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Shoreline bluff failures: A GIS assessment of susceptibility and risk for Lake Erie's north central shore (Ontario)

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Shoreline Bluff Failures: A GIS Assessment of Susceptibility and Risk for Lake Erie's North Central Shore

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In loving memory of my Grandparents:
Ivan Badger, William and Vera Robinson,
who passed away while completing my Masters Degree.

And, to Gladys Badger, who remains
as a reminder of the part they have all played
in my education, growth, and spiritual development
as we await the return of our Lord Jesus Christ.

In remembrance also of:
Michael McCormick (age 9), Dylan Just (age 9),
Nathan Just (age 11), and Jason Dean (12)
whose lives were tragically ended by a bluff failure
on the north shore of Lake Erie, August 14^{th}, 1994.

Abstract

One of the characteristic features of the north shore of Lake Erie is its steep, eroding bluffs. Combined with an increase in human presence and pressures at the shoreline, the failure of these slopes has become hazardous. Over the past two decades alone, slope failures have been responsible for millions of dollars of damage to shoreline property, as well as the deaths and near deaths of a number of individuals. Despite the seriousness of this hazard, few studies have identified specific hazard areas and their associated risk of failure along Lake Erie's north shore, and other reaches in the Great Lakes.

As a critical foundation to research described in the latter half of the thesis, this paper includes a lengthy, yet necessary, review of literature which is relevant to coastal slope failures. The nature, contributory factors, hazards and risks of coastal bluff failures are discussed, in addition to their occurrence within a global, and local context. Particular attention is given to the shorelines of the Great Lakes and Lake Erie. The literature review then examines methods of mitigating the bluff hazards and risks, including the use and benefits of Geographical Information Systems (GIS) and hazard zone mapping.

The focus of the paper is a description of GIS research recently conducted on the bluffs which line Erie's northern shore between Port Burwell and Long Point, Ontario, Canada. The study utilizes a GIS to analyse factors which contribute to the bluff failures, and ultimately, to estimate the variance in risk to these shoreline failures. Emphasis is placed upon the methods used to conduct this research, but a discussion of exploratory analysis, results, recommendations, and conclusions is also provided.

Since the hazard of bluff failures exists far beyond the borders of this study site, Lake Erie or even the Great Lakes, the methods presented in the paper will provide a useful framework for conducting similar analyses on other coastlines subject to the hazards of bluff failure. The results of the report will be used to educate the public and governing bodies of the hazards and risks along the study reach, as a means of reducing this risk, including the future loss of lives.

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List of Abbreviations

AARR	Average Annual Recession Rate
ACAO	Association of Conservation Authorities of Ontario
AS	Aqua Solutions Ltd.
CA	Conservation Authorities
CCIW	Canada Center for Inland Waters, Burlington, Ontario
CD ROM	Compact Disk Read Only Memory
CPU	Central Processing Unit
DEM	Digital Elevation Model
DEMR	Department of Energy, Mines and Resources, Canada
DTM	Digital Terrain Model
EC	Environment Canada
EOB	Edge of Bluff
ESRI	Environmental Systems Research Institute
FOC	Fisheries and Oceans Canada
GIS	Geographical Information System
GLBC	Great Lakes Basin Commission
GLSDS	Great Lakes Shore Damage Survey, Canada-Ontario
HDD	Hard Disk Drive
ICZM	Integrated Coastal Zone Management
IDNDR	International Decade for Natural Disaster Reduction
IJC	International Joint Commission
LPRCA	Long Point Region Conservation Authority
MCE	Multiple Criteria Evaluation Module
MTRCA	Metropolitan Toronto and Region Conservation Authority
NTS	National Topographic Series maps
NWRI	National Water Research Institute
OBM	Ontario Base Maps
OGS	Ontario Geological Survey

OMNR	Ontario Ministry of Natural Resources
OMOE	Ontario Ministry of Environment
OMOEE	Ontario Ministry of Environment and Energy
OMCCR	Ontario Ministry of Citizenship, Culture and Recreation
PC	Personal Computer
PCM	Pairwise Comparison Matrix
RAM	Random Access Memory
SMP	Shoreline Management Plans
TFASEI	Task Force on Available Shore Erosion Information on the Great Lakes-St. Lawrence System
TIN	Triangulated Irregular Network
TL	Terraprobe Ltd.
UCU	Unique Condition Unit
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTM	Universal Transverse Mercator coordinates
UW	University of Waterloo, Waterloo, Ontario, Canada
UWO	University of Western Ontario
WCMP	Wisconsin Coastal Management Program
WLC	Weighted Linear Combination
WLU	Wilfrid Laurier University, Waterloo, Ontario, Canada

Measurements:

