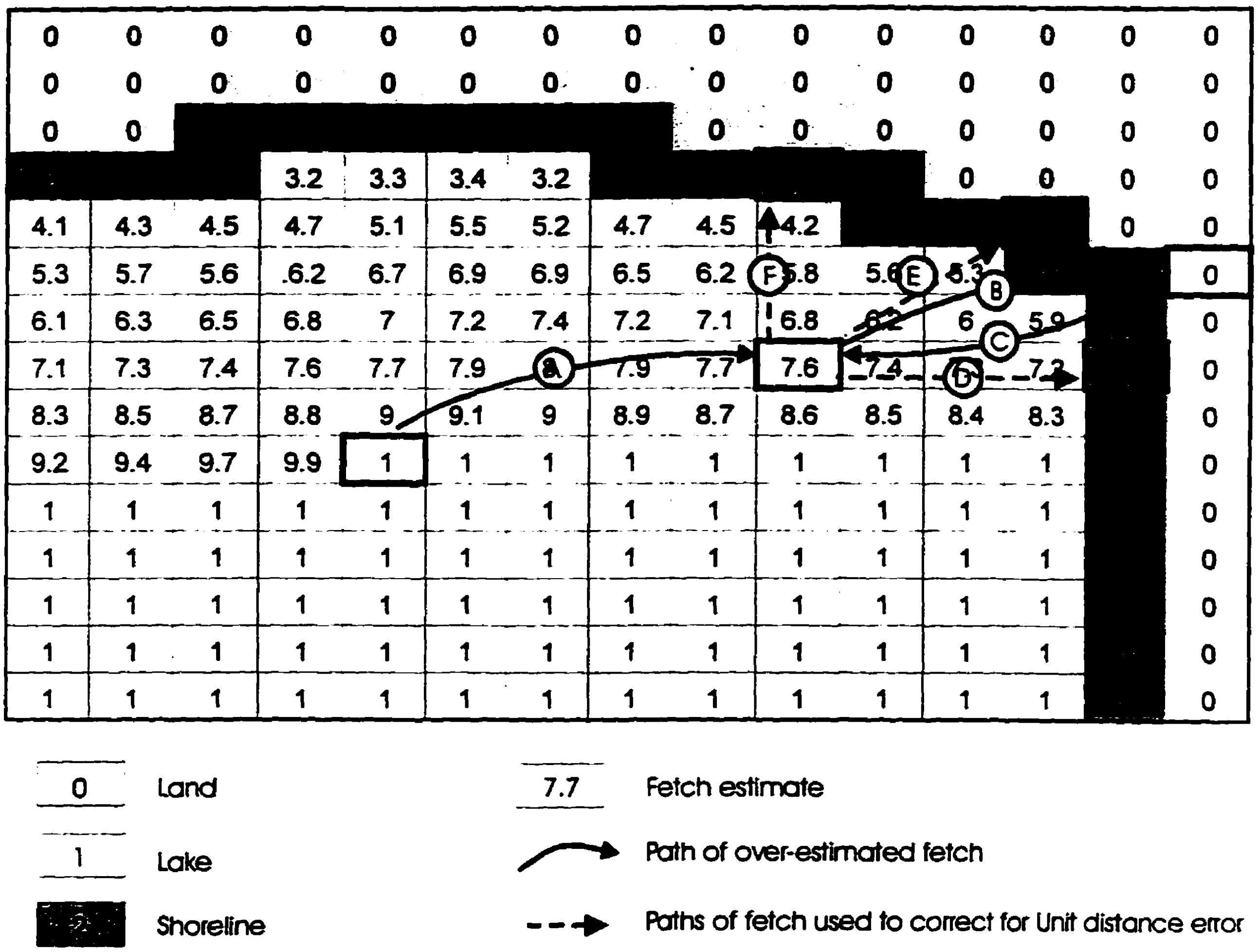


Figure 11. Estimating fetch distance. Measurements made from a lake cell to the shore on horizontal, vertical, and diagonal perform tests for the land boundary among cells which are contiguous Other measurements test for the land boundary across cells which are not adjacent, and can overestimate the fetch distance.



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	■	■	■	■	■	■	0	0	0	0	0	0	0
■	■	■	3.2	3.3	3.4	3.2	■	■	■	■	0	0	0	0
4.1	4.3	4.5	4.7	5.1	5.5	5.2	4.7	4.5	4.2	■	■	■	0	0
5.3	5.7	5.6	6.2	6.7	6.9	6.9	6.5	6.2	Ⓕ 5.8	5.6 Ⓔ	6.3 Ⓑ	■	■	0
6.1	6.3	6.5	6.8	7	7.2	7.4	7.2	7.1	6.8	6.2	6 Ⓒ	5.9	■	0
7.1	7.3	7.4	7.6	7.7	7.9	Ⓐ	7.9	7.7	7.6	7.4	Ⓓ	7.2	■	0
8.3	8.5	8.7	8.8	9	9.1	9	8.9	8.7	8.6	8.5	8.4	8.3	■	0
9.2	9.4	9.7	9.9	1	1	1	1	1	1	1	1	1	■	0
1	1	1	1	1	1	1	1	1	1	1	1	1	■	0
1	1	1	1	1	1	1	1	1	1	1	1	1	■	0
1	1	1	1	1	1	1	1	1	1	1	1	1	■	0
1	1	1	1	1	1	1	1	1	1	1	1	1	■	0
1	1	1	1	1	1	1	1	1	1	1	1	1	■	0

0 Land

1 Lake

■ Shoreline

7.7 Fetch estimate

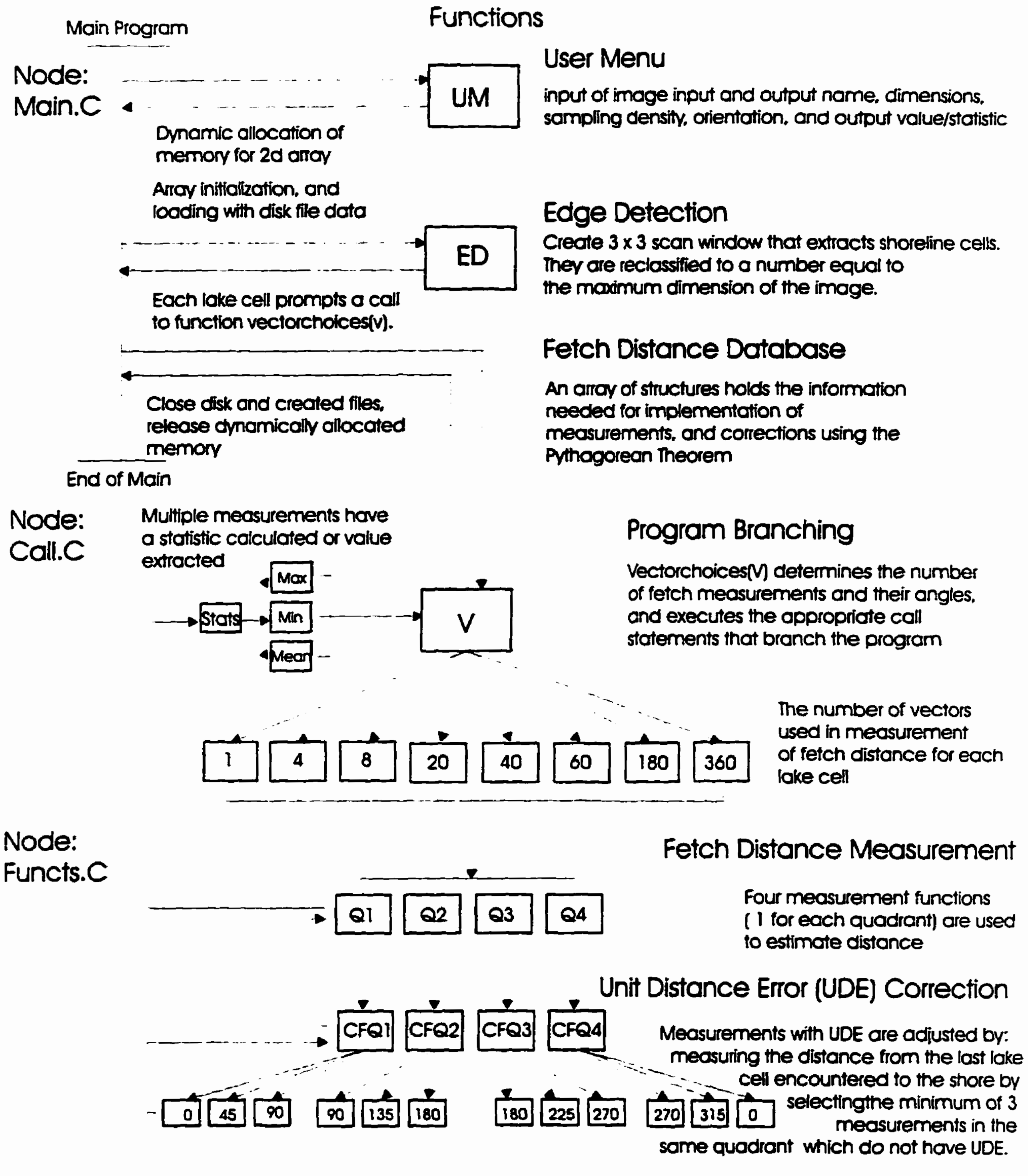
⟶ Path of over-estimated fetch

- - ➤ Paths of fetch used to correct for Unit distance error

Figure 12. Estimating fetch distance for one angle which has unit distance error (UDE). The specific angle requested over-shoots the lakes' shoreline (arrow with circle lettered B) before land is detected. The over estimate is adjusted by selecting the minimum distance of three measurements (dashed arrows with circles lettered D, E, F), which do not have a UDE from the last lake cell on that axis. The two distance estimates (A and one of D, E, F) are summed to produce the final estimate.

7.7.2 Fetch Model Structure

The fetch executable file is composed of three source code files, called nodes, which are compiled and linked together (Figure 13). The flow of the program is controlled by the node *main.c*. This node accepts user input about image details and the type of fetch statistic requested, it allocates the memory needed to execute the program, and performs file input/output functions. The image is processed from upper left to lower right three times. The first pass performs edge detection to extract shoreline cells which are used as targets for fetch measurement. In the second pass, a function in the node calls.c is called from *main.c* for each lake cell in the image. *Calls.c* implements the number and angle of measurements by program branching. The estimation of each fetch measurement is accomplished by a call to *functs.c*, which harbors the programs' measurement and statistical functions. The third and final pass through the image data by *main.c* is used to reclassify the shoreline cells back to land. At program termination, *main.c* closes all files after output of data to a disk file in Idrisi format, and releases all memory allocated.



Dynamic allocation of memory for 2d array

Array initialization, and loading with disk file data

Each lake cell prompts a call to function vectorchoices(v).

Close disk and created files, release dynamically allocated memory

Multiple measurements have a statistic calculated or value extracted

User Menu

input of image input and output name, dimensions, sampling density, orientation, and output value/statistic

Edge Detection

Create 3 x 3 scan window that extracts shoreline cells. They are reclassified to a number equal to the maximum dimension of the image.

Fetch Distance Database

An array of structures holds the information needed for implementation of measurements, and corrections using the Pythagorean Theorem

Program Branching

Vectorchoices(V) determines the number of fetch measurements and their angles, and executes the appropriate call statements that branch the program

The number of vectors used in measurement of fetch distance for each lake cell

Fetch Distance Measurement

Four measurement functions (1 for each quadrant) are used to estimate distance

Unit Distance Error (UDE) Correction

Measurements with UDE are adjusted by: measuring the distance from the last lake cell encountered to the shore by selectingthe minimum of 3 measurements in the same quadrant which do not have UDE.

Figure 13. Flow diagram showing the ANSI C fetch distance model structure and program flow.

7.7.3 Fetch Model Implementation

During program development, the fetch models were initially implemented using low resolution images with very simple geometric shapes to facilitate the validation of fetch measurements. To learn if shoreline complexity effected model results, a raster map of Southern Indian Lake, a large and complex lake in northern Manitoba, was used to test the performance of the fetch models. The ELA study lakes have relatively simple shoreline configurations, and were excluded from preliminary model testing. A lake with a complex shoreline geometry was selected to ensure that the final versions of the code were sufficiently robust for implementation on any lake.

7.7.4 The Sensitivity Trials

To evaluate the effect of sampling frequency on model results, a series of images was produced at each level of sampling frequency for the maximum, and mean fetch estimates. Visual inspection of the images and frequency histograms were used among these image sets to assess the differences in fetch results for each sampling frequency for models which offer one to many axes for measurement.

Part 3

7.8 Process Modeling: Integrating Physical and Hydrodynamic GIS models

The Lake 226 database provided a unique opportunity to investigate the effects of wave and slope process on the spatial distribution of areas which are subject to erosion, transport and deposition. The two surveys of this lake (at two different water levels, the second about 2 m lower than the first) resulted in detailed delineation of the boundary where perennial deposition occurs (known as the mud depositional boundary depth or mud DBD, Rowan et al. (1992)). The purpose was to estimate spatially the sub-surface wave base from the maximum fetch model, delineate the area of the basin exposed to wave action, and to compare the observed mud DBD with the predicted mud EBD.

Maximum fetch distance for Lake 226 was estimated using a sampling frequency of 360 axes. The map resolution was reduced by a factor of six for fetch processing. The maximum fetch map was resampled to 0.5 m resolution using nearest neighbor interpolation to provide a consistent map resolution for overlay analysis. This map of maximum fetch was used to produce another thematic map which estimated the depth to the wave base under maximal wave conditions using equation 5 from Rowan et al. (1992):

$$h > 1.66F^{0.5}$$

where h is water depth (metres), and maximum fetch (kilometers)

A subtraction overlay analysis was performed on the DEM and wave base images. The depth to the wave base was subtracted from the DEM image, and the areas with values less than or equal to zero indicated the zone where sub-surface orbital motion of water molecules contacted the substrate. This delineates the areas where substrate erosion occurs.

8. Results

Part 1:

8.1 Nearshore Classification, Substrate Assessment, and Inter-lake comparison of Substrate.

The results presented here archive at three levels of the AHC system (Busch and Sly 1992); two append at the sub-system and division/sub-division levels, while the NSCS substrate maps are at a level of detail which is not accommodated by the present AHC system. Consequently, the NSCS data is appended to the AHC as three new proposed levels (Figure 14).

Although the NSCS was an effective method for substrate assessment, the comparison of habitat in the NSA among lakes was difficult at a high level of detail due to the strong influence of parent geomorphology and the erratic nature of glacial deposition. In each lake some substrate areas were unique in terms of substrate combinations. This made complete lake-wide habitat comparisons difficult. Comparisons were possible, however, at higher levels of the AHC at the sub-system level. This involved the separation of material types in nested classes and summing the areal coverage of each material size class for each lake. However, comparisons made at progressively higher levels of the hierarchy become increasingly less sensitive to variations in habitat data. Consequently, a more general and descriptive form of nearshore habitat classification called shore-type associations (STA) is proposed based on the types of shorelines encountered.

