Wilfrid Laurier University

Scholars Commons @ Laurier

Theses and Dissertations (Comprehensive)

2004

Impacts at the coast: Climate change influences on Lake Huron's water levels at Oliphant (Ontario)

Kevin Tupman
Wilfrid Laurier University

Follow this and additional works at: https://scholars.wlu.ca/etd

Part of the Environmental Indicators and Impact Assessment Commons, and the Environmental Monitoring Commons

Recommended Citation

Tupman, Kevin, "Impacts at the coast: Climate change influences on Lake Huron's water levels at Oliphant (Ontario)" (2004). *Theses and Dissertations (Comprehensive)*. 458.
https://scholars.wlu.ca/etd/458

This Thesis is brought to you for free and open access by Scholars Commons @ Laurier. It has been accepted for inclusion in Theses and Dissertations (Comprehensive) by an authorized administrator of Scholars Commons @ Laurier. For more information, please contact scholarscommons@wlu.ca.

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisisitons et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 0-612-92281-2
Our file Notre référence
ISBN: 0-612-92281-2

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou aturement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this dissertation.

While these forms may be included in the document page count, their removal does not represent any loss of content from the dissertation.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de ce manuscrit.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

IMPACTS AT THE COAST:
CLIMATE CHANGE INFLUENCES ON LAKE HURON'S WATER LEVELS AT OLIPHANT

By:

Kevin Tupman, B.A.

Advisor:

Dr. James Hamilton

A thesis

presented to Wilfrid Laurier University

in fulfillment of the

thesis requirement for the degree of

Masters of Environmental Studies

in

Geography

Waterloo, Ontario, Canada, 2004.

© Kevin Tupman, 2004.

Abstract

Since 1998, climate change induced low water levels in the Great Lakes have caused environmental and socioeconomic impacts along most of the Great Lakes' shorelines. According to recent climate change research involving different water level scenarios, climate change over the next century may continue to cause water levels in the Great Lakes to decline. Such impacts may include wider shorelines, drying of coastal wetlands, and navigation hazards that may result in increased dredging activities. These impacts will have a strong influence on new shoreline management policies and planning.

To better understand potential future impacts, a specific methodology was developed to analyze shoreline impacts on the town of Oliphant. Bathymetric, topographic, and orthographic data sets were used to create maps and digital elevation models (DEM) displaying potential future impacts in Oliphant. A raster bathymetry DEM (BDEM) was created to survey the impact of a serious drop in lake level coupled with Oliphant's shallow bathymetry on navigation, as well as other subsequent coastal issues. Also, a triangulated irregular network model (TIN) called the Lake Level Change Model (LLCM) was designed to project possible shoreline change impacts as a result of a change in lake level. Potential water level scenarios, used in the GIS models, are the result of the combination of published general circulation model (GCM) results, and a hydrologic model. Another key part of the research methodology is a questionnaire.

According to results, the research site will be negatively impacted by a decline in Lake Huron's water levels. Coastal zone features such as the Oliphant Fen Wetland, the Oliphant Small Craft Harbour, and marine navigation will be specifically impacted.

Acknowledgments

First and foremost, I wish to thank my fiancé, Michelle Hundt. Thank you for your patience and understanding, and for giving me the needed time to complete my research and writing.

Secondly, so many thanks are given to my parents for their support. Thank you so much for everything I have taken for granted.

There are so many important members of Wilfrid Laurier University's Department of Geography and Environment Studies who need thanking. I must thank my advisor Dr. James Hamilton for his research advice not only with my thesis, but my academic career. Also, for all of his financial assistant, allowing me to finish the program. Now, where would I be without Dr. Mary Louise Byrne? Dr. Byrne was continually understanding, inspiring, and encouraging, as well as the best darn coastal geomorphologist around. I also need to thank my colleagues in the CFI lab, for allowing me to use their resources. I would not have accomplished what I did without their help.

At the University of Waterloo's Environmental Studies Department there are people who need thanking as well. I may have not found a research topic if it was not for Dr. Peter Deadman and Linda Mortsch, who both encouraged me to look into the little town of Oliphant. As well thanks are given to Ryan Schwartz, who wrote his Masters thesis on a very similar topic in Goderich, and provided advice. Also, I would like to thank Dr. Deadman and Scott McFarlane for their superb GIS knowledge and assistance. The final person who needs thanking is Richard Pinnell for all the free data that was provided through the UMD library.

Thank you everyone!

Table of Contents

List of Figures

List of Tables

List of Acronyms

AOC	Area of Concern
AOGCM	Atmospheric Ocean General Circulation Models
BDEM	Bathymetry Digital Elevation Model
CCCma	Canadian Centre for Climate Modelling and Analysis
CGCM1	Canadian Global Coupled Model 1
CHS	Canadian Hydrographic Service
DEM	Digital Elevation Model
DFO	Department of Fisheries and Oceans
DSS	Decision Support System
DTM	Digital Terrain Model
ESRI	Environmental System Research Institute
GCM	General Circulation Model
GIS	Geographic Information System
GLERL	Great Lakes Environmental Research Laboratory
GLWQA	Great Lakes Water Quality Agreement
GPS	Global Positioning System
GSC	Geodetic Survey of Canada
HadCM2	Hadley Centre for Climate Prediction and Research Climate Model 2
HCCD	Historical Canadian Climate Database
IGLD	International Great Lakes Datum
IGLLB	International Great Lake Levels Board
IPCC	Intergovernmental Panel on Climate Change
LHIAP	Lake Huron Initiative Action Plan
LLCM	Lake Level Change Model
NAD83	North American Datum 1983
NRCAN	Natural Resources Canada
NRVIS	Natural Resources Values Information System
NTDB	Natural Resources Canada National Topographic Database
NTS	National Topographic System
OBM	Ontario Base Map
OMNR	Ontario Ministry of Natural Resources
TIN	Triangulated Irregular Network
UMD	University of Waterloo Mapping and Design Library
UTM	Universal Transverse Mercator

CHAPTER 1: INTRODUCTION

1.1 Background

In the late 1990s and early 2000s, water levels in Lake Huron declined almost one metre in a few years and approached record lows set in the mid-1960s. Such lows caused severe impacts including impaired shipping and navigation and changes to shoreline properties. In the mid-1960s, record lows were set because of a period of low precipitation which began around 1961 and ended around 1965 (Changnon, 1993). The low lake levels of the early 2000s are being caused by a number of factors, including climate. In the late 1990s, Canada experienced warmer than average temperatures. The summer of 1998 was the warmest on record in Canada, the national average being 1.8°C above normal (Environment Canada, 2002c). Lake Huron is part of the Great Lakes Basin (Figure 1.1), and within the Lake Huron region, temperature was only 1°C above normal, but precipitation was 20% drier than normal (Lake Huron Centre for Coastal Conservation, 2003). As climate change continues, Lake Huron's water level will be affected.

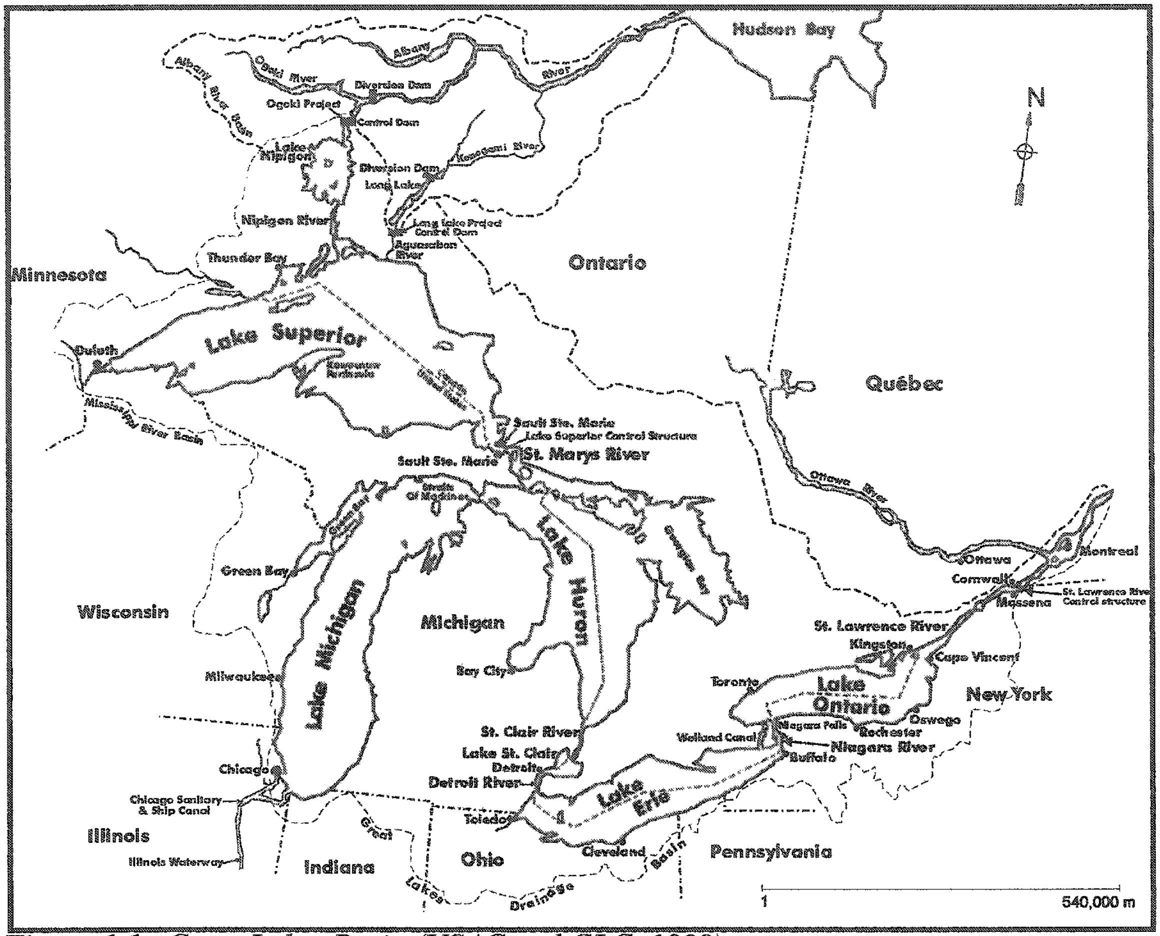


Figure 1.1 *Great Lakes Basin (USAC and GLC, 1999).*

What are the impacts of lower water levels on the Lake Huron basin ecosystem and society? If the state of the lake levels in the early 2000s is partially attributable to climate change, and they are near Lake Huron's record low, it is important to understand how future climate changes will influence the Great Lakes' water levels. In addition, it is equally important to examine how potentially lower lake levels may influence the shoreline configuration and processes.

For example, a projected decline of as much as 1 metre below the 1961 to 1990 average lake level, is forecasted for Lake Huron by 2050 (Mortsch et al., 2000). With a change of this magnitude, increased navigation and shipping difficulties, depletion of coastal wetlands, warmer and shallower waters that would influence many aquatic ecosystems, and an increase in some dynamic beach and dune processes may result.

This thesis reviews the contribution of climate change to the low lake levels of the early 2000s, examines possible future climate change influences on the level of Lake Huron, and describes impacts on shorelines. Data are collected and analyzed using a geographic information system (GIS), results of a general circulation model (GCM), historical Lake Huron water level data sets, and a personal survey.

1.2 Research Site

The site selected for this research is the community of Oliphant, Ontario, Canada (Figure 1.2), located along the western shores of the Bruce Peninsula. The town of Oliphant was chosen as the research site because the shoreline environment and community are greatly influenced by the height of water level. Oliphant's coastal zone is characterized by very low profile beaches (Figure 1.3a and b) and a shallow bathymetry. Thus, extensive areas are impacted when the lake level is low, and other large areas when the lake level is high. There are numerous islands referred to as the Fishing Islands, as well as shoreline and inland cottage properties, coastal wetlands, and a small craft harbour.

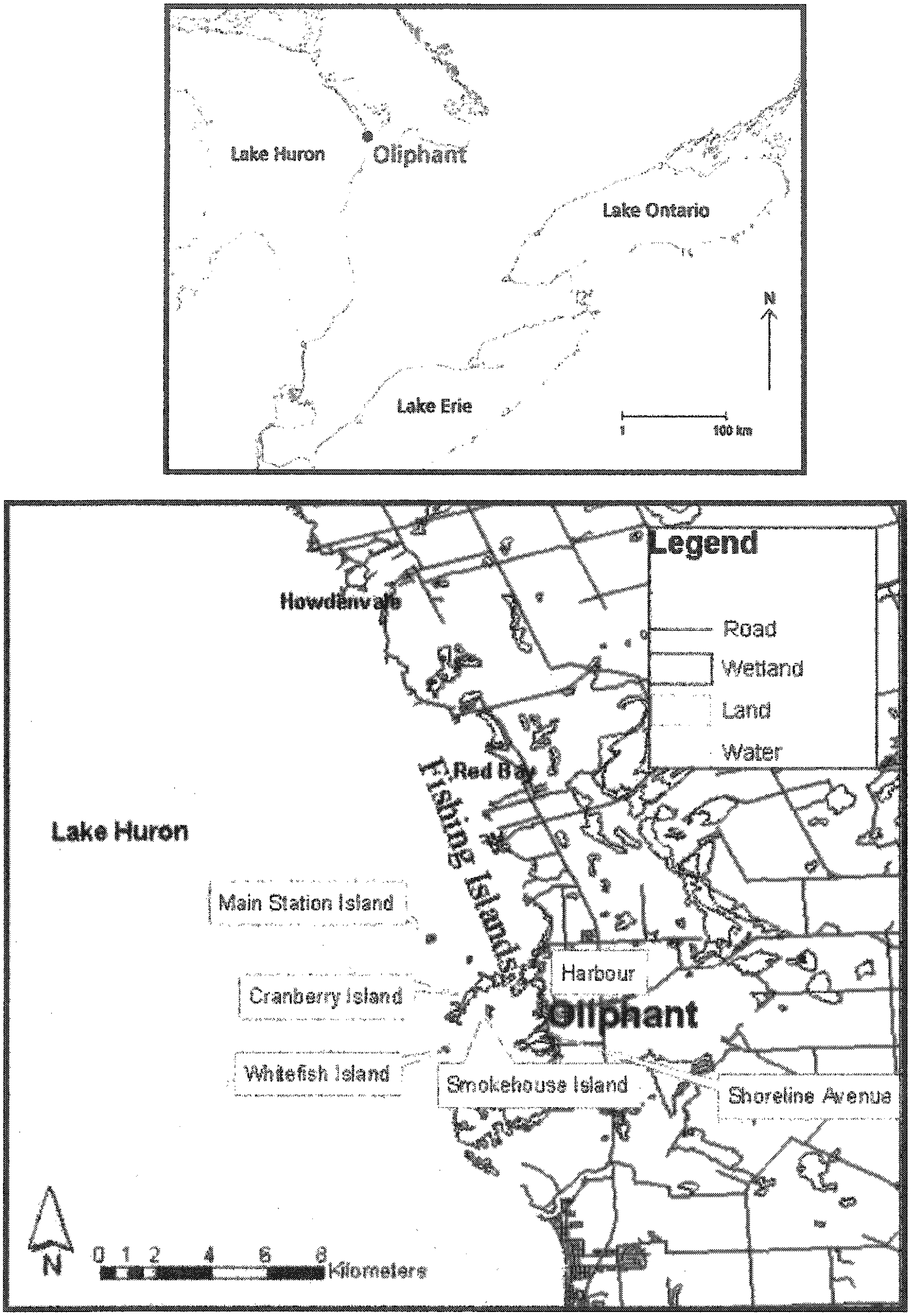


Figure 1.2 Research Site Location

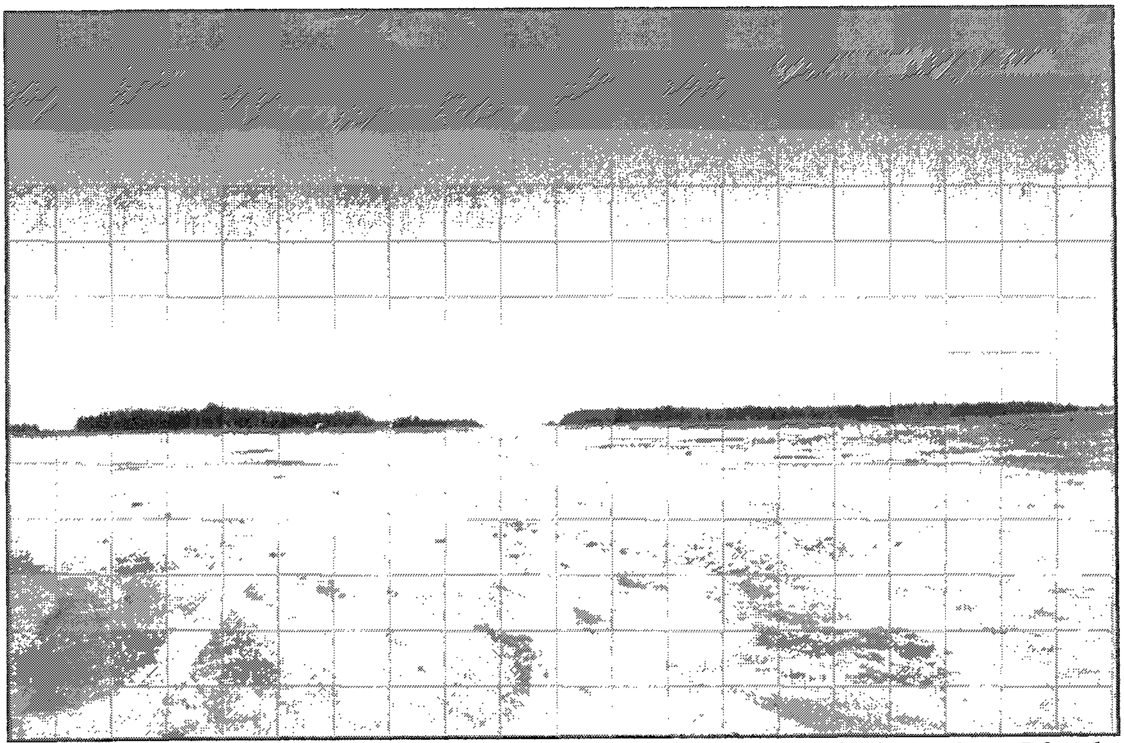


***Figure 1.3a** Exposed bed floor shoreline. Looking west towards the Fishing Islands. Vehicle tire tracks are noticeable (Tupman, 09-28-2002).*

***Figure 1.3b** Shoreline looking south from harbour. Local boat pulled up on shore, and children playing in the shallow water (Tupman, 07-20-2002).*

1.2.1 Fishing Islands

West of Oliphant, Red Bay, Howdenvale, and other small shoreline communities, is a chain of islands known as the Fishing Islands. The largest island, Cranberry Island, is approximately 40 ha in area (Cunningham, 2000), while the smallest islands are no larger than the exposed top of a shoal. Important islands west of Oliphant include Cranberry Island, Whitefish Island, Smokehouse Island, and Grand Station Island. Most of the larger islands contain cottages which often require the owner to travel by boat to the property. However, in the summer of 2001, low water levels allowed many cottage owners to drive automobiles to their island properties (personal communication, MacKenzie, 2002). The Fishing Islands are an important physical feature to the shoreline along Oliphant. They influence sediment transport, shoreline processes, and lake level patterns greatly. The Fishing Islands act as wind barriers and wave breaks, diminishing wave action along Oliphant's shoreline.

The Fishing Islands get their name from a profitable fishery which was established in the early 1800s (Cunningham, 2000). Schools of Herring, Whitefish, and Lake Trout were abundant. However, by the 1850s, this vast fishery was severely depleted (Cunningham, 2000). While there are still a variety of fish species, including small and large mouth bass, sunfish, crappy, and northern pike, these species will not sustain a fishing industry.

1.2.2 The Oliphant Fen

A fen is an alkaline wetland nourished by groundwater seepage, and is a specialized environment that supports an unusual and rich plant community (Brown, 1991). The Lake Huron shore along the Bruce Peninsula has some of the largest tracts of fen on the Great Lakes shoreline (Brown, 1991). The Oliphant Fen wetland system (Figure 1.4a and b) extends a distance of 8 km from Chief's Point Indian Reserve northwards along the Lake Huron shore to just south of Red Bay (Brown, 1991). Over this distance it varies in width from 20 to 500 metres. This makes the Oliphant Fen the largest fen complex on the Great Lakes (Cunningham, 2000). Some of the fen areas have been reduced in size and degraded by development, but the Oliphant Fen, as well as Petrol Point Fen further north, have been purchased by conservation organizations (personal communication, Brown, 2002).

***Figure 1.4a** Oliphant Fen Wetland during wet season. Near Oliphant Fen Boardwalk, looking east (Tupman, 03-30-2002).*

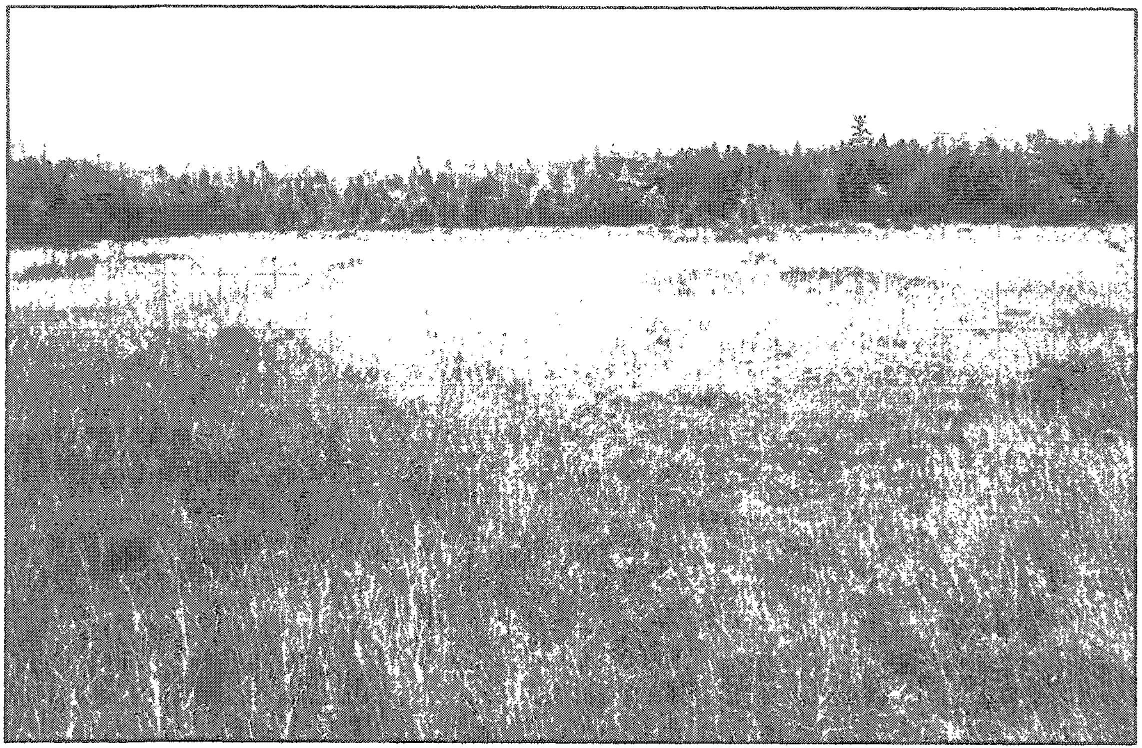


Figure 1.4b *Oliphant Fen Wetland during dry season. Near Oliphant Fen Boardwalk, looking east (Tupman, 11-09-2002).*

Also, the Oliphant Fen is one of the most alkaline fen systems in Ontario, with pH values typically in the range of 7.3 to 8.1 (Brown, 1991). The Oliphant Fen's alkalinity comes from bicarbonate ions (HCO_3-) present in the groundwater that nourishes the wetlands. The bicarbonate is produced from dissolution of dolostone and limestone bedrock, which also yields much dissolved calcium and magnesium. As well, the Oliphant Fen is different from most fens in that it does not contain peat.

The Oliphant Fen is habitat for a unique and diverse community of plant, bird, reptile and amphibian species. There are forty-one documented plant species located within the Oliphant Fen (Brown, 1991). Two of these species are provincially rare, Nutrush *(Scleria verticillata)*, which is present in its second-highest concentration after Long Point, and Indian plantain *(Cacalia tuberosa)*. A total of forty-four species of orchids are found on the Bruce Peninsula, most located within two kilometers of Lake

Huron. The largest and showiest, the pink and white queen lady's slipper *(Cypripedium reginae)*, is prevalent in the Oliphant area. Common in many fens are insectivorous plants, such as the pitcher plant *(Sarracenia purpurea)* which is seen throughout the Oliphant Fen. Twenty species of warblers, ten species of ducks, and eight species of hawks are seen during the spring and fall migrations. There are also different amphibian species throughout the fen. These examples suggest that the Oliphant Fen is an important habitat for a wide variety of organisms.

1.2.3 The Oliphant Harbour

The Oliphant Harbour is a federal government dock, and is classified as a small craft harbour owned by the Department of Fisheries and Oceans. There are two main docking areas, each containing approximately forty berths (Figure 1.5). The marina provides a launching ramp. Docks are well maintained, and are usually removed before winter to prevent damage, and are then reinstalled in spring for seasonal use. However, sometimes they are not removed, as was the case in the fall of the 2002. The overall, primary use of the harbour is for small craft (<26 feet) recreation and fishing vessels.

***Figure 1.5a** Oliphant Small Craft Harbour, showing boat launching facilities and a variety of recreational boats. Looking west from Shoreline Avenue (Tupman, 07-20-2002).*

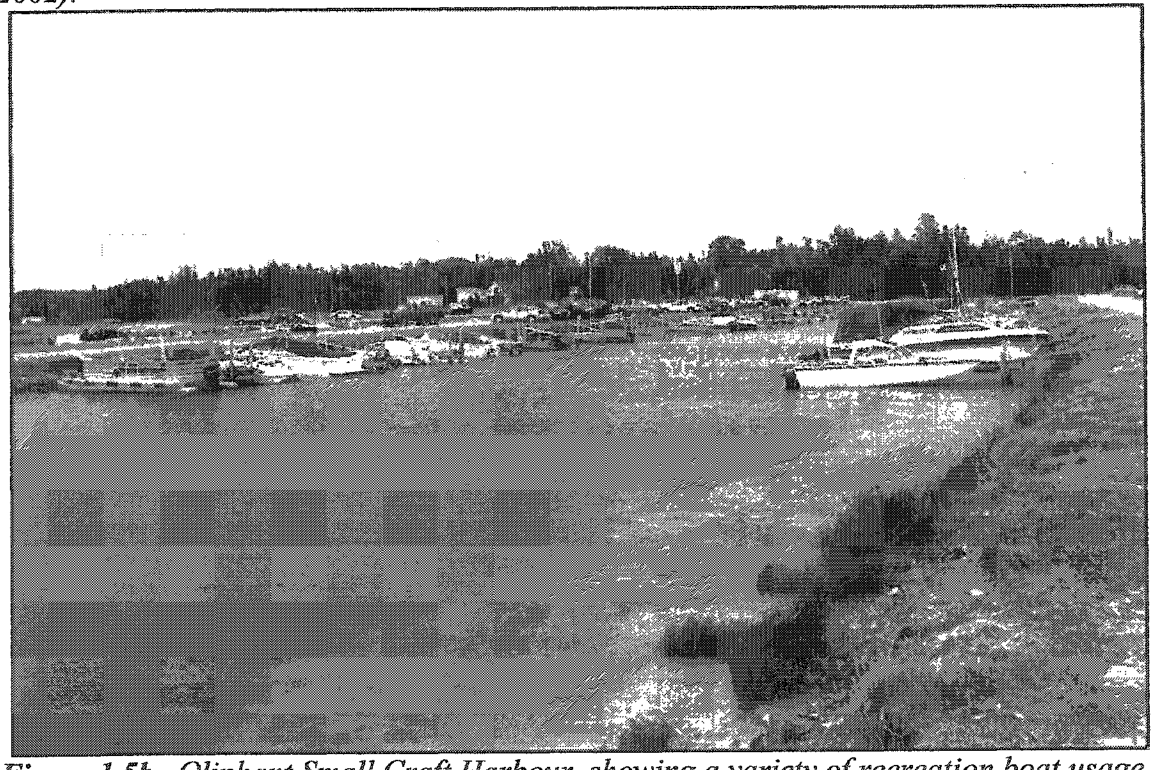


***Figure 1.5b** Oliphant Small Craft Harbour, showing a variety of recreation boat usage, and the harbour's bathymetry. Looking east from the mouth of the harbour (Tupman, 07-20-2002).*

1.3 Thesis Goal and Objectives

This thesis will attempt to describe how the changes in water level that are predicted to occur over the next fifty years will impact the Oliphant and Fishing Islands shoreline communities and ecosystem. Future water level scenarios are based on output from general circulation models (GCMs) which have been applied to a regional hydrological model. A geographic information system (GIS) is used to model shoreline change using a triangulated irregular network (TIN) and digital elevation model (DEM).

There are three main objectives of this thesis:

1. To use water level scenarios based on climate change and hydrological models, to develop a TIN and DEM which display results of the different water level scenarios over the period 2030-2050.

2. To investigate where and what impacts will be observed, focusing on the following;
    a) The Oliphant Fen
    b) Sediment Transport and Dredging in the Bay
    c) Land Use Patterns
    d) Cottage Owners
    e) Fishers, Boaters

3. To make recommendations to guide future work and management options.

1.4 Purpose & Relevance of Research

This study is relevant to recent research in the Great Lakes. Environment Canada has identified climate change impacts on lake levels as a key area of interest (personal communication, Moulton, 2001). To date there has been limited research on this topic for Lake Huron (Schwartz, 2001). Research is needed to understand the possible responses of Lake Huron's environment and ecosystem to lake level changes. Stakeholders such as cottage owners, shoreline managers and fishers would find such information useful. Knowledge of the potential impacts will help policy makers come to more informed decisions, thus mitigating the amount of impact to the study area.

1.5 Thesis Structure

This thesis contains six chapters. They include Introduction, Research Review, Methodology, Results and Analysis, Discussion, and Conclusion. Chapter 2 presents reviews on Lake Huron, climate change in the Great Lakes, the use of GIS in shoreline research, and coastal wetlands. Chapter 3 informs the reader of the thesis methodology, how general circulation models, water level scenarios, GIS, and interviews are used to better understand future impacts from low lake levels. Thesis results are examined in Chapter 4, and then discussed in Chapter 5. The final section, Chapter 6, concludes the thesis by presenting recommendations, and describing the usefulness of the research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature related to the influence and impact of climate change on Lake Huron's possible future water levels. Four major research themes are discussed in this chapter: (i) Lake Huron, (ii) climate change, (iii) GIS in Great Lakes research, and (iv) coastal wetlands in the Great Lakes. Information about Lake Huron's current and historical water levels are presented, as well as a review of regional climate. There is a review of climate change in the Great Lakes, including general circulation models, water level scenarios, and impacts. The use of GIS as a research and analytical tool in coastal studies is investigated. The focus is on aspects of 3D GIS modelling of topographical features, both terrestrial and subaqueous. The final topic is a discussion of coastal wetlands in the Great Lakes. There is a review of wetland characteristics and the physical processes that operate within them, as well as the influence of climate change on wetlands.

2.2 Lake Huron

Lake Huron is the third largest Great Lake by volume (3,540 cubic kilometers) and the second largest by surface area (59,000 square kilometers) (Michigan Office of the Great Lakes, 2002). Lake Huron's drainage basin, which covers parts of Michigan and Ontario, is the largest of the Great Lakes at 134,000 square kilometers (Michigan Office of the Great Lakes, 2002) (Figure 2.1). At its maximum, the lake measures 332 kilometers across and 245 kilometers north to south, with an average depth of 59 m and a maximum depth of approximately 229 m (Environment Canada and U.S. Environmental Protection Agency, 1995). Lake Huron may be divided into four bodies of water: the North Channel, Georgian Bay, Saginaw Bay and Lake Huron proper (Figure 2.1).

Lake Huron also has the longest shoreline within the Great Lakes' basin, extending 6,157 kilometers. The shoreline of Lake Huron is characterized by shallow, sandy beaches in the south, cobble beaches in the north, and rocky shores in the Georgian Bay area (Michigan Office of the Great Lakes, 2002). In addition, there are more than 30,000 islands (Finnell, 2002), including Manitoulin Island.

Lake Huron is part of a large multiple lake system. At the northeast end of Lake Huron, the Straits of Mackinac connect to Lake Michigan, forming a contiguous, two-lake system. In the literature, this hydrologic system is often referred to as Lake Michigan-Huron (Croley at al., 1995; Hartmann, 1990). Precipitation onto the lake, runoff from the basin, and outflow from Lake Superior (via the St. Marys River) recharge the waters of Lakes Huron and Michigan. Lake Huron discharges southward through the St. Clair River.

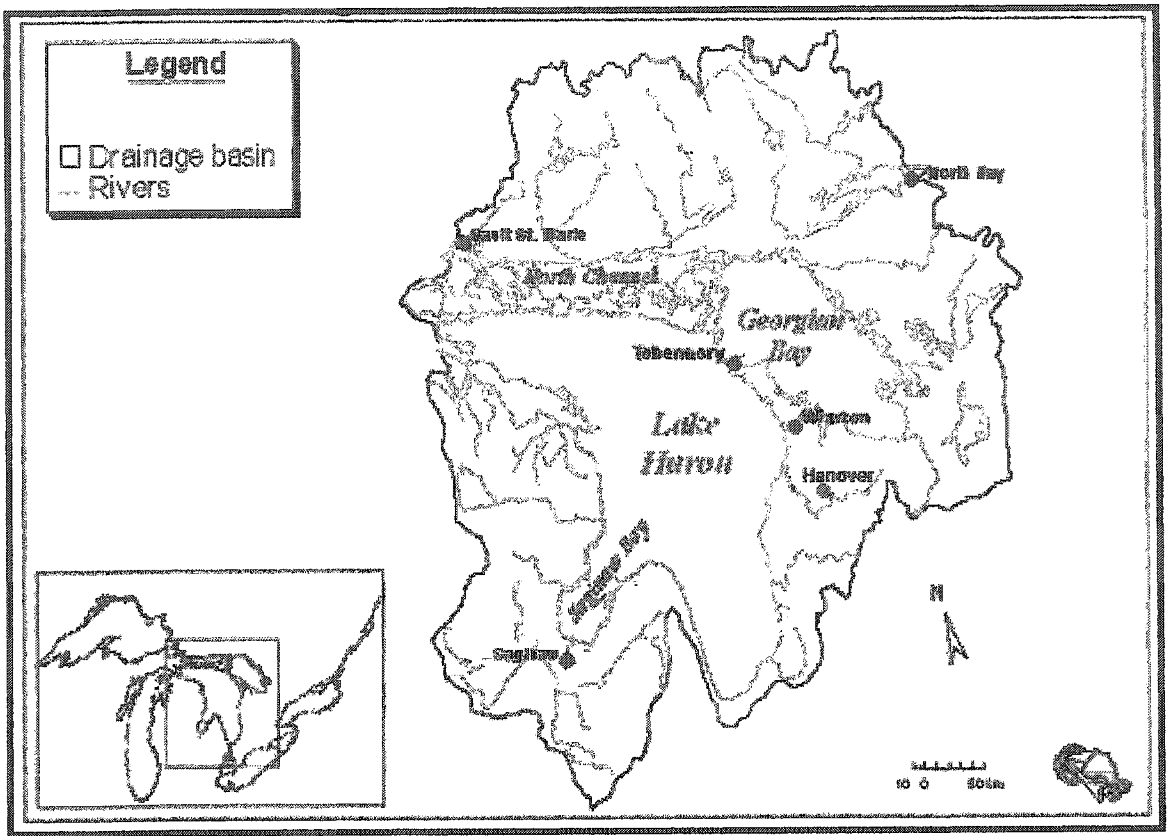


Figure 2.1 Lake Huron Drainage Basin (Michigan Office of the Great Lakes, 2002).

About 2.5 million people live within the Lake Huron basin. Populations are expected to increase in the future with significant movement toward the nearshore areas (LHIAP Update, 2002). Despite the relatively high population in the basin, there have been few research initiatives focused on its ecosystems and shoreline (Dimitrijevic, 2000). Lake Huron is the only Great Lake without a Lakewide Management Plan (LaMP). Therefore, in an attempt to address this lack of research, the Lake Huron Initiative Action Plan (LHIAP) was developed in 2000 by the US Environment Protection Agency (US EPA) and Environment Canada, with the Michigan Office of the Great Lakes. When the plan was originally drafted, the focus was "to identify efforts that need to be undertaken for the restoration and protection of the Lake Huron ecosystem" (State of the Lakes Ecosystem Conference, 2000, p.3). This focus came from the Great Lakes Water Quality Agreement (GLWQA). The GLWQA's goal is to restore and maintain the chemical, physical, and biological integrity of the Great Lakes basin ecosystem (International Joint Commission, 1978). The LHIAP examines and addresses tributaries, nearshore terrestrial and aquatic ecosystems. When the LHIAP was first drafted in 2000, it identified two key issues: (i) fish and wildlife habitat and biodiversity, and (ii) critical pollutants and beneficial use impairments (SOLEC, 2000). In January of 2002, an LHIAP Update presented status reports on a number of efforts and actions (Michigan Office of the Great Lakes, 2002). Most actions are still focusing on critical pollutants, but there is an increased recognition of the need to protect and restore important habitats, and to develop and implement new state of the ecosystem indicators for Lake Huron. In effect, the LHIAP will help protect the lake's future through the development of environmental and social indicators.

2.3 Regional Climate

The Lake Huron basin area experiences cold snowy winters and moderately warm summers (Eichenlaub, 1979). Figure 2.2 presents mean monthly temperatures and mean monthly precipitation for four locations in the Lake Huron basin. Additional data are presented in Table 2.1. Average monthly temperatures within the basin range from 22°C to –13°C. Typical precipitation values within the basin are 65 to 110 millimeters per month.