Gb	Gigabytes
km	kilometers
km^2	square kilometers
m	meters
m^2	square meters
m^3	cubic meters
masl	meters above sea level
Mb	Megabyte
MHz	Megahertz
mm	millimeters
yr/yrs	year/years

Publications:

TGGLSLS	Technical Guidelines for the Great Lakes - St. Lawrence Shoreline (OMNR 1994)
GPSS	Geotechnical Principles for Stable Slopes (TL and AS 1998)
LPRSMP	Long Point Region Shoreline Management Plan (PA, TA and PWA 1989)

CHAPTER ONE

Introduction to the Research

"Uncertainty is no excuse for ignorance, and however unthinkable the catastrophe, forecasting and planning are more rational than blind acceptance of a fate we might at least influence, if not control. Planning promotes vigilance, after all, and vigilance reduces risk." M. Monmonier (1997)

1.0 - Lake Erie, Shore Development, and Bluff Erosion

Steep, eroding bluffs characterize over 300kms of Lake Erie's northern shoreline. Stretched along the southernmost border of the province of Ontario, these coastal bluffs reach heights of over 55 meters and provide spectacular vistas of this fresh-water lake (Bemrose 1995). Not surprisingly, the wealth of Erie's natural resources and the appeal of life along its north shore has led to an increase in coastal development. Port Dover, Erieau and Port Colborne are only a couple of the numerous towns which have arisen and continue to grow along the shoreline. Large industrial and commercial establishments have also taken root, as evidenced by Ontario hydroelectric at Nanticoke, nearby Stelco steel, and the sizeable acreage of tomato greenhouses in Leamington. Erie Beach, Turkey Point, Rondeau and Long Point Provincial Park are only a few of the places that now boast cottage, vacation, and recreation areas. Meanwhile, recent development proposals, such as the Captains Cove Marina west of Long Point, testify to escalating demands for development along Erie's north shore.

The changing nature of the shoreline, however, limits its ability to accommodate human encroachment. Natural processes, such as wind, waves and running water, constantly reshape the shores of Lake Erie at normal and even low water levels. Erie's bluffs are particularly subject to modification by these physical processes, and regularly experience gradual erosion, recession, and even rapid failures. However, this phenomena is not restricted to the shores of Lake Erie. Long reaches of the Great Lakes shoreline are characterized by high unconsolidated bluffs (eg. Scarborough Bluffs near Toronto), which exhibit similar physical process and failure mechanisms. In addition, the failure of coastal bluffs and cliffs has manifested itself far beyond the local context to reaches of many of the world's coastlines, such as southern England, Australia, and western United States. Coupled with an increase in human activity, the erosion and recession of these bluffs, especially along Lake Erie, presents a serious hazard.

Over the past three decades, research and media have focussed on Erie's 'water' issues, including water quality, fluctuations in water levels, and related flooding and inundation of low-lying areas. This has largely overshadowed the 'land' issues, such as bluff failures and related land loss or human risks. Despite this focus, the erosion and collapse of these shore bluffs has cost government and local land owners billions of dollars in land losses and property damage (Foulds 1977, Kreutzwiser 1988, Keillor 1990). More tragic perhaps, is the threat which these mass movements present to human life. Bluff failures are recently responsible for the deaths and near-deaths of a number of individuals, including a young girl close to Midland, Ontario (Canadian Press, Ferris 1999), and the tragic deaths of four young boys at a park near Port Burwell in August of 1994 (Bender and Lawson 1994). Despite these 'warnings', surprisingly little has been done to investigate or estimate the hazard and risk associated with these events.

1.1 - Purpose and Objectives of the Research

As the bluffs continue to erode, and human pressures heighten along the shoreline, immediate efforts must be made to investigate the bluff hazard and to mitigate the potentially high degree of risk to those who live at, or visit the shoreline. In recognition of this problem, the purpose of this research was to:

> ***Investigate the nature of coastal bluff failures, and generate a cost-effective, time-efficient method, whereby risk associated with the bluff failures could be quantitatively evaluated, and ultimately reduced with the aid of a Geographic Information System (GIS).***