The STA classifies nearshore habitat into reaches based on an integrated perspective of the geomorphology, the adjacent terrestrial area, the shoreline configuration, and the substrate material type and pattern. The division of shoreline types into reach scale blocks of habitat data that append to the AHC at the sub-division level reduces information requirements and simplifies inter-lake comparisons. The STA does not lose the important structural features of habitat like the geomorphology, substrate type and pattern, and habitat scale and entropy (patchiness) that are commonly lost with descriptive classifiers at higher AHC levels. Although the STA is a sub-division level descriptor, it will be presented and used in concert with the group/sub-group level substrate data because its descriptive nature provides a convenient vehicle for an introduction to the study lakes.

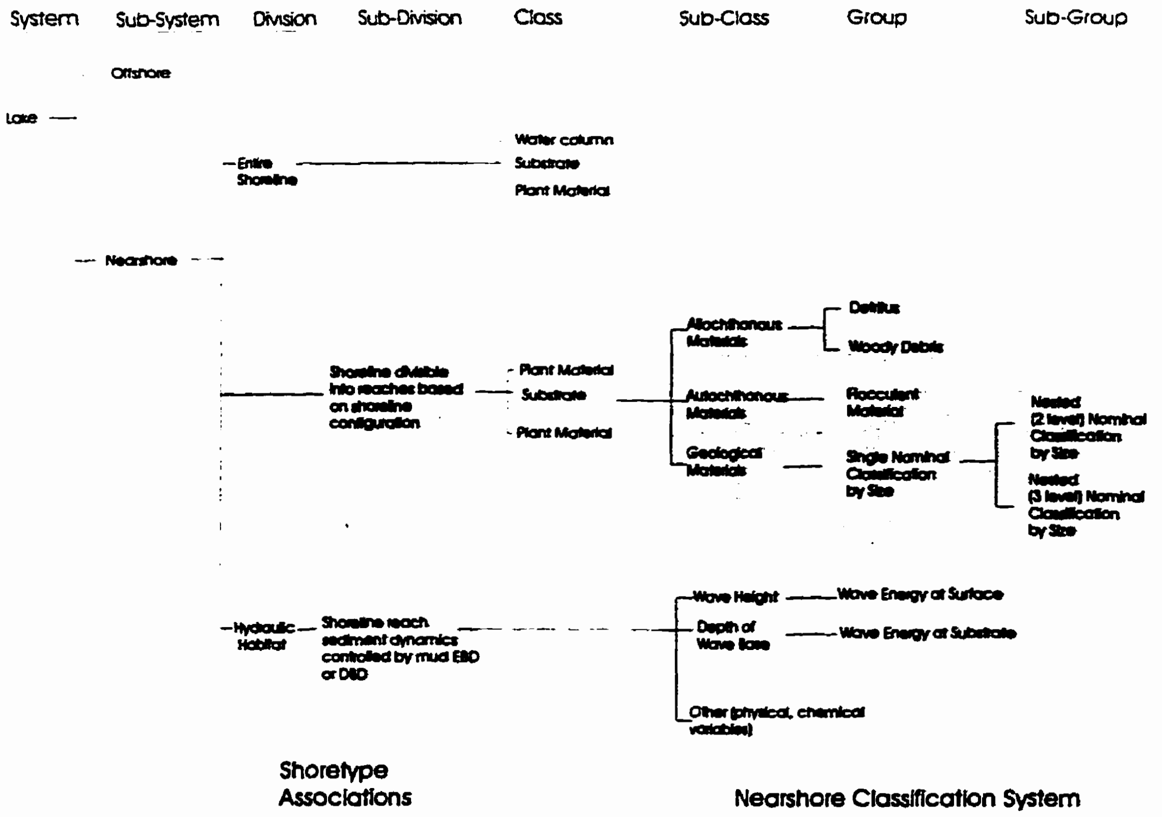


Figure 14. The Aquatic Habitat Classification System (Busch and Sly 1992) showing system to class hierarchical levels, and the proposed shoretype associations and the Nearshore Classification System which interfaces with the AHC at the class level.

8.1.1 Shore-Type Associations

To introduce the nearshore habitat data, the detailed nearshore substrate classifications were simplified to shore-type associations (modified from Todd et al. 1996). The purpose of the shore-type association here is to introduce, as an integrated unit, the more general characteristics of the interface between the epilittoral zone, the shoreline, and nearshore areas in geomorphological units which compartmentalize nearshore habitat.

Table 3. Ten simplified shoreline types were interpreted from the 6 Study Lakes at ELA.

Class 1	• Epilittoral area low slope organic bogs/boreal forest adjacent to crescent shaped shoreline, without a transgressive sand beach veneer. Nearshore area low slope, with limited shoreline berm, offshore typically deposition .
Class 2	• Epilittoral area grading from moderate to low slope with transition from boreal to fen, terminating at a crescent shaped shoreline embayment with sand beach veneer. Longshore material size gradients flank beach; offshore material gradients present.
Class 3	• Epilittoral area, shoreline configuration, and majority of nearshore substrate bedrock/boulder controlled; forms prominent point of land. Offshore material gradients absent on high slopes, present on moderate slopes. Classical headland structure
Class 4	• Epilittoral area moderate slope with mature boreal forest adjacent to meandering shoreline berm of boulder/cobble mix. Nearshore area moderate slope-gradational. Longshore material gradients absent.
Class 5	• Epilittoral area low slope organic bogs with sparse conifer. Shoreline configuration is erratic and of organic composition. Nearshore area low slope, with predominantly detritus substrate. Offshore and longshore material gradients absent.
Class 6	• Epilittoral area moderate slope with abundant exposed bedrock. Shoreline configuration and nearshore area bedrock controlled with or without pockets of boulder/cobble deposits. Nearshore area moderate slope. Longshore and offshore material gradients absent.
Class 7	• Epilittoral area high slope bedrock outcrop with discontinuous slope failures. Shoreline configuration approximately linear. Nearshore area high slope, talus boulders and fragments, non-gradational.
Class 8	• Epilittoral area high slope bedrock outcrop without slope failures. Shoreline configuration, nearshore area and slope bedrock controlled.
Class 9	• Epilittoral area low slope organic bogs. Shoreline configuration, nearshore area, and slope bedrock controlled.
Class 10	• Epilittoral and nearshore area convex with materials ranging from unconsolidated glacial tills, to large boulder lag deposits (Glacial deposit). Longshore and offshore material gradients absent. Slopes usually moderate, to high.

8.2 Sub-group Level Nearshore Area Substrate Classification

8.2.1 Lake 164

Lake 164 (Figure 15) has shorelines with the general characteristics described in classes 2, 4, 5, and 6. Classical examples of Class 2 shorelines exist as low gradient sand beaches (slopes 3-6 degrees) which lie adjacent to epilittoral fen bogs at opposite ends of the lake (on the northeast-south west axis). In the north embayment, the beach is bounded by Classes 4 to the west and 6 to the east; each shows areas of deposition as depth increases. The northeast shoreline (stations 150-400) is an erratic mix of boulder/cobble deposits with local bedrock interruptions along the reach. The south east shore at stations 627 and 800 also exhibits typical examples of class 1 embayments which occur only as minor features in the shoreline reach, but are sufficient to produce material size gradients and have slopes similar to other beaches. The south embayment is bounded by the nearshore deposition Class 5 in the south east corner where a small inlet enters the lake via low-lands (slope less than degrees). The west shoreline shows a Class 4 boulder/cobble typology with headland and embayments as only minor features. The western shoreline is interrupted by the outlet which forms an energetically quiescent back bay; organic shorelines and substrates predominate (Class 5) with slopes less than 2 degrees.

Figure 15. Lake 164 nearshore substrate distribution with pie chart indicating the 10 classes with the greatest areal coverage

The ten AHC sub-group classes with the largest areal coverage in low gradient Lake 164 (Figure 15 pie diagram) are dominated by detritus, sand, and their substrate combinations (63% of NSA). Although most of the lake appears geological from the lake surface, the subsurface characteristics reflect this low gradient basin with boulder cobble shorelines contributing only 12% areal coverage. Bedrock contributed about 4%.

8.2.2 Lake 165

Lake 165 is located immediately upstream and adjacent to Lake 164. Due to this proximity, Lake 165 has a similar substrate composition (Figure 16). Three shoreline reaches have a Class 2 beach composition: two are located at opposite ends of the lake (north west-south east axis), and also at the outlet which connects to the north beach of Lake 164. The north beach of Lake 165 and the outlet area to the west have slopes about six degrees, whereas the south beach is wider and more exposed with slopes less than three degrees. Although each of these transgressive beach features shows a relatively narrow margin of sand in the swash zone, the sand lens of the south-east beach is about twice the horizontal width of that in the north reflecting prevalent north-west winds. Each beach is bounded by areas of deposition in the offshore region. The northeast shoreline is Class 4 boulder/cobble composition with slopes from 15-20 degrees; a few Class 8 (granite) outcrops interrupt the boulder cobble berm and have slopes from 20-40 degrees. The southern end of this Class 4 reach grades to the low slopes representative of the south beach, and shows a concurrent decrease in size of bed materials (i.e. longshore material size gradient) towards the south-east beach. The lakes southern shoreline, which extends from station 0 at the west end of the beach to the lakes outlet, is mostly Class 4 structure which grades to sand offshore. This reach is interrupted by two Class 3 headland structures which separate a class 1 embayment (an embayment that has a geological swash zone bordered with a sand veneer below the water line). This embayment form is too confined to produce a crescent shaped sand beach at the shore, but does receive enough wave energy to produce limited offshore and longshore material size gradients. It also has a slope typical of beaches (i.e. less than five degrees) below the swash zone. Lakes 164 and 165 are the shallowest lakes of the series.

Lake 165

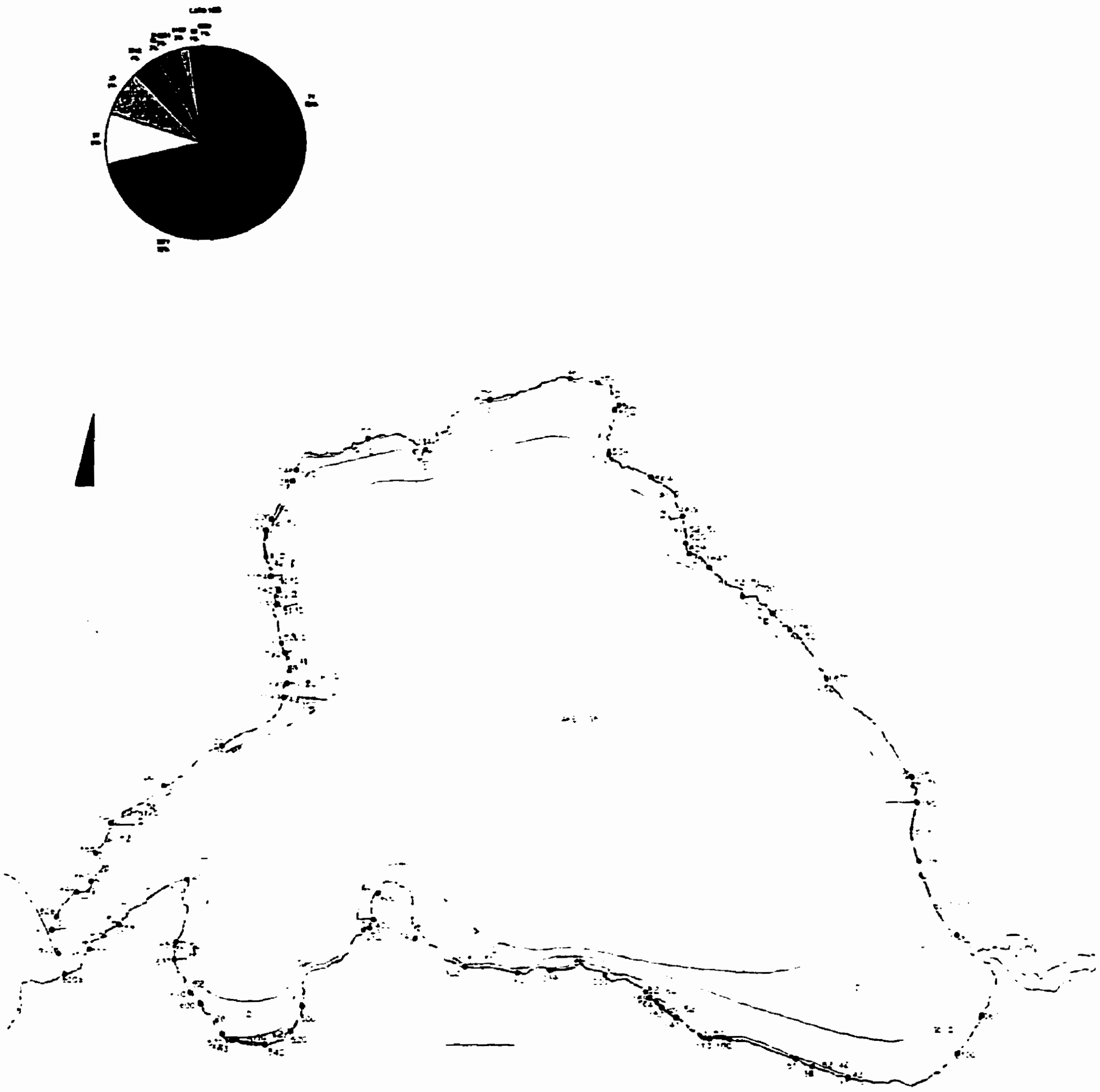


Figure 16. Lake 165 nearshore substrate distribution with pie chart indicating the 10 classes with the greatest areal coverage.

The sub-group classification for the ten most abundant classes in Lake 165 is shown as a pie diagram in Figure 16. The lake has a substrate composition similar to Lake 164, but nearly 80% of the nearshore area was dominated by sand, detritus, or combinations of these two classes. This would be expected as Lake 164 has a maximum depth which is about 70% of Lake 165, and a corresponding overall lower basin slope,. Boulder cobble shorelines contributed 8% to the NSA habitat structure which indicates that geological shorelines quickly grade into depositional environments. Lake 165 shorelines are about 8% bedrock; about twice that observed in Lake 164.

8.2.3 Lake 442

Lake 442, like the three remaining lakes of the series, is a deep lake basin. The southern shore is steep and non-gradational, while the north end is much shallower and has considerably more material and pattern diversity. Nearly 600 metres of the south nearshore area is high gradient (20-40 degree) non-gradational Class 4 boulder shoreline, which extends from the west side of the outlet to about the mid-point of the west shore at station 500. The slope of the substrate from station 500 onward decreases linearly along the shore as is evidenced by a Class 4 offshore and longshore material gradient. The north west corner of the lake is a class 1 material rimmed beach with slopes less than 6 degrees. The north end of the lake is predominantly class 4 (non-gradational) which is interrupted by a small class 5 deposition embayment, and is flanked to the east by a small class 1 site. The most notable morphology in Lake 373 occurs along the north east shore as a large class 10 sub-surface glacial boulder lag deposit, which extends as a non-gradational lobe into the main lake basin. The remaining shoreline reaches to the south on the east shore and are class 4 non-gradational shores containing slopes 12-20 degrees with class 8 bedrock interruptions where slopes approach 40 degrees. The lakes outlet is class 5 organic shores and depositional areas with large boulders in the central channel.