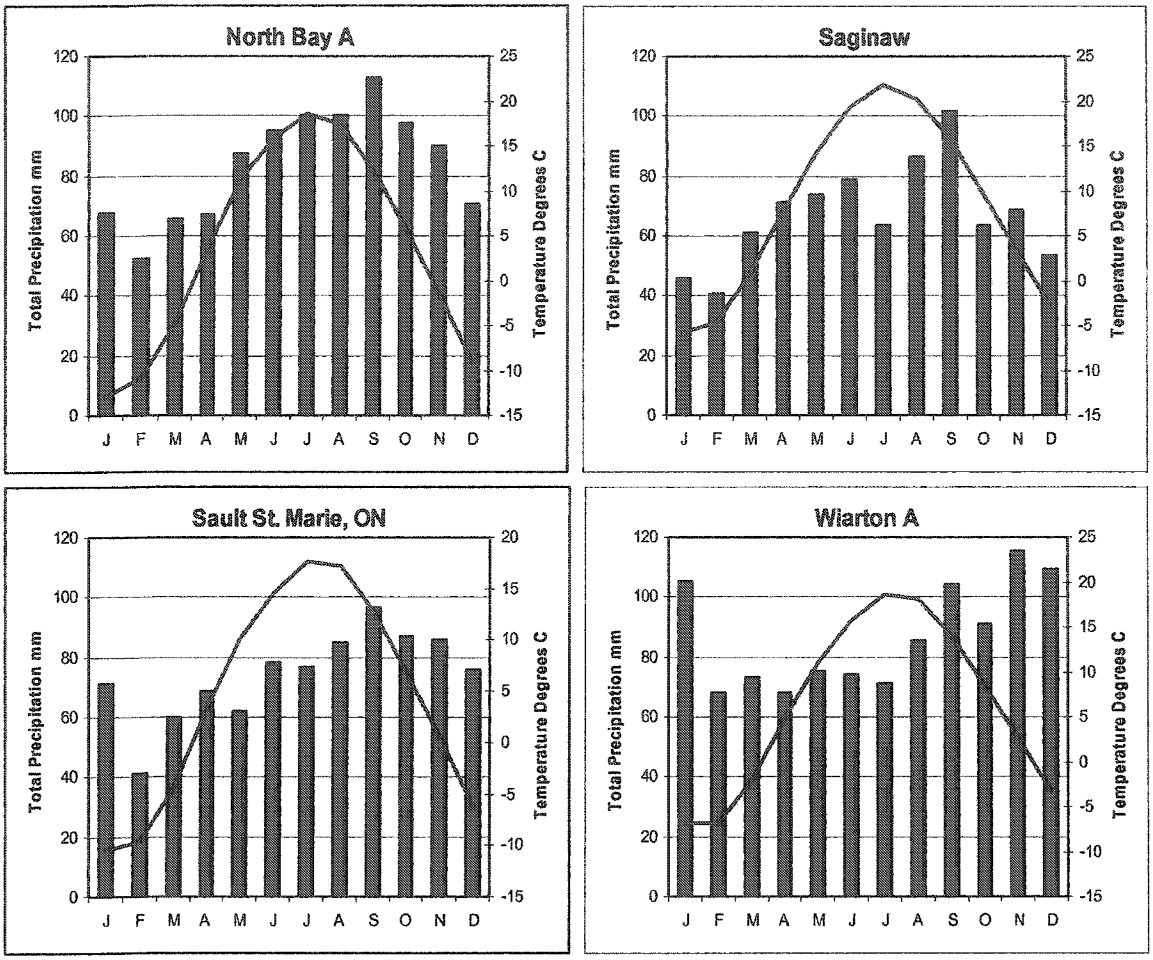


Figure 2.2 Lake Huron Basin 1971-2000 Climate Normals: Mean monthly temperature and mean monthly precipitation (Environment Canada, 2002a; NOAA, 2003).

Table 2.1 Lake Huron Basin Climate Summary. Climate Normals 1971-2000. Temperature values are in Degrees C, Precipitation values are in millimeters, Snowfall values are in millimeters to water equivalent. MXT – average annual max temp, MIT – average annual min temp, MAT – mean annual temp, TAP – total annual precipitation. Rainfall and snowfall data was not available for Saginaw. (Environment Canada, 2002a; NOAA, 2003)

Station Name	MXT	MIT	MAT	Rainfall	Snowfall	TAP
Wiarton A, ON	10.8	1.4	6.1	740.4	426.6	1041.3
North Bay A, ON	8.6	-1.1	3.8	774.6	273.4	1007.7
Sault St. Marie, ON	9.6	-1.0	4.6	634.3	302.9	888.7
Hanover, ON	11.8	0.8	6.5	787.1	261.6	1045.2
Saginaw, MI	13.2	3.4	8.3	n.a.	n.a.	824.5

The diverse weather in Lake Huron's basin is affected by three factors: air masses from other regions, the location of the basin within a large continental landmass, and the moderating influence of the lake itself (Environment Canada and U.S. Environmental Protection Agency, 1995). The changeable weather of the region is the result of alternating flows of warm, humid air from the Gulf of Mexico and cold, dry air from the Arctic. The basin's location within the large continental landmass results in a cooling effect, and a relatively large temperature range. Possibly the most influential factor is the moderating effect which the lake creates. Lake Huron is large enough that it acts as a heat sink, moderating the temperatures of the surrounding lands, cooling the summers and warming the winters. The lake increases the moisture content of the air. Under some winter conditions some of this moisture condenses as snow when it reaches land, creating heavy snowfall in some area on the downwind shores of the lake. These areas are known as "snow belts", and are the result of lake effect snow.

2.4 Climate Change

Climate change, according to the Intergovernmental Panel on Climate Change (IPCC) refers "to any change in climate over time, whether due to natural variability or as a result of human activity" (IPCC, 2001a, p.2). Over the history of Earth, the climate has changed. The glacial and interglacial cycles of the Quaternary are examples of such change. Some changes are global in scale, while others have been regional. There are a number of natural factors that contribute to these changes in Earth's climate over various time scales. First, the amount of energy radiating from the sun is not constant. Also, variations in Earth's orbit around the Sun, causes variation in the magnitude and distribution of solar energy received on Earth. There are variations in the concentration of aerosols in the atmosphere largely due to volcanic eruptions. This affects the amount of energy that is reflected and absorbed.

When energy from the sun enters the Earth's atmosphere, about 30% is reflected back to space (NRCAN, 2002), the atmosphere absorbs approximately 20%, and the balance is absorbed by the surface of the earth. Earth in turn emits radiant energy at longer wavelengths. Some of this energy escapes to space but most is absorbed in the atmosphere and re-emitted by clouds and greenhouse gases such as water vapour, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO_2). This helps to heat the surface and the troposphere (lowest layer of the atmosphere), keeping it warmer than it would be otherwise. This is known as the Greenhouse Effect.

Another natural factor similar to greenhouse gases are aerosols. Aerosols are very fine particles and droplets that are small enough to remain suspended in the atmosphere (Environment Canada, 2002b). Aerosols can reflect and absorb incoming solar radiation, changing the type and quantity of aerosols in the atmosphere, which affects the amount of solar energy reflected or absorbed.

Human activities are now recognized as an element affecting the Greenhouse Effect. A variety of human activities release greenhouse gases such as CO_2, CH_4, and NO_2. These include the burning of fossil fuels for producing electrical energy, heating and transportation. By increasing the atmospheric concentrations and by adding new greenhouse gases like chlorofluorocarbons (CFCs), humankind is capable of altering the energy balance of the planet. Also, as humans replace forests with agricultural lands, or natural vegetation with other land covers, they substantially alter the way Earth's surface reflects sunlight and releases heat. Another important factor is human-induced aerosols. Large quantities of fine particles (aerosols) are released annually to the atmosphere, both from agriculture and industrial activities. Although most of these aerosols are soon removed by gravity and rainfall, they still affect the radiation balance in the atmosphere. Whether this effect adds to, or offsets any warming trend, depends on the quantity and nature of the particles as well as the nature of the land or ocean surface below. The regional effects, however, can be significant (Environment Canada, 2002b). In 2001, the IPCC concluded, that there is new and more clear evidence that most of the warming observed over the last fifty years is attributable to human activities (IPCC, 2001a).

2.4.1 Global Instrumental Record

There are several global temperature reconstructions that have been developed from instrumental records. Figure 2.3 shows the record produced by the Climate Research Unit of the University of East Anglia (Jones and Moberg, 2003), as reproduced by the IPCC (IPCC, 2001a). Earth's surface temperature is shown as departures from the 1961-1990 mean as annual bars. "The approximate decade time scale variation is shown as a black line, which is a 10 year Gaussian filter padded padded sufficiently at each end to extend the smooth line to the beginning/ending year of the series, annual values are shows as bars" (Jones and Moberg, 2003). Note that a Gaussian filter is similar to a moving average, except the coefficient weights are designed to more heavily weight the central values in the moving window. Beginning in 1860, global surface temperatures varied little until early in the 20th century, when they began a rise until approximately 1945 (Figure 2.3). From the mid 1940s until mid to late 1970s, global surface temperatures gradually declined. Since then they have increased steadily (Figure 2.3). The overall increase in global surface temperature in the 20th century is about 0.6°C (IPCC, 2001a). The 1990s were the warmest decade in the series. The three warmest years over the record have been 1998, 2002, and 2003, and the nine warmest years globally occurred in the 1990s and 2000s (Palutikof, 2003).

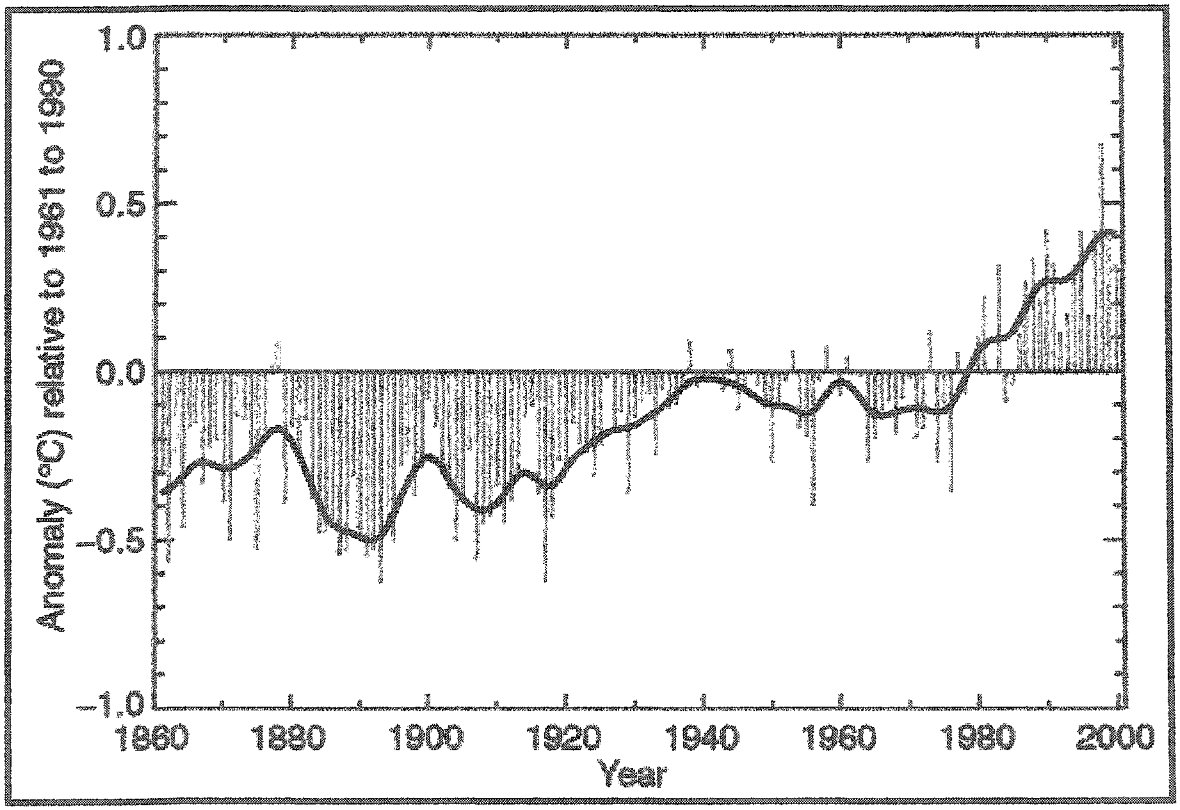


Figure 2.3 *Variations of the Earth's surface temperatures for the past 140 years. Smooth dark line is a 10 year Gaussian filter (IPCC, 2001b; after Jones et al, 1999).*

Changes have occurred in other important aspects of the global climate over the past century. Precipitation during the 20th century increased by 0.5 to 1% per decade over most mid and high latitude countries (IPCC, 2001a). Also, there has been a 2 to 4% increase in the frequency of heavy precipitation events during the 20th century.

Globally, many natural processes on Earth's surface have been affected by increased temperatures. For example, there has been a widespread retreat of mountain glaciers in non-polar regions during the 20th century (IPCC, 2001a). Also, tide gauge data has shown a global average sea level increase of between 0.1 and 0.2 metres during the 20th century (IPCC, 2001a).

2.4.2 Great Lakes Instrumental Record

"Climate in the Great Lakes is generally highly variable on time scales of one to several years, a fact that makes it more difficult to detect long-term trends" (Kling et al, 2003, p. 12). Analysis of Great Lakes climate data from the National Climate Data Center (1895-2001) and the Midwest Climate Center (1900-2000) revealed some significant shifts in temperature, total precipitation, and extreme events in recent decades (Kling et al, 2003). In the past four years, annual average temperatures ranged from 1 to 2°C warmer than the long-term average, and up to 4°C above average in winter (Kling et al, 2003). As well, both summer and winter precipitation were above average for the past three decades, making this the wettest period of the twentieth century (Kling et al, 2003).

According to data from the Historical Canadian Climate Database (HCCD), temperature in the Lake Huron basin increased between 1945 and 1955, followed by a decline to similar temperatures as felt in 1945. This was followed by a short increase of approximately 2 degrees Celsius and a decline until 1981, when temperatures fluctuated greatly, until 1992 when temperature leveled until 1998 when they quickly rose again (Figure 2.4). Precipitation records suggested a series of rapid large fluctuations (Figure 2.5). In general, precipitation increased between 1915 and 1955, then dropped suddenly,

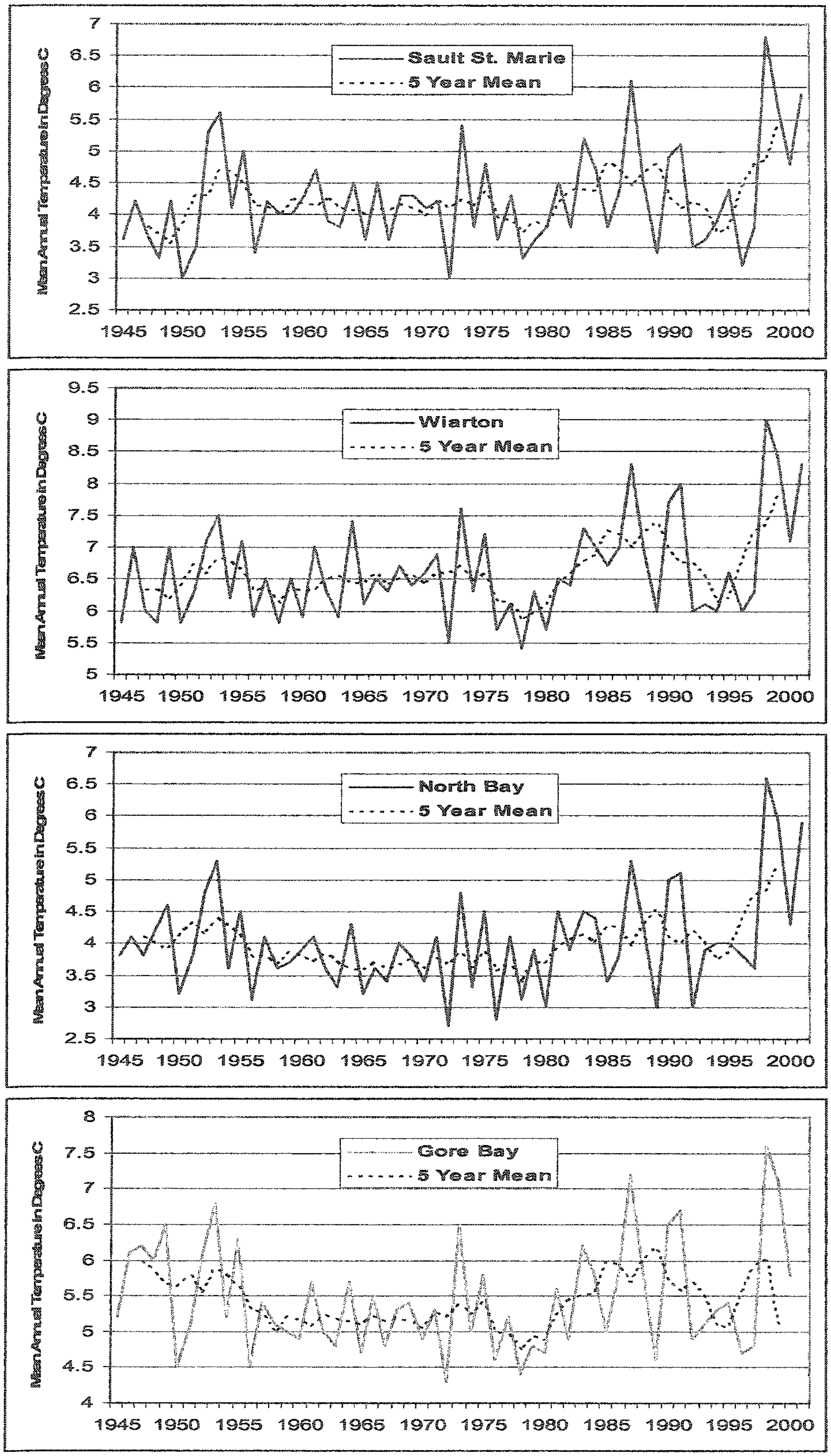


***Figure 2.4** Mean Annual Temperature of four stations in Lake Huron's Basin from 1945-2001 (HCCD, 2002).*

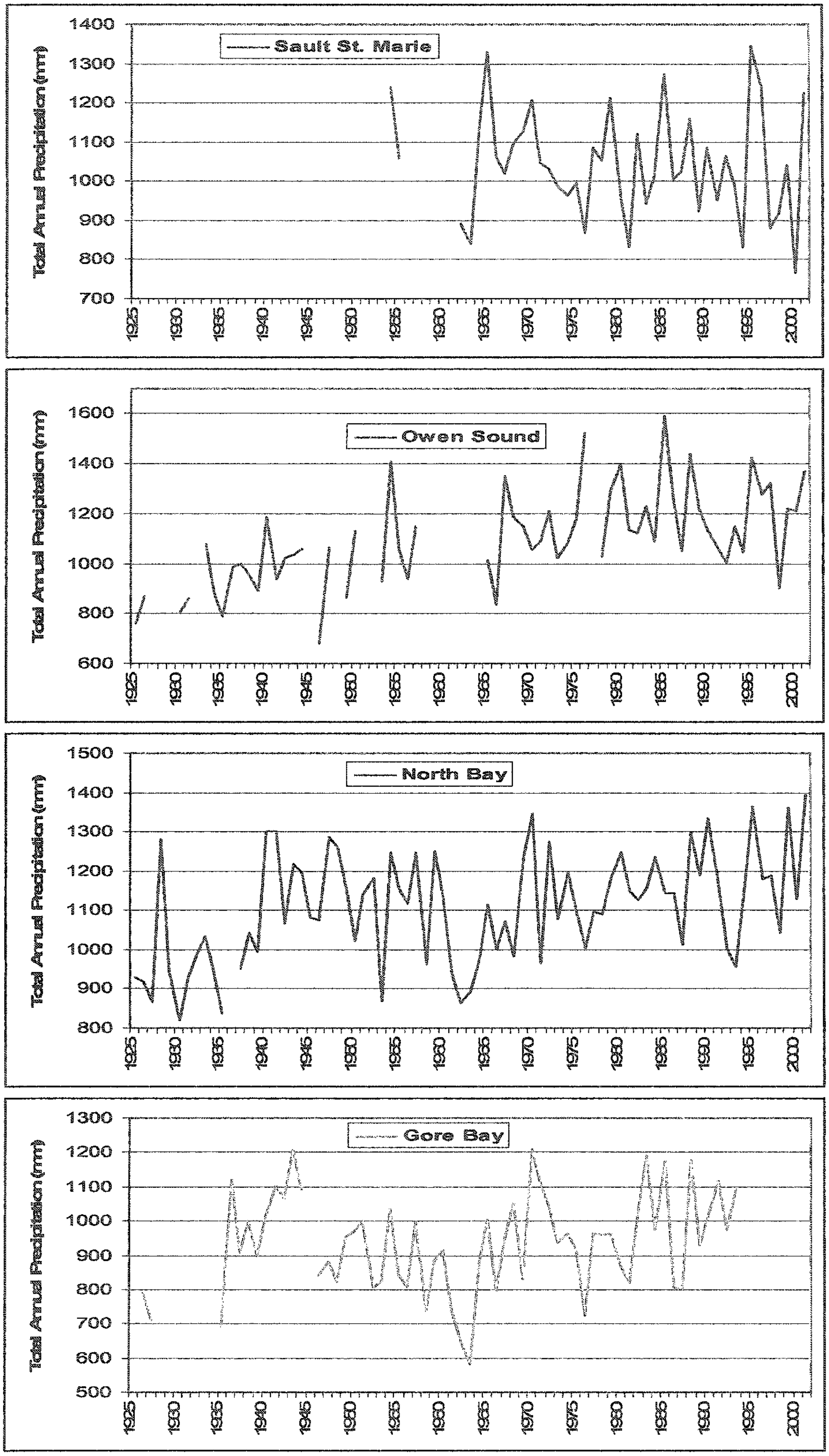


Figure 2.5 Total Annual Precipitation from four stations in Lake Huron's Basin from 1925-2001 (HCCD, 2002).

but quickly recovered and remained 980 mm and 1350 mm on average. According to the data presented, both temperature and precipitation in Lake Huron's basin have increased slightly.

2.4.3 Paleoclimate Record

To assess the global instrumental record's significance, the paleoclimate record must be reviewed. According to the paleoclimate record for the northern hemisphere, temperatures have generally decreased from year 1000 until the 20th century (Figure 2.6). Although, beginning in the 20th century, departures in temperature (°C) in the northern hemisphere have increased drastically, from a global average of -0.4 to almost +0.7 (Figure 2.6).

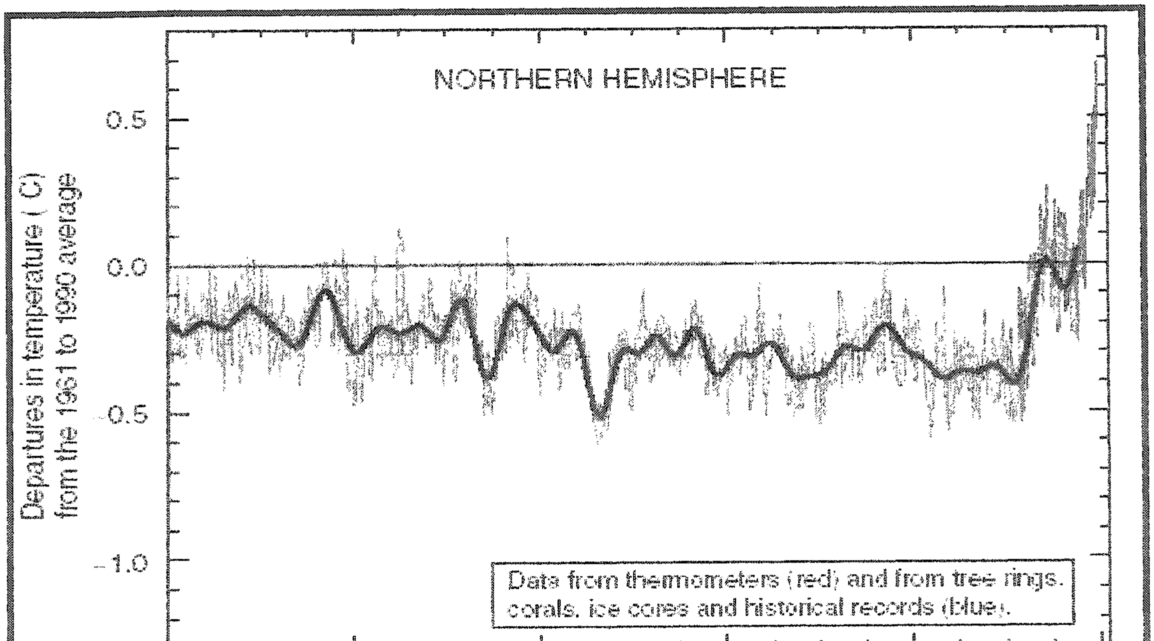


Figure 2.6 *Variations of the Earth's surface temperatures for the past 1,000 years. Grey shaded lines represent two standard error limits. (IPCC, 2001a; after Mann, et al, 1999)*

2.4.4 General Circulation Models

Numerical climate models known as general circulation models (GCM) are used to forecast changes in climate. A GCM simulates the passage of energy through the climate system from the entry of solar radiation at the top of the atmosphere to its final departure to space as longwave radiation (Environment Canada, 1994). It also simulates the effects of this energy on various elements of the climate system and calculates the outcome in terms of temperature, precipitation, soil moisture, and other climatic variables (Environment Canada, 1994).

The simulation of time-dependent historic and projected climate change with reasonably complete coupled climate models has a comparatively short history (Boer et al, 2000a). First-generation GCMs used during the late 1970s and early 1980s were limited in the amount of detail they could represent (Mortsch et al, 2000). Their resolution was coarse – individual grid cells had dimensions from about 800 to more than 1000 km horizontally - and many of their features were highly simplified (Environment Canada, 1994). Despite the important effect of highly variable soil and vegetation types on albedo, heat capacity and the moisture flux, these models generally treated all land surfaces in the same way for soil moisture calculations and offered only a few variations for albedo (Environment Canada, 1994). Similarly, the oceans in these first-generation models were represented by a simple "swamp" like ocean that evaporated water and absorbed energy but did not circulate heat (Environment Canada, 1994; Mortsch et al, 2000).

A second generation of GCMs emerged in the late 1980s, with higher resolution, more detailed representation of features and processes, and more sophisticated parameterizations (Environment Canada, 1994). These new GCM climate change simulations, referred to as equilibrium or steady state (Drake, 2002), allow for an evaluation of climate change based on an instantaneous doubling of CO_2 (2 x CO_2). Simulations were relatively complete and models consisted of a complex atmospheric GCM coupled with a simple ocean component (Boer, et al, 2000). From then they were known as a coupled atmospheric and ocean GCM (AOGCMs). In these simulation runs, doubled CO_2 concentrations are allowed to stabilize at a set parameter (2 x CO_2), and the resulting climate is measured against the model base climate represented by the 1 x CO_2 state (Schwartz, 2001). The simulation of the 1 x CO_2 climate together with the simulation of an equilibrium 2 x CO_2 climate, provided a measure of difference between the two conditions.

Still, there were some limitations with the equilibrium GCMs. Since they are run under a 2 x CO_2 or similar scenario, there is no indication of their timing of projected changes (Croley, 1990). Also, the negative effects (cooling) of sulphate aerosols is not included in the model (Boer et al, 2000a). There is no three-dimensional ocean model component (Boer et al, 2000b). Furthermore, equilibrium experiments modelled the ocean as a simple component usually consisting of a 50 m ocean mixed layer, that was incapable of representing the ocean's thermal heat capacity (Boer et al, 2000b).

As a result of these limitations in the equilibrium GCMs, recent advances in modelling techniques, computer power, and an increased knowledge of the climate system have led to the development of a new form of GCM. Transient run GCMs were developed in the late 1990s (Drake, 2000). Transient run models use AOGCMs to simulate the response of the climate system to a gradual increase in greenhouse gases and sulphate aerosols (Morstch et al, 2000). Most transient runs are developed using a 1% per year increase in greenhouse gas emissions from a base year, to the time of 2 x CO_2 at about 2050 (Boer et al, 2000). They are able to simulate both past and present conditions, and generate projections of future climates (Flato et al, 2000; Boer et al, 2000b; Johns et al, 1997). Unlike the equilibrium runs, transient GCMs are able to create a three-dimensional projection. The most advanced transient AOGCMs include a circulating ocean fully coupled to a circulating atmosphere, complex snow, sea ice, cloud and ecosystem feedback, and higher spatial resolution (Mortsch et al, 2000).

An important transient GCM used in recent Great Lakes research (Mortsch et al, 2000) is the Canadian Centre for Climate Modelling and Analysis (CCCma) Canadian global coupled model (CGCM1) (Flato et al, 2000; Boer et al, 2000a; Boer et al, 2000b). It is a three dimensional atmospheric GCM coupled to a mixed-layer ocean model. The CGCM1 incorporates a thermodynamic sea ice component and allows a realistic simulation of the ocean surface temperature distribution and ice boundaries (Magnuson et al, 1997). A second example of a transient GCM used in recent Great Lakes research is the Hadley Centre for Climate Prediction and Research HadCM2 (Mortsch et al, 2000). A full description of the HadCM2 is provided by Johns et al (1997).

The most common application of GCMs is to determine the sensitivity of the climate system to a change in one of its key elements. However, actual results are not a 100% prediction of future climate change. Instead, results provide an answer to a "what if" question such as, in the case of global warming, what the response of the climate system would be if the concentration of greenhouse gases in the atmosphere increased significantly.

There are some limitations to GCMs in general. At the regional scale such as the Great Lakes, current AOGCMs have many problems. Limitations in the reproduction of the complexities of the climate system affect the accuracy of projections of future rates of climate change and their regional characteristics (Kunkel et al, 1998). However, modellers have considerable confidence in the global-scale features of AOGCMs' results. Also, due to their still slightly coarse spatial resolution, GCMs simplify important topographical features, which can influence local climate significantly, such as mountains, coastlines, and larger bodies of water (NRCAN, 2002).

As well, there is the question of confidence. One test of a climate model is its ability to accurately simulate our present climate (Environment Canada, 1994). In fact, such a test is an essential part of every climate sensitivity experiment. Hence a model's 1 x CO_2 run not only serves as a reference or base case for comparing the results of other experiments, but also as a control for verifying and fine-tuning the model's performance. If the model produces a good approximation of the observed values and distribution of temperature, pressure, precipitation, and other climatic elements, then we can have some confidence in its results.

Despite their limitations and issues of uncertainty, GCMs are still "the most effective method of testing how an 'enhanced greenhouse effect' due to increasing atmospheric concentrations of carbon dioxide and other greenhouse gases will affect climatic processes" (Mortsch et al, 2000, p. 155). With the recent advances in transient AOGCMs, projections are available for different and multiple years, unlike the equilibrium runs. Resolution is becoming more refined, and most atmospheric processes are now included in the programming. Therefore, until there is some method that produces more accurate results, GCMs will remain the preferred method.

2.5 Lake Levels

In the Great Lakes, water levels are expressed relative to a calculated datum (low water mark) above sea level. The current datum is known as the 1985 International Great Lakes Datum (IGLD-85). Water level measurements in the Great Lakes are expressed relative to the 1985 sea level recorded at Rimouski, Quebec, near the mouth of the St. Lawrence River (USAC and GLC, 1999). The IGLD is updated every 25 to 30 years (USAC and GLC, 1999), because the basin's elevation is changing as a result of crustal movement. The previous datum was from 1955. The elevation at Rimouski acts as the reference zero point upon which chart elevations are based. The previous reference zero used for the IGLD-55 was located at Pointe-au-Pere, Quebec, but due to the deterioration of the wharf, the gauging station on site was discontinued in 1984, and moved approximately five kilometers upstream to Rimouski (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1995). In 1983, the Geodetic Survey of Canada (GSC) releveled the line between Rimouski and Pointe-au-Pere and determined an elevation of 6.263 metres above sea level for the benchmark at Rimouski. This elevation is identical to the original IGLD-55 elevation assigned to the benchmark at Point-au-Pere (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1995). Therefore, since there is no appreciable difference in the tide between Point-au-Pere and Rimouski, and there is good agreement in the GSC results, the new benchmark at Rimouski can be used to define the reference zero for the new IGLD.

According to the IGLD-85, Lake Huron's chart datum is 176.00 m. This is the elevation which represents Lake Huron's average low water level. Chart datum is selected so that the water level will seldom fall below it.

The Canadian Hydrolographic Service (CHS) records lake levels in Canada, while the National Ocean Service (NOS) is in charge of recording lake levels in the United States. Water levels are recorded using numerous floating and shoreline gauges throughout the lake. These gauges are referenced to the same vertical datums that are used for charts (Canadian Hydrographic Services, 2003). The CHS has been recording water levels since 1918. Lake Huron's record high was set in October of 1986 at 177.5 m (Moulton, 2002).

Data are available to 1860 for Lake Michigan Huron through GLERL (GLERL, 2004). During the period 1860 to 1890 the average lake level was approximately 177 m, and this was followed by a decline to approximately 176.3 m by 1895. Between 1895 and 1918, lake levels fluctuated around a mean of 176.6 m.

There are three temporal patterns of water level fluctuations on the Great Lakes each of which influences lake level by a different magnitude: long-term (2 m), seasonal (20-40 cm), and short term (50 cm - 3 m) (Quinn, 2002). Long-term fluctuations, lasting up to a few years, are the result of persistent low or high water supply conditions within the basin (Figure 2.7). Such periods culminate in extremely low levels, such as were recorded in the mid-1960s on Lake Huron, or in extremely high levels, such as in 1986 and 1987. Over that record there are periods of extreme below and above average water levels (Figure 2.7). Approximately every thirty years the Lake experiences extreme below average lake levels. In the mid thirties, sixties and late nineties, lake levels were

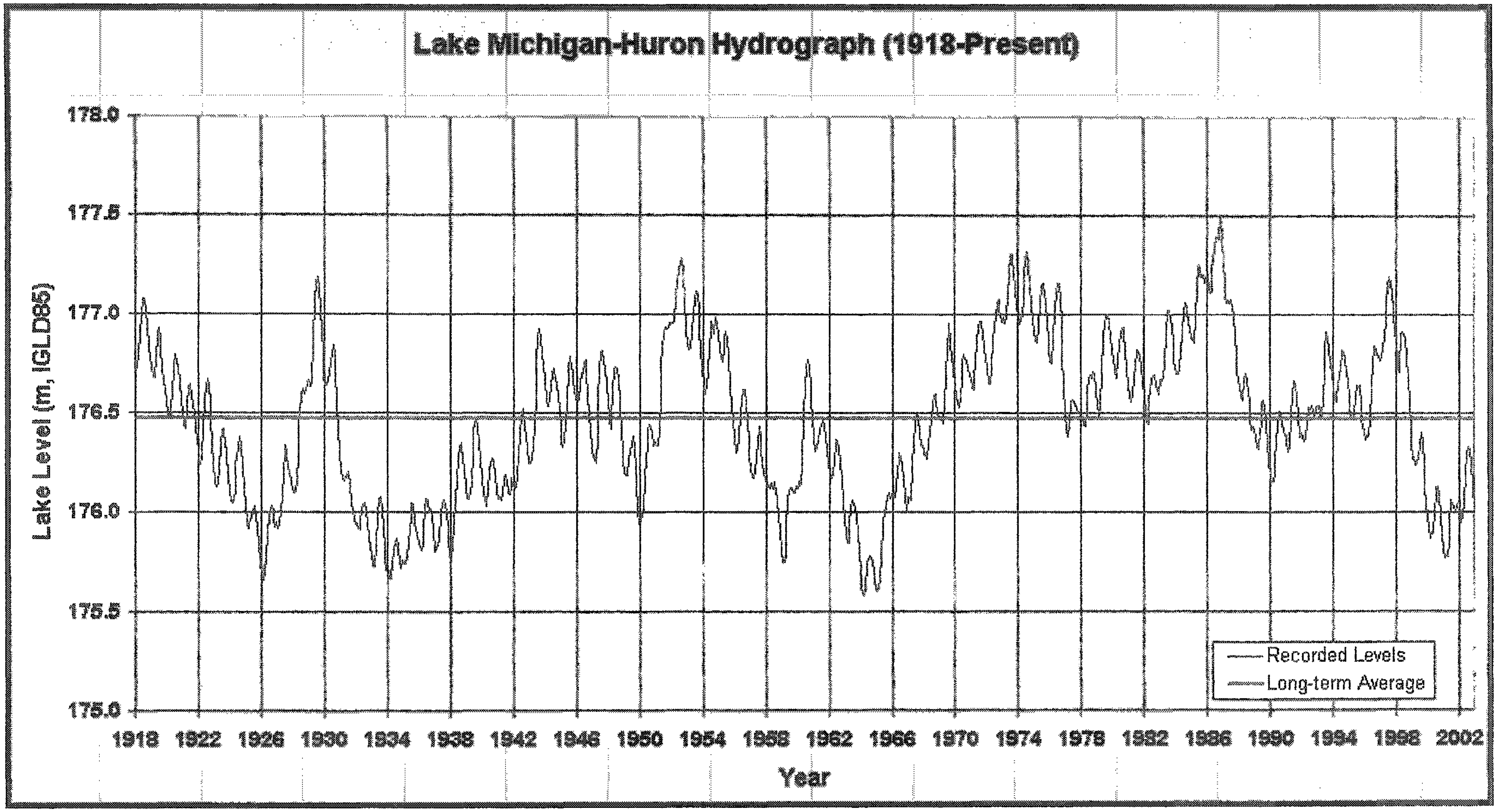


Figure 2.7 Lake Michigan-Huron historical water levels (USAC – Detroit Division, 2003).

very low. Lake Michigan-Huron's record low was set in March of 1964 at 175.58 m (Moulton, 2002). Periods of above average lake level occurred in the late twenties, mid fifties, mid seventies, mid eighties, and mid nineties. Seasonal fluctuations reflect an average annual seasonal cycle (Figure 2.8). This is characterized by higher net supplies during the spring and early summer from snow melt and precipitation, with lower net supplies during the remainder of the year. Therefore, lake level is higher in late spring and early summer, and lower in fall and winter. The magnitude of seasonal fluctuations is small, averaging about thirty centimeters (Quinn, 2002). Short-term fluctuations, lasting from a few hours to several days, are mostly caused by episodic events such as storms and ice jams. Wind and differences in barometric pressure over the surface of a lake can create temporary imbalances in the water levels. For example, on Lake Erie west winds gusting to 120 km/hr caused lake levels to differ by about 2.75 m at the two ends of the lake on April 30, 1984 (Liston and Chubb, 1985). Also, ice jams in an outlet

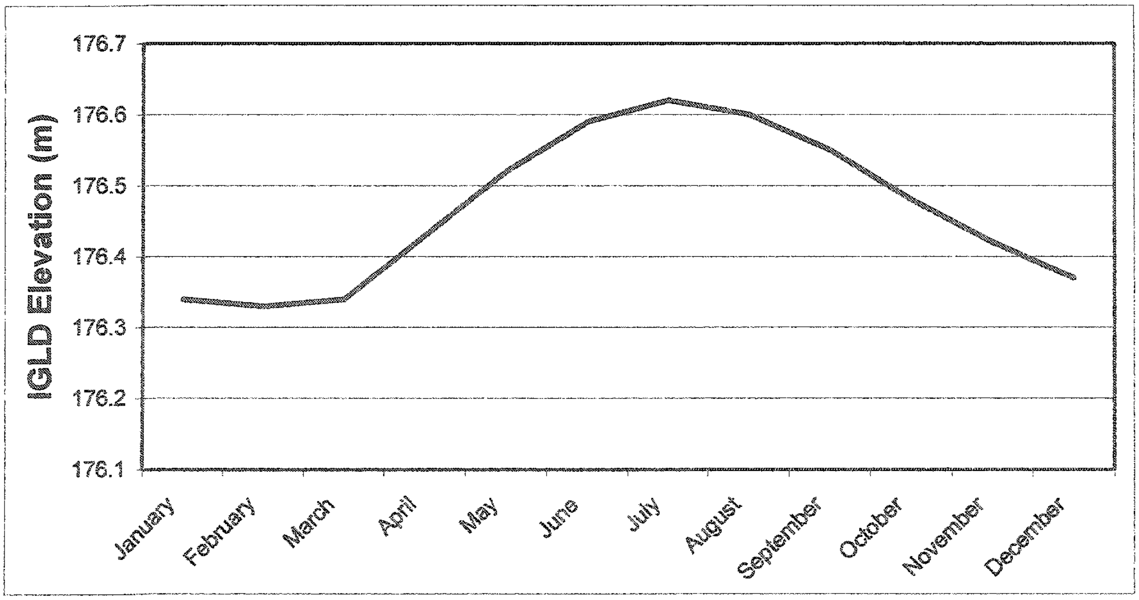


Figure 2.8 *Lake Huron seasonal water level fluctuations. Month average water levels from 1918-2002 (Moulton, 2002).*

river can drastically slow the flow of water out of one lake and into another, therefore, causing water levels to rise upstream and fall downstream. A fundamental difference between short-term variations and the seasonal and long-term fluctuations is that during short-term fluctuations, there is rarely any change in the volume of the lake.