Since this research is believed to be unique, the nature of the research will necessarily be 'exploratory', and the methods will be developed and tested using a segment of shore which exhibits similarities to bluffs and human development along the Great Lakes. Research contained within this thesis has been completed with the expectation that it will, primarily, provide a useful foundation to further Great Lakes bluff hazard research. The literature review and results of this study could be used to further enrich or modify the research methods developed for this thesis, prior to its application along other reaches of the Great Lakes. The following chart summarizes the main objectives behind the research. These objectives will guide the research so that it achieves its purpose:

i) Examine the nature of slope failures (eg. types, contributing factors), particularly in a coastal context

ii) Explore the issue of coastal slope failures in a global and local context, including the Great Lakes and Lake Erie

iii) Examine previous research conducted on bluff failures, their risks and hazards, at a local and international scale

iv) Investigate the application, benefits, and drawbacks of GIS in slope stability analysis, particularly in a coastal slope context

v) Isolate a reach of Erie's north shore for an exploratory bluff study

vi) Identify processes and factors which contribute to the spatial extent and variability of the bluff failures within this reach

vii) Collect, store, prepare, analyse and present data pertaining to these factors in a GIS

viii) Generate a method with which to estimate the 'risk' to slope failure within the study area

ix) Display the results in the form of 'risk maps'

x) Recommend ways in which this information could be used to improve shoreline management plans, and to educate shoreline residents and tourists about the bluff hazards and risks

xi) Recommend ways in which the analysis could be refined and improved in anticipation of a larger scale analysis of the Great Lakes shoreline

xii) Ultimately, the analysis and information of the research will aid in the reduction of risk of shoreline slope failures

Fundamental to the purpose and objectives of this research, is the premise that both the human and the physical aspects of the bluff hazard must be examined together in order to evaluate the level of risk. Physical aspects include factors which contribute to bluff failures, the spatial variability of these factors and, in turn, the susceptibility or probability of the event occurring at any given location along the shoreline. Human aspects include the spatial occurrence, and relative worth of human elements along the shoreline. It is the human aspect of the issue which is fundamental to evaluating or estimating the effects of such an occurrence on the well-being of humans. Together, physical and human components of the hazard can be quantitatively correlated to provide a relative estimation of risk.

This research presents several problems which, until recently, have made such an inquiry a formidable task. Firstly, it requires a great wealth of spatial data which is difficult to store or update in the form of hard copy maps. The shoreline is a highly dynamic environment, and it is desirable to be able to update information at regular intervals. Secondly, and perhaps most importantly, it is difficult to quantitatively evaluate the correlation of the physical and human elements of risk using traditional manual methods, whereby a series of maps is placed one upon another in a prescribed order. Using manual methods, it is even more difficult to evaluate the correlation of these various factors in a weighted fashion.

Computers, and GIS provide a wealth of contemporary solutions and flexibility for dealing with these issues. The hardware and software which form the backbone of these systems now offer storage capacity for large data sets, powerful analytical tools, together, in a user friendly environment. For these reasons and others, a GIS is a requisite tool in this research. GIS can be used to perform data input, management, and analysis. GIS can also be used to prepare and present the final output of the analysis, primarily through a series of 'risk maps'.

Although time, costs, and data availability will limit this study to a small 'test' segment of shoreline, this exploratory study will establish a necessary and helpful framework with which to examine other shorelines susceptible to bluff failure hazards, both globally, and locally along the Great Lakes, or other international coasts. This study will also demonstrate the benefits of a GIS in coastal risk assessment, in addition to its potential role as a decision support tool for shoreline management. The results of the study could be used to alert, educate and advise the public and various managerial bodies as to the nature, location and potential risk of coastal slope failures. Information could be used to help to formulate and evaluate land-use, and shoreline management plans including the location of recreation, industrial, commercial and residential developments. Ultimately, the research has a very practical application, in that it will help contribute to a reduction of risk, including death, to coastal slope failures.

1.2 - Organization of the Paper

This introduction has provided only a brief summary of the work and research presented in this paper. The purpose, objectives, and results of the study are discussed in greater detail in the following chapters:

Chapters Two through Four provide a critical foundation to the GIS research described in the second half of the paper, by means of an extensive review of literature which is relevant to coastal slope failures and GIS applications. Chapter Two focusses on the nature and hazard of coastal slope failures, including a discussion of the dynamics of slope failures, and factors which contribute to slope instability. Chapter Two also examines coastal slope failures from the perspective of 'hazard', 'risk', and 'vulnerability'. Chapter Three follows with an examination of coastal slope failures in a global and local context. It details the nature of coastal bluff failures, and evidences the extent to which coastal failures are a hazard and risk along international and Great Lakes coastlines. Particular emphasis is placed on the purpose and benefits of this study in light of the lack of previous bluff research along Lake Erie's shoreline. Chapter Four completes the literature review by exploring the benefits and potential application of GIS in the mapping of coastal slope failure hazards and risks.

Chapters Five through Seven are the focus of the paper, and deal with objectives 'iv' through 'xi'. Chapter Four describes the initial preparation required for the GIS analysis, including study site selection and description, issues concerned with the use of GIS, and data sources. Chapter Five describes and discusses the methods used to assess the stability and risk of Erie's north-central shore bluffs. Though this paper does not focus on an intensive analysis of the results, several important, exploratory, examinations were completed and these are also described in this chapter. Finally, Chapter Seven ends the paper with conclusions from this research, and recommendations for future investigations.