Figure 17. Lake 442 nearshore substrate distribution with pie chart indicating the 10 classes with the greatest areal coverage.

The ten most area abundant sub-group level substrate classes in Lake 442 are shown as a pie diagram in Figure 17. Lake 442 is dominated by detritus, with about 20% boulder cobble reaches, and has a relatively small proportion of sand. Lake 442 is the smallest of the study lakes, has the lowest surface wave energy, and an abundance of boulder cobble structural elements (20%). Lake 442 differs from lakes 164 and 165 primarily in its slope regime, and the availability of large materials which dampen the effects of wave energy. Most of the detrital classes were found in the north end of the lake at the outlet. Bedrock occurs as a substrate in combination with other aggregate materials, and totals 3% of the NSA.

8.2.4 Lake 373

The influences of relict processes on lake bed characteristics are evident in Lake 373; the lake can be divided into two distinct halves along the lake's long axis (Figure 18). Most of the western shoreline is geological or bedrock controlled whereas the eastern shoreline is composed of sand beaches and gradational boulder and cobble berms which grade to sand. The western shore north of station 1700 is geological (class 4 substrates with slopes from 20-26 degrees) with abundant class 8 bedrock interruptions where slopes approach 40 degrees. Between stations 1500 and 1700 on the west shore, a class 7 and 8 bedrock outcrop with a vertical cliff with slope failures and talus deposits lines the shoreline. The slopes of this reach range from 40 to 50 degrees. The east side of the lake basin is a boulder/cobble rimmed shoreline set on an expansive sand deposit. The boulder berm in the swash zone ranges in slope from 8-15 degrees, then meets the lower sand platform where slopes usually are less than 3 degrees but range to a maximum of six degrees. A prominent terminal moraine (Class 10) of glacial till on the north east shoreline underlies a homogeneous stand of red pine. At each end of the moraine, class 2 beaches are present which grade to silt in the offshore areas. The northern-most beach (station 2300) and the northwest west corner of the lake (station 2000) are class 2 pocket beaches with slopes < seven degrees. Lake 373's east sand beach is about the same scale and orientation as Lake 165's south east beach, and also has slopes of less than three degrees. The lake's inlet and outlet also are typical of low wave energy areas representative of Class 5 characteristics.

Figure 18. Lake 373 nearshore substrate distribution with pie chart indicating the 10 classes with the greatest areal coverage.

The ten most area abundant sub-group level substrate classes in Lake 373 are shown as a pie diagram in Figure 18. Although Lake 373 is the largest and deepest of the study lakes, the NSCS substrate classes at the sub-group level indicate that nearly 60% of the lake's nearshore habitat is sand with depositional characteristics. Much of the basin's western NSA is bedrock or boulder cobble combinations. The increased wave energy and its ability to regularly redistribute sand is indicated by the largest amount of sand (66%) in the lake series. Lake 373 was the only study lake that had abundant silt in offshore areas, originating from abundant glacial till in the watershed. Vertical bedrock cliffs dominate the western shore of the lake, but because these areas are high gradient they comprise only 2% of the lake's NSA. Most areas lack the detrital infill which was present in lakes 164, 165, and 442, due to higher slope and higher (and probably more frequent) mechanical surface activity. The main lake basin of Lake 373 has a habitat structure similar to that of the southern half of Lake 442; i.e. moderate to high slope with an abundance of aggregate materials.

8.2.5 Lake 377

The nearshore area of Lake 377 is dominated by boulder and bedrock. The northern shore and other shorelines of the main basin are bedrock and boulder controlled which is clearly indicated by a lack of headland and bay development in the lake's shoreline configuration. The configuration of most shorelines is typical of boulder berms with linear or meandering forms, or bedrock outcrops. The northern shore of Lake 377 (Figure 19) lies at the base of a large class 7 talus cliff with abundant slope failures; the shore is entirely large boulder deposits. The linearity of this shore reflects the shape of the parent material. This reach is approximately 700 metres long, moderate gradient (usually from 15 - 20, occasionally 25 degrees), with small and large boulders (non-gradational) to the 3 m depth. To the east of this talus reach, a very small embayment (class 1) marks a transition to a reach of class 4 shoreline which extends to the north-east inlet. The north east corner has an abundance of bedrock with boulder/cobble deposits (Class 6). The outlet is Class 4, due probably to a higher exposure than the other outlets of the other study lakes. The south east corner is a high gradient (38-50 degrees) class 8 bedrock outcrop lacking slope failures. The southern shore from station 2350 to 2550 is a classic example of class 4 non-gradational nearshore substrate. It is bounded to the west by a class 1 embayment with sand and detrital deposition and slopes characteristic of boulder rimmed pocket beaches (< 6 degrees). The south west shoreline reach extends well into the west arm of Lake 377 to about station 500. This reach is diverse with a mixture of Class 4, Class 8 bedrock interruptions, and Class 3 headlands, one of which is submerged. The west end of the lake's elongated arm is a complex mosaic of Class 5 organic shoreline (to the south with abundant detritus infill around cobble/boulder), and Class 4 shorelines (on the west and north part of the arm). The offshore properties in the western arm area are heterogeneous due to the presence of fluvial deposition from the main inlet and low slope and exposure, but includes small boulders, sand, and silt.

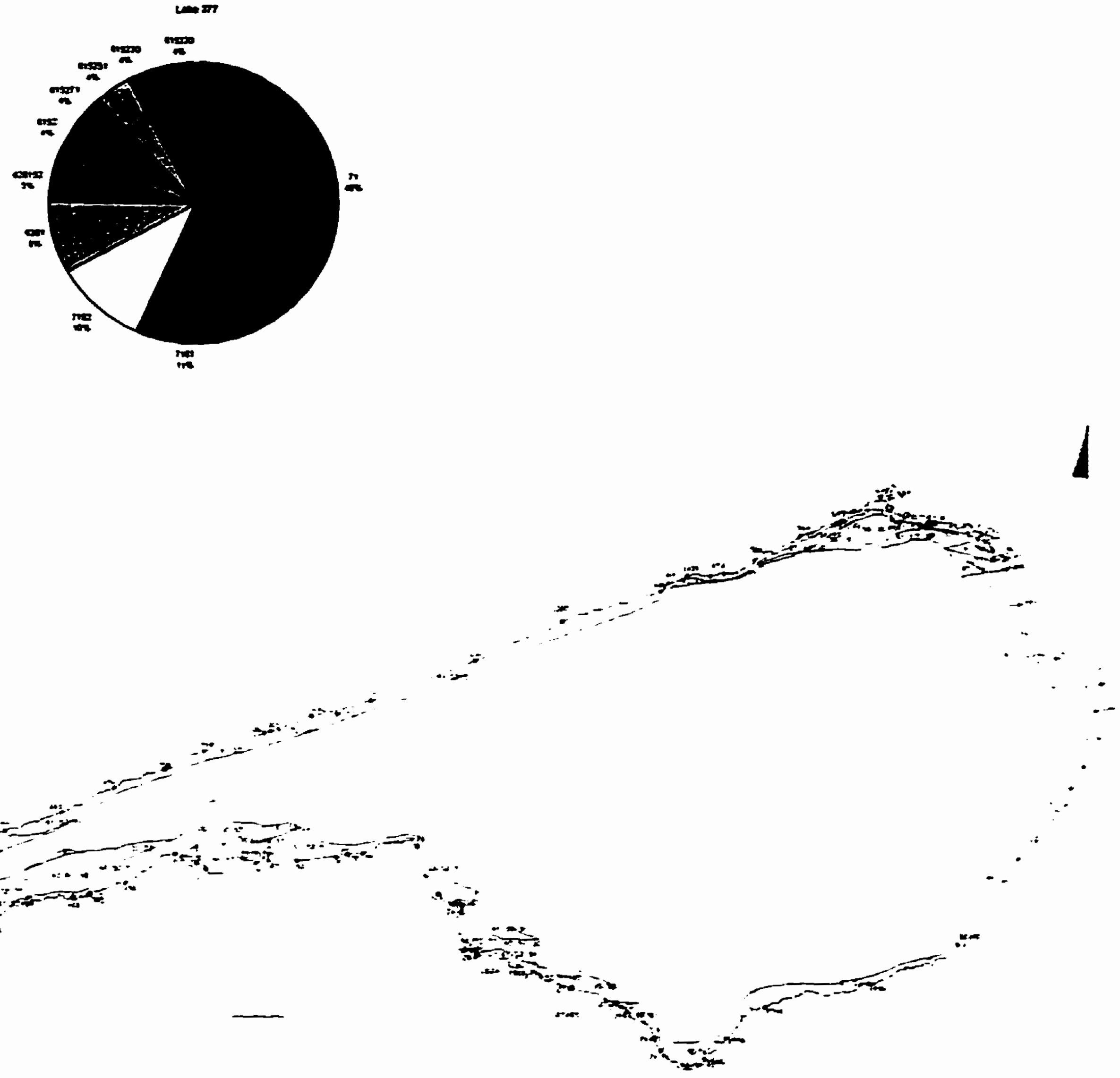


Figure 19. Lake 377 nearshore substrate distribution with pie chart indicating the 10 classes with the greatest areal coverage.

The ten most area abundant sub-group level substrate classes in Lake 377 are shown as a pie diagram in Figure 19. Detritus and combinations of detritus and boulder cobble total 67% of the NSA. Most of these classes are found in the low gradient western arm. The main lake basin NSA is mainly boulder and cobble combinations which total 33%.

8.2.6 Lake 226

Lake 226 is a deep two basin lake (Figure 20). The east basin has one small island (Class 8 north side, Class 6 south side), and a Class 4 area at the outlet on the south side of the eastern most bay. The southern shoreline in the east basin is Class 8 for 200 m then changes to Class 6 with scattered boulder deposits. A Class 1 deposition embayment with detritus overlaying a sand deposit (station 450) is flanked by a class 4 reach to the east, and a Class 8 bedrock face (30 degree slope) to the north. The south side of the narrows area is a gradational class 4 reach. It is bounded to the west by a Class 1 embayment with characteristics similar to station 450.

The west basin's south shore begins as a Class 9 shoreline (bedrock controlled), with scattered boulders and cobble. Much of the southern shore to the west is class 4 gradational with a few Class 8 bedrock outcrops. Slopes are variable and range from 18-30 degrees. The west end of the lake is a Class 2 beach with a transgressive sand veneer which ends abruptly to the north at the base of an active Class 7 talus slope. The west beach veneer grades to areas of flocculent deposition as water depth increases. This beach has slopes of about seven degrees or less, with the steeper slopes nearest the swash zone. The talus deposit area near station 1500 is non-gradational with large boulders and angular fragments, and a range in slope from 23-40 degrees. The shoreline reach to the east at station 1600 begins as Class 4 but changes in the northeast direction as a longshore material size gradient reduces the material size to gravel which again changes to a boulder berm at about station 1810. The offshore area between these two stations is a large gravel/sand flat. The north and north east shorelines of the west basin show pronounced material sorting which extends well below the lakes' present swash zone (stations 1850 -1900). These probably are relict features from fluvial processes during periods of glacial recession from a large lake to the lake's north east.

The northern shore of the east basin is a gradational Class 4 shoreline which grades from boulder to cobble and gravel at a moderate slope. The north east embayment (station 2550) is a detrital area of deposition over sand and bordered with a geological shoreline (Class 1). The east end of the lake is Class 7 with angular materials deposited in the nearshore area.

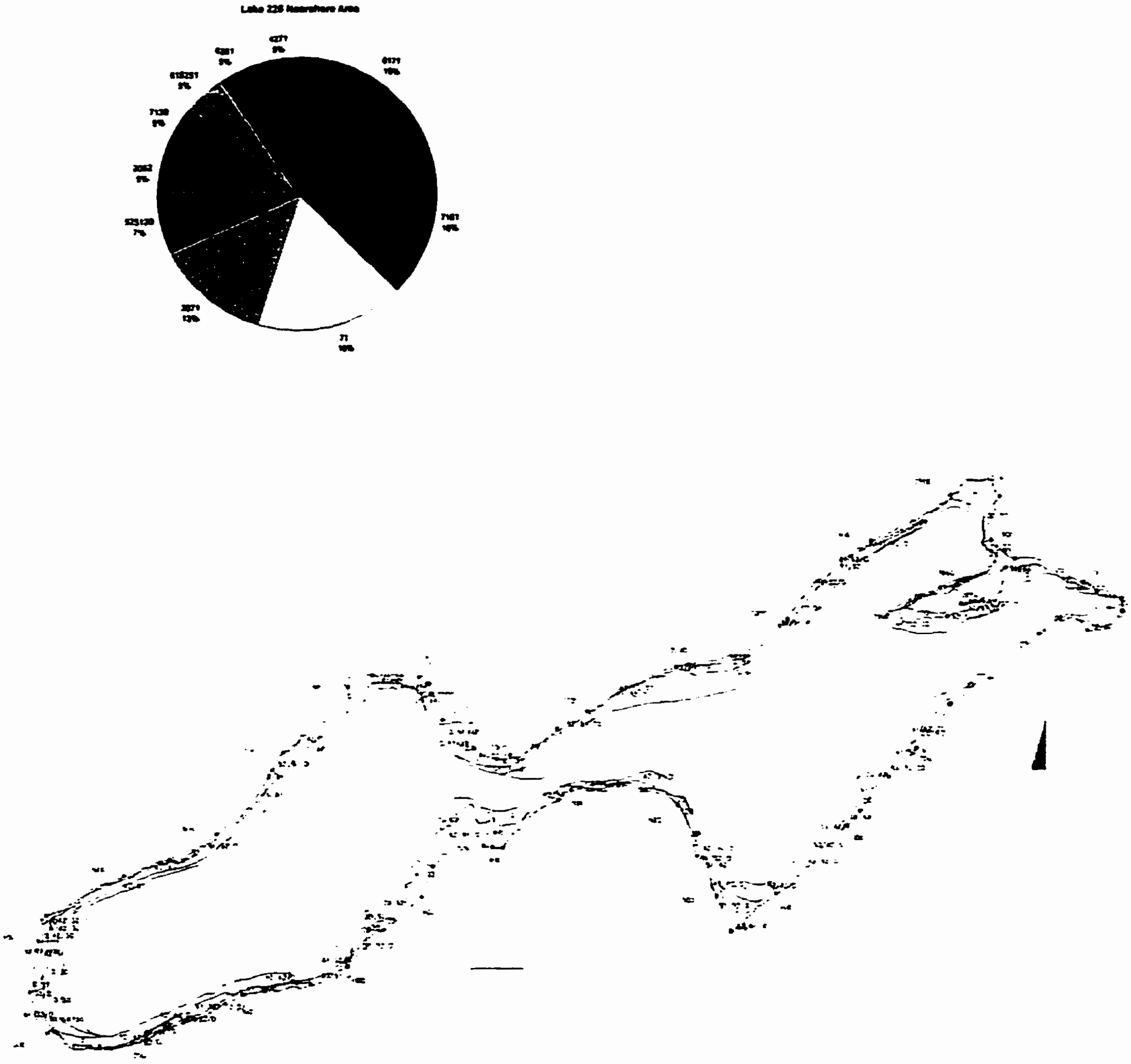


Figure 20. Lake 226 lake-wide substrate distribution; the central area is the Profundal zone of perennial deposition. The pie chart indicates the 10 classes with the greatest areal coverage.