2.5.1 Human Control of Lake Level

Water levels in the Great Lakes are influenced by a number of factors, such as diversion structures, control structures, and dredging. In 1909, a binational government organization named the International Joint Commission (IJC) was created. The IJC is responsible for ensuring that the flows (in and out) and levels in the Great Lakes system meet the terms and conditions of the Boundary Water Treaty of 1909 (USAC and GLC, 1999). Water diversion and control structures are directly controlled and overseen by the IJC, whereas dredging projects are not.

Water diversion structures exist throughout the Great Lakes system. The Ogoki and Long Lac diversions redirect approximately 206 m^3/s of water which would normally flow into James Bay, south into Lake Superior (Sanderson, 1989). The increase in lake levels caused by these two diversions amounts to approximately 6 cm on Lake Superior, 10 cm in Lakes Michigan-Huron, 7 cm in Lake Erie, and 6 cm on Lake Ontario (Sanderson, 1989). The only major diversion of water out of the Great Lakes occurs at Chicago. Water from Lake Michigan is diverted for domestic and industrial use and sewage disposal into the Mississippi River through the Illinois River (Sanderson, 1989). A maximum flow of 120 m^3/s from Lake Michigan is allowed by the United States Supreme Court. This results in a lowering of 2 cm for Lake Superior, 6 cm for Lakes

Michigan-Huron, 4 cm for Lake Erie, and 3 cm for Lake Ontario (US Army Corps, 2001). A third diversion at the Welland Canal connects Lakes Erie and Ontario. This diversion is used strictly for shipping and hydro electric generation, and there is no net control of water levels. The overall result of the three diversions is a small rise in level across the system.

Unlike diversions, control structures manage the discharge of water through some channels in the Great Lakes. The flow of water in the Great Lakes is controlled at two points: from Lake Superior to Lake Huron at Sault Ste. Marie, and from Lake Ontario through the St. Lawrence River at Cornwall (Environment Canada, 2001b). The former structure is under the control of the International Lake Superior Board of Control (Environment Canada, 2001b). At Cornwall, the International St. Lawrence River Board of Control directs the volume of water flowing out of Lake Ontario (Environment Canada, 2001b). Essentially, as a result of the operation of these control structures, Lakes Superior and Ontario experience less fluctuation in their levels.

In order to maintain commercial and recreational marine activities in the Great Lakes, there are extensive dredging activities each year, the purpose of which is to provide safe navigable waters for shipping and recreational boating. The depths of channels vary with the types of traffic. In the United States, connecting channels between the Great Lakes are maintained at depths of 9 m for the ocean-going ships which carry ore, coal, and other cargos between domestic and international ports (US Army Corps, 2002). The channels at a particular harbour may have depths up to 9 m at the entrance with progressively shallower depths as one travels upstream (US Army Corps, 2002). To maintain these depths the US Army Corps of Engineers typically removes about 3.6 million cubic metres of sediments each year from Great Lakes harbours and channels (US Army Corps, 2002).

Dredging can be used to partially control levels and outflows. Sometimes, through operation of the control structures, at Sault St. Marie and Cornwall, the levels can be manipulated in accordance with a predetermined policy, and thus, dredging may be allowed. However, occasionally when the control structures do not manage the lake levels properly, problems can arise. The levels of Lakes Michigan-Huron have been lowered by commercial dredging for gravel and by dredging operations undertaken to improve the St. Clair and Detroit Rivers and Lake St. Clair for navigation (IGLLB, 1973). As a result of dredging practices not being compensated with fill or other channel obstructions, the net effect of navigation improvements over the 20th century has been a lowering of Lakes Michigan-Huron by approximately 40 cm (De Loe, 2000).

2.5.2 Natural Controls of Lake Level

Both temperature and precipitation play vital roles in lake level. During prolonged periods of higher air temperature, lake evaporation and basin evapotranspiration are intensified, causing water to be taken from the lake and a reduction in runoff to the lake, therefore resulting in lower water levels (Figure 2.9 and Figure 2.10). Therefore, following periods of decreased air temperature and increased precipitation, water levels tend to be higher. However, the opposite can be said about periods of increased air temperature and decreased precipitation, as water levels tend to decline as a result of such climate.

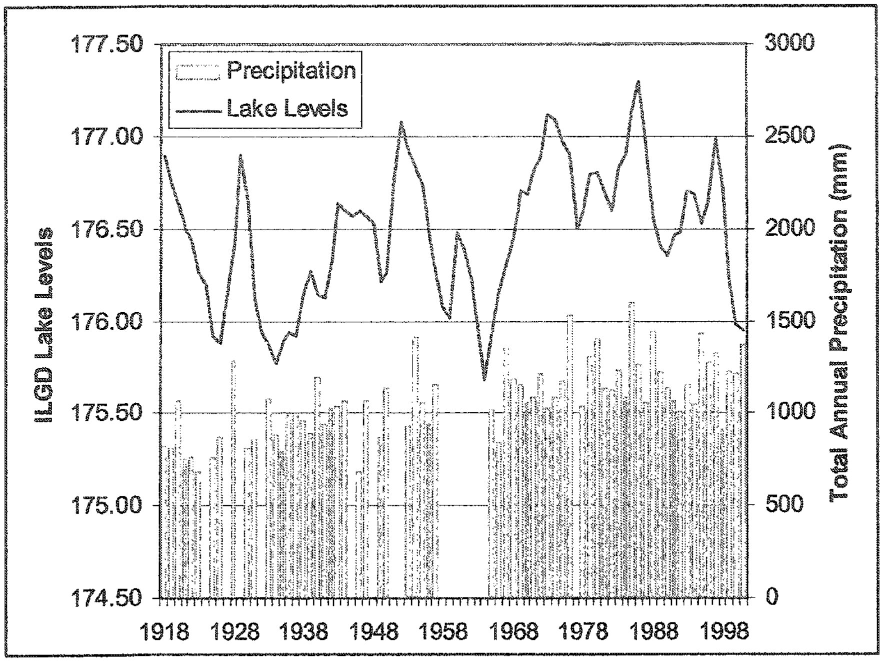


Figure 2.9 *1918-2001 Annual Total Precipitation for the city of Owen Sound, Ontario (HCCD, 2002), against Lake Huron's long term water level record (Moulton, 2002). Some precipitation data is missing from the record.*

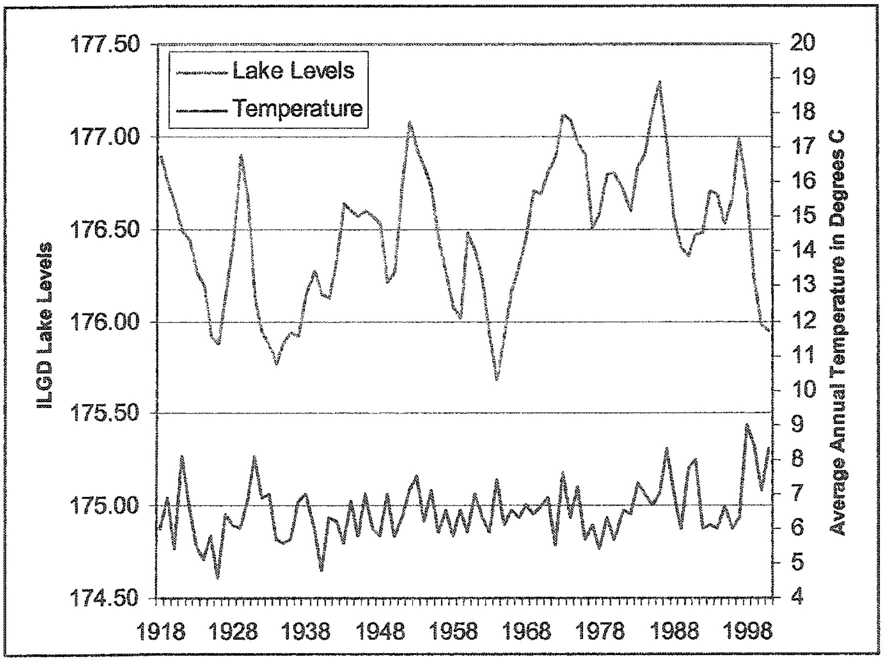


Figure 2.10 *1918-2001 Average Annual Temperatures for the city of Wiarton, Ontario (HCCD, 2002), against Lake Huron's long term water level record (Moulton, 2002).*

However, trends at a seasonal scale are slightly different. There is a more noticeable time lag between a precipitation event and higher water levels (Figure 2.11). Typically, higher amounts of winter precipitation, usually in the form of snow, thaw in the spring months, and this generally results in higher lake levels during the summer months. The time lag between precipitation events and lake level can be characterized by greater amounts of winter precipitation causing high summer lake levels.

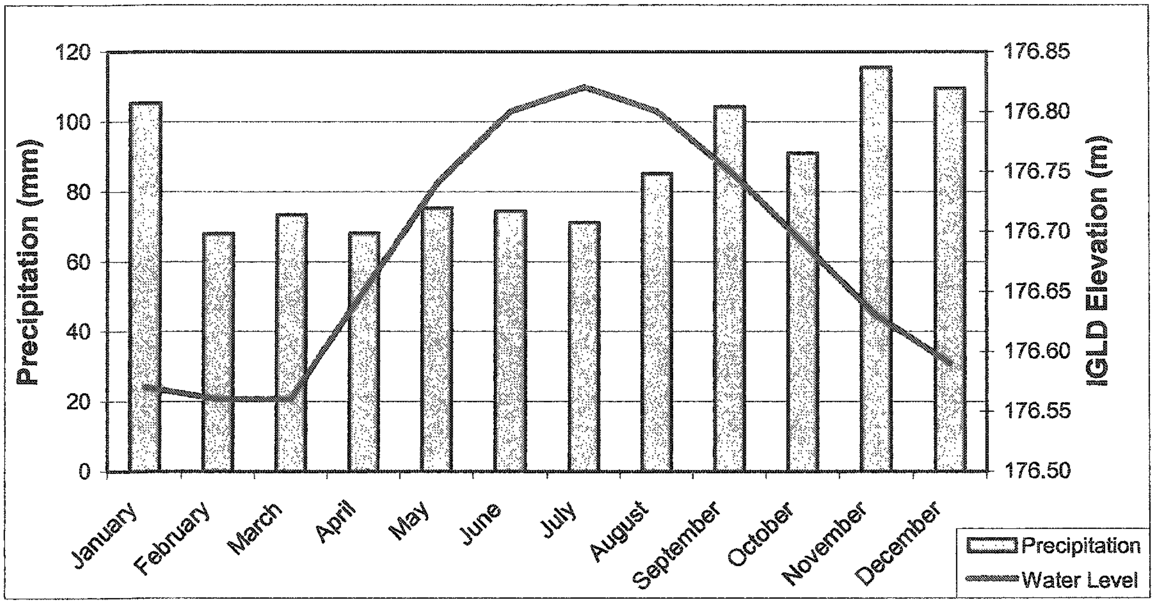


Figure 2.11 *Total Monthly Precipitation and Water Level Comparison, 1971-2001 (Precipitation Data: Wiarton A, Environment Canada, 2002; Water Level Data: Moulton, 2002)*

2.5.3 Water Level Scenarios

Water level scenarios are a representation of a range of conceivable future lake levels. These scenarios, or projections, attempt to illustrate the response and sensitivity of water resources to climate change (Schwartz, 2001).

Scenarios are derived from regional or basin hydrologic models that have been integrated with climate variables from the results of GCM simulations (Schwartz, 2001).

By linking regional hydrologic models with GCMs, it is possible to better assess regional changes associated with climate change (Croley, 1990). Hydrologic models are detailed mathematical representations of the basin's physical processes, and have been implemented with a high degree of spatial and temporal resolution (Kunkel et al, 1998). The Great Lakes Environmental Research Laboratory (GLERL) has developed a series of hydrologic models to simulate the supply and flow of water in the Great Lakes basin (Schwartz, 2001), and they have been used in much research (Kunkel et al, 1998; Croley, 1990; Hartmann, 1990).

Historically, climate impact assessments, related to Great Lakes water levels, have used climate change scenarios developed from equilibrium 2xCO_2 GCM runs (Mortsch et al, 2000). However, transient run GCMs have made a significant impact on water level scenarios in the Great Lakes. Water level scenarios developed from the CCCma's CGCM1 transient run, and hydrologic models from GLERL, forecast Lake Huron water level declines of 0.2-0.7 m by 2030 and 0.3-1.01 m by 2050, from a 1961 to 1990 average lake level (Mortsch et al, 2000). Except for Lake Ontario, these changes would be greater than each lake's natural variability (Croley et al, 1998). According to the Hadley HadCM2 scenarios, the lake levels increase up to 5 cm by 2030, and up to 3 cm by 2050 (Mortch et al, 2000).

It is important to realize that not one specific scenario is correct (Lavendar et al, 1998). A range is required to recognize and present the concept of uncertainty, that no complete emphasis should be on one single projection. This is why research involving GCMs in the Great Lakes has used both the CCCma's CGCM1 and the HadCM2. There is a significant difference in the results from these two GCMs. Also, it is important to use multiple GCMs, in the case of one GCM creating an error.

Water level scenarios developed in the late 1990s have projected results for the Great Lakes basin (Table 2.2). All lakes are likely to experience increased variability in seasonal fluctuations (Brinkmann, 2000). Lake levels may decline to or below historic low levels throughout the Great Lakes (Mortsch and Quinn, 1996). For example, in Lake St. Clair the CCCma CGCM1 scenario suggests a surface area decrease of 15%, and a volume reduction of approximately 37%; resulting in a water level decline of possibly 1.6 m, displacing the shoreline 1-6 km lakeward (Mortsch et al, 2000). Also, the timing of seasonal water level peaks and troughs may change on Lake Michigan-Huron. Peak levels, for instance, may occur more frequently in June than in August, as a result of an earlier spring thaw (Mortsch et al, 2000).

Climate scenarios and lake models have consistently predicted less runoff, more evaporation, and lower water levels in both large and small lakes in the region (Kling et al, 2003). The CCCma CGCM1 suggests warming temperatures, stable or increasing precipitation, and more evapotranspiration in the Great Lakes region for the next fifty years. This results in less runoff to the lakes and a decline in lake levels. The HadCM2 model also predicts warming temperatures, slight increases in precipitation, but no substantial change in soil moisture. When the Hadley data are input into the hydrological model, there is little change forecasted for lake levels. Recent work by Lofgren (2003), using a new model has produced results similar to the Hadley. Lofgren (2003) suggests the differences in lake levels arising from the two models (CGCM1 and HadCM2) are related to the manner in which the models address the distribution of land and water in the Great Lakes basin.

Table 2.2 *Lake Huron Water Level Scenarios*

TRANSIENT MODELS			
Reference	**2030 Projection**	**2050 Projection**	**2090 Projection**
Mortsch et al, 2000 *CCCma CGCM1*	-0.72 m	-1.01 m	
Sousounis et al, (2000a) *HadCM2*	+0.05 m		+0.05 m
EQUILIBRIUM MODELS			
Sousounis et al, (2000a) *CCC1 2x*CO_2	-0.23 m		
Sousounis et al, (2000a) *GISS 2x*CO_2	-0.47 m		

2.6 Impacts

Various scenarios have suggested considerably lower mean Great Lakes' water levels, and an increased frequency of extreme low levels, due largely to higher rates of evaporation and evapotranspiration with warmer temperatures (De Loe, 2000). These projections will create many impacts on the Great Lakes' water levels. Figure 2.12 is adopted from a Natural Resource of Canada report outlining potential impacts of climate change on water resources as a result of declining lake levels (NRCAN, 2002). This section briefly reviews the impacts presented in Figure 2.12.

2.6.1 Environmental Implications

Climate change altered water levels will impact hydrologic, atmospheric, biologic, and coastal environments in the Great Lakes basin.

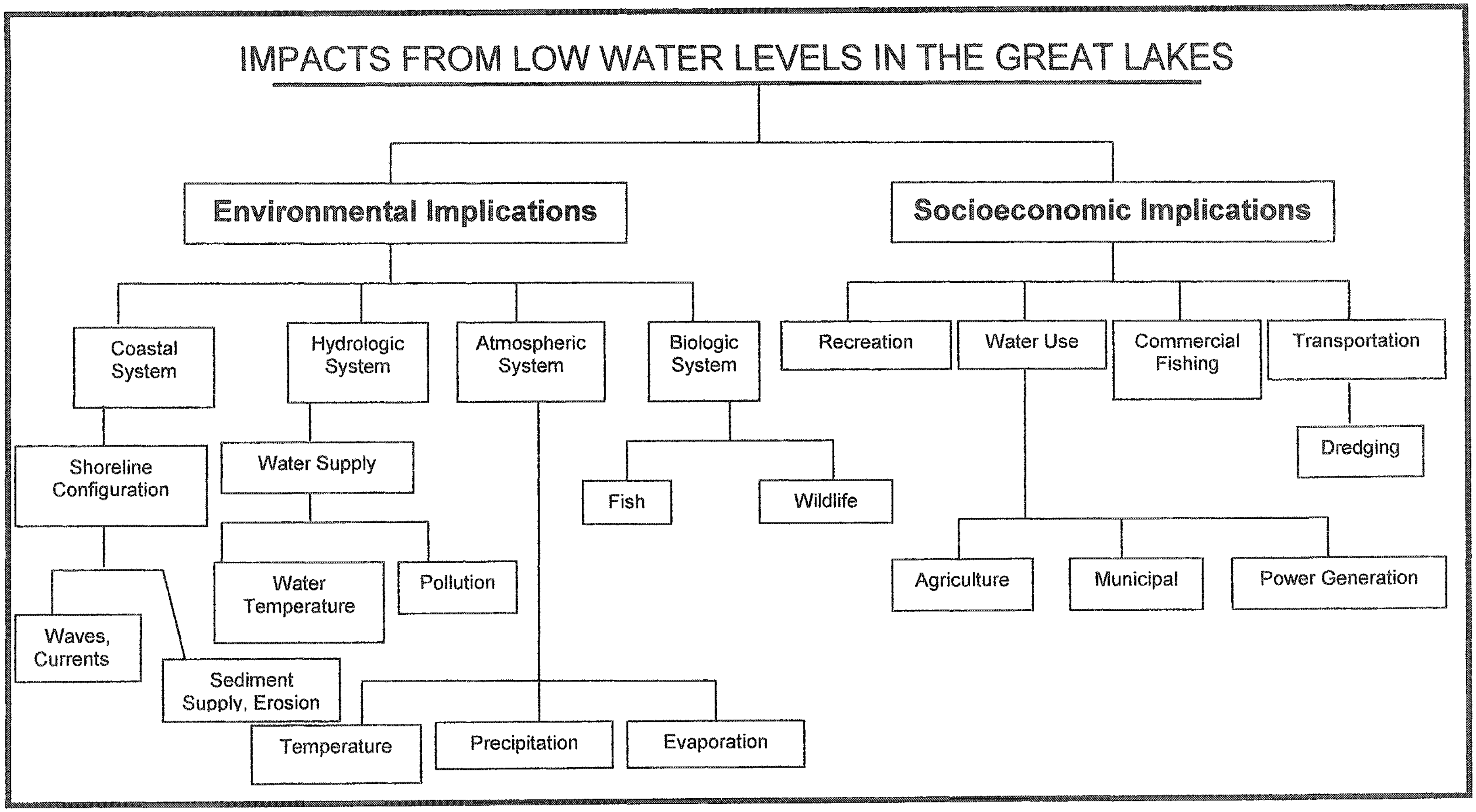


Figure 2.12 Impacts from Low Water Levels in the Great Lakes (adopted from NRCAN, 2002).

2.6.1.a Hydrologic System

A significant decline in lake level will cause problems associated with water supply. Migrating shorelines, consisting of coastal wetland, cottage frontages, and harbours will be impacted. In addition, both water temperature and water quality are influenced by supply. Biologic impacts also depend on water supply, these impacts are discussed later in section 2.6.1.c.

Water quality is influenced by fluctuating water levels. Lower lakes levels will increase the risk of toxic pollution and frequency of a algal bloom. Known Great Lakes toxins include mercury, dieldrin, and polychlorinated biphenyls (PCBs). Nutrients in runoff can produce algae blooms, and these will be more common. In the late 1990s,decreased water levels in the Sauble River mouth led to large algae blooms (Tupman, 2001). In this case, both lower water levels and increased water temperatures played significant roles.

A decline in lake level and increased air temperatures will lead to increased water temperatures. Earlier model studies project that summer surface water temperatures in inland lakes will increase by 1 to 7°C (Kling et al, 2003). Changes in water temperature and stratification will affect the fundamental physical, chemical, and biological processes in lakes. Higher water temperatures, for example, result in lower oxygen levels (Kling et al, 2003). If water temperatures remaining above 4°C throughout the year, buoyancy-induced turnovers in the fall and spring may not occur (Hartmann, 1990).

2.6.1.b Regional Atmospheric System

The Great Lakes moderate the basin's climate, because of their large size and volume. Therefore, if the water level declines and therefore reduces the lakes' surface area and volume, the basin's climate will be impacted. Temperature and precipitation throughout the basin will change (De Loe, 2000), creating impacts throughout the entire hydrologic cycle. However, the level of impact will vary throughout the basin. More noticeable change will be in locations closer to the coastal zone, while there will be less impact further from the coastal zone (De Loe, 2000). Also, a decline in lake surface water will result in a decline in evaporation, which subsequently will result in a decline in precipitation. Overall, there will be a slight change in the basin's climate as a result of lower lake levels.

2.6.1.c Biologic Systems

With an increase in air and water temperature, throughout the Great Lakes, there are general expectations of northward shifts in the geographical distribution of warm and cold water species, changes in relative abundance of species within fish communities, and changes in yields of different species (Hartmann, 1990). Also, with higher water temperatures, metabolic rates will increase and fish would need more food to maintain body size (Smith, 1991). Lake level fluctuations may also alter temperature regimes in littoral zones, thus influencing fish spawning periods and rates of food production (Liston and Chubb, 1985). Water temperature plays an important role in the Great Lakes, because there is such a diversity of fish species. Many fish species prefer cold and clear water such as walleye, salmon and trout, while other species prefer warmer water such as bass, pike, perch, and carp. Therefore, changes in water temperature may influence community structure in the lakes.

Low lake levels at improper periods may have detrimental effects on fish population. The Great Lakes' diverse range of fish species requires spawning almost year round. Certain fish species spawn in the summer, others in the fall, winter and spring. During those times, if lake levels are lower, spawning may be disrupted.

Little research has been conducted on the impacts of a lower lake level regime on wildlife (Magnuson et al, 1997). However, it has been suggested that in some areas terrestrial species will be required to travel longer distances to find a water source (Boorman, 1997; Keddy, 1985; McCormick, 1999). Wildlife such as muskrats, beavers, deer, and waterfowl species require habitat for nesting, fedding, drinking water, and grazing. If lake levels decline and the shoreline moves lakeward, wildlife will be required to adapt. Wildlife species that live near the water line, such as the beaver and muskrat, will be potentially most affected. Species that feed on fish will need to search in new locations. Overall, when the Great Lakes' water levels drop, terrestrial and waterfowl wildlife will be impacted.

2.6.1.d Coastal System

Over time, as lake levels fluctuate, a shoreline's configuration will change, and this change will influence a number of coastal processes. Waves and currents, as well as sediment transportation will be altered. Waves and currents, key components of a coastal zone, may become altered in their path, due to a change in shoreline configuration. Secondly, aeolian sediment transport may become altered because of a new shoreline configuration. New sediment supplies may become available under low lake level conditions, and this may create new sand formations such as cusps, and dunes. Overall, under significant low lake level conditions, an altered shoreline configuration may alter local coastal processes.

2.6.2 Socioeconomic Implications

Socioeconomic impacts include marine navigation or shipping and dredging, water use, hydro power generation, and the fishing industry. Often socioeconomic impacts stretch over to the environment. For example, climate change effects on society interact strongly with effects such as eutrophication, acid precipitation, toxic chemicals, and the spread of exotic species (Burton, 1985).

2.6.2.a Navigation & Dredging

During conditions of low lake levels, more trips must be made to move the same amount of cargo; this increases shipping costs, and the increase in traffic could cause backups at recognized bottlenecks in the system (e.g. Welland Canal). However, a shorter ice season could lead to an extended navigation season, contributing to better vessel utilization and a decrease in stockpiling (Hartmann 1990, Smith 1991). Despite this lengthened shipping season under a $2xCO_2$ climate, 11 months ice-free on average, Sanderson (1988) estimated that more frequent lower lake levels could increase Canadian commercial navigation costs by 30%.

According to United States Great Lakes Shipping, 2.5 cm of lost clearance due to low water, results in a loss of 90-115 metric tones of cargo at a cost of up to $11,000 per day (Quinn, 2002a). Therefore, decreased channel depths will likely require extensive dredging in both the connecting channels and harbours to maintain present shipping capabilities. However, most dredging practices are very costly. Annual basin wide costs could range between $270-$540 million on dredging and dock lowering (Smith, 1991).

Another issue with dredging is contaminated sediments. Many important channels and harbours throughout the Great Lakes systems (including 41 of the 42 Areas of Concern identified by the International Joint Commission) have severe sediment contamination problems, generally related to heavy metals or toxic chemicals (Hartmann, 1990). In these areas, adaptation to lower lake levels via dredging will be constrained by government regulations and high costs related to disposal of the contaminated dredge spoil. Currently, dredging is the most common form used to reduce the impact of lower lake levels for shipping. Still, there are problems associated with the practice, mainly cost, the possibility of contaminated sediments, and storage of the removed sediments.

At a smaller scale, a lower lake level regime would adversely impact recreational boaters and marina operators. Lower lake levels may render some marinas temporarily or permanently inaccessible. Marina docking facilities require renovation especially lowering of the docks (Figure 2.13). Also, most boat launching facilities will require reconstruction or renovation to adapt to the lower lake levels. This was the case in the Sauble River, where the boat launching ramp was deepened and extended in 2000 and 2001 (Tupman, 2001). Also, as a result of the work on the ramp, for the first time in the river, a usage fee was instituted. Even though recreation boats and marina facilities are much smaller than the larger ocean vessels, they are still impacted.

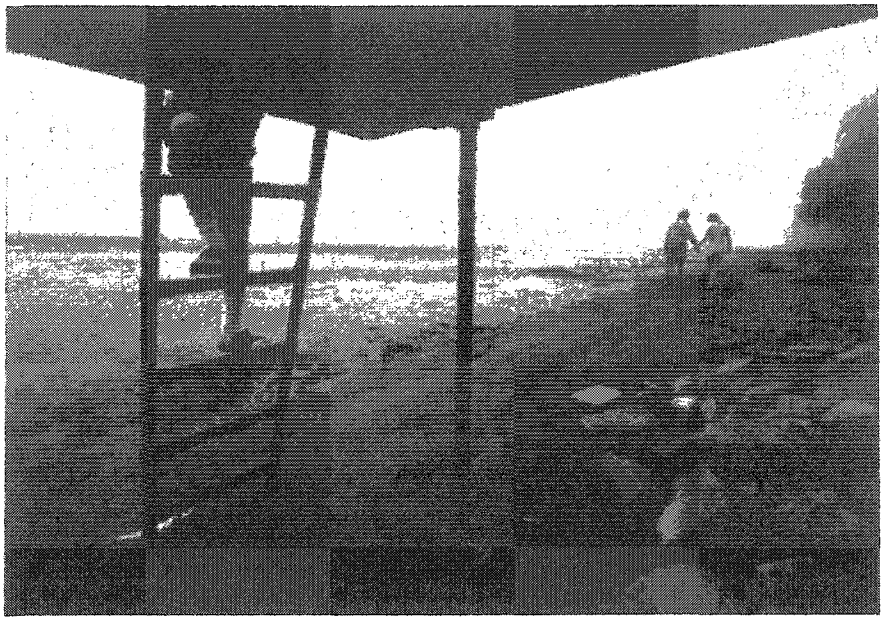


Figure 2.13 Low Lake Level Impacts on Docking Facilities (Tupman, 2002)

2.6.2.b Power Generation

Reduced lake levels may result in decreased flows and water-surface elevations that would contribute to a reduction in hydro power generation. Record low levels and flows in the mid 1960s, while less severe than climate change scenario projections, resulted in hydro power production losses of 19-26% on the Niagara and St. Lawrence Rivers (Hartmann, 1990). Sanderson (1987) estimated that Canadian hydro power plants could lose 4,165 gigawatt-hours of generating capacity, about 25% of Canadian Great Lakes generation, if record lows are reached again.

The full impact of climate change on power generation interests depends not only on the water supplies available for hydro power, cooling, or transportation, but on the changes in peak power demands that result from the increased air temperatures. During the summer months, lower flow levels are projected to reduce hydroelectric generation potential, while more frequent and intense heat waves are expected to increase airconditioner usage and therefore electricity demand (NRCAN, 2002). So, not only will future lake levels influence hydroelectric power generation, but also the demand for it.

2.6.2.c Water Use

Lower water levels will subsequently influence the amount of water that society will be able to use. Most of the 20 million people that live in the Great Lakes basin depend upon the lakes for their water supply (NRCAN, 2002). Diminishing surface-water and groundwater supplies, as a result of lower lake levels, coupled with increasing demands for these resources, would challenge all aspects of water resources management.

Declining water supplies are expected to increase competition and conflict over water and increase its value (NRCAN, 2002). The consequences of climate change for water resources depend not only on possible changes in the resource base or supply, but also on changes in the use, both human and environmental. Future water use will be affected by many factors such as population growth and pollution concentration. The main concern is population growth's effect on need. The basin's population by the year 2050 will be considerably larger. This means that fresh water demand will be much higher and much more competitive

2.6.2.d Commercial Fishing

Harbour access problems will occur due to the lowered lake levels, but changes in fisheries populations may be even more important. Fisheries production is intimately tied to wetland extent, which may be irretrievably lost as lake levels are lowered. Even if stocking programs are used to maintain fish populations, the industry may have to adjust to different species since increased water temperatures and the absence of semi-annual lake turnovers may affect which fish can be harvested at marketable levels. Additionally, climate change could indirectly affect commercial fishing operations in many areas. For example, dredging of channels and harbours will make toxic contaminants available for uptake by fish.

2.7 GIS and the Great Lakes

Geographic information systems (GIS) provide a means of monitoring and analyzing large geographic data sets at regional, national, and global scales (Schwartz, 2001). A GIS is a system for inputting, storing, manipulating, analyzing, and displaying geographic or spatial data (Congalton and Green, 1995). Also, due to their integration capabilities, GIS are able to create information by combining layers to show the original data in new ways and from different perspectives, revealing trends and relationships that may not have been previously apparent (Aronoff, 1989). Overall, GIS provides the ability to present, store, and analyze georeferenced spatial information in a number of ways.

As a result of these many capabilities, GIS has quickly become a powerful tool. GIS packages allow the user to save the map output as standard image files, such as JPEG or Bitmap. This is beneficial when uploading maps into graphic design applications or word processors, for example. Common analytical tools such as overlay, buffering, distance measurements have allowed for basic spatial analysis in ways that were less available with paper maps. In addition, the joining of an attribute table to a map allows for quick reference and statistical analysis. As technology expands GIS capabilities have expanded. In the early 2000s, there has been a greater focus on GIS with the Internet and the world wide web. Applications such as ESRI's ArcIMS, allow analysis, storage, and display over the Internet. Another popular function in the early 2000s has been 3D spatial modelling, which often allows the user to zoom, rotate and pan surfaces in 3D.

2.7.1 3D GIS Modelling

Aronoff (1989) described a model as a set of relationships or information about reality. 3D GIS modelling is an effective method through which environmental processes and impacts can be simulated, analyzed, and monitored (Carrara, 1997). GIS modelling can encompass a broad area of research across several disciplines, and most often includes a range of applications focused on surface modelling, the most common of which is the digital terrain model (DTM), or digital elevation model (DEM) (Schwartz, 2001). New spatial analysis research has used 3D GIS software to engage in characteristics of urban sprawl and population density (Booth, 1999), thus showing that 3D GIS modelling can be used in a myriad of applications. 3D GIS modelling in some fields is being used more than traditional 2D modelling (Liu, 1998).

Two main techniques in GIS software applications allow researchers to view surfaces in 3D. These two techniques are the triangulated irregular network (TIN), and raster GRID. The TIN and raster GRID are two types of digital elevation models (DEMs). DEMs, often referred to as DTMs or digital terrain models, are used to depict topography or a surface.

The TIN model (Figure 2.14) is a topological vector data model, representing a terrain surface as a set of interconnected triangular facets called a Delaunay triangulation (Aronoff, 1989). For each of the three vertices, the XY coordinates (geographic locations) and the Z coordinate (elevation) values are encoded (Aronoff, 1989). The TIN produces a more realistic surface, adapting naturally to surface changes by allowing areas of rough terrain to be represented by a large number of smaller triangles without requiring redundant data in smooth areas (Aronoff, 1989). The disadvantage of the TIN compared with a GRID representation is its initial processing is much greater, however, once the TIN file is produced, the more compact TIN representation can be more efficiently processed. Advantages of using the TIN model over the GRID model include no data redundancy, therefore fewer points and smaller files.

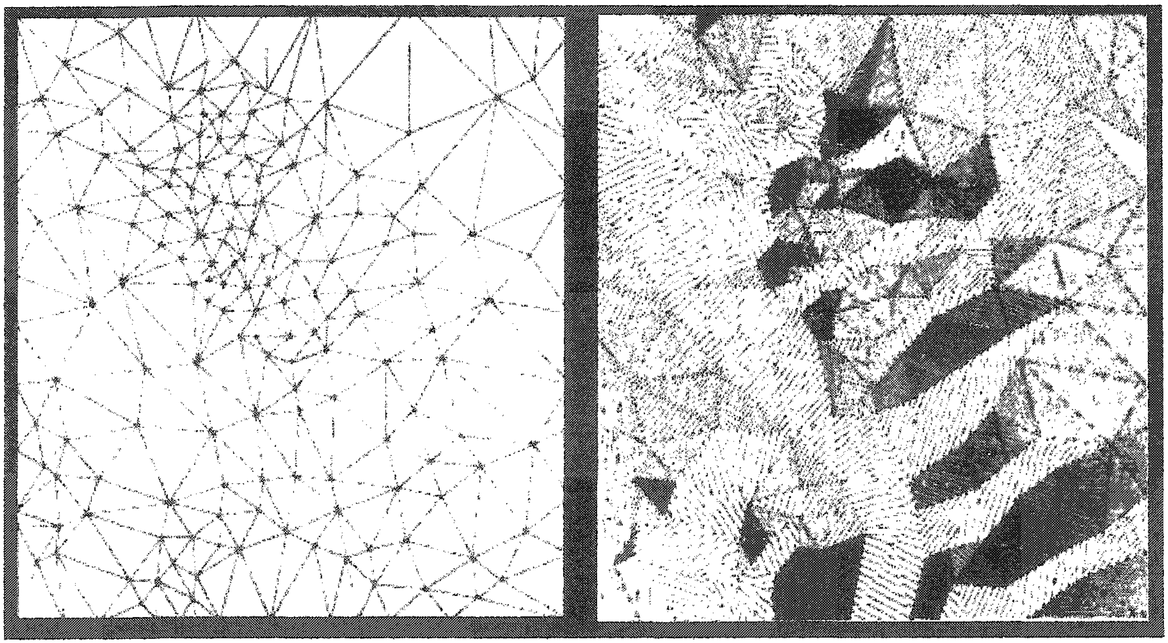


Figure 2.14 *Representation of a TIN Model (Milne, J. A., Sear, D.A., 1997).*

The GRID model (Figure 2.15) is a much simpler model. In its simplest form, the GRID model consists of a regular grid of square or rectangular cells (Aronoff, 1989). In this representation, the level of surface detail is directly related to the grid resolution or cell size (Schwartz, 2001). The location of each cell or pixel (picture element) is defined by its row and column numbers. The value assigned to the cell represents its attribute characteristic. For example a cell attribute might be elevation, and its value would be a specific elevation above a known datum. The GRID model is useful for topographical surfaces, as opposed to urban or network surfaces with many line features. A major limitation of the Raster GRID model is that it requires greater storage and processing time as compared to the TIN model.