CHAPTER TWO

Slope Failures at the Coast: Physical Dynamics, Hazards and Risks

> *"Good geography never asks where without also asking why. An insightful evaluation of hazard zone mapping ... demands a basic understanding of relevant physical processes."*
> M. Monmonier (1997)

2.0 - The Nature of Slope Failure

Hillslopes cover virtually the whole landscape. They are the land upon which forestry, agriculture, urban construction and other human activities must occur in harmony with the natural dynamics of slope gradation. The study of slope movements has encompassed over one hundred years of specialist work. During this time, there has been a considerable increase in the understanding of the form and processes which govern this displacement of material (Hansen M. 1984). The purpose of this chapter is to briefly outline some of this research, including the terminology and mechanics of slope failure, physical and human factors which contribute to these failures, and a classification of failure types. Coastal failures are influenced by both terrestrial and subaqueous processes. For this reason, the first half of the chapter focusses largely on terrestrial processes, as applied largely to inland slope failures, while the second half focusses more directly on coastal processes. Together, with a general discussion of hazards, risks and vulnerability near the end of the chapter, these topics flow naturally into Chapter Three which examines the gravity of coastal slope failures within both a global and local context.

2.1 - Terminology and Mechanics of Slope Failure

Geomorphologists maintain a keen interest in gradational processes on the surface of the earth, including weathering, erosion and gravity transfers. The force of gravity transfer, that is, the attraction of the earth's mass for bodies at or near the surface, is constantly pulling on all materials (Selby 1993). Material on mountain slopes, hillsides, bluffs and cliffs is often out of equilibrium with respect to the force of gravity (ie. meta-stable). In some cases, (excluding parallel retreat) this allows the various agents of erosion (moving water, ice and wind) to make slopes gentler and increasingly stable. The resulting process of bedrock, rock debris, soil, or snow and ice moving downslope is referred to as mass movement or mass wasting, and includes such loosely used terms as landslides, rockslides, debris flows, avalanches, and in some instances, ground subsidence (Crozier 1986, Plummer and McGeary 1993, Smith 1992). 'Slope failure' is another term often used in the context of mass movements. Since this term refers more directly to movement of materials down a slope, it will be used throughout this paper to describe any form of slope movement.

Hillslopes are examples of systems in which force and resistance are continually opposed. Often the equilibrium between the two is disrupted, the system becomes unbalanced, and slope movement begins. Carson and Kirkby (1972) and Bolt et al. (1977) provided detailed summaries of these forces and empirical research which has been conducted on the physical mechanics of hillslope failures. In a hillslope, the soil mantle is subject to two dominantly opposed forces: the force of gravity and the resistant force of shear strength. Figure 2.1 describes this relationship, where the effect of gravity is resolvable into two component forces, as indicated by the two thin, dark arrows. The normal force, is perpendicular to the slope, while shear force is parallel to the slope. The length of the arrows is proportional to the strength of each force. The steeper the slope, and the heavier the mass of material, the greater the shear force and the greater the tendency of the mass of material to slide (Plummer and McGeary 1993).

Shear strength, which is the frictional resistance of the slope material to movement or deformation, counteracts shear force. The length of the arrow representing shear strength in Figure 2.1 is proportional to its resistance. If shear strength is greater than the shear force, the material will not move and equilibrium in the system is maintained. If shear strength is reduced (for instance, with water) so that it is less than the shear force, the mass of material will separate from the underlying, stable part of the slope and begin movement (Plummer and McGeary 1993). In cohesive soils, this movement usually occurs along a deep-seated, subsurface shear plane where force has overcome resistance. In less-cohesive soils, the shear plane tends to be located closer to the surface (Whittow 1984). Finally, it must be recognized that failure of a slope does not necessarily resolve the imbalance between force and resistance. A slope failure can initiate or reactivate a subsequent failure upslope (retrogressive), downslope (progressive), or laterally through the transfer of forces, and loading, or unloading. This domino-like effect may manifest itself after periods of stability that have endured for hundreds or thousands of years (Jones 1992).