The ten most area abundant sub-group level substrate classes in Lake 226 are shown as a pie diagram in Figure 20. Deposition occurs in about 73% of Lake 226 which is the highest of the study lakes. Lake 226 is steep sided with an erratic shoreline configuration. The higher proportion of depositional area results because Lake 226 was mapped in its entirety which includes the profundal area, and also from the presence of low exposure back bays. This included the area of discontinuous deposition below the 3 m contour to the offshore zone of deposition which was not sampled in the other lakes. The boulder and cobble combinations which form the shoreline berm in much of Lake 226 have a more equal representation than found in most of the other lakes; each is about 5%. Bedrock availability in Lake 226 is about 13% of the NSA.

8.2.7 Sub-group Level Substrate Assessment

The total NSA area surveyed in the six lakes was 27 Ha., with a total shore length of 15.9 km. The study lakes each had shoreline lengths of 3 km or less, with offshore transect distances which ranged from 0 to nearly 60 m. Each 100 m reach of shoreline was classified and documented in about an hour. The amount of effort required was dependent on the complexity of substrate pattern for each reach. Most lakes were surveyed in less than two days equating to about 14 hours per day. Lakes 373 and 377 were each classified in less than 3 days. The two surveys at Lake 226 were completed in 4 days to a total depth of 7 meters. All lakes other than Lake 226 were mapped to a maximum depth of 3 meters. Table 4 describes some selected morphological and areal data for the six study lakes.

Table 4. Selected morphological characteristics of the study lakes. L = shoreline perimeter length (m), SLD = shoreline development (dimension less index; Kent and Wong 1982), # classes and polygons indicated for substrate, ZM= maximum depth (m, from McCullough and Campbell, 1993), limit of substrate data indicates the substrate data terminated at the 3 m contour or 30 m horizontal distance offshore.

Lake	Lake Area	NSA	Offshore Area	L	SLD	# classes	# polygons	Z_m	Limit of Substrate Data
									m depth\horiz. distance
164	20.44	4.89	15.55	2611	1.63	26	71	7.1	3
165	18.38	5.07	13.30	2376	1.56	29	74	4.6	3\30
226	16.38	5.15	11.23	2986	2.08	34	113	15	complete survey
373	27.94	4.73	23.21	2852	1.52	31	74	20.8	3\30
377	24.62	4.67	19.96	3071	1.75	27	77	17.9	3
442	15.27	2.62	12.65	2045	1.48	20	40	17.8	3

8.2.8 Inter-lake Comparison of Substrate

8.2.8.1 The Frequency of Substrate Class Occurrence among Lakes

Eighty five of the possible 221 combinations of classes were found among the six study lakes. Classes 71 (detritus), 61/52/51, and class 20 (bedrock) were common to all six lakes and covered 25% of the combined NSA's. Three other classes (62, 30, 30/71) were common to five of the six lakes and increased the cumulative total area to nearly 50 %. Seven and 10 additional classes were common to four and three of the study lakes, respectively. The 23 most frequent classes among lakes covered 82% of the combined nearshore area. These results are found in Appendix C by class, lake, and area.

The 20 substrate classes with the greatest areal coverage combined among lakes is shown in Figure 21. Although the study lakes appear to be dominated by geological material at the lake surface, about 40% of the area surveyed were bi-typic detritus/sand mixtures; the mono-typic detrital class area exceeded 10%. The tri-typic boulder-cobble class 61/52/51 which was evident in all lakes and covered several kilometers of shoreline combined, had only about 11% combined surface area coverage because boulder/cobble shorelines are moderate to high slope which form narrow nearshore margins when compared to low gradient sandy or depositional areas. Lake 373 contained the single largest proportion of sand substrates in the lake series, followed by Lake 164 and 165. Most other classes each equaled 2% or less of the combined NSA. Mono-typic bedrock and sand classes each occupied 5% of combined area. Pure sand is present only in the narrow swash zone of beaches in these small lakes. Bedrock usually was high gradient with a corresponding low lake surface area. Appendix D contains these results in tabular form.

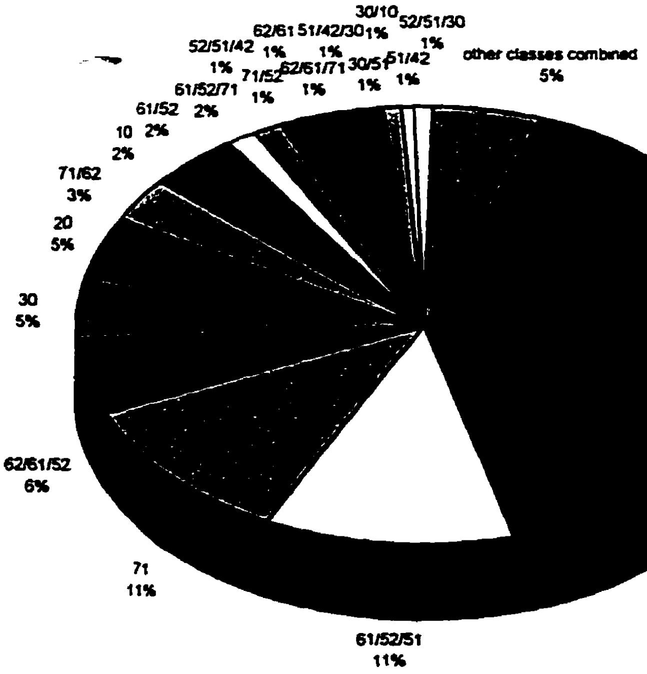


Figure 21. The 20 substrate classes with the greatest areal coverage combined among the six study lakes.

The twenty classes with the largest spatial coverage represent between 45 - 94% of the NSA for each lake (Table 5 below). The totals for lakes 164, 165, and 226 each exceeds 90%. This indicates general similarities exist among their nearshore substrate characteristics, despite lakes 164 and 165 being much shallower basins. Each of these lakes has a diversity of slope and material abundance with crescent shaped beaches. Lake 377, 373, and 442 showed reduced representation (88, 70, and 45% respectively) in the top 20 classes by area. The habitat structure of each of these basins is strongly influenced by the parent geomorphology. Lake 377 has nearly one kilometer of talus deposit shoreline, and lakes 442 and 373 have dominant structural elements remnant from glacial deposition. Lake 373 also has a near vertical granodiorite cliff which spans 200 m of the lake's western shoreline. As each of these habitat features is macro-scale relative to lake size, and has simple structural characteristics, the effect is to reduce the number of classes present (see section: trends in habitat diversity). Thus, as the formative origins of large parts of each of these NSA's has resulted in three different types of deposits, talus, boulder lag, and sand dominated till, major differences in habitat structure would be expected. This indicates that the structure of nearshore habitat in the area is strongly dependent on the heterogeneous nature of material distribution from historic processes.

8.2.9 Sub System Level Nearshore Substrate Comparisons

8.2.9.1 Trends in Substrate Diversity

The substrate diversity in the NSA of a lake results from a complex set of physical habitat forcing variables. Substrate diversity, as indicated by the number of substrate classes and polygons, is inversely related to water depth among all study lakes (Figure 22 and 23 respectively).

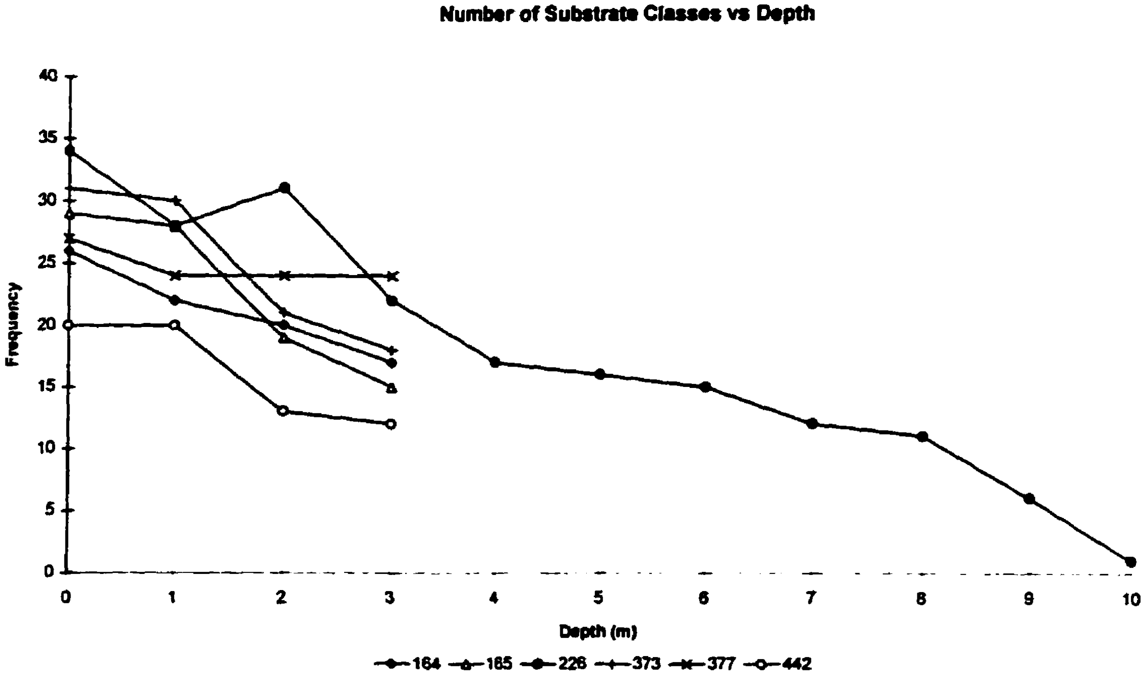
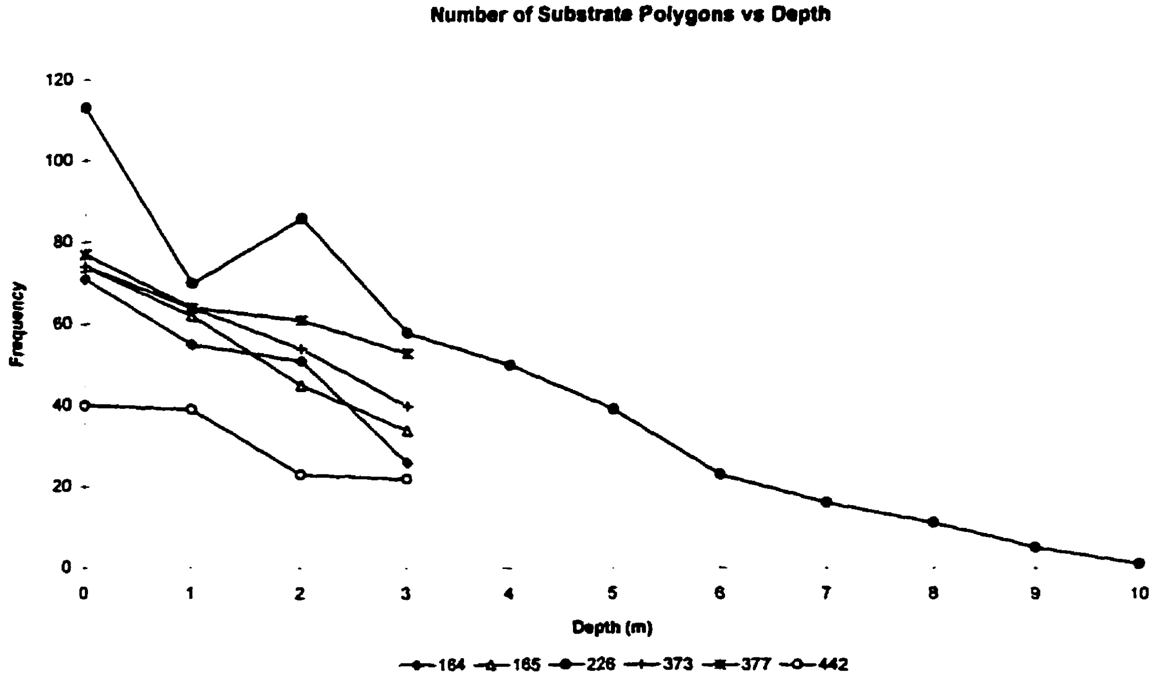


Figure 22. The number of substrate classes per depth stratum (metres) for the study lakes. Lakes 164, 165, 373, 377, and 442 surveys extended to a depth of three metres; the Lake 226 survey mapped to the lakes' maximum depth of 16 m. In Lake 226 only the profundal class was found at depth of 10 m or greater. Data points at depth = 0 indicate the total number of classes for all depth strata combined for each NSA.



Number of Substrate Polygons vs Depth

Figure 23. The number of substrate polygons per depth stratum (metres) for the study lakes. Lakes 164, 165, 373, 377, and 442 surveys extended to a depth of three metres; the Lake 226 survey mapped to the lakes maximum depth of 16 m. Only the profundal area was found at depth of 10 m or greater. Data points at depth = 0 indicate the total number of polygons for all depth strata combined for each NSA

The number of classes and polygons found in each NSA varied among the lakes and probably is dependent on the cross-linked effects of lake size, the site specific parent geomorphology, and glacial action on the landscape. These confining factors set limits on the large scale material availability, the wave energy for the sorting of bed materials, the amount of NSA that is bedrock controlled, and also the slope regimes of the basin below the wave base.

The effects of lake size and glaciation are evident in the Lake 442 class and polygon data. This lake is nearly half the size of the largest lake in the series (increasing the likelihood of homogeneous material availability), and also is the site of plentiful boulder lag deposits. Consequently, the number of classes and polygons is reduced due to confinement, deposition, and the abundance of high slope shores which are structurally simple (non-gradational). In most lakes, the number of classes at the 2m depth contour is reduced (relative to the 1m depth) because the 2m depth is below the wave base in most areas of these lakes. The lower class frequency at the 2 m depth or below indicates the classes which are derived from parent geology or glacial deposition; the gradational classes in these lakes rarely exceed 2m depth. For example, the eastern shore of Lake 373 is gradational from a boulder and cobble shoreline berm to a sand platform, and shows a corresponding decrease in number of classes. Lake 377 did not show fewer classes below 1m depth because most of this nearshore structure is forced by parent geology, and glacial action. Lake 442, with its relatively shallow and gradational north end and steep sided and non-gradational south end, shows the loss of gradational classes at 2m, but maintains a similar class and polygon number below this depth due to the non-gradational structure in the south end (and also on the boulder lag deposit). The complete basin data for Lake 226 indicate that the number of classes and polygons decrease linearly to the offshore zone of deposition.