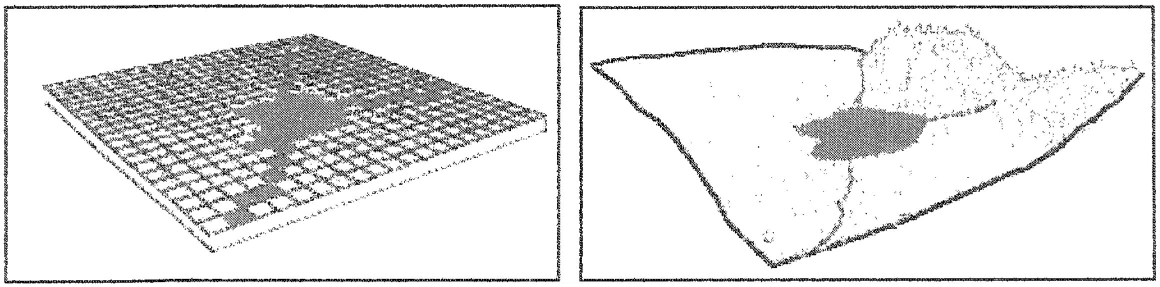


Figure 2.15 *Representation of GRID Model (Demers, 2002)*

3D GIS modelling is rooted in fundamental GIS spatial theory, but its approach to visualization and analysis is quite different (Milne, 1997). Since the data are presented in 3D, the software requires different spatial functions and analysis tools. An example of a new display function, the fly through tool, allows the user to virtually navigate over a surface as if the user were a bird or in a plane. This feature is found in such applications as PCI Geomatica and ArcINFO ArcGIS 8.x ArcScene. With further software development, more tools will allow for greater display and analysis capabilities.

2.7.2 GIS in Great Lakes Coastal Research

In Great Lakes research, the use of GIS is becoming more common in both government and non government work. The ability of GIS to integrate different types of data from multiple sources makes it useful for coastal research. It can be used in such areas as shoreline damage analysis, and shoreline migration modelling. Since the coastal zone is a diverse region, including natural physical features as well as many human features, the ability to apply multiple layers and graphics to a map allows for a range of analyses and mapping outcomes.

Many government sectors are beginning to build large Great Lakes GIS databases (personal communication, Bredin, 2002). Recently, the Michigan State's Department of Natural Resource's Roscommon, Michigan office developed a Lake Huron database. The Lake Huron GIS Project, as it is called, was designed in order to "facilitate a holistic approach to managing the Lake Huron basin (Lake Huron GIS Project, 2002, p.1)." Together, members of the Lake Huron Technical Committee collaborated to design and develop a GIS-based Decision Support System (DSS) (Lake Huron GIS Project, 2002). Through the use of this DSS, both government and non government research interests can access up-to-date data on a number of spatial and geographic topics (personal communication, Bredin, 2002).

GIS has quickly become an important tool in shoreline research. Lee et al (1996) developed a series of DEMs to assess the potential impact of climate and water levels on the Lake St. Clair and Lake Erie shoreline. Also, Badger (2000) used GIS to map slope failures on the north shore of Lake Erie. Thirdly, Liu (1998) analyzed and modelled erosion process along the south shore of Lake Erie with different GIS applications.

According to Woodroffe (2003), there are many areas of applications of GIS for coastal zone management. For example, GIS provides opportunities to better understand links between land and sea. Also, statistical modelling and impact assessment can be accomplished. GIS can handle shoreline and coastal regions just as easily as topographic regions. Terrestrial contour analysis is easily adaptable to bathymetric contour analysis (Gorman et al, 1998). Oceanographic studies quickly used GIS in research for deep sea analysis (Wright, 1997), but it has been applied to a lesser degree to coastal zone bathymetry. Still, GIS is quickly being applied to all aspects of spatial and geographic surfaces, including bathymetry.

Remotely sensed data can be used to locate areas of shallow water in the coastal zone. Troughs, deep pockets, and flat bars may become visible. Remotely sensed data can then be imported into a GIS shoreline application for further analysis or modelling. Different features can be overlayed on the image such as cottage properties, roads, and marinas. In the future, coastal applications of remote sensing will be more important.

GIS will continue to be used in research involving the Great Lakes. Its ability to display bathymetric and topographical features such as navigation channels and shorelines respectively, makes GIS a versatile resource

2.8 Wetlands

Wetlands are some of the most ecologically diverse, productive, and yet sensitive ecosystems on Earth. According to Environment Canada (2002f), wetlands are "lands that are seasonally or permanently covered by shallow water, as well as lands where the water table is close to or at the surface." Traditionally, wetlands were conserved as waterfowl breeding and feeding areas, or to a lesser extent, as spawning and nursery habitat for fish (Keddy, 2000). Today, it is realized that wetlands have many benefits such as flood control and retention, water purification, shore erosion protection, groundwater recharge, recreation, control of nutrients cycles, accumulation of sediment, and supply of detritus for the aquatic food web (Lyon and Adkins, 1995). This section will present information on coastal wetlands in the Great Lakes, how climate change may impact these wetlands, and then a specific discussion of Fen wetlands in the Great Lakes.

2.8.1 Coastal Wetlands in the Great Lakes

Wetlands of the Great Lakes shorelines are referred to as coastal wetlands. Coastal wetlands receive their source of water from either ground water or surface water. The characteristics of these wetlands are greatly influenced by lake levels. Certain types of coastal wetlands require periods of both low and high lake levels (Mortsch, 1998). This allows for exchange of nutrients, vegetation seeds, and often times, certain plant species require this natural fluctuation of lake levels (Middleton, 1999).

Many coastal wetlands can be found in areas along the St. Marys River, the North Channel, Les Cheneaux Islands, Saginaw Bay, the eastern shore of Georgian Bay (Hardy, 1982). Although, in many areas, they are threatened by development, dredging projects and drainage to create intensive recreation areas, marinas, and lakeside homes. Coastal wetlands, along with the many open and protected embayments, contribute to the complexity of Lake Huron's shoreline.

Coastal wetlands are an important part of the biodiversity of shoreline areas. Over one-third of globally significant features within the Great Lakes are strongly associated with coastal wetlands (Finnell, 2002). Eighty percent of the Great Lakes fish species can be found in nearshore areas for some part of the year and depend directly on the coastal wetlands for some part of their life cycle (Finnell, 2002). Lake Huron coastal wetlands provide nesting and staging areas for hundreds of thousands of migratory and nesting birds and waterfowl (Finnell, 2002). In addition, Lake Huron coastal wetlands provide important habitat for various amphibians and reptiles.

Like many ecosystems, coastal wetlands of the Great Lakes are, by nature, stress-dependent systems. To assess the human impact on coastal wetlands and develop rehabilitation efforts, it is necessary to distinguish between natural stressors, and human induced or anthropogenic stressors. Four of the most commonly cited and important natural stressors are lake level fluctuations, sedimentation and turbidity, ice and storms, and invasive species (Environment Canada, 2002f). Human-induced stress is generally more harmful to overall wetland health because it tends to be more persistent and of greater magnitude (Mistch, 1992). For more than 200 years, coastal wetlands have been filled, drained, and converted into either urban, agricultural, industrial, or cottage land (Environment Canada, 2002f).

2.8.2 Climate Change Impacts on Wetlands

Wetlands are important natural modifiers of water quality, and are particularly sensitive to the indirect changes in regional hydrology that climate change may influence through changes in air temperature, regional precipitation, surface runoff, snow cover, length of freezing season, ground water storage, and evapotranspiration. The structure, function, productivity, area, and distribution of wetlands are vulnerable to water supply changes that could occur with climate change, as are the ecological, social, and economic values associated with them.

Coastal wetlands of the Great Lakes are likely to suffer from decreased lake levels and from shifts in surface-water and groundwater flow patterns (NRCAN, 2002). Even though the Great Lakes coastal wetlands are adapted to a variable water supply, the projected magnitude and rate of climate change could alter the hydrology of the Great Lakes enough to disturb and damage many wetland ecosystems (Mortsch, 1998). Lake level fluctuations directly influence the extent and nature of undyked (open) coastal wetlands. A 20 cm lowering of Lake Michigan-Huron's water levels could affect 64% of all Great Lakes wetlands in the U.S. (Hartmann, 1990). The extent of the wetland environment expands and contracts with the fall and rise of lake levels. In low water years the landward margins of wetland dry and mudflats are exposed. The lakeward edge of the wetland may expand into areas where water was formerly too deep. Also, wetlands would have to adjust to a new pattern of lake level fluctuations: the timing, duration, and range of these fluctuations are critical to the wetland ecosystem response (Mortsch, 1998). An overall reduction in available wetland habitat may result. Therefore, the influence of climate change on the Great Lakes' water levels is very important to understand in order to begin to realize the future of the Great Lakes' wetlands.

Changes in the wetland habitat caused by different levels will disrupt present fauna, food supply, and sanctuary. Certain vegetation thrives in low water or dry situations, while other forms of vegetation requires more saturated conditions associated with higher lake levels. Even though most wetland vegetation require natural fluctuations, most vegetation cannot withstand extreme fluctuations. It often takes three to five years to re-establish vegetation communities in a wetland after a significant disturbance (Busch and Lewis, 1984). In rare occasions, wetland vegetation, when dried, has caught fire. When water levels disturb the natural state of vegetation, they not only hinder the vegetation, but also hundreds of bird species, and numerous forms of wildlife. Wetland vegetation is crucial to birds, wildlife, and human recreation. They therefore require remediation, and conservation policies to protect them from dangerous extreme lake level fluctuations.

In efforts to reduce damage from climate change, wetland managers throughout the Great Lakes are discussing and planning projects to protect coastal wetlands from the influences of extreme low lake levels (Mortsch, 1998). Lake level influences are warranting close attention by all wetland managers (Hardy, 1982). Wetland remediation, protection and enhancement policies and programs must consider climate change as an additional stressor of wetlands (Mortsch, 1998). Many of the wetlands along the Unites States' portion of the Lake Erie coastline have been isolated from lake level fluctuations to maintain the wetland area (Hardy 1982). They are either protected by human-made barriers or natural barrier reef type land forms. Management, conservation and protection of the Great Lakes coastal wetlands is very important, and with the increasing concern of climate change, policies and practices will have to consider how climate change will influence the Great Lakes years into the future.

2.8.3 Fen Wetlands

Fen wetlands are peat-forming wetlands that receive water from precipitation, runoff, and groundwater movement (Finnell, 2002). Information presented on panels to tourists along the Oliphant Fen Boardwalk suggest that a fen is an alkaline wetland, a specialized environment that supports an unusual and rich plant community (Brown, 1991). A fen is nutrient rich, with large amounts of calcium and magnesium (Finnell, 2002). However, nitrogen is in short supply, and oxygen saturation is relatively low, but higher than in bogs (Wetlands Canada 1988). Although fens are dominated by sedges they may also contain shrubs and trees (Federation of Ontario Naturalists, et al, 1982). Fens are commonly associated with a high water table, but with very slow internal drainage (Wetlands Canada, 1988). They are typically recharged by groundwater and runoff from surrounding mineral soils and protected embayments in the coastal region. Like bogs, they are more common in the north (National Wetlands Working Group, 1988). Rich fens can be found in Horseshoe Bay Wilderness Area, El Cajon Bay, and along the shorelines of Misery Bay, Manitoulin Island, and the Straits of Mackinac (Finnel, 2002).

Fens provide important benefits to the Lake Huron watershed, including preventing or reducing the risk of floods, improving water quality, and providing habitat for unique plant and animal communities. Great Lakes coastal fens, also known as shoreline meadow marshes, have been identified by The Nature Conservancy as globally imperiled communities (Middleton, 1999). However, these beneficial areas are being threatened by human impacts such as filling, dredging, and pollution.

In the early 2000s, only a small percentage of the fen wetlands in the Great Lakes are being protected under conservation methods (Environment Canada, 2002a). When flowers are not in season, and the pools are dried up, fen wetlands can often appear unattractive. This has resulted in groups of people trampling the wetland, polluting and disturbing its natural state. In a cause to reduce damage, some naturalist groups have taken the initiative to protect and conserve remaining wetlands. The Owen Sound Field Naturalists built the Oliphant Fen Boardwalk in 1991 to protect the unique and important Oliphant Fen Wetland (Brown, 1991). Activities such as this are becoming more visible, as the importance of coastal wetlands becomes clearer.

2.9 Chapter Summary

This chapter presented key concepts pertinent to the research of this project. Background information on these key concepts, including Lake Huron, climate change, lake levels, GIS, and wetlands, were reviewed in order to prepare for the research methodology and discussion.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter will present the methodology used to examine the distribution of climate driven lake level impacts in the Oliphant region. There is an overview of the data sources and techniques including the selection and use of GCMs, water level scenarios, questionnaire surveys, and GIS modelling techniques. A detailed description of the applications of the water level scenarios to TIN and DEM models is provided. As well, each GIS map's design and analysis is outlined in detail.

This methodology is adopted from Ryan Schwartz's (2001) Masters thesis. Schwartz used a GIS approach to examine climate change impacts on Lake Huron's water levels in the town of Goderich. Research focused on the development of a shoreline elevation model that incorporated bathymetric, topographic, and water level scenario data sets. This model was used to calculate shoreline movement, estimate potential volumes of material that may require dredging, and identify potential navigation hazards. Schwartz then evaluated the model as a tool for researchers in other studies.

3.2 General Approach

A general approach was designed for this project (Figure 3.1). In this framework inputs, outputs, and impacts, as well as the GIS software that was used, are introduced. The approach begins with priory published results from two GCMs that were linked to a Lake Huron basin hydrologic model (Mortsch et al, 2000). The results of this combination are the water levels scenarios. Included in the water level scenarios are a projected water level change. The projected water level changes are then input into a GIS where the data are used to develop terrain models. Numerous data sets are required to construct those models, including topographic, bathymetric, remote sensing and other sources. Also, multiple base maps were designed from these data. For example, attributes associated with bathymetric data were used to create a bed floor materials map. The terrain models were however, more central to the thesis. Three models were designed in the GIS, including the BDEM raster model, the Base Case Scenario TIN Model, and the Scenario TIN Model. The BDEM is used to assess navigational and dredging impacts. The Base Case Scenario TIN Model is used to map a base case water level scenario that is compared to the projected water level scenarios. The Scenario TIN Model is used to assess shoreline change impacts. Further impact assessment is done from the projected shoreline change maps, including impacts on wetland, navigation channels, and the small craft harbour.

3.3 General Circulation Models

A review of GCMs was included in Chapter 2. There are two main transient GCMs that have been used in climate change research in the Great Lakes, the CCCma

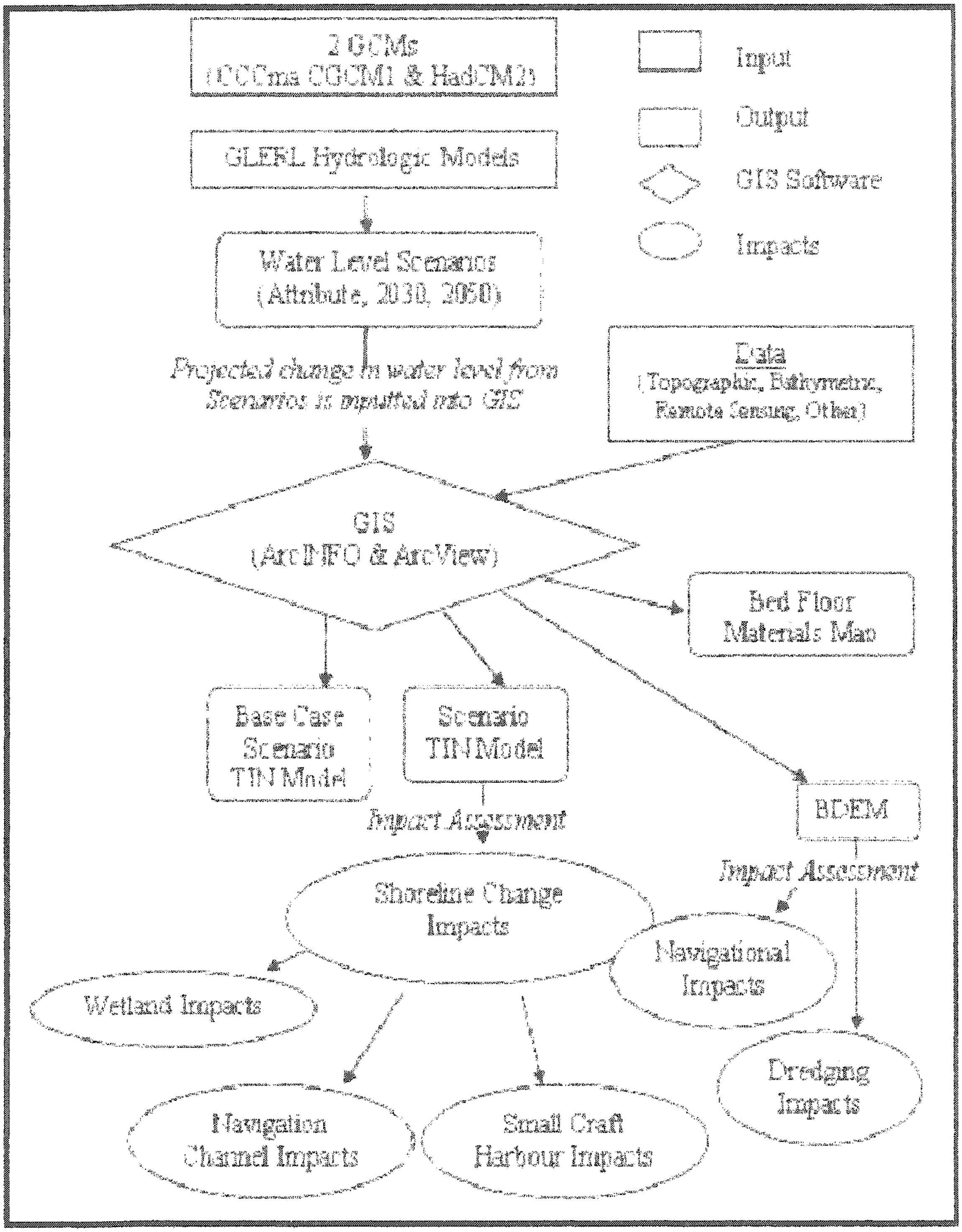


Figure 3.1 *General Thesis Methodology*

CGCM1, and the HadCM2. These transient models were selected for this thesis because they are the most advanced GCMs, and their use in the recent literature is detailed.

Output data from these GCMs are available and used as the source of future climate change information for this thesis. The CCCma CGCM1 and the HadCM2 were both selected to produce differing water level scenarios. Both GCMs are applied to Lake Huron hydrologic models resulting in different water level scenarios.

3.4 Water Level Scenarios

The main water level scenarios for this thesis are based on work by Mortsch et al (2000). Water level scenarios are developed by inputting GCM output into a basin hydrologic model. This approach is used to project plausible scenarios based on the specific GCM and hydrological model. Mortsch et al (2000) used Lake Huron hydrologic models from the Great Lakes Environmental Research Laboratory (GLERL).

A range of scenarios is normally used to assess the sensitivity of a region to climate change (Lavender et al, 1998). This results in the identification of a range of potential impacts while acknowledging there are no correct scenarios (Lavendar et al, 1998). Water level scenarios were developed for Lake Huron for 2030 and 2050 by Mortsch et al (2000). The CCCma CGCM1 and HadCM2 transient run period 1961-1990 represents the base climate; 2030 represents the period 2021-2040 and 2050 represents the years 2041-2060 (Mortsch et al, 2000). Lake level projections are based on the change between the hydrologic base case and the transient scenarios being used. Projected lake level changes are then subtracted from their respective base case levels to derive a projected water level for Lake Huron. In addition to the water level scenarios from Mortsch et al (2000), there are four other scenarios used to provide a more complete visualization of possible water levels. These arbitrary scenarios use the same hydrologic base case water level as in Mortsch et al (2000), from which arbitrary water level changes are projected. Table 3.1 summarizes the different scenarios, base case time periods and water levels, projected level change, and the projected lake levels in metres (relative to the IGLD-85).

Table 3.1 *GCM Water Level Scenario (CCCma & Hadley data from Mortsch et al, 2000).*

GCM Scenario	Base Case Period	Base Case Water Level (m)	Projected Water Level Change (m)	Projected Lake Level (m)
CCCma 2030	1961-1990	176.62	-0.72	175.90
CCCma 2050	1961-1990	176.62	-1.01	175.61
Hadley 2030	1961-1990	176.62	+0.05	176.67
Hadley 2050	1961-1990	176.62	+0.03	176.65
Arbitrary 1	1961-1990	176.62	-0.50	176.12
Arbitrary 2	1961-1990	176.62	-1.25	175.37
Arbitrary 3	1961-1990	176.62	-2.00	174.62
Arbitrary 4	1961-1990	176.62	-2.75	173.87

The scenarios presented in Table 3.1 provide an indication of possible future lake levels. These scenarios were then applied to a group of GIS models in order to display and analyze potential impacts in the region of Oliphant. In using the projected water level change on Lake Huron, a DEM can spatially display a new shoreline and areas of concern.

3.5 Geographic Information Systems

Through the use of GIS, maps are produced that present data on the impacts of a lower lake level in the Oliphant region. This section discusses the GIS data sources, as well as an overview of the individual models used to present and analyze the impacts of a lower lake level in the Oliphant region. For a more detailed description of the GIS design and application, refer to Appendix A.

Based on their widespread availability, this thesis uses ESRI's ArcINFO ArcGIS 8.1 and ArcView 3.2 software. Data are readily available in the appropriate format for these programs. ArcINFO ArcGIS 8.1 facilitates a desirable combination of spatial analysis and visual display, in two and three dimensions. Henceforth, ArcINFO ArcGIS 8.1 will be referred to as ArcINFO. The second software application, ArcView 3.2, was used for a number of small specific applications.

3.5.1 Data Sources

Data sets containing information on bathymetry, shoreline location, topography and human and physical features were acquired. As well, satellite imagery was used to display the research site.

Bathymetric data were purchased from the Canadian Hydrographic Service (CHS) through a digital broker, Nautical Data International. Provided in Arc export file format (.e00), the data were then converted into an ArcINFO coverage file using the import command (Import 71) in ArcView. The data set comprised of four coverage files, two point files and two arc files, at a scale of 1:10,000. The data set represents field sheets 1200120 (Chiefs Point to Cranberry Island) and 1200119 (Cranberry Island to Little Red Bay), which were surveyed in the summer months of 1991-1994, by the CHS, Department of Fisheries and Oceans (DFO), and Terra Surveys. Together, the field sheets cover an area between $44^{o}48'07.634$ N and $44^{o}40'00.258$ N Latitude, and $81^{o}22'45.592$ W and $81^{o}15'08.284$ W Longitude. Point files represent sonar readings of the bathymetry off the shoreline of Oliphant. More than 17,000 sonar readings were taken. Depths were recorded in metres and decimetres, and elevations and clearances were in metres above the sounding datum (176 m). Arc files represent a mixture of attributes such as contours, subaqueous pipes and survey sight lines. There is no set contour interval. Contours are depths in metres, with the following depths 2, 5, 10 and 20 metres. The data are projected using the Universal Transverse Mercator projection (UTM), for zone 17. The North American Datum 1983 (NAD83) was used as the horizontal datum, and the Lake Huron IGLD 85 (176 m) was used as the vertical datum. Figure 3.2a and Figure 3.2b display examples of the data set.

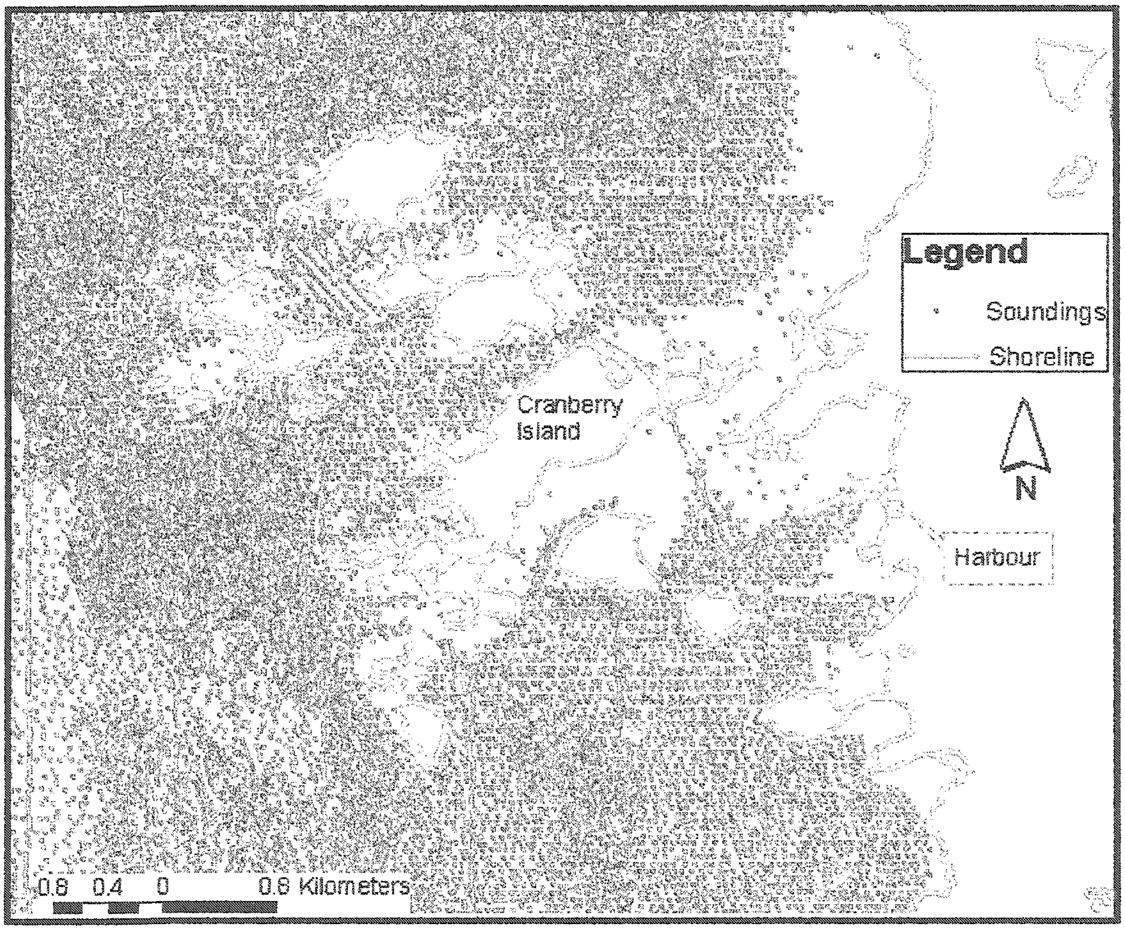


Figure 3.2a *Sample of Sounding Data from Bathymetry Data Set (CHS, 2002). Shoreline data is from NRVIS data set. The shoreline shown represents the water level from 1994, according to the OBM maps.*

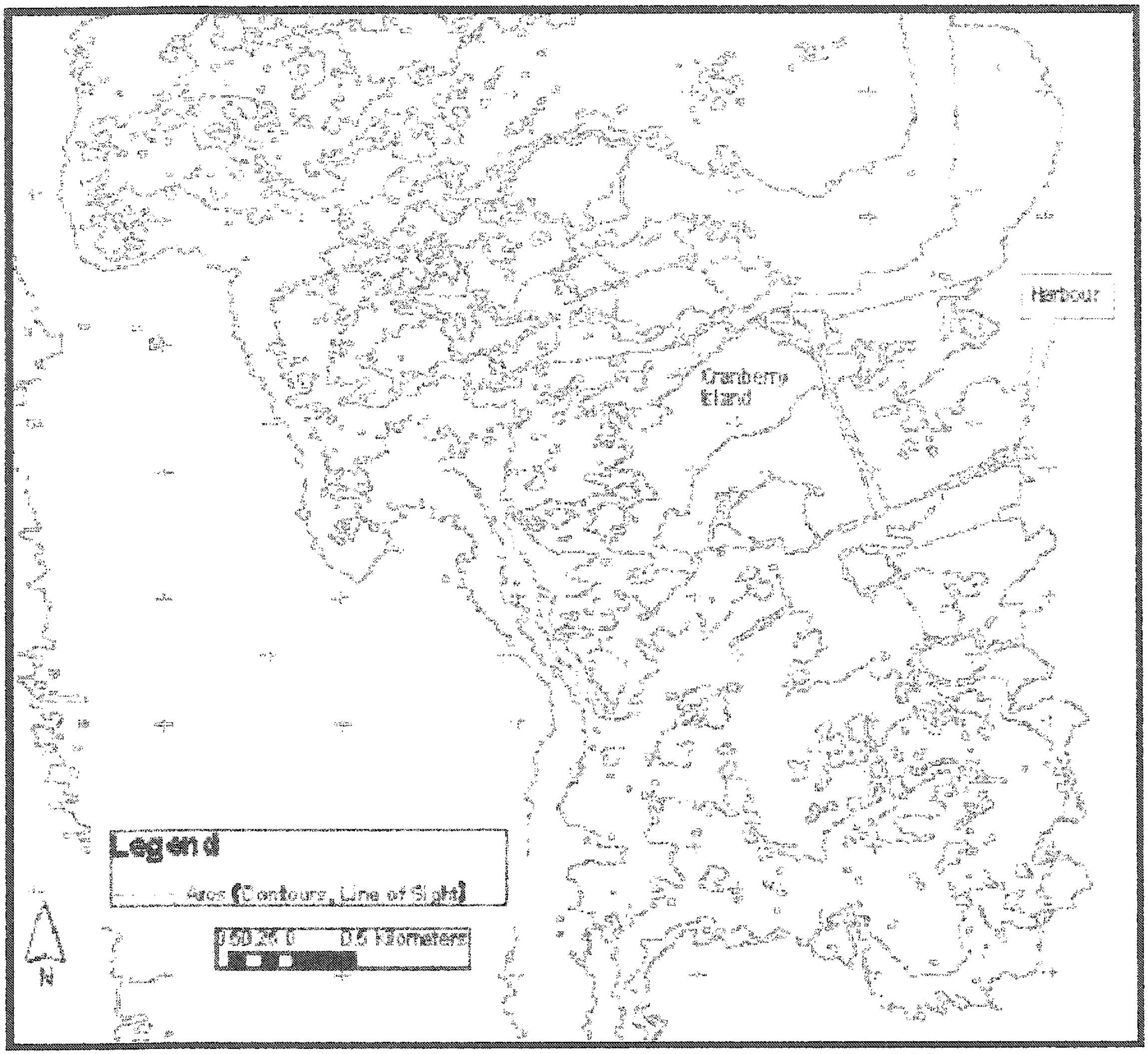


Figure 3.2b Sample of Arc Data from Bathymetry Data Set (CHS, 2002).

As seen in Figure 3.2a, there are some zones where sounding points are absent. These missing values are the results of low water conditions during the survey period. The survey period being 1991-1994, consisted of slightly lower than average lake levels. Areas with no data values therefore represent areas of no or little water, and therefore, no sounding was recorded. As a result, in these locations, DEM interpolation will be less accurate.

Ontario Base Maps (OBM) were accessed through the Natural Resources Values Information System (NRVIS) of the Ministry of Natural Resources (MNR). This database is housed at the University of Waterloo's Mapping & Design (UMD) library. The following files were ordered, water body (shoreline), OBM index, buildings, contours, wetlands, watershed arcs (rivers), watershed polygons (inland lakes). The data are at a scale 1:10,000 allowing for a more detailed analysis. Similar to the bathymetry data set, the NRVIS data are projected using UTM, zone 17 at NAD83. Collectively, these data are used to develop a shoreline TIN model.

Topographic data from the National Topographic System (NTS) were acquired from the Natural Resources Canada National Topographic Database (NTDB). The data were ordered through the UMD library. Two 1:50,000 NTS map sheet areas were used: 41 A11 and 41 A14. Each data set contained a mixture of point, line, and polygon shapefiles, totaling 51 files in 41 A11, and 44 files in 41 A14. These data were used as a reference, although certain shapefiles were used more frequently for modelling, such as the road and building shapefiles and the Lake Huron water body polygon from each region. Again, the data are projected using a UTM zone 17 and NAD83 datum.

Four remotely sensed images were acquired from the Canadian Centre for Topographic Information through the UMD library. The data are CanImage files, which are raster images in GeoTiff format that contain information from Landsat 7 Enhanced Thematic Mapper Plus. These orthoimages have been resampled to 15 m pixel size and are georeferenced to the NTS at a 1:50,000 scale (Centre for Topographic Information, 2002). Production of the CanImage files began in the year 2000, with the goal to produce a Landsat 7 orthoimage coverage of the entire Canadian landmass within three to five years (Centre for Topographic Information, 2002). The four orthoimages covered the same two NTS zones as acquired from the NTDB. The orthoimages may comprise seven spectral bands: a panchromatic band and six multispectral bands (Centre for Topographic Information, 2002). They are produced in accordance with NAD83, using a UTM projection at zone 17, to keep all data sets compatible. The bands selected for this thesis are visible green (band 2), visible red (band 3), and near infrared (band 4), each with no enhancement. These bands were combined to produce a false colour composite that is useful in distinguishing between land and water.

3.5.2 Bathymetry DEM

A separate Bathymetry DEM (BDEM) was generated to display the impacts from a lower lake level on navigation. Traditionally, DEMs have been designed for topographic data, but their use can be easily transferred to bathymetric surfaces. In the early 2000s, many oceanographic studies are using DEMs for ocean shipping vessels and marine mining expeditions (Wright, 1997). Therefore, having a DEM which can display the bathymetry offshore of Oliphant would be very useful for navigation issues.

The BDEM was developed from the bathymetric data set. In ArcView, using the Convert to Grid command, two raster GRIDs were created from the two point coverages. Since not every point within the coverage represents a depth sounding, only points that contained depth sounding attributes were selected and converted to a GRID. After these points were selected, the two raster GRIDs were mosaiced (brought together) using the mosaic command in the ArcView raster calculator module. The output was a single GRID image referred to as the BDEM. The BDEM was loaded into ArcGIS ArcScene to visually analyze and display the image in 3D. An appropriate colour ramp and vertical exaggeration were assigned when viewing the BDEM in 3D.

When considering each water level scenario, the BDEM's elevation values were altered to match the change in lake level, thus producing a new BDEM. Since the BDEM represented bed floor elevations, values were increased to match a decline in lake level. Instead of the water surface lowering, the bed floor is rising up. Even though this is not realistic, it represents the same effect of a shallower water body. By altering the BDEM's elevation according to each scenario, impacts on depth, and specifically the navigation channels, would be clearly visible. This was seen as a benefit for recreational boaters, fisherman, and the harbour master (McKenzie, 2002). For clearer and more precise visualization, a legend class size of fifteen colour blocks was used to display the BDEM. Lastly, a blue colour ramp was selected to represent the surface as being bathymetry depths below water surface.

3.5.3 TIN Models

TIN models were developed using the bathymetry and NRVIS data sets. The TIN models were created in ArcINFO using the Create TIN function. Three contour shapefiles were used to generate the TIN models. They included two contour files from the bathymetry data set and one from the NRVIS data set. The bathymetry contour files came with the data set, and were generated from the sounding data. When the TIN was created, bathymetric contours decreased in elevation, and topographic contours increased in elevation. First, a base case water level scenario TIN (Base Model) was created (see Figure 4.3). There can be many different Base Models. A Base Model presents a water level scenario that is used as a reference or beginning point to which future scenarios are compared. The base case water level scenario used in the methodology is 176.62 m (Table 3.1). In the TIN models the shoreline is represented as beige, land as green to red, and water as blue (e.g. Figure 4.4). A key component of this model is the Lake Huron waterbody shapefile polygon which is draped onto the model. This polygon is from the NTS data set. The waterbody shapefile's base height value is then changed to represent any fluctuation in lake level (e.g. compare Figures 4.5 and 4.6). However, this does not change the polygon's actual shape. Instead, the waterbody shapefile appears to cut through the TIN model; the only part of the waterbody that is visible is what is on top of the TIN.

3.5.4 Shoreline Change Analysis

Shoreline change analysis was essentially done by applying the different water level scenarios to the base height of the Lake Huron waterbody shapefile polygon that is draped over the Base Model. The entire process was done in ArcINFO. When changing the base height value of the polygon, new land becomes exposed or covered. The result is a TIN model which displays a new shoreline location. This model is referred to as the Lake Level Change Model (LLCM). The new shoreline location can then be compared to the shoreline location in the Base Model to see which areas will be impacted. The LLCM can also be applied to help map impacts on different areas of concern.

As part of the shoreline change analysis, the new beachfront area was examined. Contours were created, from the LLCM TIN surface, at a one centimetre interval. From these contours, two contours were selected. The first contour represented the most inland limit of the beach, and the second, represented the new waterline location after a change in lake level. These two contours were then imported into ArcINFO Workstation to build a new waterfront polygon. This was accomplished in ArcPLOT by drawing two short arcs between the north and south limits of the two contours lines, thus closing the two lines together, making the polygon image. In ArcINFO, this new polygon was built and given topology. The polygon was then loaded into ArcGIS and a new waterfront area was calculated. In order to compare the new waterfront area to the old waterfront area, the same process was conducted from two separate contours, one representing the waterline before a change in water level, and the other representing the most inland limit of the beach. Now a total beachfront area could be calculated by adding the area of the old beachfront and the area of the new beachfront.

Waterline recession was also examined. This was accomplished by drawing multiple straight arcs across the new beachfront area polygon, and then calculating the average length of the arcs. The value represents the average waterline recession across Oliphant's shoreline.

3.5.5 Areas of Concern

Potential areas of concern include the Oliphant Fen Wetland, the small craft harbour, shallow bars, and the Gut and Smokehouse channels (Figure 3.3). Therefore, impact studies using the BDEM, TIN models, and different base maps were generated to examine potential future impacts as caused by low lake levels. The purpose of these maps is to display locations of possible environmental and socioeconomic impacts that will be felt throughout Oliphant.