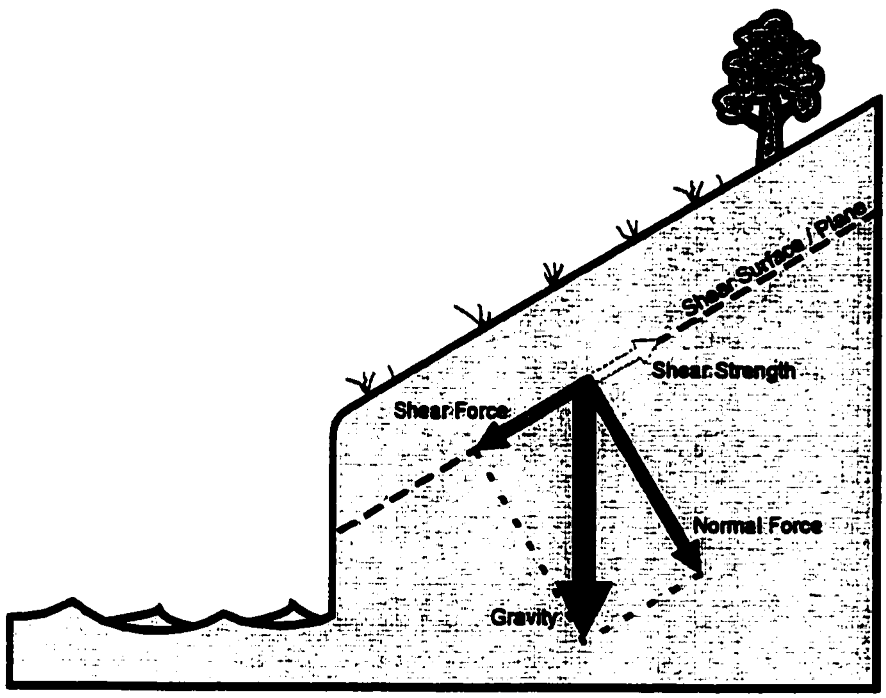


Figure 2.1: Force and resistance in slope systems (modified from Carson and Kirkby 1972; Plummer and McGeary 1993).

2.2 - Factors Contributing to Slope Failure

It is difficult to determine the type and likelihood of a slope failure event because numerous factors interact in complex and often subtle ways to destabilize slopes. Despite progress over the past century, there is still an incomplete understanding of the factors which control and trigger slope movements (Rowbotham 1995).

Among other methods, the factors responsible for slope failure can be classified by their interactions and either i) increase the shear stress, or ii) decrease the shear strength (Dunne and Leopold 1978, Goudie 1993, Selby 1993, Varnes 1984). Table 2.1 uses this scheme to summarize, though not exhaustively, some of the important factors responsible for slope destabilisation, and their mechanisms. Many of the factors listed are physical in nature, yet human factors often play an equal, if not greater, role in destabilizing slopes (Goudie 1994, Hansen A. 1984). Table 2.1 acknowledges this problem, and indicates whether the primary source or influence behind the factor may be physical or human in nature.

To discuss each of the factors listed in Table 2.1 would require space that exceeds the purpose and intent of this thesis. In order to discuss slope instability factors in a more meaningful way, factors pertinent to the research site and used in this study, will be discussed in more detail, and in the context of a coastal slope environment, in Chapter Five. For detailed descriptions of all the factors listed in Table 2.1, the reader is referred to works compiled by Bromhead (1992), Crozier (1986), Selby (1993), Varnes (1984), Alexander (1993), and Zaruba (1982), among many others.

Table 2.1: Factors which contribute to the instability of slopes, including those which increase shear stress or decrease shear strength (modified from Rowbotham 1995).

FACTORS WHICH INCREASE SHEAR STRESS			
No.	**Type**	**Major Mechanism**	**Influences**
1	Removal of Lateral Support	*i)* Stream, water (eg. lake) or glacial erosion of slope toe *ii)* Subaerial weathering, wetting, drying, frost *iii)* Slope steepness increased by failure *iv)* Quarries, pits, seawalls, removal of toe slopes (eg. road cuts)	P P P H
2	Overloading	*i)* Weight of rain, snow, talus, water bodies *ii)* Fills, waste piles, structures (eg. pools, houses, infrastructure)	P H
3	Transitory Stresses	*i)* Earthquakes, ground motions, and tilt *ii)* Vibrations from human activity (eg. traffic, blasting)	P H
4	Removal of Underlying Support	*i)* Undercutting by running water (eg. piping, wave action) *ii)* Subaerial weathering, wetting, drying, frost action *iii)* Subterranean erosion (solution of salts, limestones) *iv)* Mining activities, creation of lakes	P P P H
5	Lateral Pressure	*i)* Water in interstices *ii)* Freezing of water, salt or mineral wedging *iii)* Swelling by hydration of clay	P or H P P
6	Increase of Slope Angle	*i)* Regional tectonic tilting *ii)* Volcanic processes *iii)* Landscape alterations (eg. excavations, grading)	P P P
FACTORS WHICH DECREASE SHEAR STRENGTH			
1	Composition and Texture	*i)* Weak materials (eg. sedimentary clays) *ii)* Loosely packed materials *iii)* Smooth grain shape *iv)* Uniform grain sizes	P or H P P or H P or H
2	Physico-chemical Reactions	*i)* Cation (base) exchange *ii)* Hydration of clay *iii)* Drying of clays *iv)* Solution of cements	P P P P
3	Effects of Pore Water / Water Inputs	*i)* Buoyancy effects *ii)* Reduction of capillary tension *iii)* Viscous drag of moving water on soil grains, piping *iv)* Lubrication of shear surface, decreased material cohesion	P or H P or H P or H P or H
4	Changes in Structure	*i)* Spontaneous liquefaction *ii)* Progressive creep with reorientation of clays	P P
5	Vegetation	*i)* Removal of trees (ie. reducing normal loads, removing cohesion of tree roots, raising water tables, increased soil cracking).	H