Although the study lakes range in size (almost 2 x; which might explain why some lakes have more classes or polygons), no discernible trend was apparent when lake size was plotted against the number of classes or polygons. This indicates that substrate diversity of the study lakes in this region is dominated by the erratic results of past glacial processes.

However, a lake's contemporary shoreline configuration archives the summation of past and present landform and lacustrine process on lake NSA structure. The interpretation of shoreline configuration can indicate the origin of the landform (parent geology vs. lake driven substrate form), and consequently, its structural composition. The study lake shoreline configurations can be divided into 5 types. Linear forms indicate shores or vertical cliffs of bedrock, or near the source of talus deposits. Shorelines that have a slight meandering form are predominantly a boulder and cobble combination, and usually show offshore material size sorting. Prominent headland and embayment shorelines feature crescent shaped shores associated with beaches, areas of transition (which indicate the change from shoreline stability at the headland to unstable condition on the beach and the corresponding longshore material sorting), and the offshore or non-gradational structure of the moderate to high slope headland. Highly irregular shores are found only in areas with low wave exposure.

The sub-group level maps demonstrate that substrate structure at a shoreline reach scale is simple when geology or glacial action are the substrate-forming variables. Substrate structure is more diverse when materials are redistributed due to wave action, in either offshore or longshore directions. Substrate diversity is greatest in reaches that encompass well developed headlands and bays. The terminus of the headland generally is non-gradational, which changes to an offshore material gradient as depth decreases towards the embayment. As a wave progresses towards the embayment the wave energy is further diminished, and the offshore material gradient at moderate slope changes to a wedge-shaped longshore material gradient with decreasing offshore extent and slope until its terminus where the crescent shaped beach begins. Wave-driven substrate structure therefore, tends to be more patchy with relatively small substrate units due to a rapid decrease in mechanical energy in either offshore or longshore directions. In comparison, parent geology and glacial process produce more homogenous and much larger substrate units than those formed by waves in small lakes. These reproducible patterns in nearshore habitat structure, which vary from linear and simple to convoluted and diverse, support the use of the Shoreline Development Index (Kent and Wong 1982) to indicate shoreline and littoral area complexity.

Consequently, it was not surprising that the number of substrate classes and polygons among lakes was correlated to the shoreline development (Figures 24 and 25 respectively).

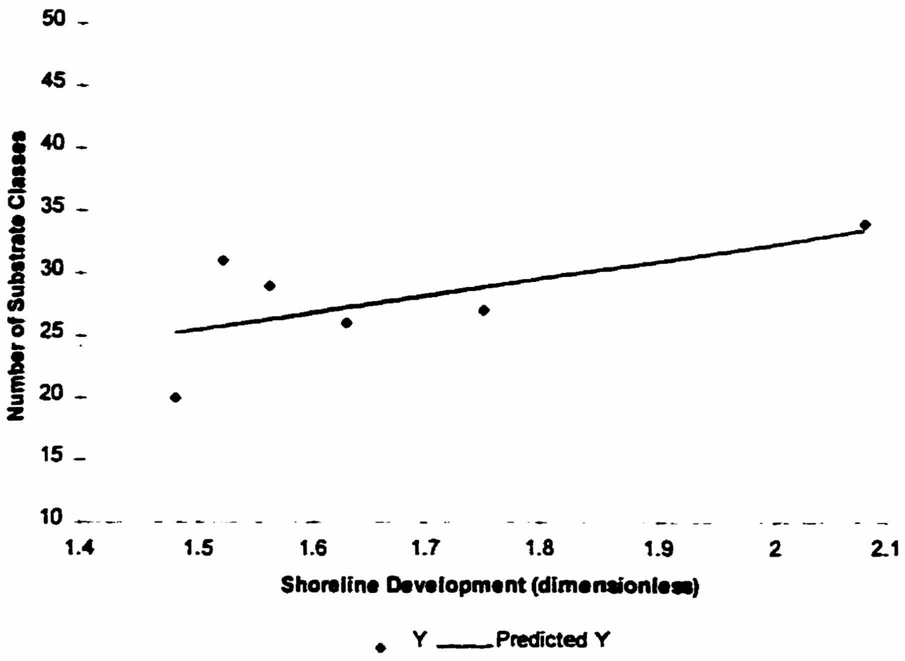


Figure 24. The number of substrate classes vs. the Shoreline Development index. Regression equation: $y = 13.857x - 4.691$, $r2 = 0.42$, $n=6$.

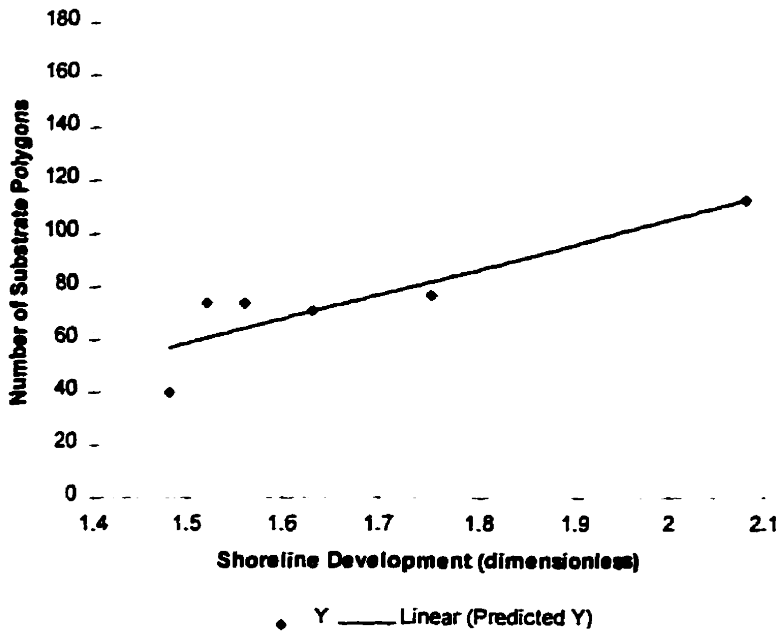


Figure 25. The number of substrate polygons vs. the Shoreline Development index. Regression equation: y = 92.423x - 79.513, r2 = 0.78, n = 6.

8.2.9.2 Total Areal Coverage by Substrate Class

When the areal coverage for each of the classes was summed at the sub system level of the AHC System and plotted as a frequency histogram, the study lakes can be divided into two groups based on nearshore substrate class abundance (Figure 26). All lakes showed a nearly normal shaped frequency distribution from classes 41 (gravel) to 62 (lg. boulder), but Lakes 442 and 377 have a predominance of larger materials, primarily cobble and boulder; the detrital, sand, and silt classes which are found on low slopes were relatively infrequent. In contrast, lakes 164,165, 373, and 226 showed frequency spikes in the detrital and sand classes with diminished representation for gravel, cobble, and boulder. Lakes 226, 377, and 165 showed frequency spikes for bedrock. Lake 373 was the only lake with a notable amount of silt found in the offshore area of deposition. This was due probably to the availability of silt as a constituent of the till deposited in the Lake 373 drainage basin.

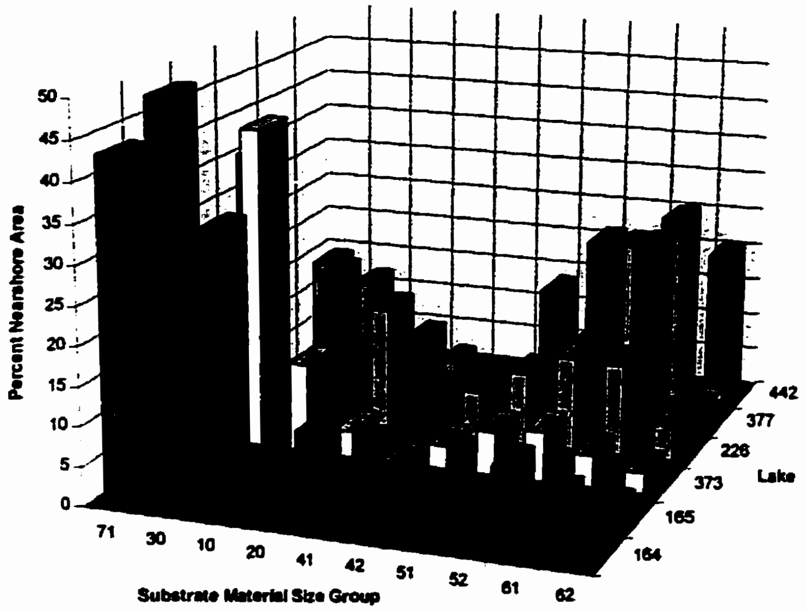


Figure 26. Percent areal coverage for each substrate class summed at the sub system level of the AHC System.

Part 2

8.3 Modeling Fetch Distance

Preliminary investigation of the fetch distance models on the Southern Indian Lake raster image included the production of fetch maps and histograms. The results for sampling frequency are presented first, followed by a description of selected properties of surface waves for the study lakes.

8.3.1 The Effect of Sampling Frequency on Fetch Patterns: the sensitivity trials

The effect of sampling frequency on fetch model results for the maximum, and mean fetch estimates, a series of images was produced at each level of sampling frequency (i.e. 4, 8, 20, 40, 60, 180, 360 axes). Visual inspection of the images and frequency histograms were used to assess the differences in fetch results for each sampling frequency.

8.3.1.1 Maximum Fetch Distance

A maximum fetch distance estimate results from the extraction of the largest value from the sampling set. The effect of sampling frequency on maximum fetch is shown in Figure 27. The distribution of maximum fetch became progressively smoother when sampling frequency was increased from 4 to 20. A further increase in sampling frequency, however, also increased the range of distance observations from which the maximum value was extracted. This increase in range produced a corresponding increase in the spatial heterogeneity of fetch among contiguous cells in some areas of the Southern Indian Lake image. Thus, increased sampling frequency decreased the amount of generalization for the maximum fetch pattern. All levels of sampling frequency for the maximum fetch images exhibit a spatial heterogeneity of fetch values which exceeds that of the corresponding mean, or minimum fetch. This artifact, however, will not be present in lakes with simple shoreline configurations and few islands.

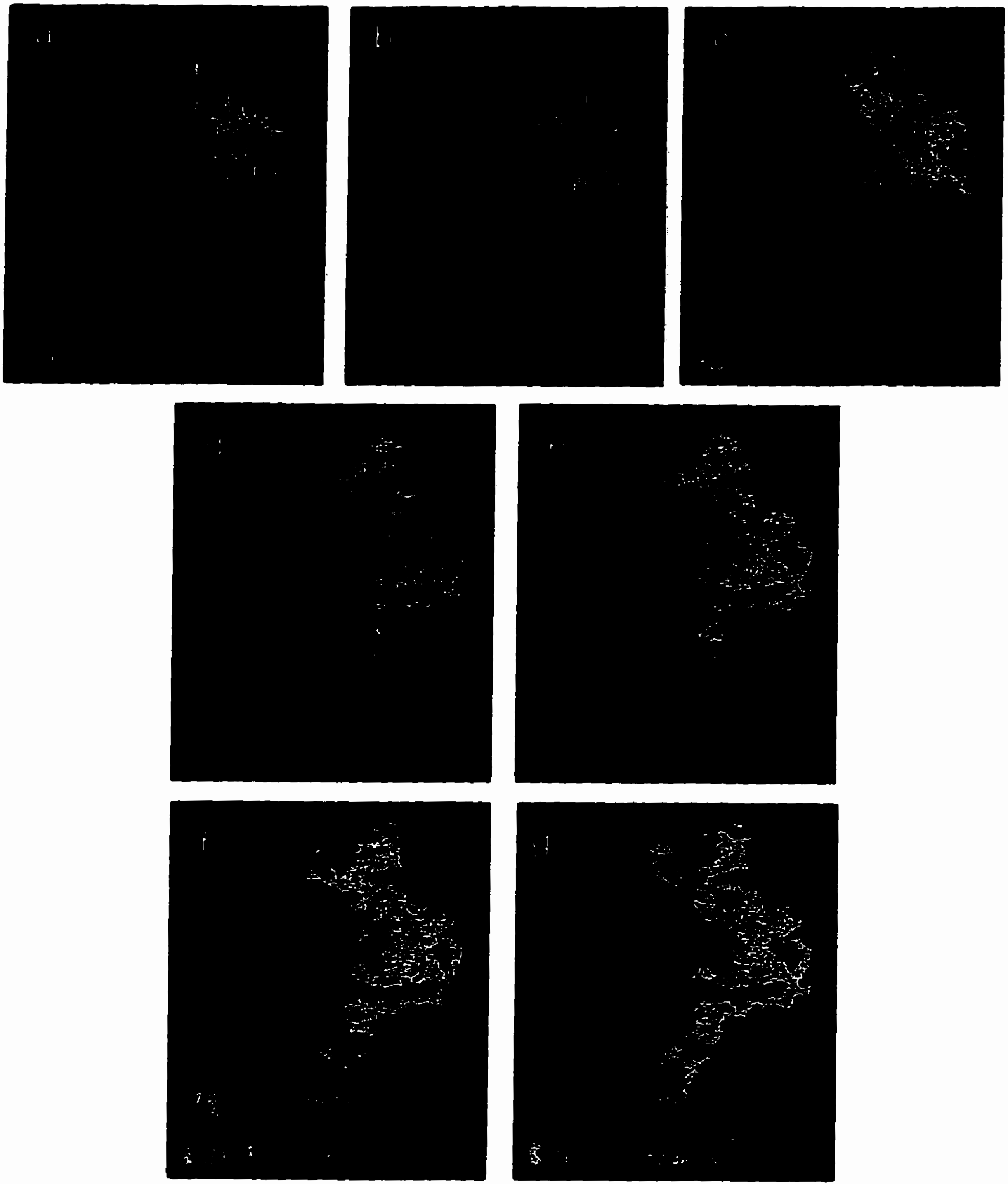


Figure 27. Maximum fetch distance four southern Indian Lake using 7 sampling frequencies: a) 4, b) 8, c) 20, d) 40, e) 60 f), 180, g) 360.

Histograms of maximum fetch (Figure 28) showed a shift from a left skewed unimodal distribution to a bell-shaped normal curve. Increased sampling frequency, starting at the 20 axis model, also showed an increase of spikes at higher frequencies. This occurred because the use of more measurements increased the probability that some axes may make measurements to disparate parts of the lake through groups of islands or through small narrows, which are only possible in specific directions.