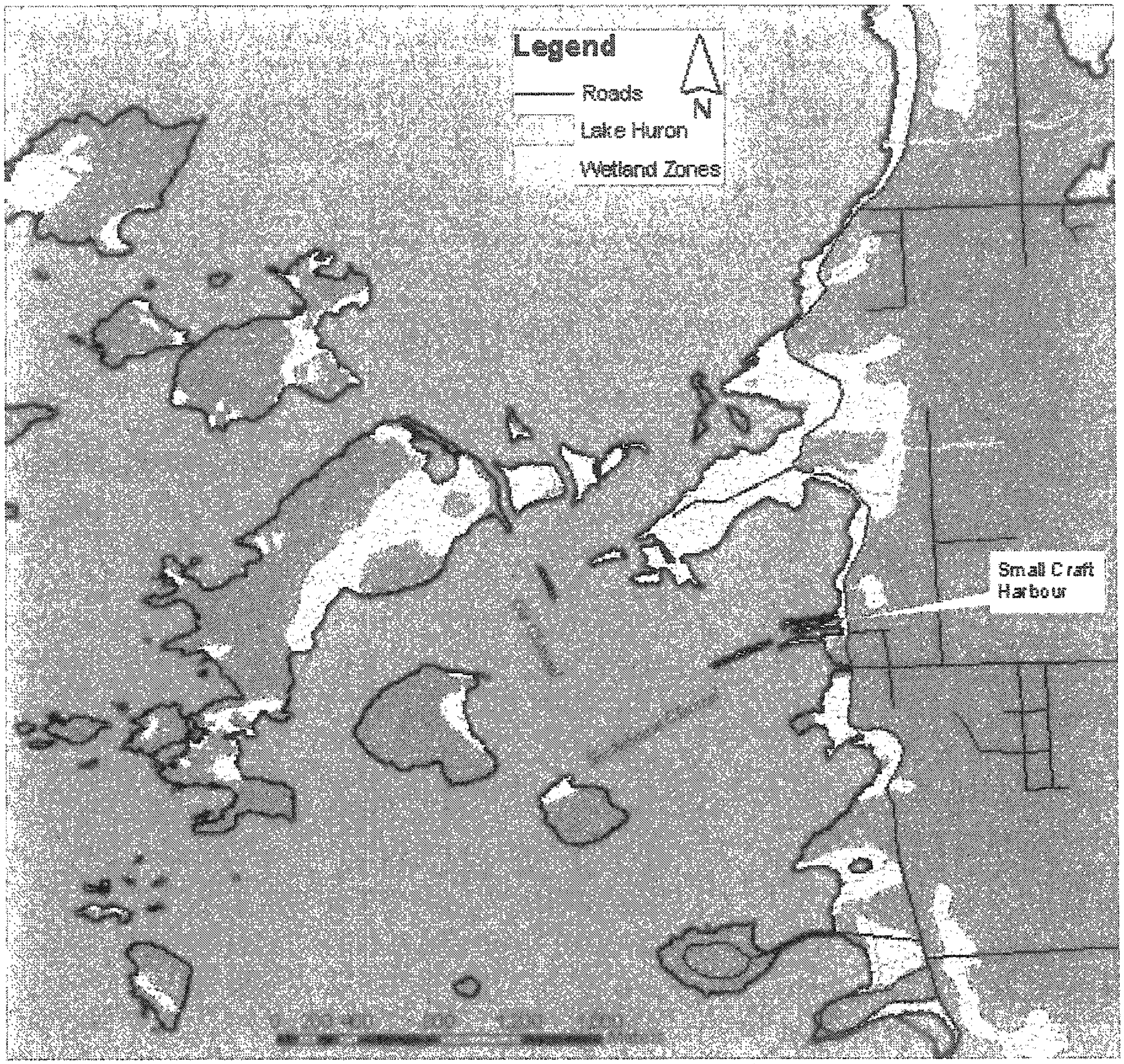


Figure 3.3 *AOCs Base Map. Map data is taken from the NRVIS data set.*

Located between Cranberry Island and Shoreline Avenue is a large sand bar. If Lake Huron's water level declines significantly, there will be a large flat sand platform throughout much of the coastal zone. Such a large and flat sand platform could increase aeolian sediment transport, possibly resulting in sand dune creation. This large platform is best displayed using the LLCM in ArcINFO. When inputting certain water level scenarios into the LLCM this large sand platform becomes clearly visible. The LLCM can be used to determine how low the lake level needs to be before the entire platform becomes uncovered. It is important to understand the location and extent of the sand platform for marine navigation and shoreline management issues.

Potential impacts on the Oliphant Fen wetland were assessed by using the LLCM in ArcINFO. Wetland zone locations (Figure 3.3) were mapped by draping the wetland zone polygons from the NRVIS data set onto the Base Model. This map acted as a reference base map for reference against future scenarios. Since potential impacts are influenced by the location and extent of the new shoreline, potential impacts on the wetland zones were assessed by draping the polygons onto the LLCM. Potential impacts were viewed by comparing the waterline location between the wetland base map and the LLCM. The further the waterline from wetland zones the greater level of risk of impact.

Presently, the small craft harbour is surrounded by an extensive sand beach on the south side, and a wetland zone on the north side. The harbour is only accessible by boat through a routinely dredged channel. By using both TIN models, possible impacts on Oliphant's small craft harbour will be mapped. The harbour is best mapped using the Base Model, and how it will be impacted is best mapped using the LLCM. Impacts were assessed in a similar manner to how the wetland's impacts were assessed. The harbour location is clearly noticeable on the Base Model, but when certain water level projections are applied to the LLCM, the harbour becomes impacted. By using the LLCM, ranges of impacts can be determined according to different potential future lake levels.

Impacts on the navigation channels, the Gut and Smokehouse Channels, were assessed using the LLCM and the BDEM. First, a channel dredge line shapefile was digitized to be overlaid or draped onto different maps. Information and location for the channel dredge line was taken from the bathymetry data set's line coverage files. Figure

3.4 displays the general location of the Gut and Smokehouse Channels. The BDEM was used to display areas where the forecasted depth will be seen as a navigable hazard. This process was outlined in section 3.5.2. The LLCM was used to display the areas that will become emergent and would therefore limit navigation. By draping the channel dredge line over the LLCM, it could be understood whether the locations would be impacted or not. Information gathered from the BDEM and the LLCM based on the location of the dredging channel line will determine the channel's usefulness in the future.

Additional information on the impact of a lower lake level on navigation is provided by examining the bed floor material type in the coastal zone. According to local fisherman and recreational boaters, Oliphant is known as a hazardous place for boating (personal communication, McKenzie, 2002). Its coastal zone is characterized by numerous shoals and sand bars, dangerous boulder and rock fields, as well as occasional ship wrecks. From examining the bed floor material type in the bathymetric data set, a choropleth maps were created displaying bed floor zones according to material (Table 3.2). These maps are presented as Figures 4.17 and 4.18 in chapter 4. These maps were designed in ArcView using a Create Thiessen Polygons extension. Each thiessen polygon vertices was represented by a sounding that contained bed floor material attributes. These soundings were taken from the bathymetry data set. The default 1% buffer was used in creating the thiessen polygons, because this buffer produced a suitable representation of the surface, when compared to navigation charts. The output, in shapefile format, was zones of specific bed floor material. Bed floor material polygons were remapped in ArcINFO. The thiessen polygon approach was used, because it produced a generalized representation of the bathymetry's bedfloor materials in choropleth format. Such a map is more visually appealing as compared to a dot map showing the raw data (Figure 3.4). In this case, more information could be gathered quickly from a choropleth map, compared to a dot map. With a better understanding of the bedfloor material, dredging practices are able to map out new channels with greater ease, because they will be able to dredge areas that do not contain a significant amount of boulders or rocks. By understanding where sand concentrations are, instead of rocks and boulders, marine navigation and channel dredging are simplified.

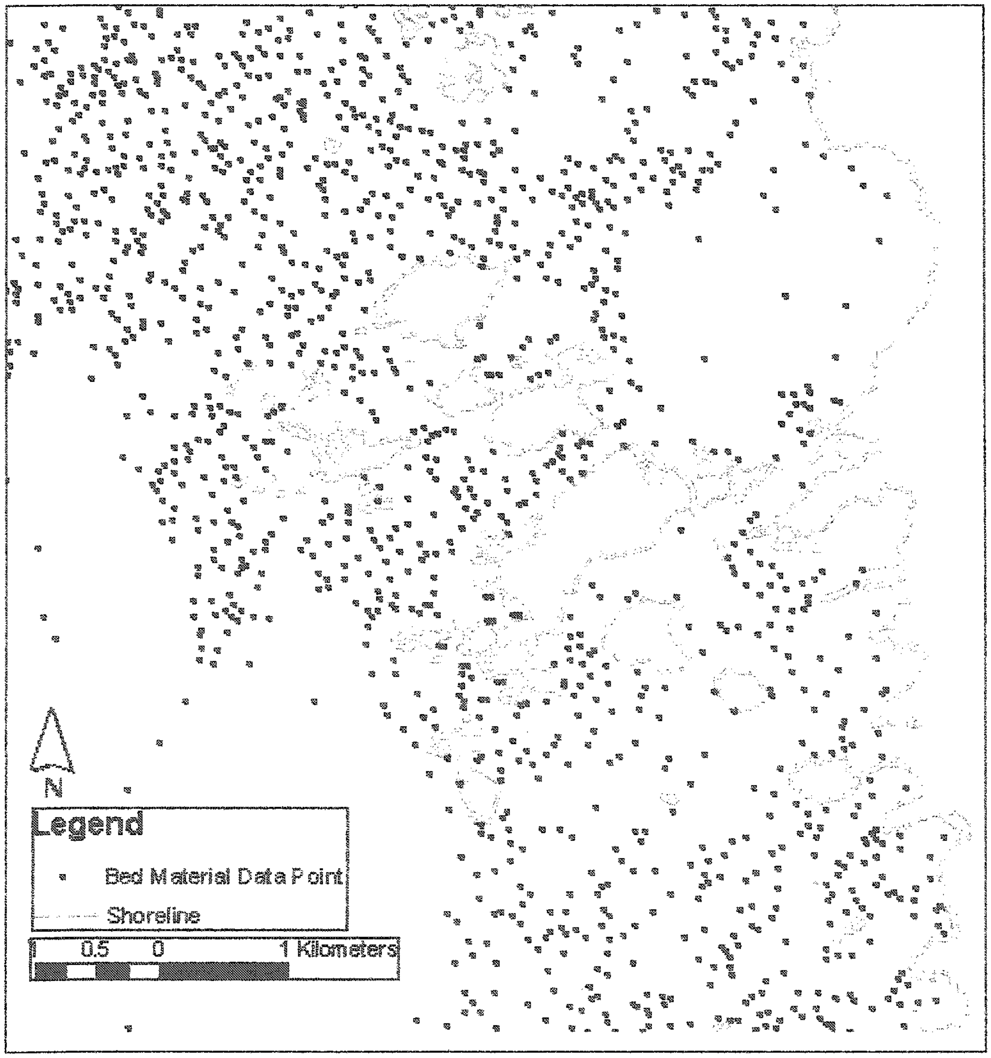


Figure 3.4 *Bed Floor Material Raw Data Points, (CHS, 2002). 1994 Shoreline (NRVIS, 2002).*

Table 3.2 Bed Floor Material Types from Bathymetry Data Set. Rock Awash is rock which is exposed at any lake level (CHS, 2002).

Bed Floor Material Type
Sand
Boulder
Rock
Rock Awash
Stones
Gravel
Mud

3.5.6 Orthoimage

Remote sensing has often been associated with geographic information systems (Aronoff, 1989). Therefore, a remote sensing application were developed to aid in the visualization of the shoreline location. Remote sensing data was used to verify the location of the shoreline, islands, shallow and deep waters, and wetland zones. An orthographic image was produced from the CanImage Landsat 7 data.

In respect to this thesis, remotely sensed data are useful because changes in shorelines and depth are clearly visible under certain bands. Dredged channels become visible, and exposed shoals and bars are noticeable also. In ArcINFO, the presentation of the Landsat 7 data was designed to display the surface as visually natural as possible, making water bodies appear blue, and land appear green. This was accomplished by changing which bands were set as blue, red, or green in the legend. In doing so, certain bands penetrated shallower water bodies displaying the bed floor. In general, light blue tones represent shallower water, and dark blue tones represent deeper water. Such a map will be useful for shoreline planning and management purposes, as well as marine navigation and dredging practices or policies.

3.5.7 Error

The methodology contained a few issues of error, and therefore they are presented in this section to provide the reader with some background information on issues of accuracy and probability.

3.5.7a Data Sources

As briefly mentioned earlier in section 3.5.1, the Bathymetry data set has concerns with its level of completeness. It seems this is the case because the area's elevation is very flat. Possibly, during the surveying, certain areas were dry at the time, and were not included. Still, the available point data that represents sounding information was useful. Acoustically measured depths from 1991 to 1994 were positioned by Madnovox MX300 DGPS receivers to a positional accuracy of +/- 10 metres. Where recorded soundings required Lidar airborne surveying, positional accuracy was +/- 5 metres. Also since the LLCM used the bathymetry data set there was some concern. Although, the LLCM also data from the NRVIS data set. In this data set, contour intervals of 5 metres at a scale of 1:10,000 provided useful and accurate topographic results. However, at a scale of 1:30,000, the contours which were used to develop the LLCM, had an accuracy level of +/- 5 metres. Overall, the data used for the GIS modelling was good, and its level of accuracy was useful for this scale of research.

When considering the level of accuracy of the water level scenarios it is important to understand that there is considerable variability in projected climate and lake levels that arise from the application of GCM data to hydrological models. Generally, it is difficult to quantify the level uncertainty associated with climate change, and therefore an evaluation of a range of possibilities is important when investigating such scenarios.

3.5.7b GIS Techniques

Therefore, when the data were applied to the models it was difficult to design accurate maps. In the case of the LLCM, the development of a true to reality shoreline could not be accomplished when building the TIN models. When the raster GRID and TIN models were created, a more generalized interpolation was conducted because of the fewer data points. Therefore, the model results would be less accurate in certain zones. When analyzing results from the LLCM, it seemed that the elevations were off by one metre. This was confirmed by setting the lake level elevation to present day (summer 2002) levels, and then comparing the shoreline extent in the model to reality. The model displayed a surface with more water, when in reality, there was much less water. In order to correct this, it was required to increase the base water level datum by one metre. This resulted in a more accurate shoreline according to the base datum. Generally, this shows that there is a significant level of uncertainty and probability associated with these models. Some results have a low level of probability, and therefore should not be taken at face value.

3.6 Questionnaire Survey

A questionnaire was developed with the purpose of investigating the perceived environmental and socioeconomic impacts that are associated with a lower Lake Huron water level by local residents. This survey was specifically designed to understand how the public is impacted by low lake levels. Ten multiple choice questions (Appendix B) were presented to thirty participants. Questions focused on lake level impacts from the past, present, and possible future fluctuations, as well as adaptation issues and concerns, and general lake level issues. Each question was designed for a specific purpose. First, is the public impacted more by low or high lake levels? Second, how will the public prepare for future possible impacts as caused by low lake levels? And thirdly, what does the public know about impacts from fluctuating lake levels, or what is impacted by fluctuating lake levels?

A sample size of thirty participants was selected based on a sample population of approximately between two and three hundred. Participants were generally chosen randomly, but occasionally they were selectively chosen when they were clearly recognizable as one of the specific categories. Categories include fisherman, cottage owners, recreational boaters, retail/commercial owners, and tourists. Most often, participants were chosen by just meeting them along the shoreline or at the marina, but occasionally, it was required to knock on doors. The names of participants were never asked in order to keep records and responses confidential. As well, the participants' ages were not asked, as long as they appeared to be adults. Participants seemed willing and interested, and therefore were easy to interview. Approximately eight hours were spent finding and interviewing local residents. Interviews were conducted on two separate occasions, September 28, 2002, and October 12, 2002. These dates were chosen because they were Saturdays, which meant more potential interview participants would be in Oliphant. Each interview's duration ranged on average from eight to ten minutes, depending on the participant's interest.

3.7 Chapter Summary

This chapter described the thesis methodology. The thesis water level scenarios were presented and summarized in Table 3.1. A detailed examination of the GIS methodology was outlined, including how the water level scenarios are applied to the GIS models. Lastly, an overview of the questionnaire methods was outlined. In Chapter 4, results from the application of the water level scenarios to the BDEM and TIN models, as well as the questionnaire are presented.

CHAPTER 4: Results and Analysis

4.1 Introduction

With the purpose of investigating and displaying the distribution of potential impacts resulting from a decline in Lake Huron's water level, this chapter presents the results of the GIS and survey methodology. Results from the two main GIS models are presented and discussed. Potential impacts based on multiple maps produced from the GIS models are reviewed, with specific focus on the Oliphant Fen wetland, the shoreline/sand platform, the small craft harbour, and dredged channels.

4.2 Models

Section 4.2 presents the BDEM and LLCM maps created in ArcINFO. The two models displayed in section 4.2 are presented in their most basic format, meaning no alterations to the data have been applied, and no water level scenarios have been applied. Also, no shapefiles or extra layers have been draped onto the models.

4.2.1 BDEM

The BDEM (Bathymetric Digital Elevation Model) is raster GRID image presented in 3D (Figure 4.1). The image presented in Figure 4.1 is a representation of the entire BDEM as created by bathymetric soundings from the CHS.

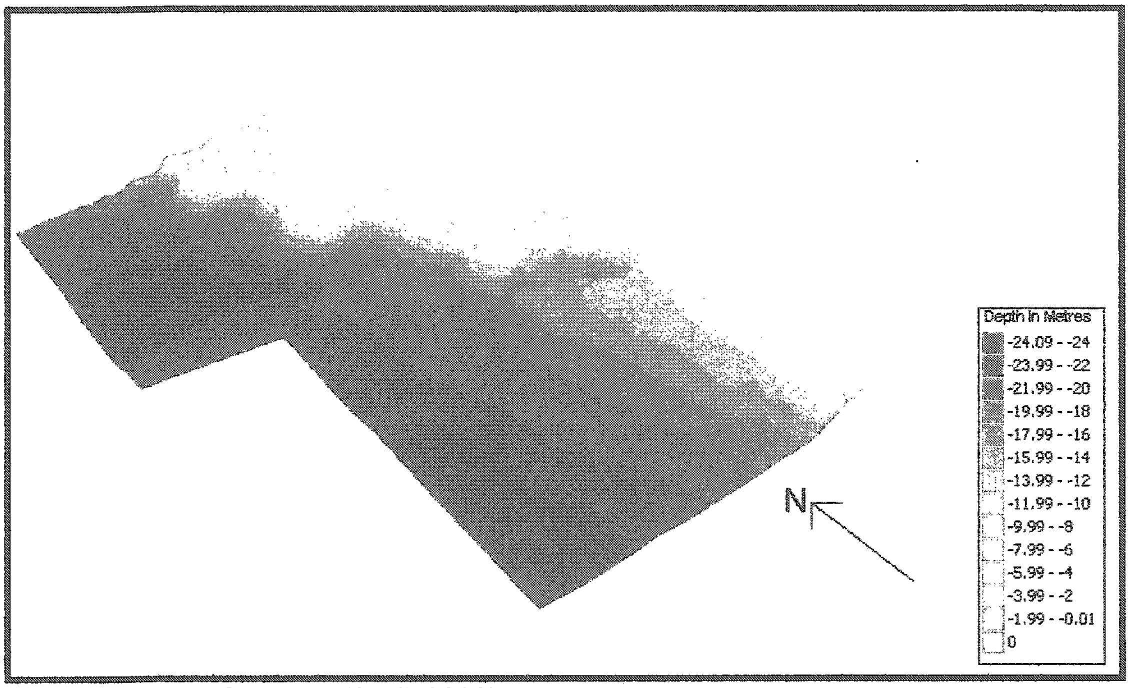


Figure 4.1 *Final BDEM (CHS, 2002).*

General comments on the BDEM image are as follows. Figure 4.2 displays a more zoomed in view of a portion of the BDEM. This figure more clearly shows how the BDEM is useful in examining changes in depth. One downfall of final image comes from the quality of the data. Some locations have been interpolated based on a smaller number of data points, resulting in a less accurate representation of the bathymetry. These issues will be expanded on later in the report. Overall, the BDEM is very useful and efficient, and can be easily configured to help model coastal zone impacts.

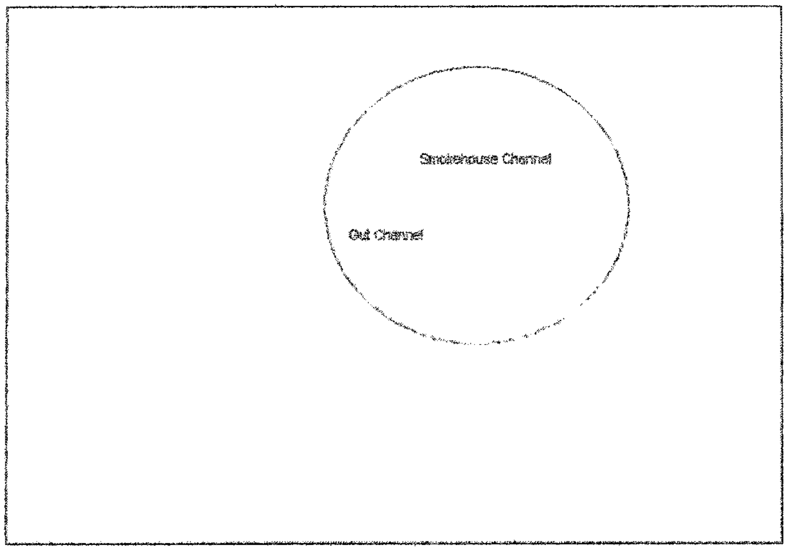


Figure 4.2 *Gut and Smokehouse Channels in BDEM (CHS, 2002).*

4.4.2 LLCM

The LLCM (Lake Level Change Model) is a TIN model, presented in 3D (Figure 4.3). This has been created by using both topographic and bathymetric data. Using the LLCM, it is possible to display a waterline at any location within the elevation limits of the bathymetric and topographic surfaces. This is a great benefit, because the TIN surface area is large. Therefore, any waterbody elevation value could be inputted into the software and a new waterline could be developed. LLCM is straightforward, and has provided helpful results. Depiction of the bathymetry and topography of the research site when compared to ortho-imagery is accurate for this level of research. One issue which has arisen, however, is that since the LLCM is viewed in a 3D rendering software, the view angles once set, must remain constant. Changing any view angles resulted in distortion, and because of the software's capabilities, this has resulted in noticeable changes in the waterline location. As well, the possibility of distortion seems to be caused by the TIN methodology. Still, overall, the LLCM's ease of use and level of accuracy has resulted in a useful model.

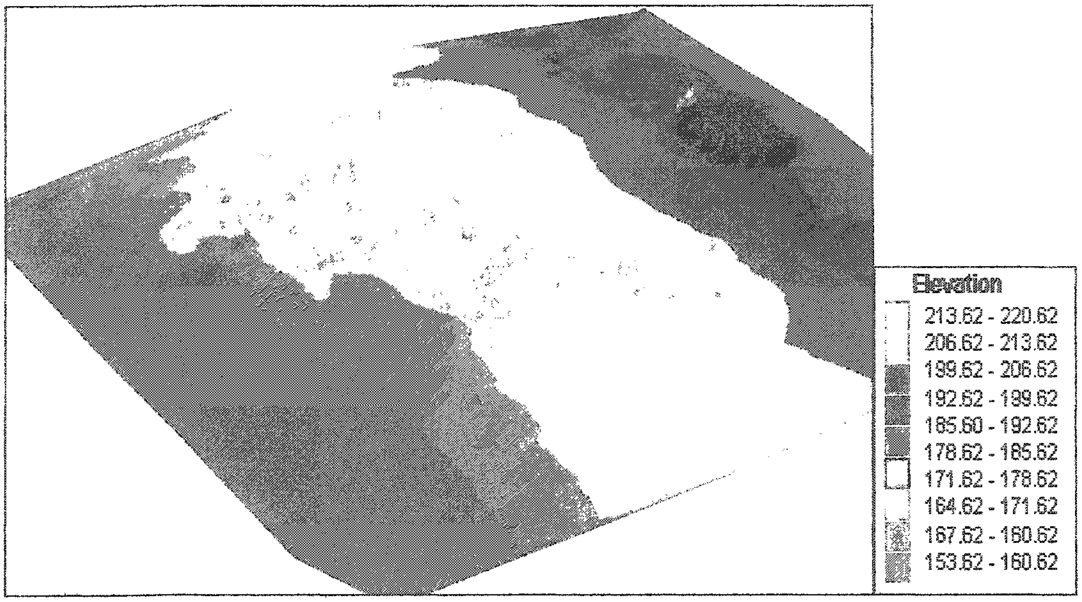


Figure 4.3 *Base TIN Model (CHS, 2002. NRVIS, 2002). Elevation is IGLD metres above sea level. No waterbody shapefile is draped on the TIN surface.*

4.3 Impact Analysis

Section 4.3 reviews the potential impacts on three specific shoreline concerns in Oliphant. These impacts were assessed using the BDEM and LLCM. The three key concerns include the shoreline/sand platform, the Oliphant Fen wetland, and navigation which includes the small craft harbour and the dredging channels.

4.3.1 Shoreline Impacts

The different water level scenarios were mapped against the Base Model (Figure 4.4) using the LLCM. Results included different waterline locations, widened or shortened waterfronts, which could result in a change in sediment availability for aeolian transport. No attempt has been made to access the change in currents and sediment redistribution that would arise from the shoreline changes. The following map displays Oliphant's shoreline as depicted by the Base Model. Again, the water level used in the

Base Model is the 176.62 m IGLD, which is the long term average for the period 1961-1990. This period includes both the record low and record high lake levels. For each map in section 4.3.1 the following is the case: blue represents Lake Huron at a specified water level, yellow represents waterfront at an elevation range of 176.62 to 181.62 metres, green represents inland at an elevation range of 181.62 to 190.62 metres, and red represents inland at an elevation range of 190.62 to 199.62 metres.

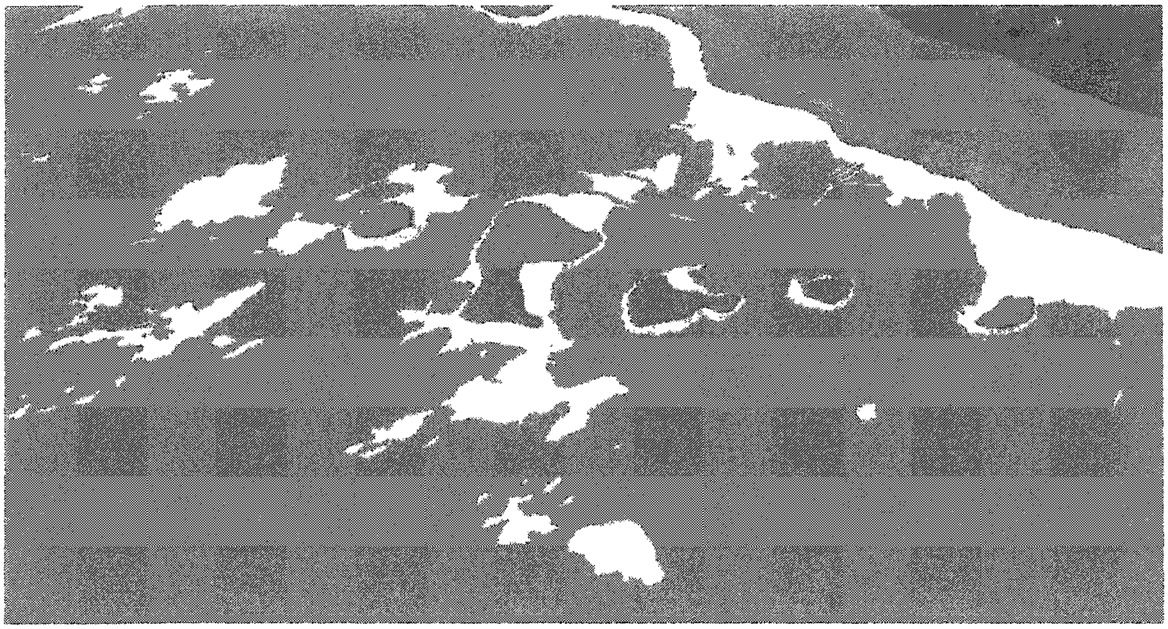


***Figure 4.4** LLCM Base Model. Lake level is 176.62 metres IGLD*

In order to assess shoreline change impacts, three water level scenarios were chosen to project new shorelines (Schwartz, 2001). Only three scenarios were chosen, because other scenarios did not show the range of potential impacts as much as the CCCma 2050, HadCM2 2050, and A4. As well, many other scenarios' results were very similar to each other, and therefore would produce similar impacts. The subsequent water level scenarios were chosen to represent possible future shorelines: CCCma 2050 (-1.01 m), HadCM2 2050 (+0.03 m), and Arbitrary 4 (-2.75 m). These values in these scenarios are relative to the 1961 to 1990 mean lake level. These scenarios were chosen because they presented the greatest range of conditions along the waterfront of Oliphant. The A4 scenario (-2.75 m) is considered an extreme case and has a low probability. Shoreline change impacts based on the three water level scenarios are presented in Figures 5 to 7. Refer to Figure 4.4 to assess any shoreline change, and therefore the location of possible impacts.

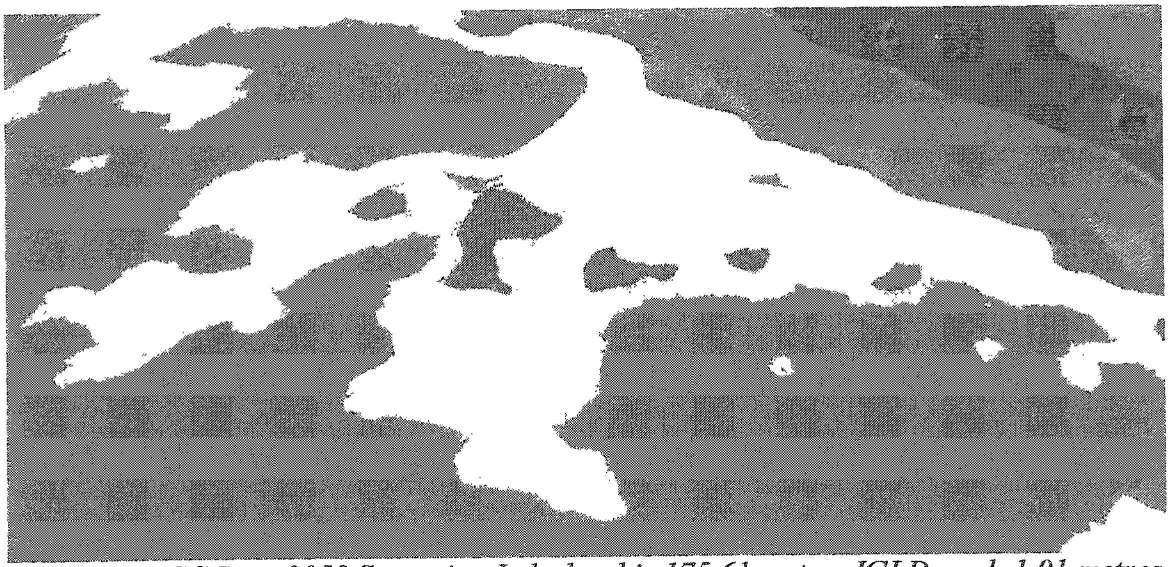


Figure 4.5 *CCCma 2050 Scenario. Lake level is 175.61 metres IGLD, and -1.01 metres below the 1961 to 1990 mean.*

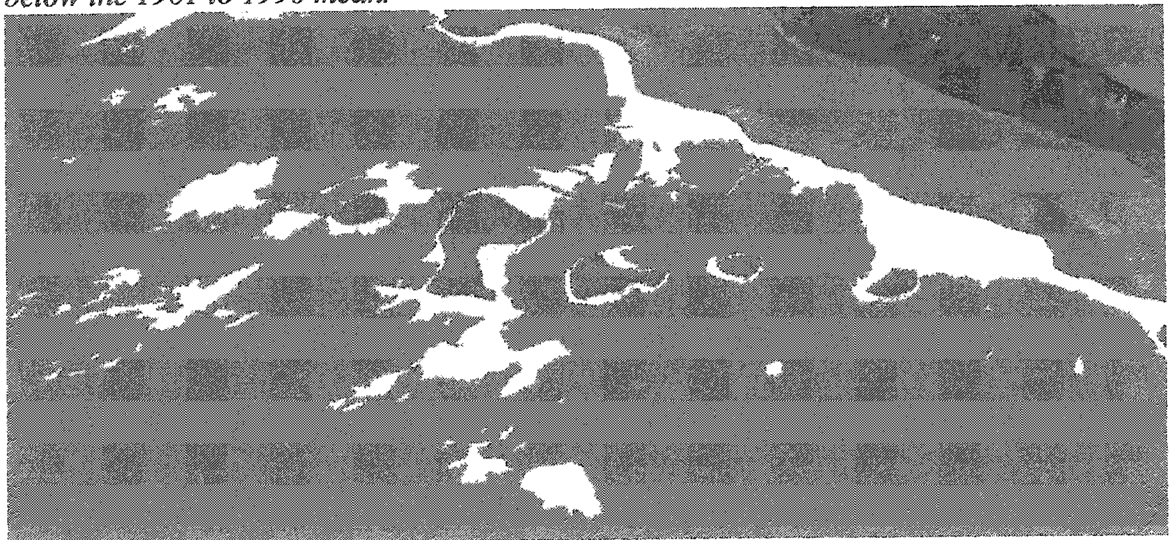


Figure 4.6 *HadCM2 2050 Scenario. Lake level is 176.65 metres IGLD, and 0.03 metres above the 1961-1990 mean.*

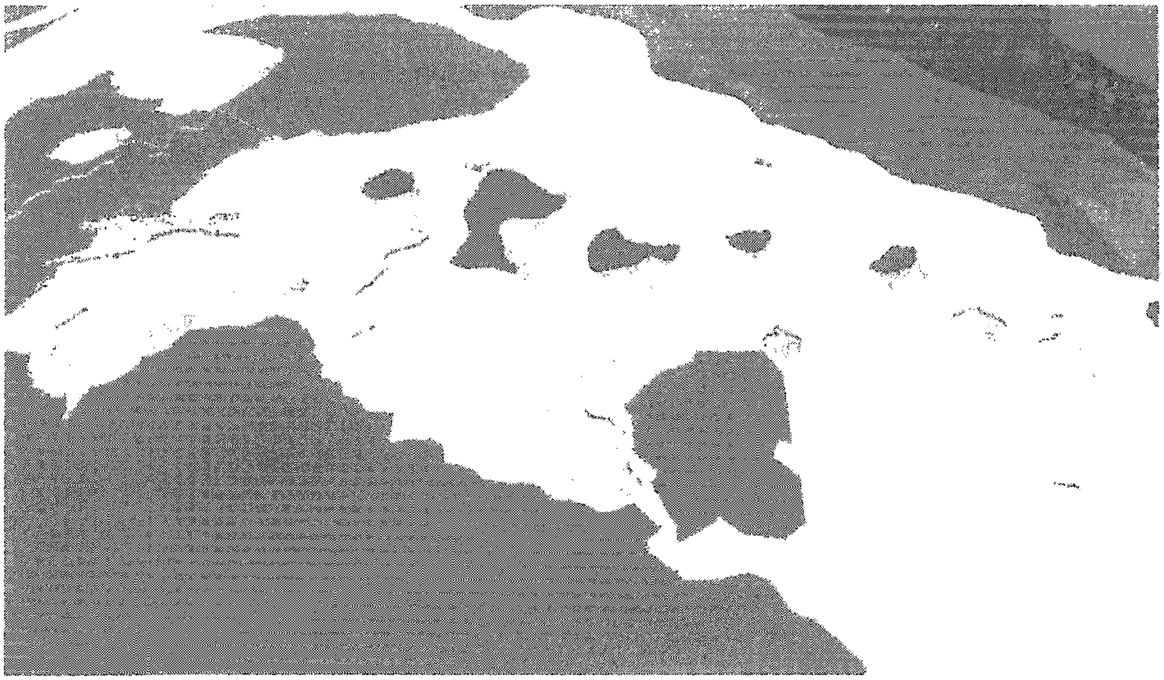


Figure 4.7 *Arbitrary #4 Scenario. Lake level is 173.87 metres IGLD, and is -2.75 metres below the 1961-1990 mean.*

According to the three scenarios displayed in the previous pages, the range of impacts between the different water level scenarios are quite different. Potential negative shoreline changes will be the greatest from the A4 scenarios followed by the CCCma 2050 scenario. However, according to the data, there will be likely little negative shoreline change impacts based on the HadCM2 2050 scenario, as the water levels will slightly increase. Although, there would still be a possibility for increased shoreline erosion, but no negative impact for navigation.

Figure 4.8 displays the new waterfront area based on the CCCma 2050 scenario. The unique shape representing the possible new waterfront is created because of the combination of the Fishing Islands and the shallow bathymetry. Most of the islands become joined to mainland. In the more central region of Oliphant, somewhat perpendicular to the harbour, is a larger peninsula. North and south of this new peninsula are large bays. The A4 scenario, when analyzed by area, showed slightly similar results. Table 4.1 summarizes the new waterfront area and average waterline recession distance based on the CCCma 2050 scenario (-1.01 metres below the 1961-1990 mean).