Notes: P=Physical influences H=Human influences

2.3 - Classification of Slope Failures

A great variety of forces, processes, materials and factors can combine to destabilize a slope. Consequently, there is a large variety of slope failures that occur. Many attempts have been made to generate a generally acceptable classification of failure types (eg. Crozier 1986, Hansen M. 1984, Varnes 1984), and although a number of systems are used by geologists and engineers, none have been universally accepted. Instead, the debate continues amidst a confused, vague, and misused array of terminology and schemes (Hansen M. 1984). Some classification schemes are very complex and useful only to the specialist, while others are fairly simple and seek to distinguish between failure types using several of the following criteria: velocity and mechanisms of failure, material, mode of deformation, geometry of the moving mass, and, water content (Carson and Kirkby 1972, Selby 1993, Varnes 1958). In order to recognize and examine slope failures within a coastal context, particularly within the research site discussed later in this paper, it is helpful to set forth a general classification of slope failure types. The classification used in this study is summarized in Table 2.2. The focus of this scheme is the **i)** type of movement, but the **ii)** rate of movement, and a general indication of the **iii)** type of material is also included as a useful reference, and can also be used to help classify slopes. Though slope failures could be classified using other methods, these schemes were felt to best suit the interpretation of risk within the study area. The type of material influences the magnitude and physical size of the failure. The speed of the failure affects the ability of human elements to prepare for an event.

Table 2.2: Classification of slope failures by type, and rate of movement. Typical materials are also indicated (modified from Plummer and McGeary 1993).

TYPES OF MOVEMENT	VELOCITY OF MOVEMENT *Slowest* → Increasing Velocities → *Fastest*			
	Less than 1 cm/year	1 mm/day to 10 km/hour	1 to 8 km/hour	Velocities greater than 4 km/hour
FLOW		←	Debris Flow	→
	Creep	Earthflow	Mudflow	Debris avalanche Rock avalanche
SLIDE		← ← ←	Debris slide Slump Rockslide	→ → →
FALL				Rockfall Debris fall

Notes: - Rates listed are typical velocities for each type of movement
- Debris refers to a mix of materials (eg. soil, rocks, vegetation, or snow and ice)
- Earth refers to consolidated or unconsolidated soils

The *type of movement* depends largely on the nature of the geologic environment, including material strength, slope configuration and water content or pore water pressure (Smith 1992). Figure 2.2 illustrates these movements, including flows, slides and falls. Each of these is described at length by Varnes (1958). Bromhead (1992) also provided an excellent discussion of these three movements in a coastal context, using examples from the south coast of England and Wales. In *flows,* the downslope movement of the displaced mass takes on the form, velocity and distribution of a viscous fluid (Figure 2.2a). Slip surfaces within the moving mass are usually not visible and often there is more or less continuous internal deformation of the material rather than a narrow zone of shearing. Flows are generally short-lived and material will typically consist of high