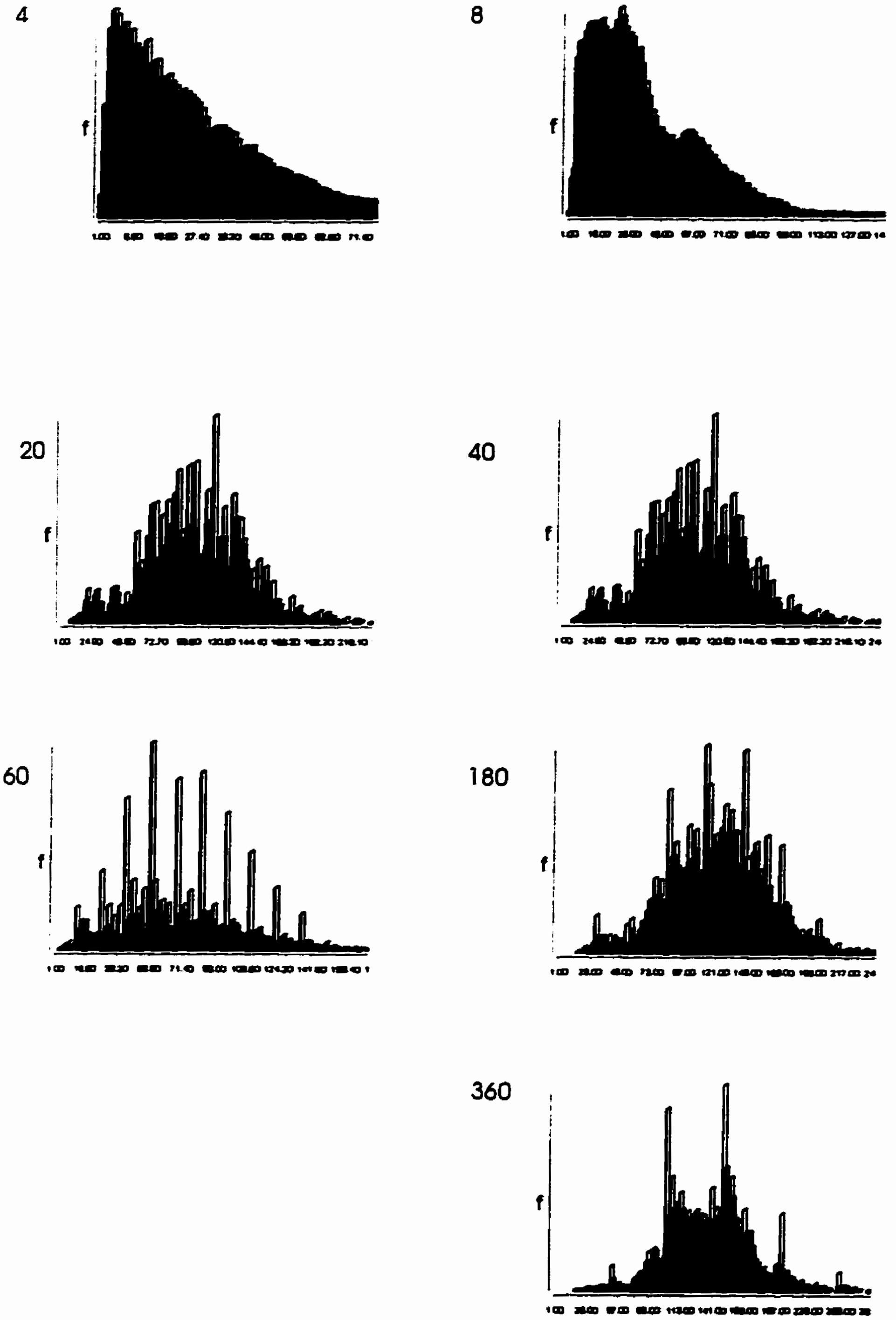


Figure 28. Frequency histograms for maximum fetch distance of Southern Indian lake at 7 sampling frequencies.

Maximum fetch distance is well suited to predict the maximum wave conditions on lakes and shorelines. Maximum fetch may not effectively describe the dominant hydraulic regime in lakes with erratic shorelines and back bays because measurements made between tightly grouped islands or narrows may produce fetch values of several times the magnitude of the other fetch measurements. Although maximum fetch results are more spatially variable, the maximum will be least likely to under estimate hydraulic conditions.

8.3.1.2 Mean Fetch Distance

Mean fetch distance characterizes the location of each lake cell as an average distance relative to a maximum of 360 other shoreline cells. The sampling frequency controls the accuracy of the fetch pattern. The sensitivity analysis for Southern Indian Lake shows that the patterns of fetch change from a relatively coarse spatial distribution with distinct boundaries visible along the axes measured, to a progressively smoother pattern as sampling frequency is increased to 360 axes (Figure 29). The use of four axes in the estimation of mean fetch shows that offshore areas have values that are larger than the values of nearshore areas. However, the dominant spatial pattern in this map results from the interaction between the number of axes used, and the shoreline configuration of the lake. The 8 axis model smoothes the fetch pattern slightly, but the detailed shoreline of the lake continued to reveal the program's sampling design as hard boundaries. Such dramatic changes in fetch value do not simulate the viscous and refractive properties of surface waves observed in lakes. Consequently, a higher sampling frequency (e.g. 60, 180, 360) would be preferable in most applications, especially in lakes which have a high shoreline development index. The mean fetch distance models which implement fewer measurements may under or over-estimate fetch for some cells of the image, depending on the distribution of land relative to that cell.

Figure 32. Mean fetch distance for Southern Indian Lake using 7 sampling frequencies: a) 4, b) 8, c) 20, d) 40, e) 60, f) 180, g) 360.

Increased sampling frequency (60,180,360) measured the shoreline configuration more effectively as the "hard boundaries" (shown in the 4 and 8 axis results) were smoothed from the use of a mean collected from a more complete set of measurements (Figure 29 d, e, f). The smoother fetch patterns evident in the 180 and 360 frequency trials do not underestimate fetch due to incomplete directional sampling, and are superior spatial models because smooth changes in fetch value can simulate wave refraction and also wave energy gradients along shorelines.

The effect of sampling frequency on the distribution of mean fetch is shown as a frequency histogram in Figure 30. Low sampling densities (i.e. 4, 8) produce a skewed distribution, whereas the 40 to 360 axis models show a progressive positive shift in the mean frequency (range 12 - 26 distance units) which produce a more normal shaped distribution. Increased sampling frequency measured the lake basin configuration more precisely; this is evident in the histogram series as a change from a unimodal distribution in the 4 and 8 axis models to a multi-modal distribution at higher levels of sampling frequency.

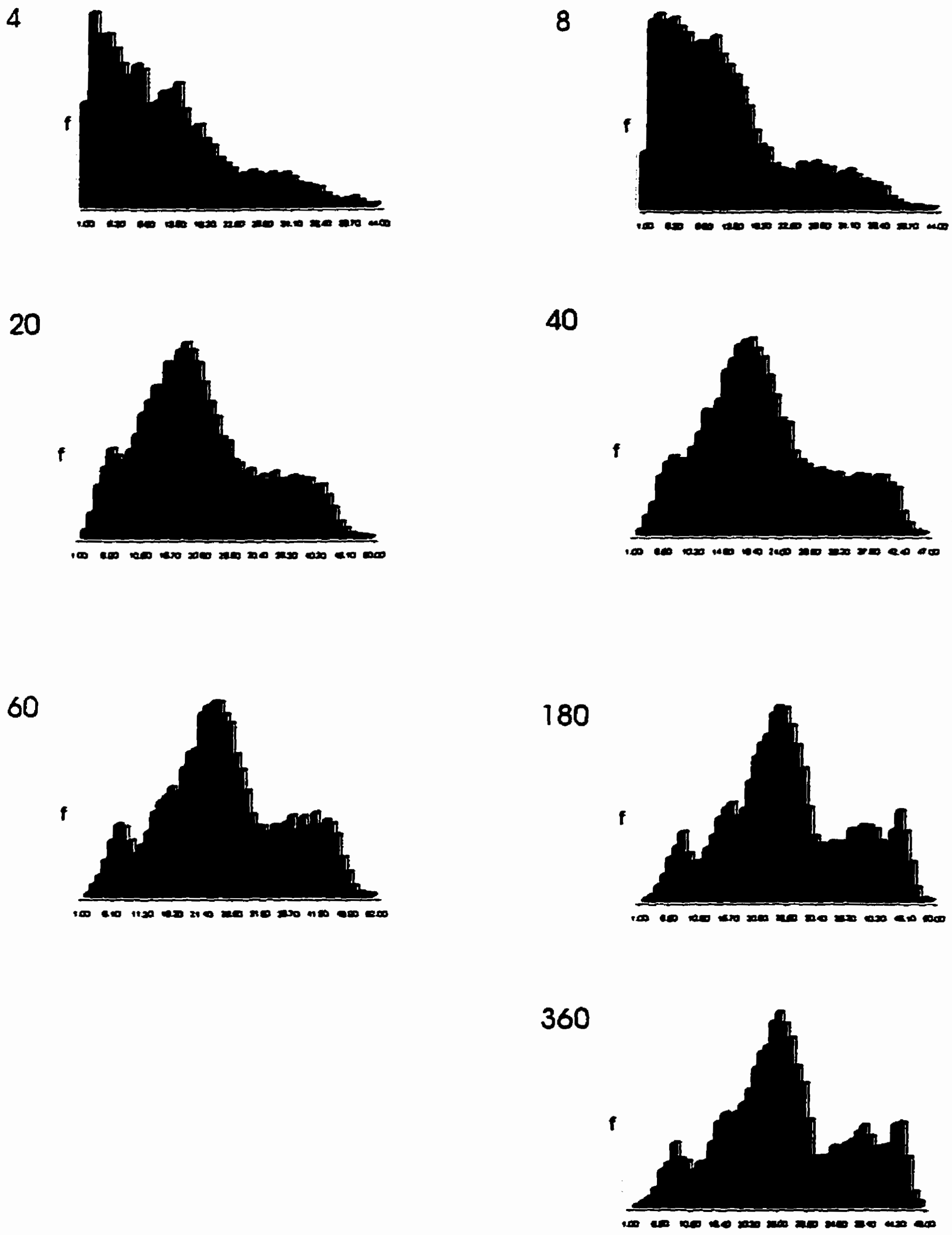


Figure 30. Frequency histograms for mean fetch distance of Southern Indian lake at 7 sampling frequencies

Mean fetch is ideal for use in physical habitat models to compartmentalize areas of lakes to delineate offshore/nearshore/back bay zones. The model is a good descriptor for estimates of exposure, and consequently will also provide a means to model shoreline energy gradients in embayed shorelines.

8.3.1.3 Effective Fetch Distance

The pattern of effective fetch in Southern Indian lake is shown in Figure 31 from three angles: a) 315, b) 270, and c) 90 degrees. The cosine-integrated result of effective fetch produced smooth fetch patterns which is probably the best simulation of wave refraction around shoreline features when compared to maximum and mean fetch.

Figure 31.The pattern of effective fetch in Southern Indian Lake from three source wind angles: a) 315 degrees, b) 270 degrees, c) 90 degrees. Cosine smoothing appears to simulate wave refraction around headland and groups of islands, as well as energy gradients along shorelines.

The pattern of effective fetch in Southern Indian Lake showed smoothing sufficient to simulate wave refraction around headland and groups of islands, as well as energy gradients along shorelines.

Summary

The fetch results for Southern Indian Lake improved as the sampling frequency was increased. The greater the sampling frequency, the higher the probability that the fetch estimate approaches the true value. A lower sampling frequency reduces the accuracy of the fetch estimate, as it leaves some number of possible wind axes unmeasured. The accuracy of fetch pattern is intimately coupled with sampling frequency and the configuration of a lake's shoreline.

Insufficient sampling frequency can be recognized by the presence of "hard boundaries" in the fetch patterns of the map which are indicated by where fetch values show sudden changes. These hard boundaries appear linear and do not simulate the properties of waves commonly observed in lakes. The flexibility of sampling frequency in the fetch distance program's can be used to determine which level of generalization is most appropriate for each application. Lakes with simple shorelines will have similar results across all sampling frequencies per model, but lakes with more convoluted shores require more detailed spatial sampling that can be achieved only at higher sampling frequencies.

Maximum and mean fetch models in the study were applied on Lake 226. Lake 226 was chosen for analysis because the entire lake area was mapped including the boundary of offshore deposition. This allowed a comparison of the predicted mud EBD and observed mud DBD, and also to demonstrate the effect of slope on material redistribution.

Part 3:

8.4 Process Modeling: Integrating Physical and Hydrodynamic GIS models

The distribution of maximum fetch using a sampling frequency of 360 is shown in figure 32.

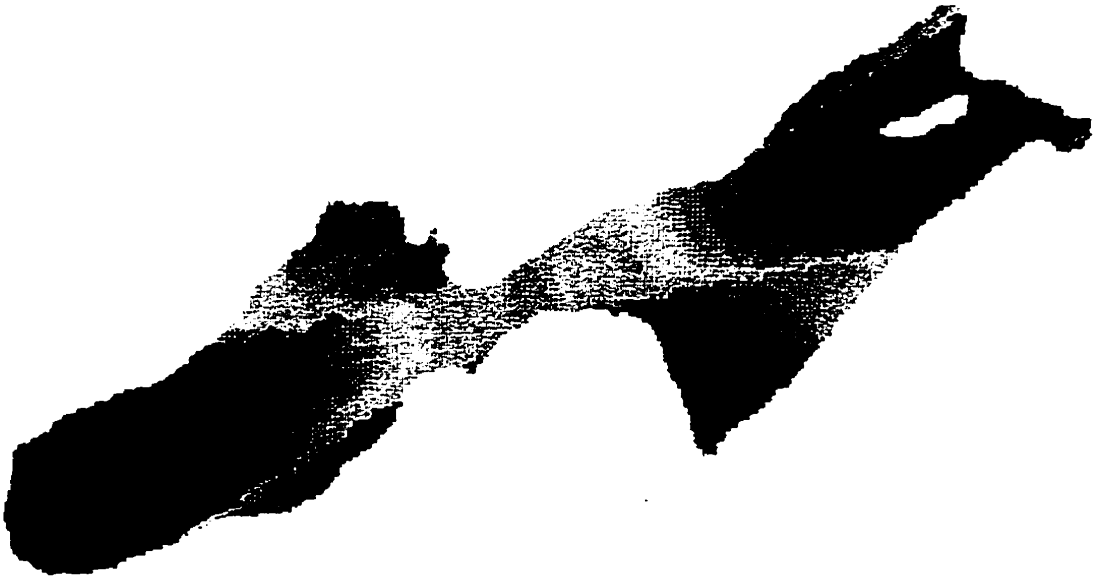


Figure 32. Maximum fetch for Experimental Lake 226 (sampling frequency =360).