Table 4.1 Shoreline Change Analysis

Previous Area	11.8 km^2
New Area	19.15 km^2
Difference	7.4 km^2
Ave. Waterline Recession	1,200 m

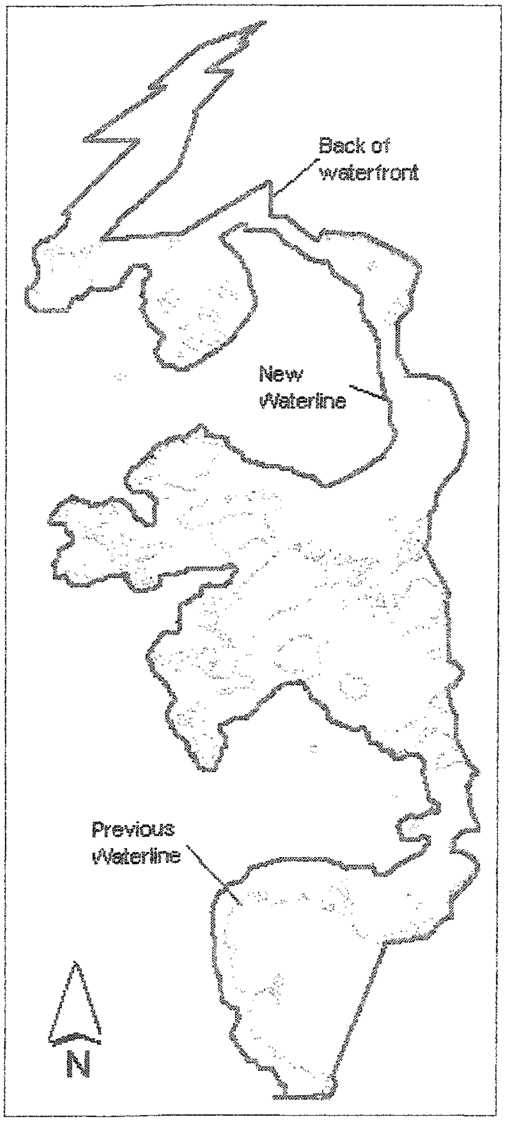


Figure 4.8 New Waterfront Areas according to the CCCma 2050 scenario.

Since the HadCM2 2050 scenario projected a water level increase of 0.03 m, there is little or no negative impact from shoreline change. Also, based on the visual display of the software and its analysis capabilities, shoreline change analysis was not considered for the HadCM2 2050 scenario. Some sections of the shoreline had no change. A focus was given to the CCCma 2050 and A4 scenarios, which projects a substantial amount of shoreline change.

4.3.2 Wetland Impacts

According to the NTS database, there are wetland zones behind Shoreline Avenue, along the water line, and along the shores of the Fishing Islands (Figure 4.9). It is important to understand that these wetlands are shore adjacent coastal wetlands, where the elevation is within a certain range of the mean water level. Therefore, the projected water level changes will impact each one of these wetland zones, even the unconfined zones. Potential ares of wetland change were mapped using the CCCma 2050 (Figure 4.10) and A4 (Figure 4.11) scenarios with the LLCM.

Figure 4.9 *Oliphant Fen Wetland Zones. Wetland zones are taken from NTS dataset, and represent wetland zones in 1989. Lake level is 176.62 metres IGLD.*

Figure 4.10 *Wetland Impact from CCCma 2050 Scenario. Lake level is 175.61 metres IGLD.*

Figure 4.11 *Wetland Impact from A4 Scenario. Lake level is 173.87 metres IGLD.*

Figures 4.10 and 4.11 show that most areas of the Oliphant Fen wetland have the potential to be markedly impacted by a significant decrease in Lake Huron's water level. The existing wetlands will become far removed from the new shoreline. It is expected that this would be accompanied by de-watering of the wetlands and trigger changes in the vegetation. These issues will be discussed later in Chapter 5. Wetland zones situated within the Fishing Islands will be impacted less, as compared to other wetland zones located on the mainland near Shoreline Avenue. From Figures 4.10 and 4.11, it appears there is little difference in the severity of impacts. Scenario A4, because of the lower lake level will cause more impact, but the difference between the A4 and CCCma 2050 scenario is small.

4.3.3 Navigation Impacts: Small Craft Harbour and Dredging

Assessing the locations of impact on navigation, the small craft harbour and dredging operations required several maps. Both the BDEM and the LLCM were used to map these distributions. As well, a bed floor material map was created to further help map areas of concern in regards to navigation and dredging.

Water level scenarios were applied to the BDEM to plot zones of hazardous navigation based on depth. However, when the CCCma 2050 and A4 scenarios were applied to the raster BDEM, results were poor in displaying accurate marine depth. This is due to the data's surveying techniques. Certain surveying locations were underwater at the time of the survey. Also, this method resulted in visually similar maps when the CCCma 2050 and A4 were compared. As an example, a 176.62 m base case lake level and the CCCma 2050 scenario are plotted below (Figure 4.12 and 4.13).

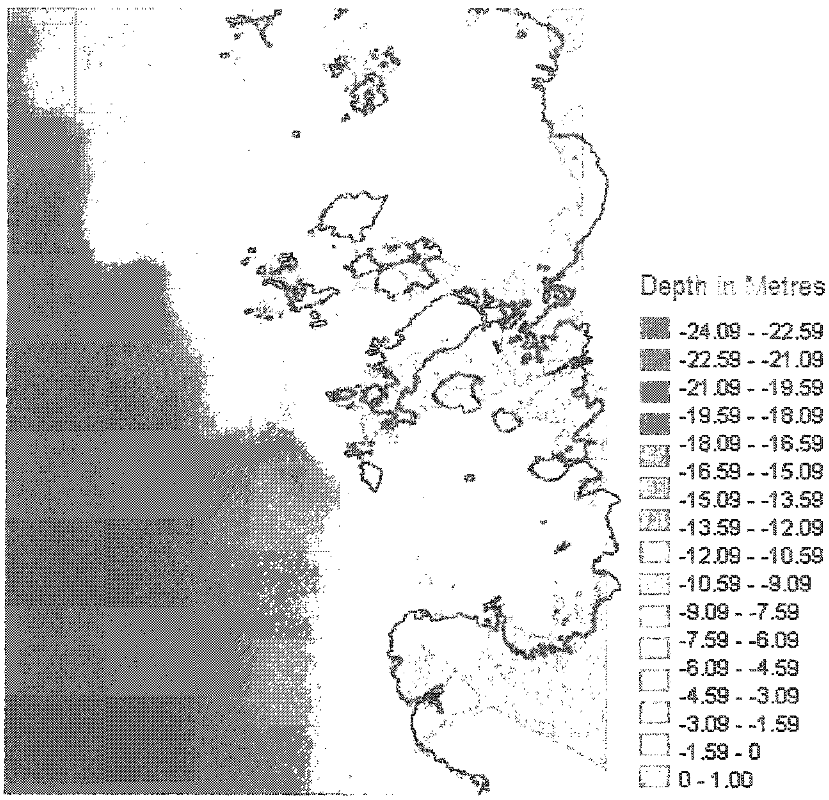


Figure 4.12 *Hazardous navigation zones using the BDEM with a 176.62 m Datum. Shoreline is from bathymetry dataset.*

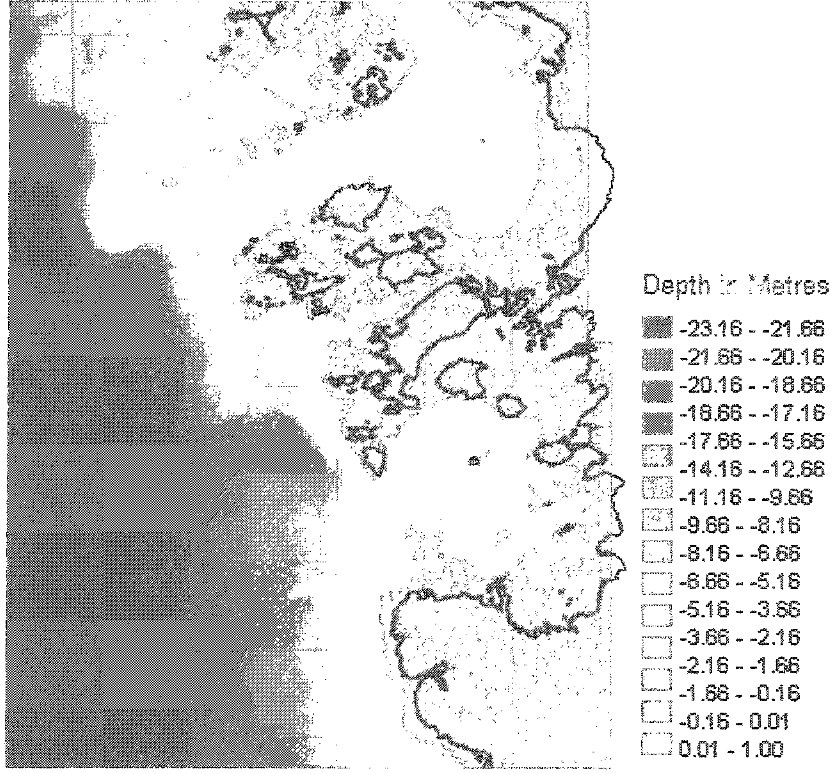


Figure 4.13 *Hazardous navigation zones using the BDEM with the CCCma 2050 Scenario. Lake level is 175.61 metres IGLD. Shoreline is from bathymetry dataset.*

However, this method is still useful for mapping new shoreline areas, similar to the TIN models. Also, the BDEM, when used with potential future water level scenarios, is still useful for developing navigation charts. This method was slightly more difficult than the LLCM, as it was a longer process, involving the manipulation of the entire BDEM elevation values as well as its legend to allow for a more visually accurate map. Overall, when dealing with one scenario, and not multiple scenarios, this method of modeling changes in depth for navigation purposes is effective and useful.

From the mapping results it appears the navigation channels will be substantially impacted. Note that this assessment only considered the Gut and Smokehouse Channels (Figure 4.14), as they are the main navigation channels and are dredged most frequently. Also, this assessment does not suggest any new dredging plans and routes as there will be too many variables to consider. For example, the distance between the current location of the small craft harbour and the new waterline would be over a kilometer in length. Therefore, this study only attempts to present the level of potential impact incurred on the channels that are normally dredged. Potential impacts were reviewed by comparing the current location of the channels to future shoreline changes according to the results of the CCCma 2050 and A4 scenario as presented in the LLCM. Figures 4.15 and 4.16, display the navigation channels draped onto the LLCM with the CCCma 2050 and A4 scenarios being applied. From Figures 4.15 and 4.16, the current locations of the Smokehouse and Gut Channels will be compromised by the lake level changes projected by the CCCma 2050 and A4 scenarios. While there are impacts on the existing channels under both scenarios, the A4 scenario shows the channels are farther removed from the new shoreline.

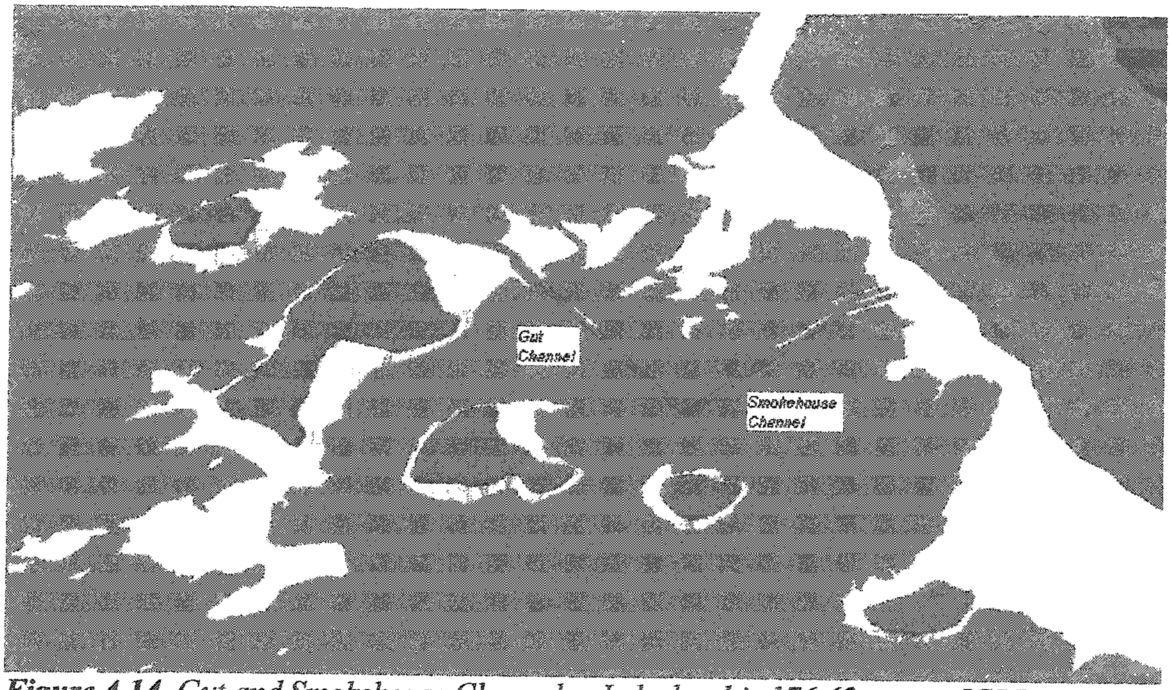


Figure 4.14 Gut and Smokehouse Channels. Lake level is 176.62 metres IGLD.

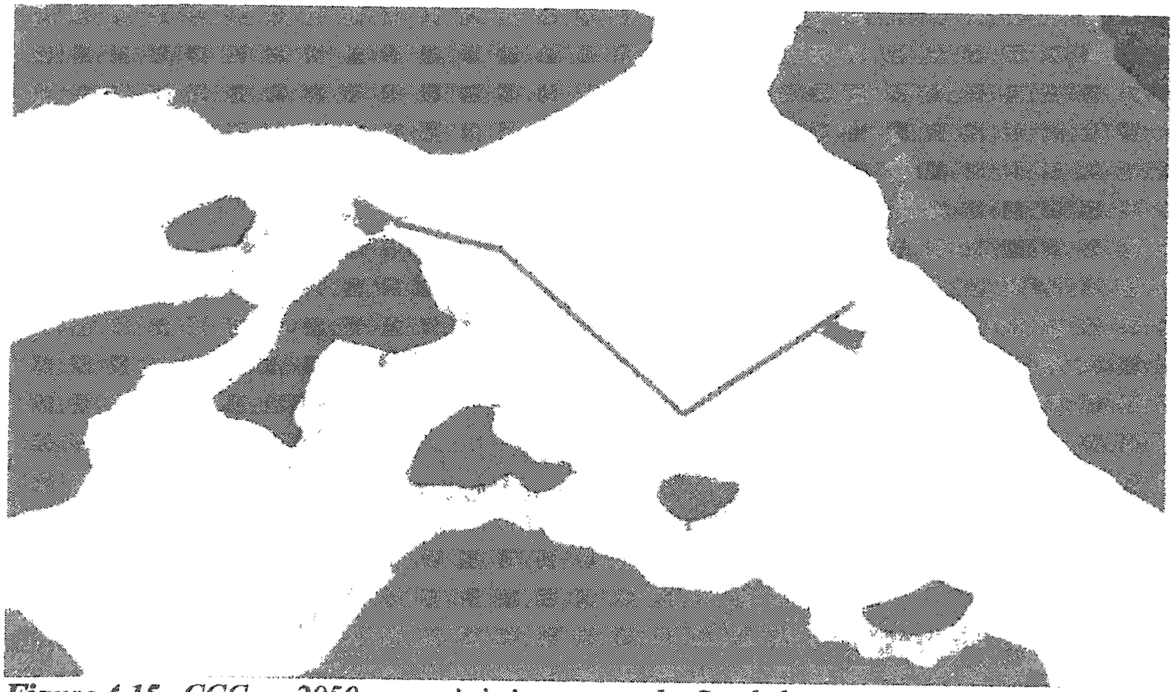


Figure 4.15 CCCma 2050 scenario's impact on the Smokehouse and Gut Channels. Lake level is 175.61 metres IGLD.

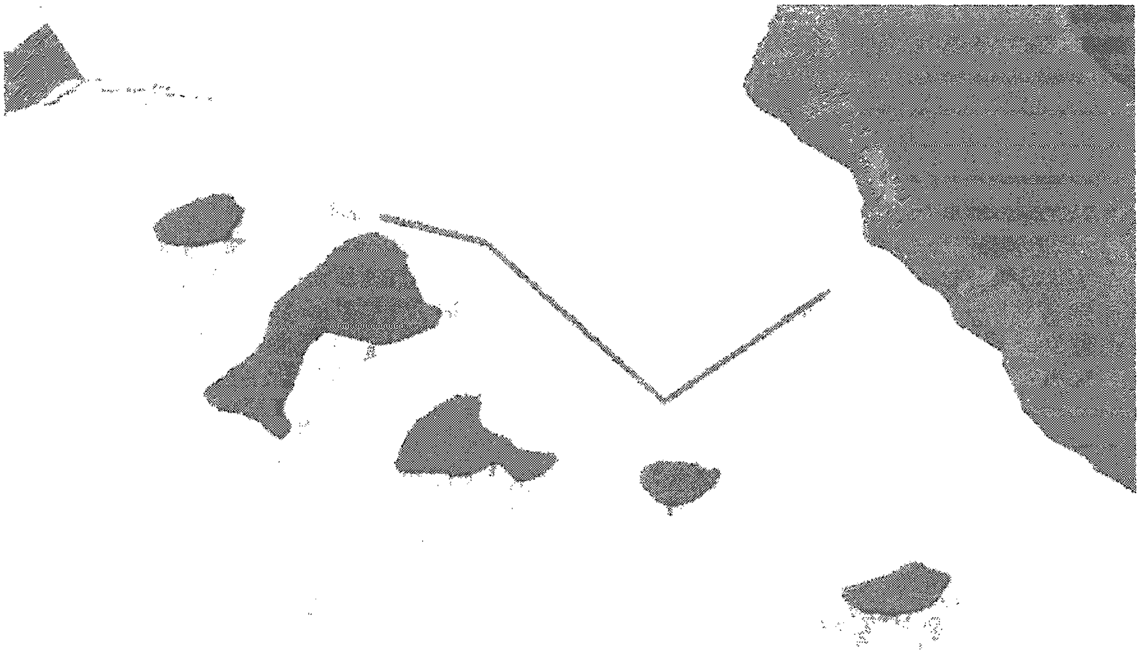


Figure 4.16 *A4 scenario's impact on the Smokehouse and Gut Channels. Lake level is 173.87 metres IGLD.*

Dredging and developing navigation channels requires a clear understanding of the present bed floor materials. Results from the bed floor material type map (Figure 4.17) provided a representation of the distribution of different bed floor materials. Figure 4.18 shows the channels in their current location. They are situated where the bed floor is mostly sand, which presumably makes dredging easier. When the Theissen polygons were draped on the TIN surface, gaps and slivers were visible. Therefore, the bed floor characteristics map does not show changes in depth, and is not in 3D.

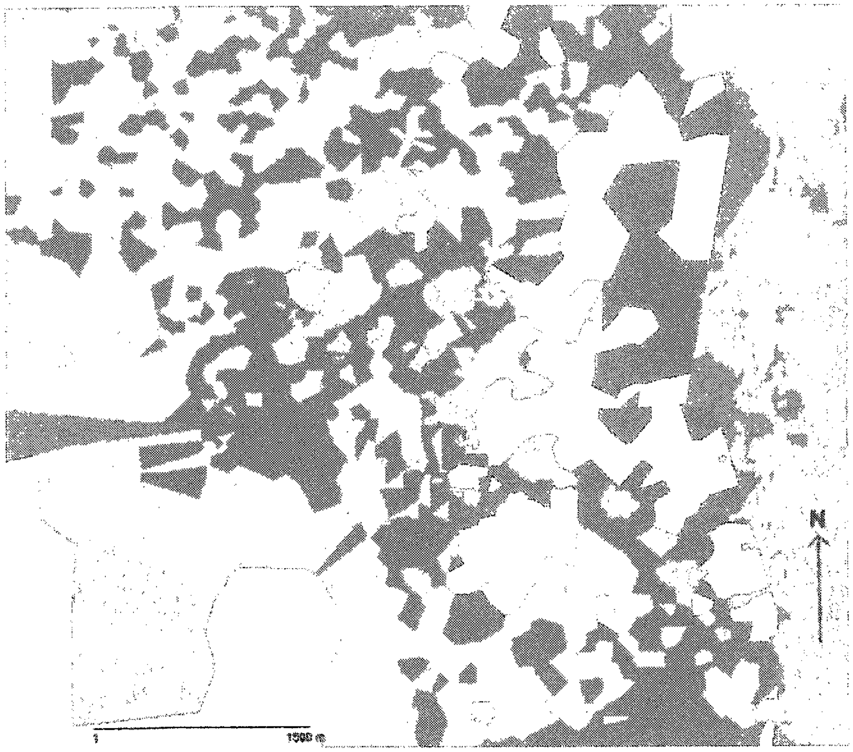
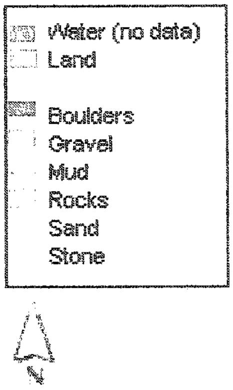


Figure 4.17 Bed Floor Material Type Map



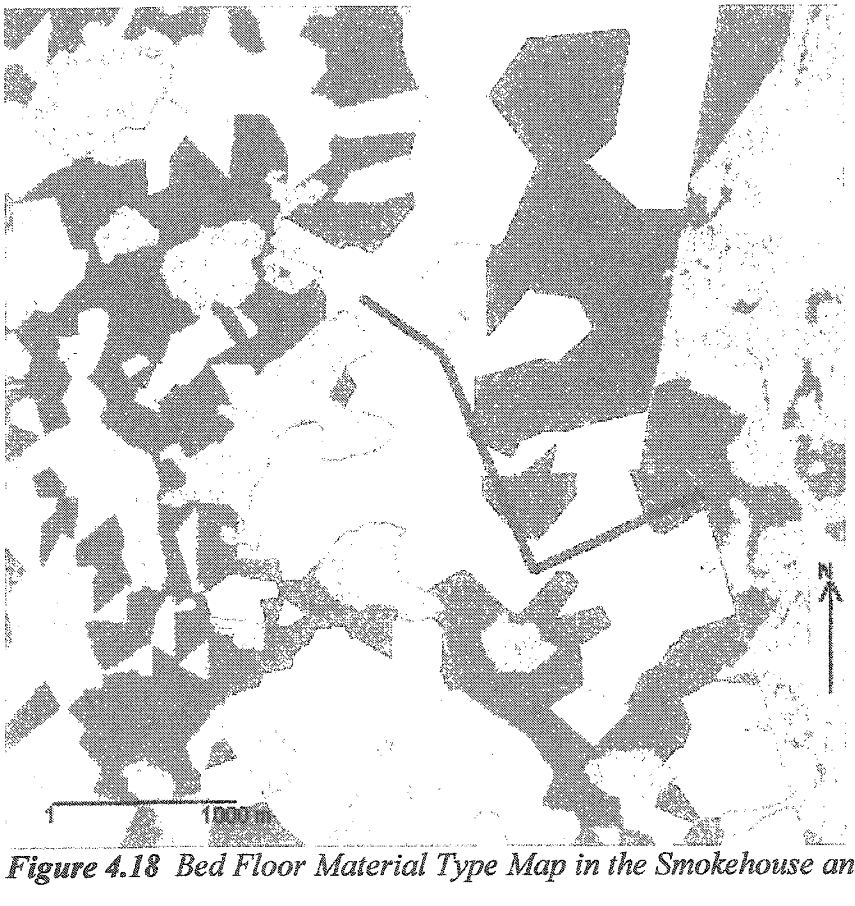


Figure 4.18 Bed Floor Material Type Map in the Smokehouse and Gut Channels

Finally, the small craft harbour will be impacted severely, mainly because of its location (Figure 4.19). A harbour requires easy access to water, but according to the LLCM results with the CCCma 2050 (Figure 4.5) and A4 scenarios (Figure 4.6), without extensive dredging and at its current location, the harbour will be completely isolated from the new shoreline. These results suggest the small craft harbour at its current location will not be viable by the year 2050. The only scenario which would suggest a beneficial result for the small craft harbour is the HadCM2 2050 scenario.

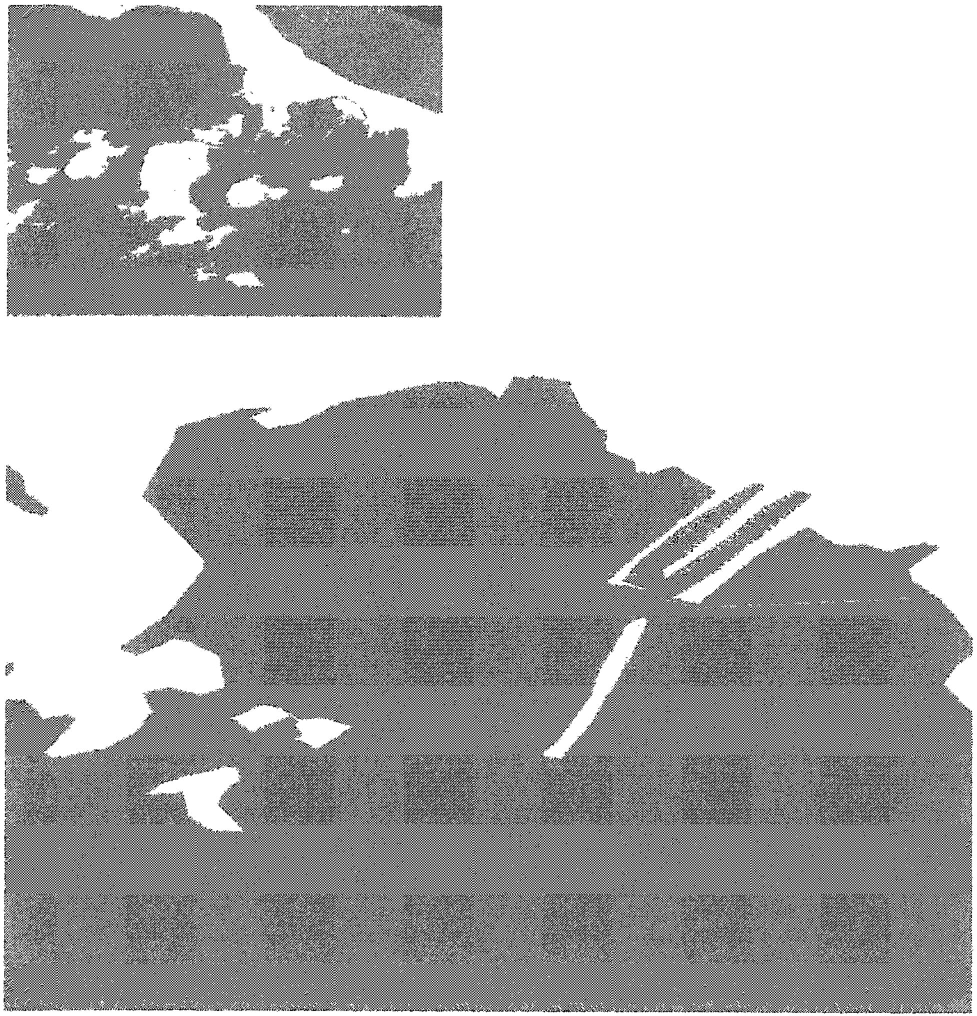


Figure 4.19 *Small Craft Harbour Location. Lake level is 176.62 metres IGLD.*

4.4 Orthoimagery Accuracy Test Results

A false colour composite was generated from the Landsat 7 data (Figure 4.20). The image shows the shoreline and specific coastal zone features. The Smokehouse and Gut Channels are the navigation routes and appear as linear features that cut the shore platform. Water surfaces are characterized by dark blue and black for deep waters, and a lighter blue for more shallow waters. As well, the image clearly displays a number of areas of concern in regards to depth. In some shoreline areas, green hues are visible, indicating the presence of vegetation. These areas when compared to other maps, suggest that they are part of the Oliphant Fen Wetland. Occasional zones of pink represent exposed sand bars. Overall, the final Landsat 7 image is useful for verifying the location of the shoreline, islands, shallow and deep waters, and wetland zones.

4.5 Public Interviews

When all interviews were complete, data were compiled and categorized into five different groups based on the respondents association with Lake Huron. The five categories included: recreational boater, fisherman, cottage owner, retail/commercial owner, and tourist. The number of respondents in each category breaks down as follows: 13 cottage owners, 7 recreational boaters, 5 fisherman, 3 tourists, and 2 retail/commercial owners. This was the result of a random survey.

The survey results show a number of important pieces of information (Appendix B). Most of the participants (26 of 30) do not prefer low lake levels, and associate lower lake levels with a range of negative impacts. When considering the different groups of people surveyed there were some differences. In general, cottage owners, retailers,

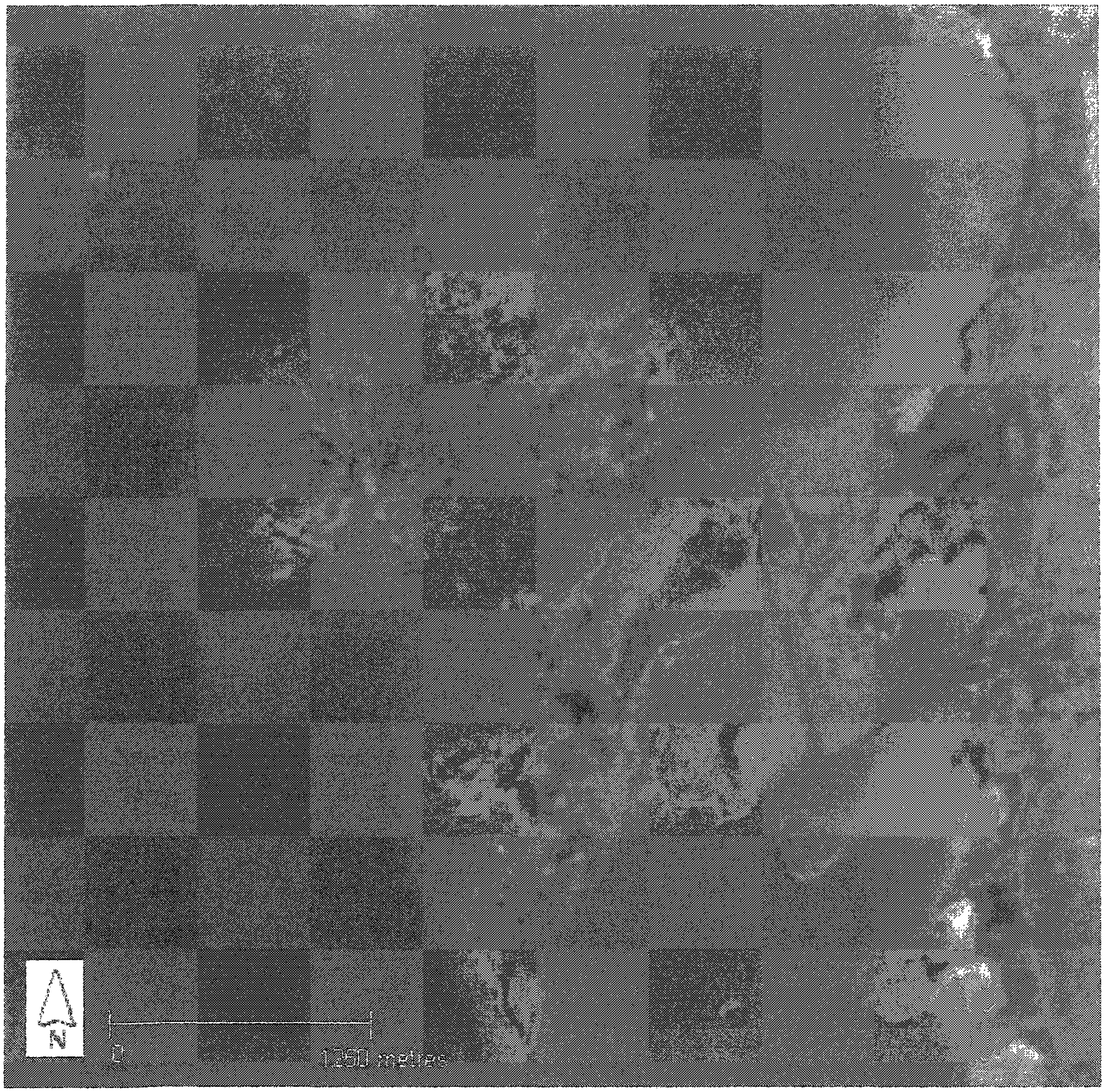


Figure 4.20 *Landsat 7 Orthoimage.*

and tourists felt that they would be impacted by low water levels less than recreational boaters and fisherman. Most people are impacted by low lake levels, or some form of significant change in lake level. Still, there are a wide range of opinions when it comes to how individuals will be impacted by potential future low lake levels. Responses to the questionnaire are presented in Appendix C.

4.6 Chapter Summary

The results presented in this chapter provide information relevant to residents of Oliphant, and shoreline management issues in the area. Both the BDEM and the LLCM served as useful and effective methods of analyzing shoreline impacts in the Oliphant area. The CCCma 2050 and A4 scenarios projects the most negative impacts for all features, while the Had2 2050 projects no negative impacts. According to the public survey, the most visibly negative impact in the minds of most residents is the large sand platform. In the study area, new shoreline area of approximately 19.15 km^2 is predicted by a 1.01 m decline in Lake Huron's water level. A further discussion of these results is presented in the next chapter.

CHAPTER 5: Discussion

5.1 Introduction

Chapter five discusses the implications of the results presented in chapter four. The impacts of lower lake levels on the community of Oliphant are examined and mitigation and adaptation measures are discussed.

5.2 Impacts in Oliphant

Results show that climate change lowered water levels in Lake Huron will impact the environment of Oliphant. Likely impacts include:

1. a wider beach;
2. increased aeolian sediment transport;
3. migration of the Oliphant Fen Wetland towards the new waterline;
4. dewatering of some of the exiting Oliphant Fen Wetland;
5. decreased viability of the harbour;
6. increased need for dredging.

In addition, lower lake levels may hamper recreation and reduce fishing opportunities. Collectively, these possible impacts will trigger much shoreland policy debate.

5.2.1 Wider Beach Impact

The bathymetry offshore of Oliphant is characterized by a very low profile, therefore, the impact even a small decline in lake level will be considerable, causing a large beachfront to be created (Figure 4.8). The Fishing Islands may become joined to land, forming a large peninsula. According to the CCCma 2050 projection, the shoreline will migrate approximately 1,200 m lakeward, uncovering an area of 7.4 km^2. The total beach area would then be 19.15 km^2. This new beachfront may be unattractive to many people. The surface's texture will largely be silty sand and poorly drained because of a low gradient (Figure 4.18). According to some residents of Oliphant, this type of beach is not aesthetically pleasing. Based on samples taken at two locations across the beach, one further inland, and the second further towards the waterline, average grain size is approximately 0.149 millimetres or 2.75 phi, thus making the sediment a fine sand. Some finer sediments were also found in the exposed bed floor. Also, since the bed floor has been under water, a variety of organisms have lived in the sediment, some dying and breaking down, and others producing waste. This can result in a darkening of the sediment colour, which is less pleasing to the eye when compared to an attractive brownish-yellow sand beach. Overall, the increased beachfront from a decline in lake levels will not be appreciated by some residents.

5.2.2 Increased Aeolian Sediment Transport Impact

The fine textured sands that are expected to be exposed on the new beachfront are susceptible to entrainment and transport by wind (Pethic, 1984). This will cause an increase in aeolian sediment transport off the flat beachfront. Due to a north-south orientation of the shoreline, the prevailing westerly winds will cause much sediment to be transported across Shoreline Avenue onto many cottage owners' properties. Sand particles are brought into the cottages, and are seen as a nuisance to clean up. During past low water conditions, when large amounts of sediment were exposed, shoreline properties and the few commercial properties were blanketed by aeolian transported sediments. According to some Oliphant residents, they do not wish to have to deal with the possibility of accreting sand dunes. However, if potential future low lake level conditions occur, long periods of increased aeolian sediment transport can be expected.

5.2.3 Migration of the Oliphant Fen Wetland Impact

According to Middleton (1999), the distribution of wetlands reflects the available source water, whether lake water, groundwater, or precipitation. Fen wetlands are normally groundwater fed (Mitsch and Gosselink, 1993), and to some degree that is the case in Oliphant, but much of the recharge at Oliphant comes from precipitation and surface water from the lake. In the case of the Oliphant Fen Wetland, alkaline groundwater seeps to the surface in the shore zone. When Lake Huron's water level drops, the local water table will be lowered and the groundwater seepage will continue at the new shoreline. The existing fen will loose some of its water and some Fen zones will migrate, move, or expand towards other sources of water. The Fen also receives some of its water supply from precipitation (personal communication, McKenzie, 2002), and the balance from the lake. Therefore, potential future low lake levels may disrupt the natural pattern of the Fen's water supply.

If a migration of the Fen occurs, secondary impacts will be felt. Depending on how the Fen migrates, wildlife will be at risk because they will be required to travel farther in search of water and food. Most wetland zones are protected by shrub bush and forested zones that provide protection from predators. If the wetland moves lakeward, there will be less protection, especially from large Ospreys common to the area. If the Fen does migrate lakeward, many people in Oliphant as well as tourist may not appreciate the new type of shoreline, consisting of wetland vegetation such as the Pitcher Plant, and wetland amphibians such as the red-spotted newt or the northern water snake. According to numerous conversations, residents and tourists prefer a clean, sandy shoreline.

Figure 5.1 *Confined Wetland Zone behind Shoreline Ave. Wet patches of water are result of recent rain event. (Tupman, 10-12-20002)*

5.2.4 Dewatering of the Oliphant Fen Wetland Impact

Another impact of the lower lake levels is that many sections of the Fen will not be allowed to migrate because they are blocked by Shoreline Ave (Figure 5.1). This will cause these wetland zones to possibly dry out completely and cease to be classified as wetland, unless recharged through human intervention (Busch, 1984). Wetland plant species will become less common, due to the lack of water (Burton, 1985). Numerous wildlife species that normally use the Fen for habitat will be required to find new habitat. Wetland zones further inland will likely dry up and no longer be classified as wetland (Busch, 1984, Geiss, 1985). If Lake Huron's water level declines to levels forecasted by Mortsch et al (2000), there will be significant impacts on the Oliphant Fen wetland.

5.2.5 Harbour and Dredging Impacts

Results indicate that the Oliphant small craft harbour will be negatively impacted by the future lower water level scenarios described in the previous chapter. The harbour launching ramp (Figure 5.2) was difficult to use during the low water conditions in the early 2000s, but if record lows are reached, the ramp will require serious renovation. Figure 5.2 also shows impacts on docking facilities. Many of the harbour's docks have been lowered and require access from a boardwalk ramp, which is extended down slope from land to the dock. Lower lake levels may also cause problems navigating throughout the harbour. Due to marine traffic churning up sediment and keeping the harbour deep enough, it is rarely dredged. Even though the harbour is a registered small craft harbour, it is not uncommon to have two or three fishing vessels up to thirty feet along the pier, located at the mouth of the harbour. Therefore, channels into the harbour need to be deep enough to support these larger fishing vessels.