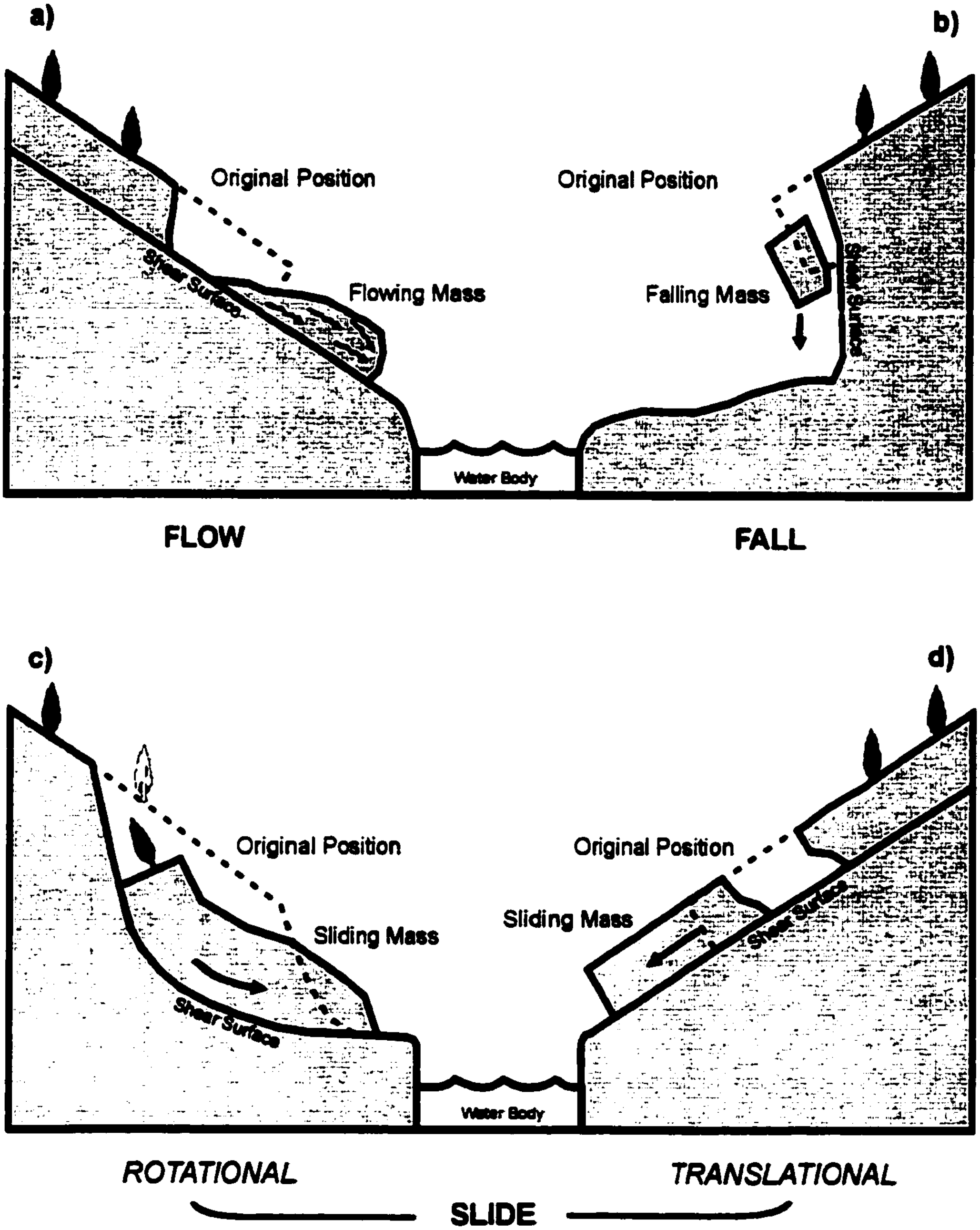


Figure 2.2a-d: Classification of coastal failure types by type of movement, including flows, falls and rotational or translational slides.

proportions of water or compressed air, in addition to fluidised soil and debris such as rock fragments, fine granular material and detritus (Dunne and Leopold 1978).

Slide means the descending mass remains relatively coherent, moving along one or more well-defined shear plane surfaces. The result is a pattern of scars and depositional features of which the most common are the two shown in Figure 2.2c and 2.2d. In a translational slide, the descending mass moves along a plane approximately parallel to the slope of the surface. A rotational or 'spoon-shaped' slide involves movement along an arcuate plane, the upper part moving downward while the lower part moves outward. The slipped material will be deposited on the slope in either a hummocky or a lobate form, depending on the water content (Varnes 1958). Slides, such as landslides, generally include both bedrock and the overlying soil (Plummer and McGeary 1993).

Finally, a *fall* occurs when material free-falls or bounces down a slope with little or no interaction between one moving unit and another (Figure 2.2b). Falls are generated on the steepest hillslope faces and occur where undercutting has transpired, or where there are discontinuities such as joints or bedding along which weathering can take place. The movement in a fall is very fast and material usually consists of rock, or of cohesive soil (Dunne and Leopold 1978).

The *type of material* forms the basis for many slope failure classifications or even sub-classifications. Material is particularly important to investigate, as it influences the type of failure movement. Long stretches of coast may exhibit several types of materials, and therefore, several different types of failure movements. Crozier (1986), and Plummer and McGeary (1993) distinguished between three main types of material from which the descending mass may originate. These are displayed in Table 2.2 and include i) bedrock (rockslides), which is a solid, cohesive material, ii) cohesive soils (landslide), which includes clays, silts, tills, and other compacted glacial material, and finally iii) non-cohesive soils (landslide) or materials such as gravel, and sand. Plummer and McGeary (1993) also included snow and ice (avalanche), as well as debris (debris slide), which may contain a mixture of the previous materials, including rock, soil, and detritus. Beyond this simple classification, some extend themselves to account for the type and size of the grain particle. Since each material exhibits physical properties which can change the way it moves upon failure, these schemes further help to explain the mechanics of a failure (Hansen M. 1984). For instance, rock in a rockslide may be classified as either granite, gneiss or sandstone, while soil in a landslide may be classified as clay, sand or loess (Bolt et al. 1977).