The predicted mud EBD was shallower than expected in low gradient environments with high exposure. Also, in areas of reduced exposure, the predicted mud EBD indicated areas of erosion where deposition occurred.

The maximum depth to the wave base for Lake 226 was estimated to be 1.68 m. The mud DBD was found at a depth below that of the mud EBD for most of the lake, even on the low gradient beaches where both boundaries coincide (Rowan 1992). Such results would be expected in areas of moderate to high slope because gravity will redistribute materials to depths below the mud EBD.

The estimated mud EBD and the observed mud DBD were nearly coincident (Figure 33) for areas with slopes less than 10 degrees. Thus, in Lake 226 the critical slope threshold which increases the depth of the mud DBD below that of the mud EBD is approximately 10 degrees.

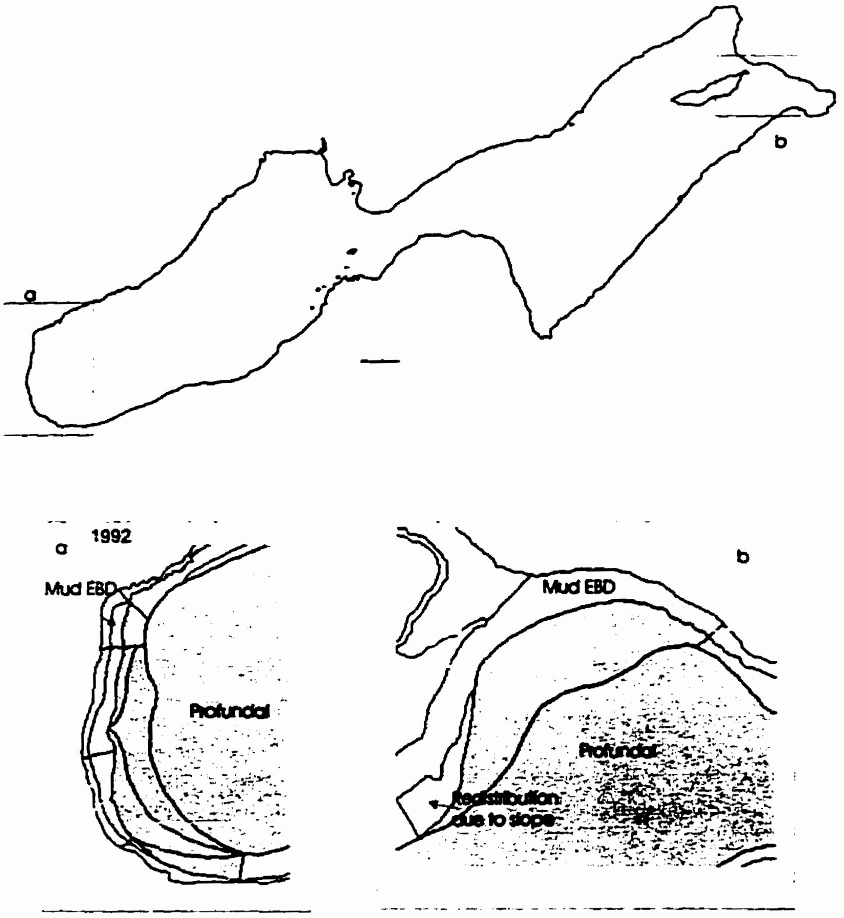


Figure 33. The predicted mud Energy Boundary Depth (mud EBD) for experimental Lake 226. a +b windowed regions showing very close correspondence between the predicted mud EBD and the observed mud deposition Boundary Depth (mud DBD- also called the profundal zone). The margin between the mud EBD and the mud DBD in frame (b) also shows the effect of slope (>= 10 degrees) in sediment redistribution.

The nearly coincident boundaries of the predicted mud EBD and the mud DBD also suggests that maximal wave conditions are the formative conditions on Lake 226. Although sub maximal waves were shown to provide the maintenance of the mud DBD on the mid-to-large sized lakes studied by Rowan et al., small lakes in the shield may have reduced wind velocity and wave properties due to local topography. These topographic effects suggest that wave properties derived from maximum fetch are more appropriate for use in small lakes than are critical wave heights.

The second concern regarding the use of maximum fetch in the prediction of the mud EBD in Lake 226 included erroneous results for five small areas of deposition with low exposure (Figure 34). These confined locations do not exhibit erosion shoreline characteristics due to a confinement and aspect which does not face the predominant wind directions. The prediction of erosion in these areas resulted because maximum fetch assumes that the wind will occur in all directions with equal proportion and magnitude. Although this bias does not appear to be unreasonable for most other areas of Lake 226 due to the close correspondence of the observed and predicted mud DBD's, it is an oversimplification of the site conditions in secluded back bay areas.

Figure 34. The areas of Lake 226 where erosion, transport, and deposition occur. Areas which were observed as depositional but were predicted within the mud EBD are indicated as overestimates.

To correct maximum fetch estimates in secluded areas would involve including numeric weights which simulate wind direction and magnitude information, which is beyond the scope of this investigation. However, mean fetch can be used to delineate the areas of over-estimated wave energy parameters. Visual query of a mean fetch image (Figure 35) indicated that the breakpoint where mean fetch data should replace overestimated mud EBD's in back bay areas with depositional characteristics is approximately 0.15 km (Figure 36).

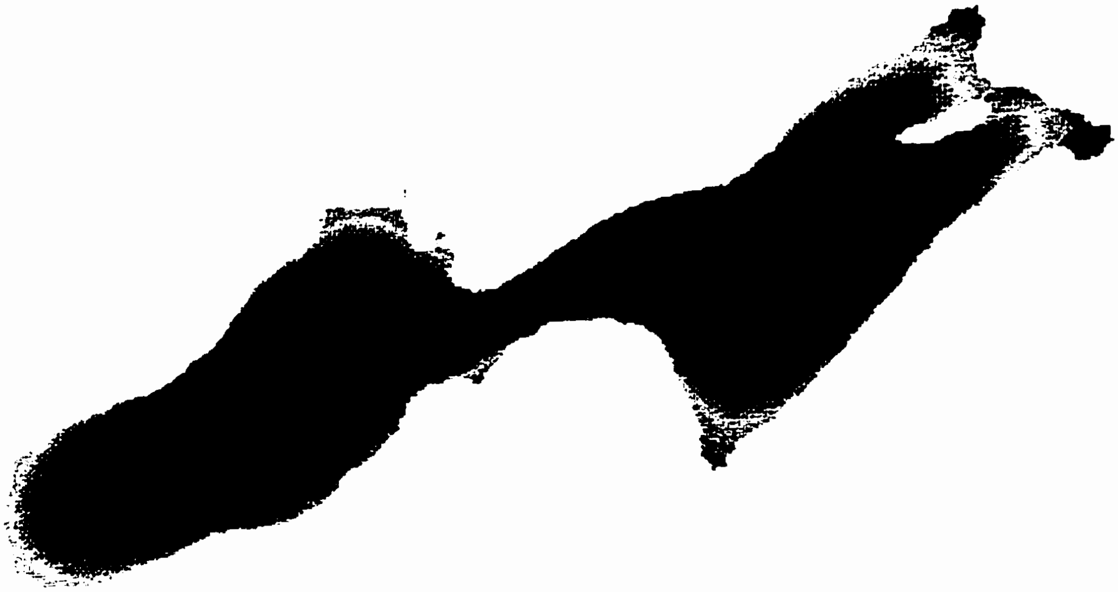


Figure 35. Mean fetch distance for Lake 226 using 360 axes for measurement.

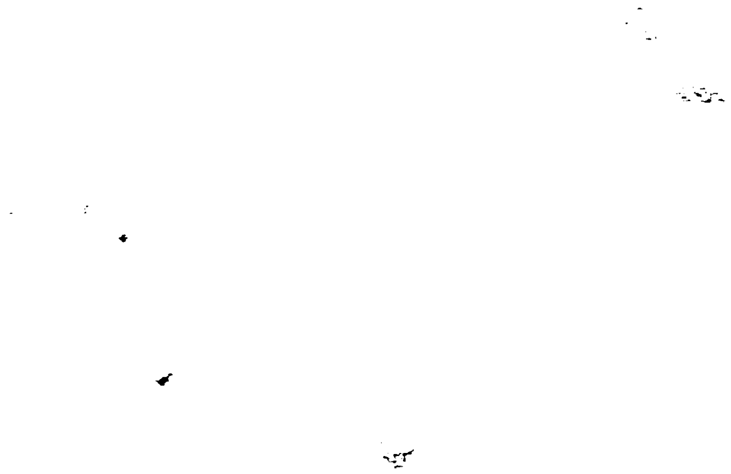


Figure 36. The areas in Lake 226 with mean fetch less than 0.15 km. These sites can be used to delineate areas where maximum fetch produced over-estimated wave parameters.

9. Discussion

9.1 Critique of Methods:

The NSCS sampling design effectively documented material patterns and sorting in the NSA of the ELA study lakes. The NSCS did, however, encounter problems in capturing the features of some bedrock outcrops (e.g. Lake 377; station numbers 1762-1800). Substrate materials were classified adequately, but the orientation of the transects do not capture the occasionally irregular configuration of bedrock. This was expected as bedrock is not modified by shoreline processes. The number of such locations is small relative to the total number of bedrock areas; most are parallel to shore and are classified satisfactorily.

Another limitation of the offshore transect sampling design involved a termination of the transects due to an arbitrary cut-off point determined by distance or depth(e.g. 30 m or 3 m water depth). Comparisons between basins that do not meet the offshore zone of deposition are not equitable if basin slopes are not similar. Because lakes 164,165, 442, 373, 377 were mapped only to 3m depth and had different bottom slopes, the offshore zone of deposition was encountered only intermittently. Consequently, these databases could not be used to test wave predictions as was done in Lake 226. Their use here was therefore limited to inventory, preliminary comparisons, and description. However, because sub-surface wave action is probably less than 3 m in these lakes the habitats produced by wave action were mapped entirely.

The classification of materials by size, for a few of the lakes with lower visibility, involved a change in assessment from visual means near shore to texture inferred from the aluminum probe in deeper areas where the bottom was no longer visible. Although the shift from a visual to textural assessment suggests that the precision of classification decreased with increasing water depth, the complexity of substrate structure also decreased with increasing depth in the clear lakes. This effect was quantified at Lake 226 one year after the lake survey when the water level was 2 m lower due to a controlled water level draw down. Substrate reclassification during a visual inspection of the dry substrates (which were below the limit of visibility at the original survey water level) were only modified for 3 sites which totaled less than 0.5% of the NSA. The effect of the visual\textural assessment bias, therefore, is also small.

The use of horizontal area to inventory and compare lake substrates underestimates habitat availability as a function of slope and material size characteristics. This effect increases with an increase of slope. Consequently, low gradient beaches or depositional areas are better descriptions of substrate availability than are moderate to high gradient areas. In addition, the nested form of classification adequately describes material combinations, but the three dimensional area of the surface is not archived.

9.2 The Nearshore Substrate Classification System and Taxonomy

The NSCS will probably inventory any type of NSA substrate available in the Precambrian Shield. The NSCS nested structure performed well. Three material classes are sufficient to accommodate material size variation evident in this region, and is simple enough for an efficient visual assessment of substrate character. In the field it is easier to classify an area with a varied size distribution of materials using two or three classes than to deliberate which one of the two or three will be represented as a mono-typic class as has been done with most other systems. Very few locations in the study lakes appeared to have four classes. It is not recommended that classification systems contain more than three nested groups due to the large number of material combinations that can result (e.g. the number of combinations possible using the NSCS equals 221).

The following classes can be merged to simplify the present NSCS: classes 41 and 42 (gravel), and below the depth of visibility classes 71 (flocc.) and 72 (detritus) as a generic depositional class. The poly-typic classification structure is a valuable method because only low and high slope areas have homogenous material compositions. Consequently, the nested structure of the substrate classification system retained much of the variability evident in the field that most other classification systems do not. This is advantageous in systems which are the focus of detailed aquatic study, like the ELA lakes, because excessive data reduction in the field limits the usefulness for other purposes. If necessary, data reduction by omission of one or two classes in a poly-typic classifier is best done post hoc in the GIS attribute database.

Small lakes in the Precambrian Shield have nearshore habitat structures which are dominated by the parent material and the effects of glacial action on the landscape. Such small lakes have limited hydraulic material sorting. At the sub-group level of detail, many areas of lakes have substrate compositions that are unique. The complete statistical comparison of such pattern data can be achieved only when the data are reduced in complexity from spatial to aggregate data at higher AHC levels. Although the sub-group level substrate pattern data can be reduced in complexity by aggregating classes perhaps to form comparisons at the AHC class level, it is beyond the scope of this work to do so. Results from the ELA suggest about twenty types of substrate classes categorize most areas of lakes at the sub-group AHC level. However, the wide array of substrate types can be grouped into ten shoreline type associations which demonstrate reproducible patterns in substrate materials based on the shape and slope of the shore.

9.3 Inter-lake Comparison of Substrate.

The shoreline development morphometric index (SLD) has been used widely to indicate the complexity of the littoral area and its value in describing biological production in the littoral area. However, the links between the SLD, physical structure of the NSA, and biological relationships have not been demonstrated. The SLD index was of considerable interest to Wetzel (1977) "because it reflects the potential for greater development of the littoral communities in proportion to the total volume of the lake". Although the SLD index has been used as an index of littoral area complexity (Kent and Wong 1982), biological community structure (Wetzel 1977), and nearshore habitat availability (Kent and Wong 1982), this study has demonstrated statistically that the SLD is correlated with NSA substrate diversity, the major component of physical habitat in the NSA.

The relationship between substrate diversity and SLD occurs because a lake's shoreline configuration is the net product of the interaction among all habitat forming and maintenance variables. Shorelines which are linear are formed by parent geomorphology and tend to have homogeneously distributed mono or bi-typic material composition (bedrock cliffs or talus boulders) with simple pattern distribution, due mostly to the forces of high slope. Conversely, crescent shaped shorelines adjacent to headlands are formed by gradients of wave energy and have diverse (usually tri-typic material combinations) but predictable pattern distributions that respond to these gradients. Such headland and beach habitats have longer shoreline lengths than linear reaches, and high substrate diversity due to the development of offshore and longshore material size gradients. The SLD index, therefore, can be used as an index substrate diversity because the shape of a shoreline indicates the structure and pattern of the adjacent sub aqueous habitat.

The diversity of substrates and scale or patchiness probably are inversely related. A lake with substantially more classes and material polygons usually will have a patchy distribution with smaller mean substrate areas. For example, large sections of similar habitat, e.g. derived from talus deposits or beaches, reduce the number and spatial complexity of substrates. The substrates between headlands and beaches have the highest substrate diversity due to the development of offshore and longshore material size gradients which produce many but smaller habitat units.