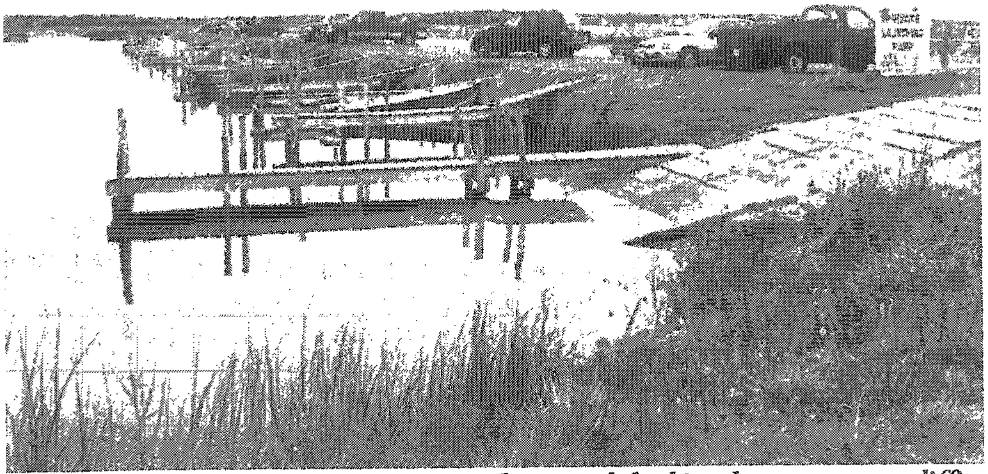


Figure 5.2 *Harbour Impacts: Launching and docking become more difficult during low water conditions. (Tupman, 10-12-2002)*

However, based on the results of the research, lower lake levels may create the need for more frequent dredging in the Oliphant region. In the early 2000s, due to lower lake levels in the Great Lakes, frequency and cost of dredging practices have increased. In the first half of the year 2000, in Lake Michigan, dredging costs increased 25% to 40% (Milwaukee Journal Sentinel, 2000). In the case of Oliphant, dredging has been more frequent in the early 2000s. Dredging in Oliphant is contracted out by the township to a private company. The Gut Channel was dredged completely in 2000 and 2001, and 80% of Smokehouse Channel was dredged in 2000 (personal communication, McKenzie, 2002). Each time, the dredged material consisted of approximately 90% sand, 10% mixed rock and stone (personal communication, McKenzie, 2002). These channels are usually dredged every four to fives years, but in recent years, they have been dredged extensively in some areas, almost every year. Without the dredging of these channels, navigation would not be possible. According to one boater in the survey, "you can be boating along over sand and before you are aware, you're in boulders; it is very scary at times." There have been many boat propellers damaged while boating around and near the Fishing Islands (personal communication, McKenzie, 2002). Dredging is an important practice in Oliphant, but with potential low lake levels, cost and frequency will increase.

5.2.6 Shoreland Policy Debates

It is common to see large cottage structures, harbours, and commercial properties situated as close to the water as possible; this is especially the case in Oliphant. Shoreline Avenue runs parallel to the beach in Oliphant (Figure 1.2), and along almost the entire road are cottage properties. When the water level of Lake Huron declines, there is the possibility that many new shoreland policies will be required to inform shoreline property owners of their title rights. This may require new regulations and/or bylaws to inform people of their property rights. New shoreline management practices for the newly exposed land will become an important issue, causing the possibility of many debates and policy meetings.

5.3 Resident's View on Impacts

Shoreline residents and cottage owners often have a strong voice and concern for shoreline management. Areas with a high concentration of cottage development, cottagers are seen as an important stakeholder in decision making (Scott and Parker, 1996). Cottage owners with long-term ownership are familiar with the impacts from changing lake levels, and therefore, they express great interest in shoreline management.

However, many are unaware of the impact climate change will have on Lake Huron's water levels. More specifically, shoreline property owners and cottagers are not effectively aware of the natural fluctuation of the Great Lakes water levels, and the potential impacts from such fluctuations that are found at the shoreline. Scott and Parker (1996) discuss how cottage owners are impacted by different water levels on the Great Lakes shoreline, stating that cottage owners are in somewhat of a unique dilemma, as their activities are sensitive to both extreme high and extreme low lake levels. High lake levels increase the threat of flooding and erosion, while low lake levels restrict them from some of their recreational activities (i.e., boating, fishing). Scott and Parker (1996) also noted that many Great Lakes' shoreline cottage owners are not aware of the cost of severe lake level change. According to their results most people feel that human activities are not primarily responsible for lake level changes. However, most people surveyed either agreed or strongly agreed that the government manages the levels for shipping and hydro-electric interests. Also, people surveyed felt that lake levels could be managed with physical structures such as dams and diversions. Table 5.1 summarizes their results.. This table conveys clearly that some cottage owners are not aware of how the Great Lakes water levels fluctuate.

Table 5.1 *Cottager Profile on Great Lakes Water Level Issues (Scott and Parker, 1996)*

Question	Strongly Agree	Agree	Disagree	Strongly Disagree	Don't Know
1.	13%	24%	21%	29%	14%
2.	35%	35%	6%	6%	18%
3.	17%	37%	15%	13%	18%

1. Human activities are primarily responsible for water level changes (n-7133).
2. The government manages the levels of the lakes to satisfy the needs of shipping and hydo-electric power interests (n-7234).
3. Lake level management with the use of physical structures such as dams and diversions will stop most flooding and erosion (n-7136).

The local residents from Oliphant and tourists visiting Oliphant have a wide range of opinions on how they will be impacted by potential future low lake levels. Many are aware of the influence a small change in lake level can have on the Oliphant shoreline, as they are familiar with the regular annual lake level fluctuation. However, many cottage owners are not aware of the potential impacts to come as a result of the scenarios in Mortsch et al (2000). North and south along Shoreline Avenue, property owners are expanding their activities lakeward onto what they perceive is their property. Picnic tables are placed around stone crafted fire pits along the beach in front of many properties, each with its own personal walkway across flood barriers, dunes, and wetland zones. In 2002, many property owners along Shoreline Avenue removed vegetation and maintained turf across the road from their property and established patios, fire pits, and gardens. Figure 5.3, a photograph taken in late September 2002, clearly shows an example of one property owner's attempt to "beautify" the shoreline across from the property. This example suggests that some shoreline property owners feel that they have rights to the newly emergent beachfront.

5.4 Adaptation

While the emphasis in the climate change policy field remains predominantly on mitigation, issues relating to adaptation are receiving more recent attention (De Loe and Kreutzwiser, 2000). Natural Resources Canada (2002, preface) defines adaptation, in the context of this thesis, as "activities that minimized the negative impacts of climate change and position us to take advantage of new opportunities that may be present." Successful adaptation has been defined by Smith (1997, p.251) as "either providing the same or a similar level of services to society, or returning a natural system to its original state of health." Adaptation is seen by many scientists and policy makers as a powerful option to reduce the negative impacts of climate change, or to take advantage of the positive effects (Tol et al, 1998).

Figure 5.3 *Waterfront Cottage Expansion. Waterfront grass is cut, and landscaped with flowers and a stone fire pit. (Tupman, 09-28-2002)*

There are different forms of adaptation. Adaptation to climate variability and change can be autonomous or planned (Maciver and Dallmeier, 2000). Autonomous adaptation takes place without intervention of an informed decision maker. Planned adaptation requires strategic actions, based on an awareness that climate is changing and that action is needed to respond to such change. Adaptation can also be characterized as reactive or pro-active, depending on the timing, goal and motive of its implementation (Maciver and Dallmeier, 2000). Reactive adaptation takes place after impacts of climate change have occurred, while pro-active adaptation takes place before impacts are apparent.

In order for adaptation to work effectively in any sector, it requires that a few key questions be addressed: adaptation to what, why or for what reason, and is it worth it (Burton, 1997). First, "adaptation to what" looks at what impacts are driving the need to implement adaptation measures. This must be carefully reviewed. What specifically is a community or the environment adapting to? If society was to adapt to a $2xCO_2$ scenario, the adaptation measures would be too large. Instead, there must be a clear understanding of the specific impacts to enable an assessment of impacts and adaptations to be as precise as the policy makers require (Burton, 1997). For example, in Oliphant, due to climate change induced low lake levels, people will need to adapt to a more hazardous boat launching ramp.

The second question, "why or for what reason," focuses on why adaptation is being offered. When a natural system adapts to climate change, it is usually to maintain function. For example, if water temperatures increase as a result of increased air temperatures, fish species that require colder and more oxygen rich water, such as trout, may migrate to new locations that are more suitable. In regard to society, our reasons for adaptation can be very different. They can be centered on financial gain, survival, the environment, and perhaps personal or group preference. It would be more appropriate for society to adapt to a specific effect of climate change for reasons of survival or preservation of the environment. Instead, society often acts for financial gain or personal preference. For example, if society decided to build large water control structures at some location in the Great Lakes, just for efficient and sustainable hydroelectricity, there would be more negative impacts on the environmental and short-term financial negative impacts.

The third question, "is it worth it", addresses the decision on whether some form of adaptation is financially sound or environmentally sustainable. Increased environmental risks and large monitory expenses as a result of adaptation are not positive, but if adaptation measures focus on environmental sustainable and not financial gain, then it is important to continue with whatever method is approved. Overall, whatever the environment or society is adapting to, it should be clear what specific things need adapting to, why, and is it worth it.

5.5 Possible Methods of Adaptation in Oliphant

In order for residents, cottagers, and tourists to cope with the future lake level declines along Oliphant's coastal zone, they will have to examine a number of strategies. Adaptation provides an opportunity to reduce environmental and socioeconomic impacts.

5.5.1 Adapting to Impacts of a Wider Beach

The ability to adapt to such a large and undesirable beachfront (Figure 5.4 and 5.5) is limited. Without controlling the lake levels, there is little that can be done to prevent impact. Still, there are some measures which can be taken to reduce the impact. The beachfront can be cleaned by raking, but without disturbing any wetland vegetation. This process is done along Sauble Beach, just ten minutes south of Oliphant. Recreational activities which take advantage of such open areas can flourish. Overall, it will be difficult to adapt to such a larger beachfront.

An area of concern is the increase in vehicles on the beach. Instead of walking possibly more than a kilometer to the lake, people will tend to drive across the beach (Figure 5.5). In order to reduce the impact from vehicles, "no driving" signs can be

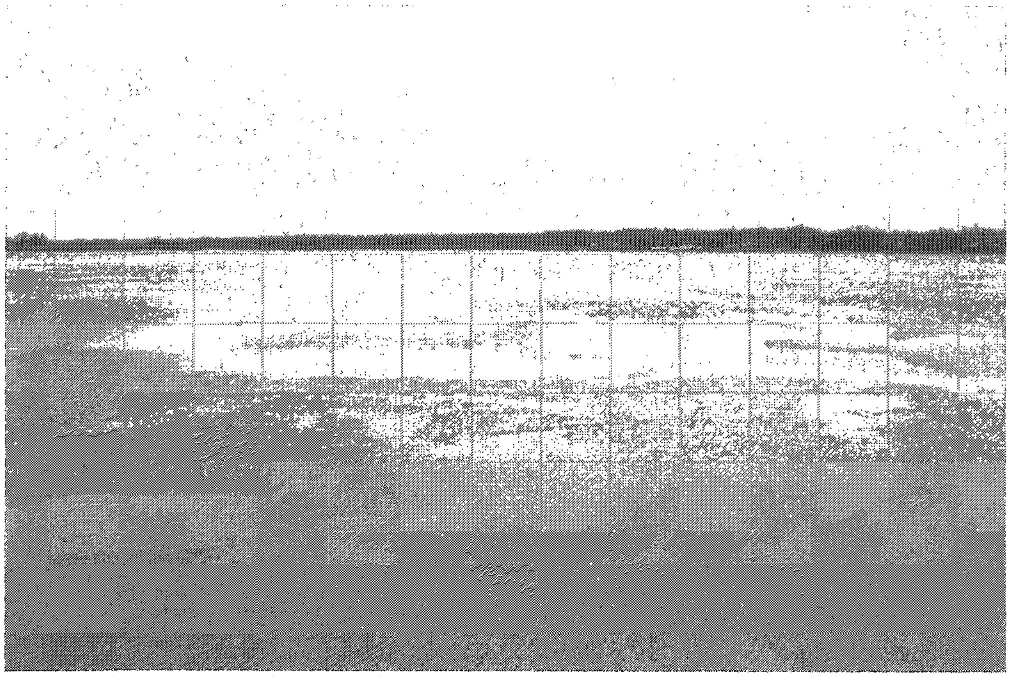


Figure 5.4 *Exposed Sand Flats during 2002 Low Water Conditions. Looking east. (Tupman, 11-09-2002)*

Figure 5.5 *Cottage Owners Walking to the Fishing Islands. Looking west. Photo taken near the harbour. (Tupman, 07-20-2002)*

posted, or natural vegetation marking laneways can be constructed to funnel vehicle traffic to reduce the area traveled on. This will reduce the area that is disturbed and allow the beach processes to act naturally.

5.5.2 Adapting to Increased Aeolian Sediment Transport

Traditionally, aeolian sediment transport has been combated by either trapping sediment or blocking the path of flow. The most environmentally sound method of doing so is to encourage the development of dunes along the shoreline. This can be accomplished by introducing sand dune grass species such as marram *(Ammophila Spp)*. Such a grass species, common along Lake Huron's shores, is key to the development of embryo dunes, which are the initial dune formation that grow into larger dune formations. Sand dunes would reduce sediment transport along the shoreline, and therefore reduce the amount of sediment transported into the cottages, homes, and stores of Oliphant. If such dune formations develop, then the public will need to become aware of their importance in trapping airborne sediments, as well as their level of sensitivity.

Large boulder protection barriers along certain locations of Shoreline Avenue, although installed to prevent flooding and wave uprush, have also acted as a blockade for sediment transport (Figure 5.6). In some locations, sediment blown particles have filled in the small pockets between rocks and boulders. Still, the likelihood of these barriers developing to actual sand dunes is not likely. Therefore, marram *(Ammophila Spp)* grass should be introduced in locations shoreward of these barriers.

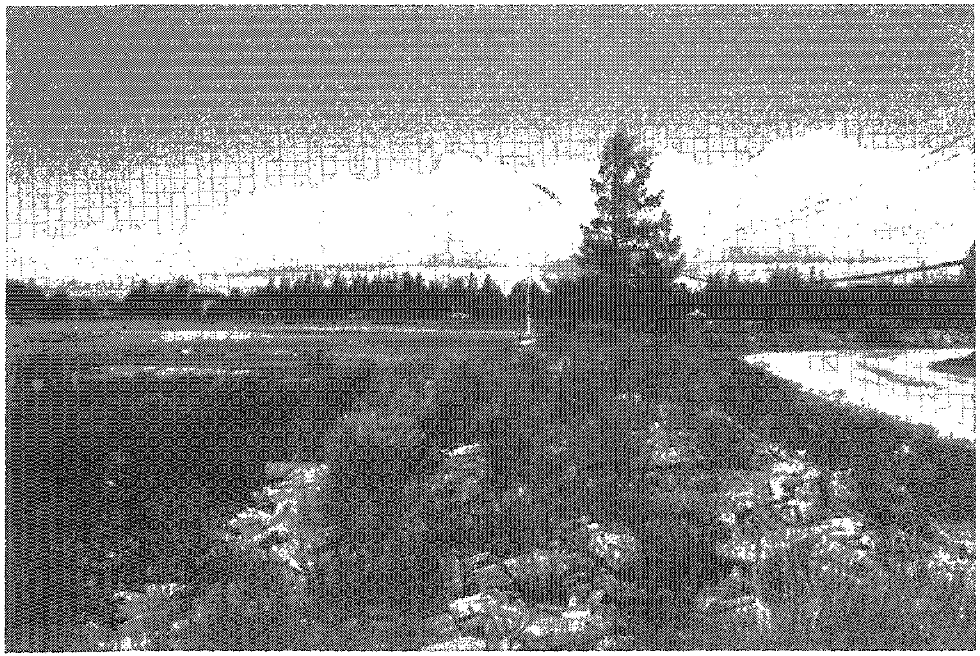


Figure 5.6 Shoreline Hardening in Oliphant. Shoreline Ave to the right. Shoreline hardening was established in late 1980s after record high water levels. Water level is clearly low, as it is not visible. (Tupman, 08-25-2002)

5.5.3 Adapting to the Migration of the Oliphant Fen Wetland

Most likely, when Lake Huron's water levels drop, the Oliphant Fen Wetland will adjust to the changing hydrology. That form of adaptation will be a migration shoreward or a change in its area. To assist this process, there are some management and restoration options available (Environment Canada, 2002d). Simple and cost effective methods of adaptation include encouraging wetland vegetation growth in new areas by seeding (Keddy, 2000), and delineating wetland areas by signage and fencing, thus displaying where wetland zones are and encouraging people to stay out of the wetland.

Overall, the Oliphant Fen Wetland will be impacted greatly by climate change, and the residents of Oliphant must realize this. It will be extremely important that residents, cottage owners, and tourists not mistake the dried lands for habitable shoreland. Similar to what was accomplished with the development of the Oliphant Fen Wetland

Boardwalk, tourists and property owners have to learn not to trample over existing, migrating, and possible new wetland zones. For the coastal wetland to adapt successfully, there must be little interference by human activities.

5.5.4 Adapting to the Dewatering of the Oliphant Fen Wetland

In regard to water supply for the Oliphant Fen wetland, there are some methods of increasing supply. One potential method of providing water to the Oliphant Fen wetland is to redesign some of the current culverts (Figure 5.7) through Shoreline Avenue. If the culvert inflows on the wetland side are raised above the elevation of the wetland, runoff and groundwater seepage losses to Lake Huron will be reduced, as Shoreline Avenue will function as a leaky dam. Alternatively, water could be pumped from the lake to the wetland, or narrow channels could provide lake water to the wetlands during storm surges or seiches. Regardless, regular renovation of the drainage works will be required as the shoreline configuration changes, and the waterline moves farther away. While this method seems to be the most environmentally sensitive method of providing freshwater to the wetland zones that are blocked by Shoreline Avenue, it would require costly engineered channels. Overall, similar to adapting to the migration of the Fen, adapting to the dewatering of the existing Fen will be difficult. Providing a useful supply of water to the existing Fen will require the cooperation of the local residents and substantial investment, or the Fen will start to decrease in area.

Figure 5.7 *Supplying Lake water to a Confined Wetland Zone with a piping system underneath Shoreline Ave. (Tupman, 04-22-2002)*

5.5.5 Adapting to Harbour and Dredging Impacts

A great deal of renovation and adaptation will be required in the harbour. One possible method of adapting to a change in lake level is to use floating docks. Some small craft harbours and marinas throughout the Great Lakes over the years have used floating docks as a method of adapting to changes in lake level (Tupman, 2001). Floating docks can be constructed in many ways, with different materials. The most common approach utilizes environmentally safe, large empty barrels or drums, beneath a wooden dock. The barrels float on the water and adjust to changes in lake level. In order to keep the docks stationary they are fixed somehow to the shore, and sometimes anchored on the bottom. If the specific dock is anchored, they often cannot adjust quickly enough to flash flooding. One approach to fixing this problem is to adjust the length of rope or chain to the anchor. One problem with floating docks is that they can be expensive when used in large facilities, and dangerous if they break loose in a storm (personal communication, McKenzie, 2002). The Oliphant small craft harbour is able to accommodate approximately eighty boats, ranging in size from ten to twenty four feet, on average. Floating docks are available that could moor all boats which are common to the harbour. The floating dock method would be a viable option, and works well with changes in lake level, but would represent a substantial cost.

Another concern with the Oliphant small craft harbour is its ramp. Expensive renovation to the ramp will be required. With a significant decline in lake level, and the current state of the ramp, only a few boats might be able to launch. If the harbour remains in its current location, and is dredged to satisfy boat owners, then the ramp would require a complete overhauling. The ramp would need to be extended and the slope possibly changed as well. In extending and changing the slope of the ramp or installing an alternative, a new concrete slab would be required.

The Gut and Smokehouse Channels are the most important marine navigation channels in the Oliphant region (Figure 4.14). Also, they are the most frequently dredged channels in the area. The channels are clearly marked with channel markers, providing safe access to the small craft harbour (Figure 5.8), and out to the deeper waters of Lake Huron. On the right side of Figure 5.8, old dredged material has become covered with vegetation, making the dredged material seem less attractive. If lake levels drop according to the suggested water level scenarios, these channels will have to be either dredged extensively or new channels will have to be made. In either case, adaptation in the form of dredging will be required. As well, it is likely that the frequency of dredging will need to increase, and new dredging regulations may need to be established.

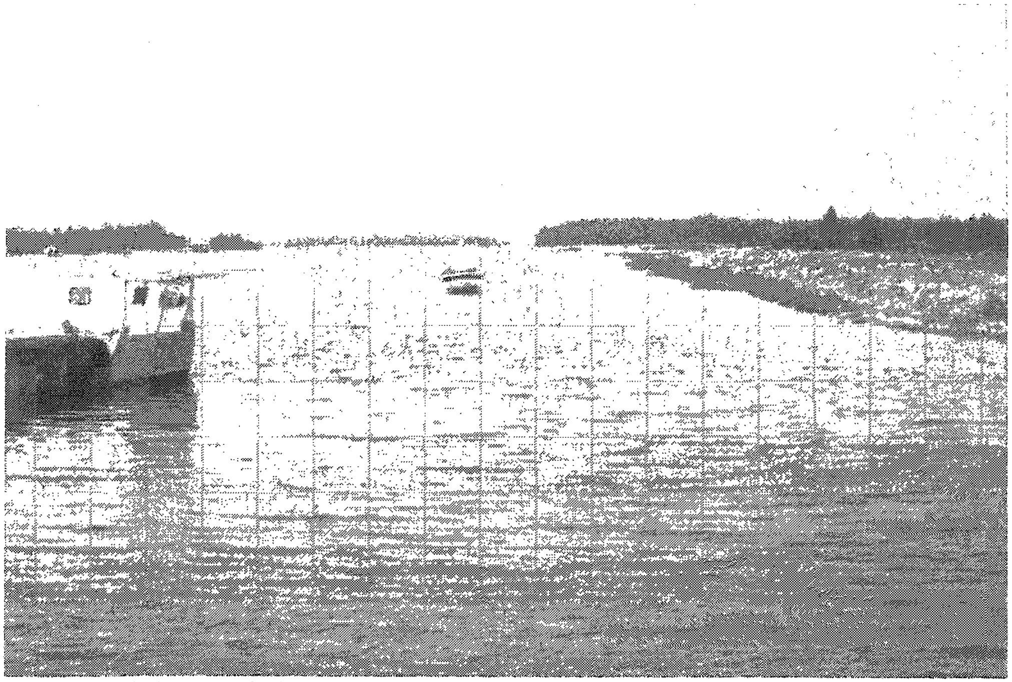


Figure 5.8 *Smokehouse Channel into Harbour. Dredged Material on the right. (Tupman, 07-06-2002)*

A common problem with dredging happens when you reach bedrock, and there is no material available to be dredged. In the channels' current locations, the bed floor is mostly sand, allowing for easy dredging. How much sand is left, or how long it will last is a difficult question. Luckily, due to high amounts of lacustrine sediment transport, so far this has not been a problem in this area of the Fishing Islands (personal communication, McKenzie, 2002). There is a large supply of sediment, and it is well known in Oliphant that the channels often fill in. However, with a decline in lake level, there will be less sediment transport, as the large sand flats will be above water.

If the Gut and Smokehouse Channels ever reach a point when they can no longer be dredged, then the only possibly remedy would be to create new channels. In order to accomplish this, the use of the bed floor materials map (Figure 4.18) and BDEM (Figure 5.9) will be important, as will navigation charts. New channels will need to be mapped according to bed floor material type, distance to deeper water, environmental impact, and cost. However, if the lake levels fall much lower, the small craft harbour will need to be moved lakeward. As long as new channels are not required, and the current channels can continue to be dredged, and that pro-active management is used, then serious negative impacts can be minimized.

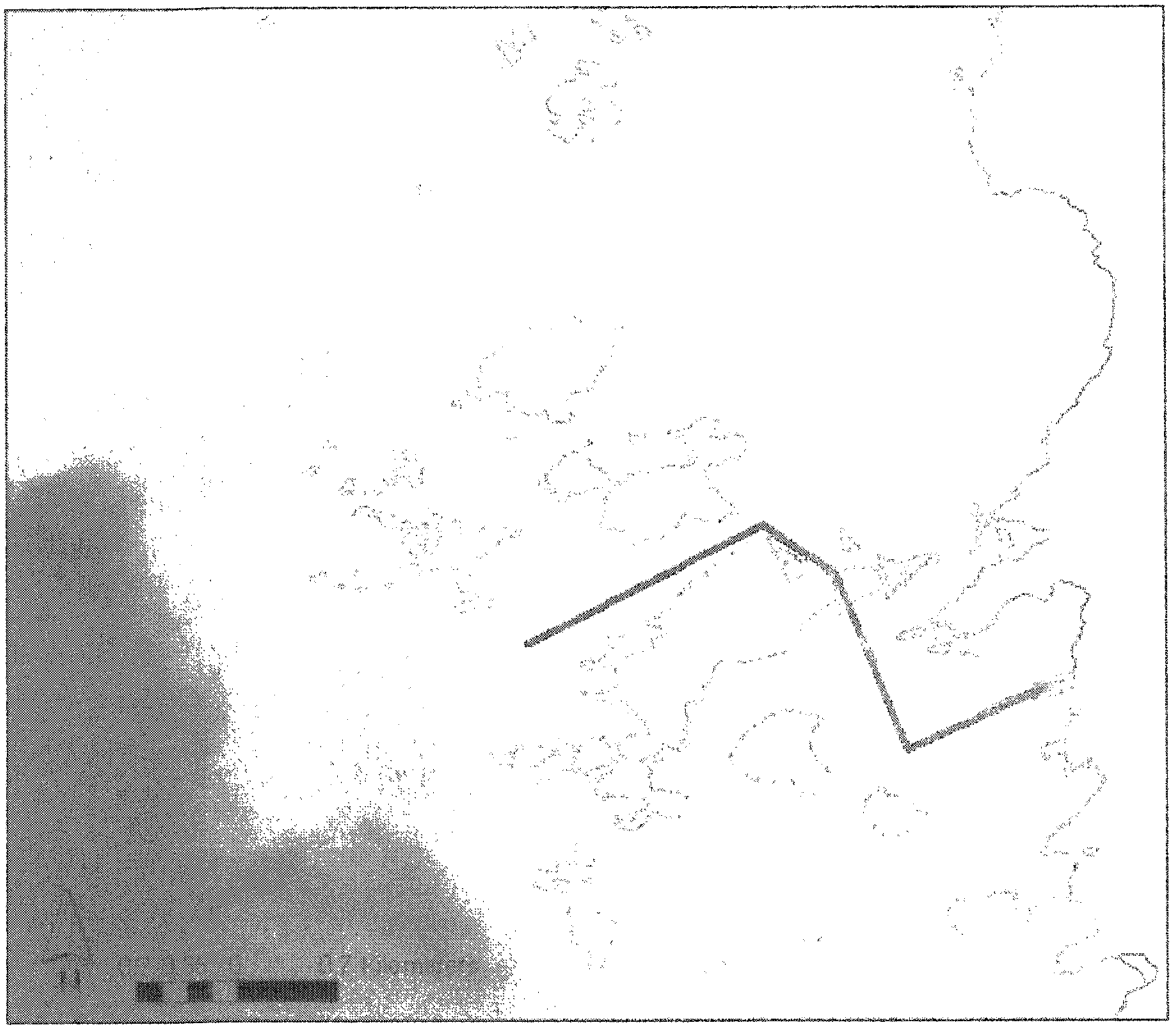


Figure 5.9 *BDEM showing dredged channels, and possible locations for new channels. Red lines represent the current channels, while yellow lines represent possible new channels.*

5.5.6 Shoreland Policy Response

The final concern about a lower lake level is whose responsibility it will be to manage the new waterfront. Decreased lake levels may require discussions on shoreland planning and policies throughout the Great Lakes. There is a need to identify and inform stakeholders of the impacts, appropriate shoreline management policies, and possible adaptation measures (OMNR, 2001). Cottage owners and associations, non-governmental organizations, conservation authorities, provincial, state, and federal governments, and transportation companies are some of these key stakeholders. At the local level, new shoreline management regulations will be required, such as plans that will control where development is permitted. These plans will need the advice and counsel of all the groups just mentioned, and possibly many more. Such planning constitutes an actual form of adaptation. Planning can be reactive or pro-active, but whatever type of adaptation, they need to consider what they are adapting to, why they are adapting, and if it is worth it.

In the case of the residents in Oliphant, when asked how they would adapt to the new land, there were different responses. When asked if cottage owners would sell their shoreline property, not a single person said that they would. Worry about property values and taxes are a concern. In order that residents of Oliphant have their questions answered, they will need to have meetings with the township, the Grey Sauble Conservation authority and themselves as a cottage association. What society must not do as a method of adaptation is to allow shoreline properties to develop closer to the new waterline. Even small stone patios with fire pits are not recommended. These measures, as well as others, need to be presented to the residents of Oliphant. New shoreline management policies will be required to develop a strong understanding of how society can adapt to an expanded shoreline.

5.6 Chapter Summary

The Oliphant Fen wetland, the small craft harbour, shoreline properties, and a very shallow and flat beachfront will be greatly impacted by the decline of Lake Huron's water level. In order for the land owners of Oliphant to reduce the potential impacts on the surrounding environment, they will need to adopt a number of adaptive measures. Examples which may work include: planting to encourage wetland migration, planting to encourage the establishment of dunes to trap windblown sediment, the development of shoreline waterways adding fresh water to confined wetland zones, increased dredging, installation of floating docks in the harbour, shoreline grading and cleaning, restrictive shoreland policy regulations, as well as, allowing natural environmental adaptation to occur.

CHAPTER 6: Conclusions

6.1 Introduction

This thesis examined possible future water level scenarios for a site on the Lake Huron shoreline. The research was accomplished by reviewing possible environmental and socioeconomic impacts, based on literature review and mapping results from GIS analysis. This was followed by a number of suggested mitigation measures. In this final chapter, main findings are reviewed, as well as future recommendations.

6.2 Main Findings

First and foremost, according to some potential future lake levels, a variety of environmental and socioeconomic impacts may be felt in the town of Oliphant and its surrounding landscape. These findings are the result of the mapping techniques which suggest specific impacts. The impacts include changes to the local shoreline, possible wetland migration and dewatering, increased risks to marine navigation, increased costs for dredging, increased aeolian sediment transport, and increased maintenance costs for the small craft harbour. Due to these and other impacts, a number of shoreland policies may be looked at by the local, regional, provincial and potentially, federal governments. However, these suggested impacts, based on the mapping results have a level uncertainty. There is a low level of probability that some of the extreme mapping results will occur. Many of the results are based on potential scenarios and show examples and averages of possible future impacts.

Secondly, there are a number of possible adaptation measures that can be implemented to reduce potential future impacts. The list of measures reviewed will better prepare local residents, cottage owners, fishermen, recreational boaters, and tourists for the possible future impacts. These measures included: cleaning the larger waterfront area, sand dune grass planting, more wetland zone signs and sensitive area information, renovation of culvert and drainage works to encourage surface water to drain into the wetland, installation of floating docks and a new launch ramp, and new navigation channels. Possibly the most important form of mitigation will come from different government authorities, who will design new shoreline management policies. This process will be very lengthy, and involve a more than just government authority. Important private stakeholders and cottage associations should be involved as well.

Overall, this research has outlined a list potential impacts and a list of ways to adapt to or reduce their level of harm. Therefore, specific impacts were listed, and followed by mitigation measures that target each individual impact.

6.3 Future Recommendations

The first recommendation looks at the research's data and its level of accuracy and completeness. Due to a number of data related concerns, there are some errors associated with the mapping results. Therefore, realizing that the data sets had concerns, it is recommended that methods be implemented to obtain better data. Issues of data accuracy and completeness may have been alleviated with field surveying and digitizing, as well as more paper maps. For example, data accuracy might have been corrected in the field with a Global Positioning System (GPS). Also, the use of better and more up-to-date aerial photographs as a reference source would have been helpful. Shoreline features, especially along the Fishing Islands may have been clearer with improved aerial photographs. As well, it would be more beneficial to have all data sets at the same scale, preferably 1:10,000. Overall, results would have been more effective if the data was of better quality.

The second recommendation is that, due to its local significance, more research into the Oliphant Fen wetland should have been accomplished. The wetland is important environmental feature in Oliphant, and there were very few results found for the wetland. The literature does not discuss in great detail how fen wetlands are affected by changes in lake level in regard to migration. Therefore, it was difficult to assess the complete level of impact that the wetland may feel. Still, because of its level of local significance, it is recommended that future research should look at how fen coastal wetlands naturally adapt to changes in lake level.

Thirdly, the results from this research should be provided to stakeholders. The following groups should be informed of this research's results, Grey Sauble

Conservation Authority, South Bruce Peninsula Township, the Town of Oliphant, Lake Huron Centre for Coastal Conservation, and the Owen Sound Field Naturalists. The map results and adaptation measures suggested in the previous chapter would be very important to these groups, because it would be these groups that would implement any mitigation measures, as they are the key stakeholders that would be concerned with the issues discussed in this research.

The final recommendation is that, in the future, this research be applied to other shoreline regions throughout the Great Lakes. The methodology is portable and can be applied to any type of coastal location in the Great Lakes. This research would be very useful for locations such as Toronto or Chicago harbour, Long Point, and Honey Harbour. Therefore, this methodology can be, and in some circumstances, should be applied to different coastal locations in the Great Lakes.

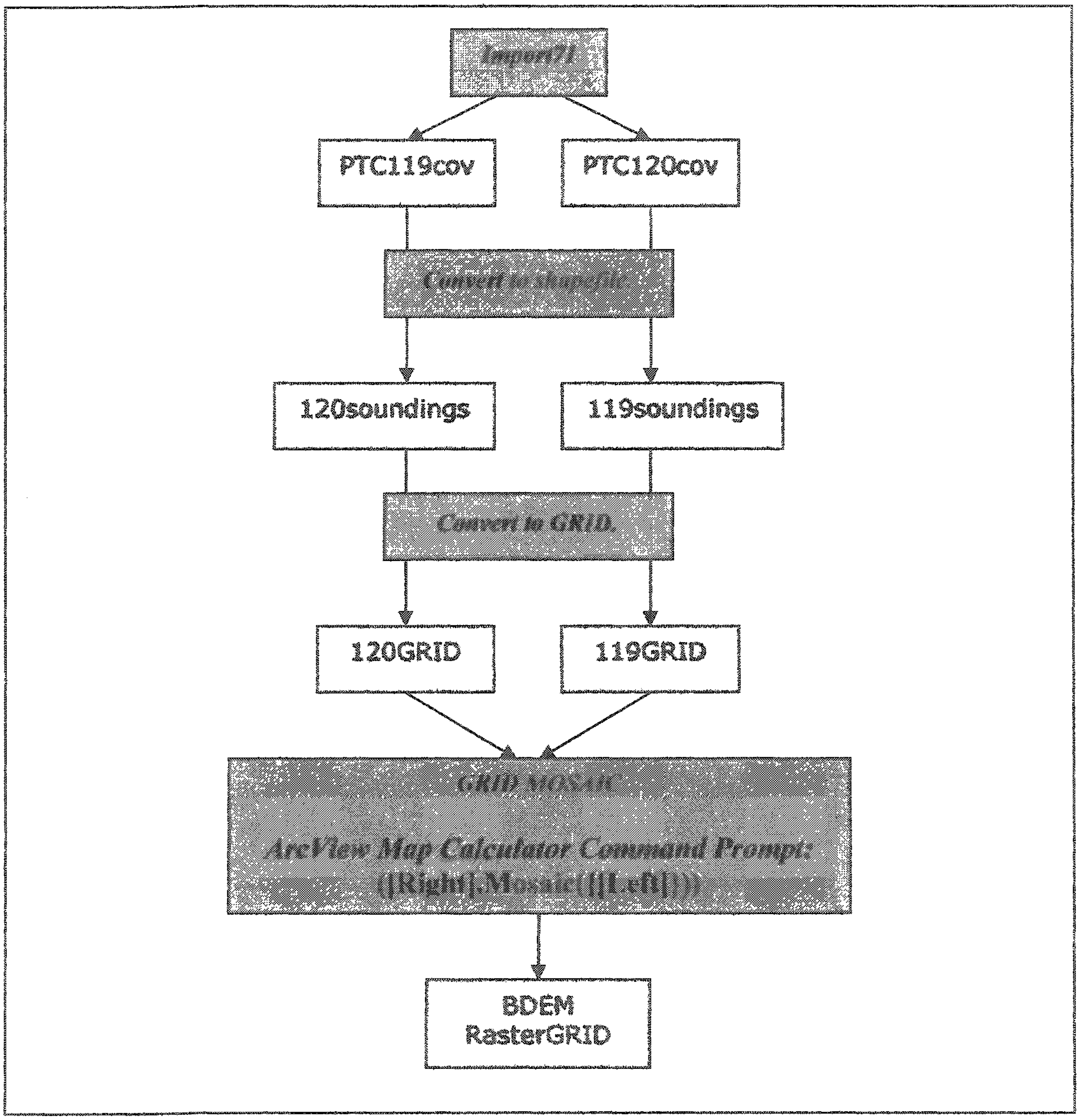
APPENDIX A

CARTOGRAPHIC COMMUNICATION MODEL FOR GIS METHODOLOGY

GREEN BOXES = COMMANDS
YELLOW BOXES = FILES AND RESULTS

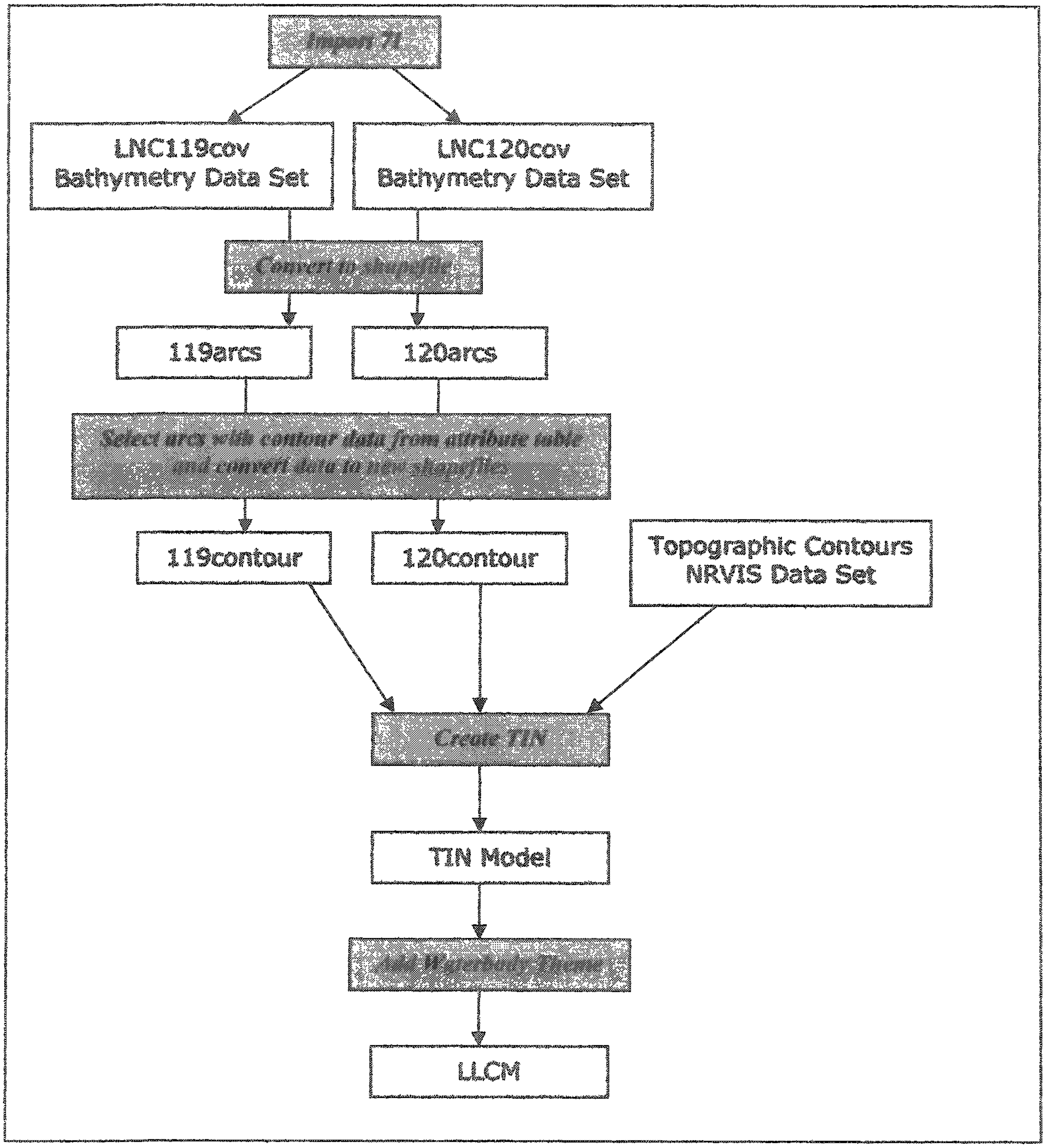
Bathymetry Digital Elevation Model

Data sources: Bathymetry data set. Files were delivered in ArcExport format.