9.4 Classification of Nearshore Substrates

The NSCS sub-group substrate data, which can be interpreted as type "S" (small) scale data, are ideal for the study of lake processes, the development of spawning suitability models, or other similar work which has high information requirements. However, the comparison of lake habitats is difficult with type S data. The statistical treatment of the data using aggregative tabular summaries at the sub-system level can be used as a general indicator of habitat type availability, but this type of comparison removes the important spatial information regarding habitat diversity, scale, entropy, and patchiness. Type S data from the Precambrian Shield are best suited to detailed inventory, modeling, or to develop understanding between fish and habitats.

Comparisons of habitat structure among lakes should capture the important aspects of habitat without information loss. Type M (medium) data, like the proposed STA classification is a more reasonable vehicle for inter-lake habitat comparisons. The STA is superior in this regard because the more general essence of the habitat structure is retained, without having to accommodate the specific locations of habitat boundaries within the shore type.

The collection of type S or M data and the reduction of this type of data into more general types of information as type M or L (large scale) offers a step wise procedure to work with classified data at different level of detail. Thus, using type "S" data in a hierarchical framework, detailed data sets can be generalized and used for other purposes which have lower information requirements.

The understanding of the structure and function of physical habitat through inter-lake comparisons requires a consistent classification approach with stratification variables which do not impose arbitrary limits to the data (e.g. arbitrary offshore data boundary determined by depth). Inter-lake comparisons can be equitable only when performed on data sets based on system process (e.g. predicted mud DBD) and geomorphology (e.g. segment shorelines into reaches).

9.5 Fetch Distance Modeling

The options for varied sampling frequency offer a practical flexibility in terms of computing time. However, the precision of fetch sampling is dependent on the sampling frequency, and the lake shoreline configurations. A lake which has a simple shoreline geometry can be sampled equally well with relatively few or many measurements. Lakes with more complex shorelines require an increase in sampling frequency to produce smoother fetch patterns. This is probably why Jensen et al. (1992) used 360 axes rather than the 8 axis point model used by Harvey et al. (1989).

Because lake morphology is the primary control of slope and wave properties, and that morphology is so varied among lakes, it is unlikely that one widely accepted sampling frequency will be suitable on all lakes. The spatial precision of wave energy and substrate mapping therefore, will depend on the shoreline configuration, which is dependent on map scale (Kent and Wong 1982) within lakes. Large lakes can have simple or complex shorelines; large lakes with high SLD will have detailed sediment distribution patterns which require high image resolution and also extended processing time. The flexibility of the fetch program sampling frequency can minimize long processing requirements, and also can be used to learn the relationship between sampling frequency, SLD, and the minimum amount of sampling required to effectively delineate sediment patterns.

9.5.1 Choosing an appropriate Fetch Distance Estimate

Process modelling in lakes involves a chioce of wave property models. Although a few are available, the comparison of wave energy surrogates by Hakanson (1983) and Rowan et al. (1992) indicate that some estimates may be more effective than others to show cause-effect relationships on lake bed dynamics. At present, maximum fetch is the most likely candidate the linkage with Airy deep water wave theory. Further, the analysis using maximum fetch and exposure by Rowan et al. (1992) acknowledge that their models are not suited to all types of or sites in lakes. Also, because Rowan's methods were not spatial, the areas of lakes which do not conform to their model are unknown. Thus, at present, no single fetch model can predict the spatial sediment distribution in all areas of lakes.

9.6 Process Modeling: Integrating Physical and Hydrodynamic GIS models

The spatial estimation of maximum fetch on Lake 226 showed that the predicted mud EBD in confined bays can be over estimated. These sites were predicted to have an erosional mud EBD to about 1 m depth but in fact showed deposition. In such areas, the aspect of the bay determines the predominant wind direction, its periodicity, and magnitude, and the corresponding wave size properties. This over-estimate indicates that waves of maximum size are infrequent at this angle because the periodicity and magnitude of source winds are not equal over the 360 degree range. In areas with higher exposure, the effect of this bias is small because most of the mud DBD was very close to the predicted mud EBD in Lake 226, excluding areas where slope redistributes fine sediment.

The prediction of the mud EBD using available techniques therefore, must integrate the results from maximum and mean fetch to compensate for overestimated wave parameters. In Lake 226, the sites with overestimated wave energy have mean fetch values about 0.15 km or less.

10. Conclusions and Recommendations

Prediction of the distribution of aquatic habitats requires knowledge of the processes which form and maintain them. The strongest merit for using GIS for assessment of lake habitats and dynamics is the ability to understand the formative and maintenance processes and how they vary over space and time. A GIS can be used to infer process by interpreting spatial patterns in habitat data.

Two methodological requirements are needed to infer process from pattern: 1) standardization of classification systems and, 2) the delineation of habitat boundaries based on natural break points in habitat structure (e.g mud DBD and shoreline configuration). The construction of predictive habitat models is now feasible due to developments in digital technology and classification systems, but such models are unavailable due to a lack of standardized baseline information studies. EIA's and habitat management strategies will therefore remain in the inventory phase until such data and models become available.

Hierarchical classification systems provide an ordered framework for the archive of spatial data at different levels detail. The AHC is a strong tool for aligning objectives, data requirements, techniques for data aquisition, and the handling and interpretation of spatial data. Aquatic Environmental Impact Assessment would benefit from the use of hierarchical classification techniques.

The AHC hierarchical structure offers flexibility for habitat comparisons at different levels of spatial detail. Comparisons become more simplified at higher AHC levels, but the spatial and structural properties that are key to habitat interpretation are lost. Low AHC levels are therefore more suited to site specific inventory, development of fish habitat suitability models, or process modeling. The division and sub-division levels provide a moderate level of detail and are best suited to habitat description or general areal comparisons. At this level spatial pattern data can be inferred in the form of STA's, but not delineated within reach-scale habitat units. Data archived at the system or sub-system level are simple, or if data are derived from lower in the hierarchy they are aggregative.

The integration of GIS fetch distance models with the study of lake dynamics requires further development. Maximum fetch is probably the best model for development due to supporting wave theory, and can be improved with the inclusion of numeric weights for each fetch measurement axis to account for wind direction, periodicity, and magnitude. An optimal validation would include detailed site maps with observed mud DBD's, and observed wave properties, which could then be linked directly to wind data.

The development of dynamic GIS lake models for EIA's can provide review panels and habitat managers a useful tool for predicting the general structure of aquatic systems. Information can be provided regarding the spatial distribution of the nearshore and offshore areas, and also delineate the areas of erosion, transport, and deposition. This study has shown that such predictions are now feasible. The prediction of NSA material types in the area of erosion and transport, however, will be more difficult. The use of slope, wave, and substrate maps in this study indicated that areas with slopes of less than three degrees and mean fetch of 0.15 km are depositional; beaches have slopes less than seven degrees with mean fetches less than 0.15 km or less, and areas with slopes greater than seven degrees tend to be geological. Homogenous bedrock slopes varied but usually exceeds 40-45 degrees. When multi-lake data sets that span a range of scales become available EIA panels may be able to predict the form of lake habitats at the AHC division or sub-division level using only a bathymetric map, a fetch program, and data on material size and NSA slope.

Knowledge of process in the NSA will assist fish habitat managers and EIA panels to determine which environmental variables are key to the habitat management or impact decision. GIS models which can predict substrate types and areas of erosion, transport, and deposition in lakes, will provide for understanding, a priori, the large scale changes expected in the structure of habitat in flooded lakes, and to identify key sites to assess change in detail. The improved understanding of process will allow EIA's to move from a case by case inventory practice to a predictive capacity which is essential to complete system-wide EIA's in large or remote aquatic ecosystems.

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12. Appendix A

Nearshore Substrate Classification (NSCS) data sheet used during site surveys.

DATA SHEET FOR NEARSHORE SUBSTRATE CLASSIFICATION

Thematic Layer 1: Surficial Material

Station Number.............
Water Level.................
Date(D/Mo/Yr):..............
Time:........-..............
Survey Crew:................
....
....
# of accompanying maps:....
Aerial Photo. targets
  Distance (m):............
Photographs:
  Role #:...................
  Photo. #:.................
  Feature ID:..............
  ....

Class Name	Class	Size (mm)
Silt/Clay	1.0	Texture
Bedrock	2.0	Solid Rock
Sand	3.0	0.062-4
Gravel		
- fine	4.1	4 - 8
- coarse	4.2	8 - 64
Cobble		
- small	5.1	64 - 128
- large	5.2	128 - 256
Boulder		
- small	6.1	256 - 1024
- large	6.2	1024 - 4096
Detritus	D	
Flocc.	F	

Lake perimeter stations start at meter 0. Systematic station interval = 50 m.

DEPTH INFORMATION

Station #	Distance-1m	Distance-2m	Distance-3m	Distance-4m	Distance-5m

SUBSTRATE PATTERN DIAGRAM

13. Appendix B

Integer codes assigned to substrate class combinations

land	0	61	59	51	127	30	188
72	1	6152	60	5142	128	3020	189
71	2	6151	61	5141	129	3010	190
7162	3	6142	62	5130	130	3041	191
7161	4	6141	63	5120	131	3042	192
7152	5	6130	64	5110	132	3051	193
7151	6	6120	65	5152	133	3052	194
7142	7	6110	66	5161	134	3061	195
7141	8	6162	67	5162	135	3062	196
7130	9	6171	68	5171	136	3071	197
7120	10	6172	69	5172	137	3072	198
7110	11	615271	70	514271	138	302010	199
7172	12	615251	71	514241	139	20	200
62	13	615242	72	514230	140	2010	201
6261	14	615241	73	514220	141	2030	202
6252	15	615230	74	514210	142	2041	203
6251	16	615220	75	514171	143	2042	204
6242	17	615210	76	514130	144	2051	205
6241	18	615171	77	514120	145	2052	206
6230	19	615142	78	514110	146	2061	207
6220	20	615141	79	513071	147	2062	208
6210	21	615130	80	513020	148	2071	209
6271	22	615120	81	513010	149	2072	210
6272	23	615110	82	512071	150	10	211
626171	24	614271	83	512010	151	1020	212
626152	25	614230	84	42	152	1030	213
626151	26	614220	85	4241	153	1041	214
626142	27	614210	86	4230	154	1042	215
626141	28	614171	87	4220	155	1051	216
626130	29	614130	88	4210	156	1052	217
626120	30	614120	89	4251	157	1061	218
626110	31	614110	90	4252	158	1062	219
625271	32	613071	91	4261	159	1071	220
625251	33	613020	92	4262	160	1072	221
625242	34	613010	93	4271	161		
625241	35	612071	94	4271	162		
625230	36	612010	95	424171	163		
625220	37	52	96	424130	164		
625210	38	5251	97	424120	165		
625171	39	5242	98	424110	166		
625142	40	5241	99	423071	167		
625130	41	5230	100	423020	168		
625120	42	5220	101	423010	169		
625110	43	5210	102	422071	170		
624271	44	5261	103	422010	171		
624241	45	5262	104	41	172		
624230	46	5271	105	4130	173		
624220	47	5272	106	4120	174		
624210	48	525171	107	4110	175		

624171	**49**	525142	**108**	4142	**176**
624130	**50**	525141	**109**	4151	**177**
624120	**51**	525130	**110**	4152	**178**
624110	**52**	525120	**111**	4161	**179**
623071	**53**	525110	**112**	4162	**180**
623020	**54**	524271	**113**	4171	**181**
623010	**55**	524241	**114**	4172	**182**
622071	**56**	524230	**115**	413071	**183**
622010	**57**	524220	**116**	413020	**184**
621071	**58**	524210	**117**	413010	**185**
		524171	**118**	412071	**186**
		524130	**119**	412010	**187**
		524120	**120**		
		524110	**121**		
		523071	**122**		
		523020	**123**		
		523010	**124**		
		522071	**125**		
		522010	**126**		

14. Appendix C

The number of classes common among study lakes with area of each class listed by lake. The total number of classes used on the study lakes was 85. Only 23 are shown below.

							No. Common	
Class	**164**	**165**	**226**	**373**	**377**	**442**	**Classes**	**(ha)**
615251	0.18	0.09	0.03	0.25	1.80	0.44	6	2.80
71	0.38	1.87	0.19	0.09	0.01	0.20	6	2.74
20	0.15	0.36	0.15	0.11	0.33	0.01	6	1.11
3071	0.62	1.57	0.03	2.49		0.21	5	4.92
30	0.32	0.42	0.00	0.24	0.15		5	1.14
6261		0.05	0.06	0.01	0.09	0.04	5	0.24
6152	0.16	0.08	0.05		0.16		4	0.45
525142	0.00		0.01	0.23	0.09		4	0.33
626171		0.02	0.05	0.03		0.12	4	0.22
5142	0.15		0.01	0.01	0.02		4	0.19
7130	1.48		3.60			0.02	3	5.10
626152				0.13	0.17	1.07	3	1.38
615271			0.21	0.02	0.15		3	0.38
7152			0.20	0.05	0.03		3	0.27
514230	0.02			0.13	0.04		3	0.19
7162	0.75					0.07	2	0.81
10	0.05			0.53			2	0.58
3010	0.16				0.06		2	0.22
3051	0.10				0.11		2	0.21
525130			0.00		0.18		2	0.18
Total	4.53	4.47	4.58	4.31	3.40	2.19		23.48
% Lake NSA	92.61	91.33	93.66	88.10	69.45	44.76		86.54

15. Appendix D

The 20 classes with the greatest areal coverage for the combined NSA and the total area (hectares), and % lake NSA for each class.

Class	Area Rank	164	165	226	373	377	442	No. Common Classes	(ha)
7130	1	1.48		3.60			0.02	3	5.10
3071	2	0.62	1.57	0.03	2.49		0.21	5	4.92
615251	3	0.18	0.09	0.03	0.25	1.80	0.44	6	2.80
71	4	0.38	1.87	0.19	0.09	0.01	0.20	6	2.74
626152	5				0.13	0.17	1.07	3	1.38
30	6	0.32	0.42	0.00	0.24	0.15		5	1.14
20	7	0.15	0.36	0.15	0.11	0.33	0.01	6	1.11
7162	8	0.75					0.07	2	0.81
10	9	0.05			0.53			2	0.58
6152	10	0.16	0.08	0.05		0.16		4	0.45
615271	11			0.21	0.02	0.15		3	0.38
525142	12	0.00		0.01	0.23	0.09		4	0.33
7152	13			0.20	0.05	0.03		3	0.27
6261	14		0.05	0.06	0.01	0.09	0.04	5	0.24
626171	15		0.02	0.05	0.03		0.12	4	0.22
3010	16	0.16				0.06		2	0.22
3051	17	0.10				0.11		2	0.21
514230	18	0.02			0.13	0.04		3	0.19
5142	19	0.15		0.01	0.01	0.02		4	0.19
525130	20			0.00		0.18		2	0.18
Total		4.53	4.47	4.58	4.31	3.40	2.19		23.48
% Lake NSA		92.61	91.33	93.66	88.10	69.45	44.76		86.54