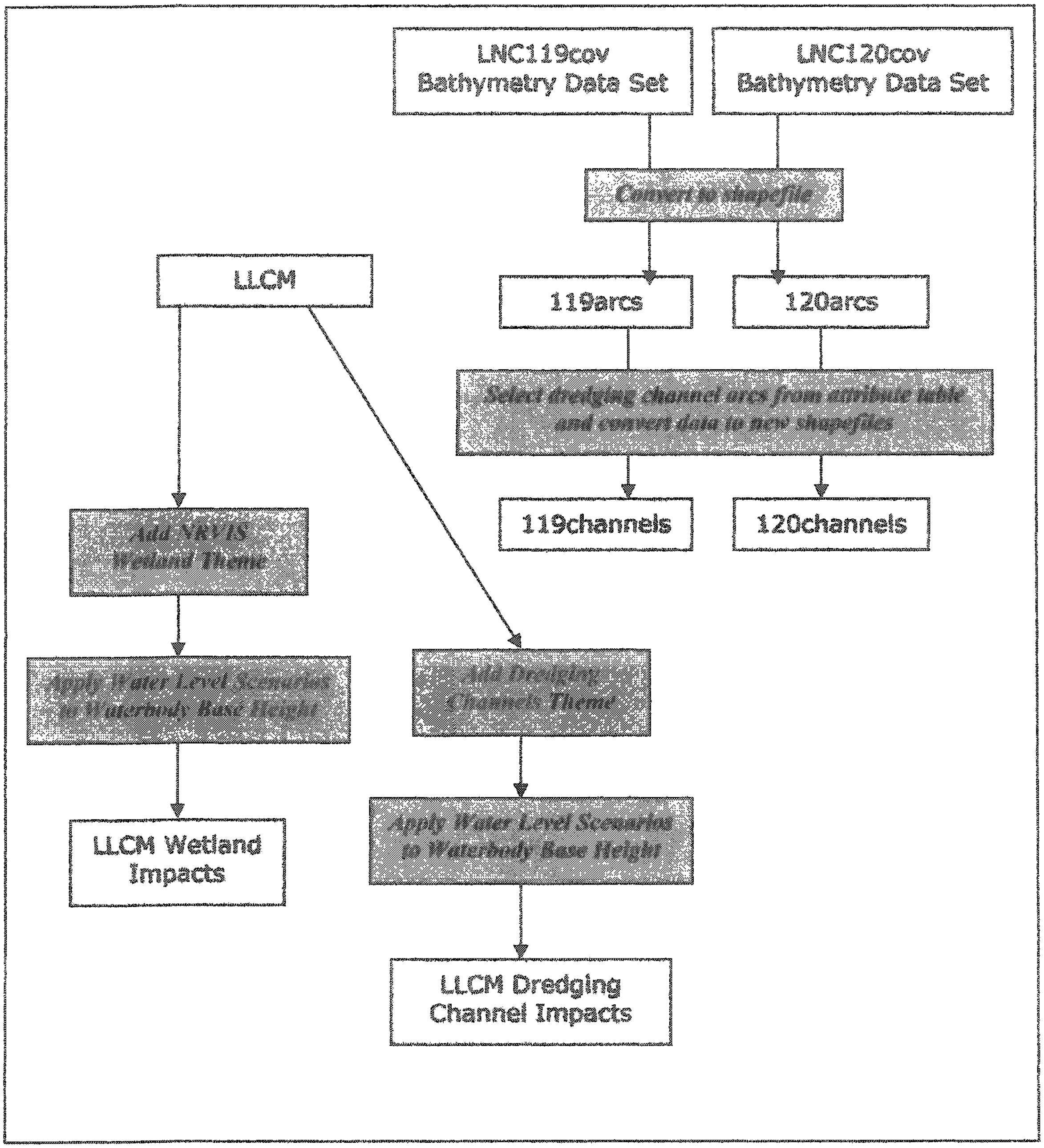
Lake Level Change Model (LLCM)

Data sources: Bathymetry and NRVIS data sets.



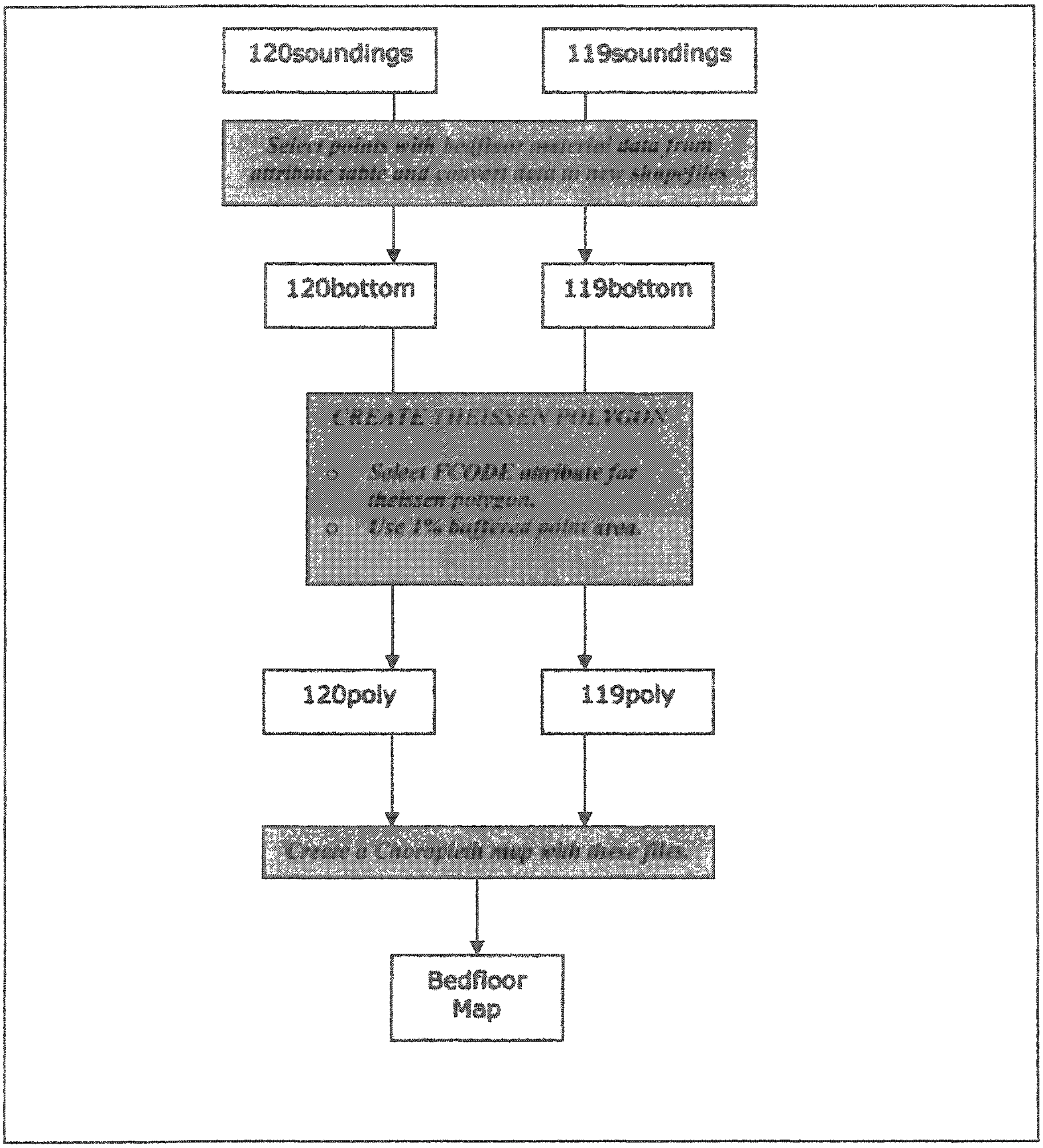
LLCM Applications

Data sources: NRVIS and NTS data sets.
Refer to the LLCM flow chart for how LNC119cov and LNC120cov were generated.



Bedfloor Characteristics Map

Data sources: Bathymetry data set.
Refer to BDEM flow chart for how 120soundings and 119soundings were generated.



APPENDIX B

QUESTIONNAIRE RESULTS

1. a) I have been negatively impacted by the current low water levels in the following ways? (Check all that apply)

- ☐ Low water tables create poor water quality and/or little supply
- ☐ I am unable or experience difficulty launching my boat/personal watercraft.
- ☐ The beach is too large, shallow and polluted.
- ☐ Boat navigation is more difficult.
- ☐ Wetlands have dried up and become unattractive aesthetically.
- ☐ I have not felt any negative impacts.

b) Have you been negatively impacted by the current low water levels in any other ways? (Please list)

2. a) I have been negatively impacted by past high water levels in the following ways?

- ☐ The shoreline was eroded and was unattractive.
- ☐ The shoreline was flooded and was unattractive.
- ☐ There was no beach for swimming.
- ☐ The water table was too high.
- ☐ I have not felt any negative impacts.

b) Have you been negatively impacted by past high water levels in any other way? (Please list)

3. Do you prefer higher than average water levels or lower than average water levels?

- ☐ High
- ☐ Low

4. On a scale of 1 to 5, how would you rate the importance of suitable water levels? Meaning, is it important to you that water levels do not affect your activities.

- ☐ 1 (not important)
- ☐ 2
- ☐ 3 (somewhat important)
- ☐ 4
- ☐ 5 (very important)

5. Have extreme low or high water levels dissuaded you from going to Lake Huron?

- ☐ Yes
- ☐ No
- ☐ Sometimes

6. Have low water levels hindered or stopped you from conducting certain activities?

- ☐ Yes
- ☐ No
- ☐ Sometimes

7. In your opinion, which one of the following is most negatively impacted by low water levels?

- ☐ Marinas (dredging)
- ☐ Water table
- ☐ Aquatic habitat
- ☐ Boat access
- ☐ Wetlands
- ☐ Beaches
- ☐ Lake Huron's water quality
- ☐ Lake Huron's water supply

8. Considering the impacts associated with low water levels, how should we respond to future low water levels?

- ☐ Divert water into the Great Lakes to raise the level.
- ☐ Prepare budgets to be used to relieve impacts.
- ☐ Dredge marinas and river mouths.
- ☐ Reduce our consumption of water.
- ☐ Develop new shoreline/land policies for land owners.
- ☐ Reduce emissions to reduce global warming.

9. How will you prepare for future low water levels?

- ☐ Sell my property.
- ☐ Sell my boat.
- ☐ Anchor my boat further out, or move my dock further out.
- ☐ Find more suitable swimming locations, where water is deeper and cleaner.
- ☐ Low water levels will not bother me.

10. How would you describe yourself when associated with Lake Huron?

- ☐ Recreation Boater
- ☐ Fisherman
- ☐ Cottage Owner
- ☐ Retail/Commercial Owner
- ☐ Tourist

Question	Answer							
	A	B	C	D	E	F	G	H
1a)	8	11	25	24	18	0		
2a)	3	10	10	0	16			
3	26	4						
4	0	0	3	14	13			
5	1	19	10					
6	13	0	17					
7	3	0	3	2	6	5	5	7
8	5	3	2	13	2	5		
9	0	1	12	15	2			
10	7	5	13	2	3			
Cottage Owners								
1a)	3	1	13	9	8	0		
2a)	2	4	5	0	7			
3	9	4						
4	0	0	1	9	3			
5	1	9	3					
6	2	0	11					
7	0	0	1	0	2	5	1	5
8	2	2	0	6	2	1		
9	0	0	1	11	1			
Recreational Boaters								
1a)	2	5	5	7	3			
2a)	0	2	3	0	3			
3	7	0						
4	0	0	0	3	4			
5	0	4	3					
6	5	0	2					
7	1	0	1	1	2	0	1	1
8	0	0	1	5	0	1		
9	0	1	5	1	0			
Fisherman								
1a)	0	4	2	5	3			
2a)	1	1	0	0	3			
3	5	0						
4	0	0	0	0	5			
5	0	4	1					
6	4	0	1					
7	1	0	1	1	0	0	1	1
8	2	1	1	0	0	1		
9	0	0	5	0	0			

Retailers								
1a)	0	1	2	1	2			
2a)	0	1	0	0	1			
3	2	0						
4	0	0	0	1	1			
5	0	2	0					
6	1	0	1					
7	1	0	0	0	0	0	1	0
8	1	0	0	0	0	1		
9	0	0	1	0	1			
Tourists								
1a)	0	0	3	2	2			
2a)	0	2	2	0	1			
3	3	0						
4	0	0	2	1				
5	0	0	3					
6	0	0	3					
7	0	0	0	0	2	0	1	0
8	0	0	0	2	0	1		
9	0	0	0	3	0			

Responses to questionnaire. Letters represent the different choices available each question.

REFERENCES

Abdelguerfi, M., Wynne, C., Cooper, E., Roy, L., Shaw, K. (1998). "Representation of 3-D elevation in terrain databases using hierarchical triangulated irregular networks: a comparative analysis." International Journal of Geographic Information Science **12**(8): 853-873.

Aronoff, S. (1989). Geographic Information Systems: A Management Perspective. Ottawa, Canada, WDL Publications.

Aspinall, R., Matthews, K. (1994). "Climate change impact on distribution and abundance of wildlife species: an analytical approach using GIS." Environmental Pollution **86**: 217-223.

Badger, N. J. (2000). Shoreline bluff failures: a GIS assessment of susceptability and risk for Lake Erie's north central shoreline. Department of Geography and Environmental Studies. Waterloo, Ontario, Wilfrid Laurier University.

Beatley, T., Brower, D.J., Schwab, A.K. (1994). An Introduction to Coastal Zone Managment. Washington D.C., Island Press.

Beletsky, D., Saylor, J.H., Schwab, D.J. (1999). "Mean Circulation in the Great Lakes."Journal of Great Lakes Research **25**(1): 78-93.

Bishop, C. T. (1990). "Historical Variation of Water Levels in Lake Erie and Michigan-Huron." Journal of Great Lakes Research **16**(3): 406-425.

Boer, G. J., Flato, G., Ramsden, D. (2000a). "A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century." Climate Dynamics **16**(6): 427-451.

Boer, G. J., Flato, G., Reader, M.C., Ramsden, D. (2000b). "A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the twentieth century." Climate Dynamics **16**(6): 405-427.

Boorman, D. B., Sefton, C.E.M . (1997). "Recognizing the Uncertainty in the Quantification of the Effects of Climate Change on Hydrological Response." Climatic Change **35**: 415-434.

Booth, B. (1999a). Getting Started with ArcInfo 8. Redlands CA, USA, ESRI INC.

Booth, B. (1999b). Using ArcGIS 3D Analyst. Redlands CA, USA, ESRI INC.

Bredin, J. (2002). Personal Communication

Brinkmann, W. A. R. (2000). "Causes of variability in monthly Great Lakes water supplies and lake levels." Climate Research **15**: 151-160.

Brown, L. (1991). Panels for Oliphant Fen Boardwalk. Owen Sound, Ontario, Owen Sound Field Naturalists.

Brown, L. (2002). Personal Communication

Bruce, J. P. (1984). "Great Lakes levels and flows: past and future." Journal of Great Lakes Research **10**: 126-134.

Burton, I. (1997). "Vulnerability and Adaptive Response in the Context of Climate and Climate Change." Climatic Change **36**: 185-196.

Burton, T. (1985). The Effects of Water Level Fluctuations on Great Lakes Coastal Marshes. Coastal Wetlands. P. H.H., F.H., D'Itri. East Lansing, Michigan, Lewis Publishers: 3-14.

Busch, W. D., Lewish L.M. (1984). Responses of Wetland Vegetation to Water Level Variations in Lake Ontario. Third Conference on Lake and Reservoir Management, Washington D.C., U.S. Environmental Protectional Agency.

Canadian Hydrographic Service (2002). Bathymetry Data Set Metadata.

Canadian Hydrographic Service (2003). Vertical datums and water levels. Source: http://www.chswww.bur.defo.ca/danp/datums_e.html

Carrara, A., Bitelli, G., Carla, R. (1997). "Comparison of techniques for generating digital terrain models from contour lines." International Journal of Geographic Information Systems **11**(5): 451-473.

Centre for Topographic Information (2002). CanImage Standards and Specifications. Sherbrooke, Quebec, NRCAN.

Changnon, S. A. (1989). Changes in climate and levels of Lake Michigan-Huron and impacts and adjustments at Chicago. Sixth Conference on Applied Climatology, Charleston, S. Carolina, American Meteorological Society.

Chao, P. (1999). "Great Lakes Water Resources: Climate Change Impact Analysis with Transient GCM Scenarios." Journal of the American Water Resources Association **35**(6): 1499-1507.

Clair, T. A. (1998). "Canadian Freshwater Wetlands and Climate Change." Climatic Change **40**: 163-165.

Clarke, K. C. (1999). Getting Started with Geographic Information Systems. Upper Saddle River, NJ, Prentice-Hall, Inc.

Cohen, S. J. (1986). "Impacts of CO2 Induced Climatic Change on Water Resources in the Great Lakes Basin." Climatic Change **8**: 135-153.

Colbern, T. E. (1990). Great Lakes: Great Legacy, The Institute for Research on Public Policy.

Congalton, R. G., Green, K. (1995). The ABCs of GIS: An Introduction to Geographic Information Systems. Wetland and Environmental Applications of GIS. J. M. John G. Lyon, Lewis Publishers.

Croley, T. E. (1990). "Laurentian Great Lakes Double-CO2 Climate Change Hydrological Impacts." Climatic Change **17**: 27-47.

Croley, T. E., Quinn F.H., Kunkel, K.E., Changnon, S.A. (1998). "Great Lakes Hydrology under Transposed Climates." Climatic Change **38**: 405-433.

Cunningham, D. (2000). Fishing Islands, QAYAQ.
Source: http://www.geocities.com/Yosemite/Gorge/4657/Autumn00.html

De Loe, R., Kreutzwiser, R (2000). "Climate Variability, Climate Change and Water Resources Management in the Great Lakes." Climatic Change **45**: 163-179.

DeMers, M. N. (2002). GIS Modeling in Raster, John Wiley & Sons, INC.

Drake, F. (2000). Global Warming - The Science of Climate Change. London, Arnold.

Eatherall, A. (1997). "Modelling Climate Change Impacts on Ecosystems using Linked Models and a GIS." Climatic Change **35**: 17-34.

Eichenlaub, V. (1979). Weather and Climate of the Great Lakes Region. Notre Dame, Indiana, The University of Notre Dame Press.

Environment Canada (1994). Modelling the Global Climate System. Downsview, Ontario.

Environment Canada (2001a). Great Lakes Fact Sheet: Putting an Economic Value on Wetlands - Concepts, Methods and Considerations.

Environment Canada (2001b). Water Levels Fact Sheet.
Source: http://www.on.ec.gc.ca/glimr/intro-e.html

Environment Canada (2002a). Canadian Climate Normals 1971-2000.

Environment Canada (2002b). Climate Change Overview - Factors affecting global climate.
Source: http://www.ec.gc.ca/climate/overview_factors-e.html

Environment Canada (2002c). Climate Trends and Variations Bulletin (Summer)

Environment Canada (2002d). Great Lakes Fact Sheet: Great Lakes Coastal Wetlands - Science and Conservation.

Environment Canada (2002e). What is Climate Change?
Source: http://www.climatechange.gc.ca/english/issues/what_is/index.shtml

Environment Canada (2002f). Where Lands Meets Water: Understanding Wetlands of the Great Lakes. Toronto, ON, Environment Canada: 72.

Environment Canada and U.S. Environmental Protection Agency (1995). Great Lakes Atlas.

ESRI INC. (1995). Understanding GIS - The ARC/INFO Method. Redlands CA, USA, ESRI INC.

Federation of Ontario Naturalists, D. o. A. G., Ryerson Polytechnical Institute (1982). Wetlands Research in Ontario. The Ontario Wetlands Conference, Ryerson Polytechnical Institute, Toronto, Ontario, Ryerson Polytechnical Institute.

Findlay et al, (2002). Canadian National and Regional Annual Temperature and Precipitation Departures. Trend's 93 and Climate Trends and Variations Bulletin.

Finnell, E. (2002). Lake Huron the Lake in the Middle, Office of the Great Lakes, Michigan Department of Environmental Quality.

Flato, G. M., Boer G.J., Lee, W.G., McFarlane N.A., Ramsden, D., Reader, M.C., Weaver, A.J. (2000). "The Canadian Centre for Climate Modeling and Analysis global coupled model and its climate." Climate Dynamics **16**(6): 451-469.

Frederick, K. D., Major, D.C. (1997). "Climate Change and water resources." Climatic Change **37**: 7-23.

Geis, J. W. (1985). Environmental Influences on the Distribution and Composition of wetlands in the Great Lakes Basin. Coastal Wetlands. F. H. D. I. H.H. Prince, Lewish Publishers INC.

GLERL (2004). Lake Michigan-Huron Water Levels in Metres.
Source: http://www.glerl.noaa.gov/data/now/wlevels/plot/Michigan-Huron.png

Gorman, L., Morang, A., Larson, R. (1998). "Monitoring the coastal environment; part IV: Mapping, shoreline changes, and bathymetric analysis." Journal of Coastal Research **14**: 61-92.

Gottgrens, J. F., Swartz, B.P., Kroll, R.W., and Eboch, M. (1998). "Long-term GIS-based records of habitat change in a Lake Erie coastal marsh." Wetlands Ecology and Management **6**: 5-17.

Government of Canada and the USEPA (1995). Great Lakes Atlas.

Growley, T. J., North, G.R. (1991). Paleoclimatology. New York, Oxford University Press.

Hardy, P. (1982). Coastal Wetlands: Managing a Fluctuating Resource. The Ontario Wetlands Conference, Toronto, Department of Applied Geography Ryerson Polytechnical Institute.

Hartmann, H. C. (1990). "Climate Change Impacts on Laurentian Great Lakes Levels." Climatic Change **17**: 49-67.

HCCD (2002). Historical Canadian Climate Database. Climate Monitoring and Data Interpretation Division, Climate Research Branch, Meteorological Service of Canada. Version December 2002.
Source: http://www.cccma.bc.ec.gc.ca/hccd/

International Great Lakes Levels Board (1973). Regulation of Great Lakes Water Levels Report to the International Joint Commission.

International Joint Commission (1978). Great Lakes Water Quality Agreement of 1978.

IPCC (1995). IPCC Second Assessment - Climate Change 1995. A Report of the Intergovernmental Panel on Climate Change.

IPCC (2001a). Summary for Policy Makers: A Report of Working Group 1 of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change.

IPCC (2001b) Scientific Basis. A Report of Working Group 1 of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change.

Johns, T., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F.B., Senior, C.A., Tett, S.F.B., Wood, R.A. (1997). "The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation." Climate Dynamics **13**: 103-134.

Jones, P. D., Moberg, A. (2003). "Hemisphere and large-scale surface air temperature variations: An extensive revision and an update to 2001." Journal of Climate, **16:** 206-223.

Jones, P.D., New, M., Parker, D.E., Martin, S. and Rigor, I.G. (1999). "Surface air temperature and its changes over the past 150 years." Reviews of Geophysics, **37**: 173-199.

Keddy, P. A., Reznick, A.A. (1985). Vegetation Dynamics, Buried Seeds, and Water Level Fluctuations on the Shorelines of the Great Lakes. Coastal Wetlands. F. H. D. I. H.H. Prince. Lewish Publishers INC.

Keddy, P. A. (2000). Wetland Ecology - Principles and Conservation. Cambridge, Cambridge University Press.

King, D. L. (1985). Nutrient Cycling by Wetlands and Possible Effects of Water Levels. Coastal Wetlands. F. H. D. I. H.H. Prince, Lewish Publishers INC.

Klein, R. J. T., Nicholls R.J., Mimura, N. (1999). "Coastal Adaptation to Climate Change: Can the IPCC Technical Guidelines be Applied?" Mitigation and Adaptation Strategies for Global Change **4**: 239-252.

Kling, G., et al, (2003). Confronting Climate Change in the Great Lakes Region.

Kunkel, K. E., Changnon, S.A., Croley II, T.E., Quinn, F.H. (1998). "Transposed Climates for Study of Water Supply Variability on the Laurentian Great Lakes." Climatic Change **38**: 387-404.

Lake Huron Centre for Coastal Conservation (1999). What are the Possibilities? Projected Climate Change Scenarios for the Lake Huron Region. Lake Huron and Climate Change, May Issue.

Lavender, B., J.V. Smith, G. Koshida, L.D. Morstch, eds. (1998). Binational Great lakes St. Lawrence Basin Climate Change and Hydrologic Scenarios Report. Toronto, Environment Canada.

Lawrence, P. (1995). "Development of Great Lakes shoreline management plans by Ontario conservation authorities." Ocean & Coastal Management **26**(3): 205-223.

Lawrence, P. (1997a). "Integrated coastal zone management and the Great Lakes." Land Use Policy **14**(2): 119-136.

Lawrence, P. (1997b). Linking Geomorphology and Ecosystem Management to Improve Decision-Making on Great Lakes Shoreline Flooding and Erosion Hazards. Canadian Coastal Conference.

Lawrence, P. (1998). "Ontario-Great Lakes Shoreline Management: An Update." Coastal Management **26**: 93-104.

Lee, D., Moulton, R., Hibner, B.A. (1996). Climate Change Impacts on Western Lake Erie, Detroit River, and Lake St. Clair Water Levels, Environment Canada and the Great Lakes Environmental Research Laboratory.

Lenters, J. D. (2001). "Long-term Trends in the Seasonal Cycle of Great Lakes Water Levels." Journal of Great Lakes Research 27(3): 342-353.

Liston, C. R., Chubb, S. (1985). Relationships of Water Level Fluctuations and Fish. Coastal Wetlands. H. H. Prince, D'Itri F.M., Lewish Publishers, INC.

Lofgren, B.M. (2003). "A model in simulation of the climate and hydrology of the Great Lakes Basin." Climate Dynamic, submitted.

Lofgren, B. M., F.H. Quinn, A.H. Clites, R.A. Assel, A.J. Eberhardt, and C.L. Luukkonen (2002). "Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs." Journal of Great Lakes Research **28**: 537-554.

Lyon, J. G., Adkins, K.F (1995). Use of GIS for Wetland Identification, The St. Clair Flats, Michigan. Wetland and Environmental Applications of GIS. J. M. John G. Lyon, Lewis Publishers.

Maciver, D. C., Dallmeier F. (2000). "Adaptation to Climate Change and Variability: Adpative Management." Environmental Monitoring and Assessment **61**: 1-8.

Magnuson, J. J., Webster, K.E., Assel, R.A., Bowser, C.J., Dillon, P.J., Eaton, J.G, Evans, H.E., Fee, E.J., Hall, R.I., Mortsch, L.R., Schindler, D.W., Quinn, F.H. (1997). "Potential Effects of Climate Changes on Aquatic Systems: Laurentian Great Lakes and Precambrian Shield Region." Hydrological Processes **11**: 825-871.

Mann, M.E., Bradley, R.S. and Hughes, M.K. (1999). Northern Hemisphere temperatures during the past millennium: Influences, uncertainties and limitations. Geophysics Research Letters. **26**: 759-762.

McCormick, M. J., Fahnenstiel, G.L. (1999). "Recent climate trends in nearshore water temperatures in the St. Lawrence Great Lakes." Limnology & Oceanographer **44**(3): 530-540.

McKenzie, M. (2002). Personal Communication.

Meadows, G. A., Meadows, L.A., Wood, W.L., Hubertz, J.M., Perlin, M. (1997). "The Relationship between Great Lakes Water Levels, Wave Energies, and Shoreline Damage." Bulletin of the American Meteorological Society **78**(4): 675-683.

Michigan Office of the Great Lakes (2002). Draft LHIAP 2002: On-going Restoration Efforts and Action Plan. Lansing, Department of Environmental Quality: 7.

Middleton, B. (1999). Wetland Restoration - Flood Pulsing and Disturbance Dynamics, John Wiley & Sons Inc.

Milne, J. A., Sear, D.A. (1997). "Modelling river channel topography using GIS." International Journal of Geographic Information Systems **11**(5): 499-519.

Milwaukee Journal Sentinel (2000). "Global warming may take Great Lakes gulp" Source: http://www.climateark.org/articles/2000/2nd/glwarmma.htm

Mistch, W. L. (1992). "Combing Ecosystem and Landscape Approaches to Great Lakes Wetlands." Journal of Great Lakes Research **18**(4): 552-570.

Morstch, L. D. (1998). "Assessing the Impact of Climate Change on the Great Lakes Shoreline Wetlands." Climatic Change **40**: 391-416.

Morstch, L. D., Hengeveld, H., Lister, M., Lofgren, B., Quinn, F., Sivitzky, M., and Wenger, L. (2000). "Climate Change impacts on the Hydrology of the Great Lakes - St. Lawrence Basin." Canadian Water Resources Journal **25**(2): 153-179.

Morstch, L. D., Quinn F.H. (1996). "Climate change scenarios for Great Lakes ecosystem studies." Limnology & Oceanographer **41**(5): 903-911.

Morstch, L. D., Quinn F.H. (1997). Adapting to Climate Change and Variability in the Great Lakes-St. Lawrence Basin, Toronto, Ontario, Canada, Environmental Adaptation Research Group (EARG), Environment Canada.

Moulton, R. (2002). Lake Huron historical water level record data.

National Wetlands Working Group (1988). Wetlands of Canada. Ottawa, Ontario, Montreal Quebec, Sustainable Development Branch, Environment Canada, Polyscience Publications Inc.

Natural Resouces Canada (2002). Climate Change Impacts and Adaptation: A Canadian Perspective - Water Resources.

Natural Resources Canada (2003). NTS Metadata

Nicholls, R. J., Hoozemans, F.M.J., Marchand, M. (1999). "Increased flood risk and wetland losses due to global sea-level rise: regional and global analyses." Global Environmental Change **9**: 69-87.

NOAA, 2003. Climatography of the United States No. 81 Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1971-2000.

NOAA-GLERL (2002).
Source: http://www.glerl.noaa.gov

O'Brien, M., Valverde, H., Trembanis, A., Haddad, T. (1999). "Summary of Beach Nurishment Activity Along the Great Lakes' Shoreline 1955-1996." Journal of Coastal Research **15**(1): 206-219.

Palutikof, J. (2003). CRU Information Sheet no. 1: Global Temperature Recod, Climate Research Unit.

Pethic, J. (1993). "Shoreline adjustments and coastal management: physical and biological prowesses under accelerated sea-level rise." The Geographic Journal **159**(2): 162-168.

Quinn, F. H. (2002a). "Secular Changes in Great Lakes Water Level Seasonal Cycles." Journal of Great Lakes Research **28**(3): 451-465.

Quinn, F. H., Assel, R.A., Sillinger, C.E. (2002b). Hydro-Climatic Factors and Socioeconomic Impacts of the Recent Record Drop in Laurentian Great Lakes Water Levels. 13th Symposium on Global Change and Climate Variations, Orlando, Florida.

Ramraj, R. (1994). "The WRDA of 1986: Background and Beneficial Use of Dredged Material with Particular Reference to the Great Lakes." Journal of Coastal Research **10**(1): 30-38.

Reinelt, L. E., Velikanje, J., Bell, E.J. (1991). "Development and Application of a Geographic Information System for Wetland/Watershed Analysis." Computer Environment and Urban Systems **15**: 239-251.

Royal Botanical Gardens (2002). "Science and Conservation RBG
Source: http://www.rbg.ca/pages_sci_conserv/sci_conserv_proparadise.html

Sanderson, M. (1987). Implications of Climate Change for Navigation and Power Generation in the Great Lakes. Windsor, Ontario, Great Lakes Institute.

Sanderson, M. (1989). "Water Levels in the Great Lakes - Past, Present, Future." Ontario Geographer **33**: 1-21.

Schneider, S. H., Root, T.L. (1996). "Ecological implications of climate change will include surprises." Biodiversity and Conservation 5: 1109-1119.

Schwartz, R. (2001). A GIS Approach to Modelling Potential Climate Change Impacts on the Lake Huron Shoreline. Geography. Waterloo, University of Waterloo.

Scott, D. J., Parker, P.K. (1996). "Ontario Cottage: Impacts and Responses to the Great Lakes Shoreline Hazard." The Great Lakes Geographer 3(1): 53-66.

Smit, B., Burton, I, Klein, R., Wandel, J. (2000). "An Anatomy of Adaptation to Climate Change and Variability." Climatic Change 45(223-251).

Smith, J. B. (1991). "The Potential Impacts of Climate Change on the Great Lakes." Bulletin of the American Meteorological Society 72(1): 21-28.

Smith, J. B. (1997). "Setting Priorities for adapting to climate change." Global Environmental Change 7(3): 251-264.

Smith, J. B., Lavender, B., Auld, H., Broadhurst, D., Bullock, T. (1998). Adapting to Climate Variability and Change in Ontario, Environment Canada.

Smith, J. B., Pitts, G.J. (1997). Regional Climate Change Scenarios for Vulnerability and Adaptation Assessment.

Sousounis, P., Bisanz, J.M. (2002a). Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. Great Lakes Overview. Ann Arbor, Mich., University of Michigan.
Source: http://www.geo.msu.edu/glra/assessment/assessment.html

Sousounis, P. (2002b). The Potential Impacts of Global Warming on the Great Lakes Region, First National Assessment of the Potential Consequences of Climate Variability and Change.
Source: http://www.climatehotmap.org/impacts/greatlakes.html

State of the Lakes Ecosystem Conference (2000). Lake Huron Initiative Action Plan Report.

Thumerer, T., Jones, A.P., Brown, D. (2000). "A GIS based coastal management system for climate change associated flood risk assessment on the east coast of England." International Journal of Geographic Information Systems 14(3): 265-281.

Tol, R. S. J., Frankhauser, S., Smith, J.B. (1998). "The scope for adaptation to climate change: what can we learn from the impact literature." Global Environmental Change 8(2): 109-123.

Tupman, K. (2001). Understanding and Adapting to Great Lakes Water Level Changes: A Study of the Impacts of Changing Water Levels of Lake Huron on Sauble Beach, and the Sauble River Mouth. Geography and Environmental Studies. Waterloo, Wilfrid Laurier University.

Tupman, K (2002) Digital Camera Photos of Research Site and Bruce Peninsula Shoreline.

US Army Corps (2002). Dredging: Great Lakes Navigation Maintenance. Source: http://www.lrd.usace.army.mil/gl/dredge.htm

US Army Corps - Detroit Division (2003). Lake Huron Hydrograph.

US Army Corps and Great Lakes Commission (1999). Living with the Lakes - Understanding and Adapting to Great Lakes Water Level Changes.

Williams, D., Lyon, J.G. (1995). Use of Geographic Information System Database to Measure and Evaluate Wetland Changes in the St. Marys River, Michigan. Wetland and Environmental Applications in GIS. J. M. John G. Lyon, Lewis Publishers.

Wright, D. J., Goodchild, M.F. (1997). "Data from the deep: implications for the GIS community." International Journal of Geographic Information Systems **11**(6): 523-528.