Finally, the *velocity of movement* describes the speed at which a slope movement develops and moves (Plummer and McGeary 1993). Velocity is an important distinguishing feature in classifying slope failures, and has a particularly large effect on the ability of humans to prepare for such an event, and the force with which the mass may impact objects in its path (Bolt et al. 1977). Table 2.2 classifies each type of movement by typical velocities, between which, there are a wide range of failure types and descriptive names. Soil creep is a very slow, continuous, downslope movement of soil or unconsolidated debris. Its rate of movement may only be a few centimetres per year, and therefore, present only a long-term hazard to infrastructure. In contrast, a rockfall involves rapid movement of a mass of bedrock from an inclined surface of weakness at the rate of many metres per second (Hansen M. 1984). The rapidity, and force of this movement makes it difficult to avoid, and requires a substantial protective structure to ensure the well-being of human elements in its path. For these reasons, the emphasis of the research in this thesis is on rapid failures, due to their increased risk to humans.

2.4 - Coastal Slope Failures

The coastal zone is a highly dynamic and regenerative ecosystem. If left alone, its natural mechanisms operate to maintain an equilibrium between all living things and the geophysical environment (Beatley et al. 1994). Carter (1988) cautioned, however, that the dynamics of the coast are "rarely simple, and it is often advantageous to adopt a holistic or systems approach for solving problems" (Carter 1988, 1). This approach was recently echoed at the 1992 United Nations Earth Summit in Brazil, when Agenda 21 recommended that the "national management of coasts be integrated in content" (Cicin-Sain 1993, 11). Integrated Coastal Zone Management (ICZM) is multi-purpose oriented, and seeks to analyse the implications of development, conflicting uses and interrelationships between physical processes and human activities (Cicin-Sain 1993).

Coastal slopes and failures are an excellent example of the complexity of coastal dynamics, and the need to examine the coast in an 'integrated' manner. Though they are influenced by many of the terrestrial processes discussed in the preceding section, they must also be examined in light of aeolian and coastal processes, in addition to human interests and activities. The purpose of this section is to discuss terminology, and important processes and influences on coastal bluffs and failures.

2.4.1 - Coastal Research and Slope Terminology

Significant research and an academic knowledge of the coastal zone did not begin until its strategic importance during World War Two (Pethick 1984). Coastal slopes exemplify this lack of coastal research, and despite the fact that most severe examples of accelerated slope instability occur at the coast (Goudie 1993), most sources only discuss slope failures from an 'inland' perspective (Grainger and Kalaugher 1988).

In an excellent overview of sea cliffs, their processes, profiles, classifications, hazards and general lack of research, Emery and Kuhn (1982) estimated that steep slopes occur along 80 percent of the world's coast, and are found in all latitudes. Even with such a wide and varied geography, most geomorphological texts devote no more than a few pages to coastal slope form and process (eg. Davis 1994, Pethick 1984). Many sources refer to coastal slopes simply as 'cliffs', but do not attempt to classify the variations in these landforms, or clearly define distinctions which they do make (eg. Emery and Kuhn 1982, Davis 1994, Sunamura 1992). Several sources, however, attempt to classify coastal slopes as either 'cliffs' or 'bluffs and earth cliffs' (Davis 1994, May 1977). This distinction is based largely on the dominant material of the slope, of which there is a wide range across the globe (Davis 1994).

The terms 'bluff' and 'cliff' are used in this paper to distinguish between different types of coastal slopes, while the term coastal slopes is used as a general reference to both bluffs, and cliffs. Davis (1994) and several dictionaries of physical geography (eg. Small and Witherick 1995) use the term 'cliff' in the context of slopes that are consolidated, and largely formed of rock. The term 'bluffs', though never clearly defined, is used in the context of unconsolidated slopes (Davis 1994, May 1977). This type of coastal slope exhibits high erosion rates (Davis 1994). Typically formed by the erosion of glacial sediments and older coastal deposits, such as dunes, their most important characteristic is a tendency towards instability and rapid change, unlike cliffs where change is relatively infrequent and particularly localized (May 1977). In most cases coastal slopes are not defined by their height, and they are simply regarded as a relative landform implicitly defined by "a marked break in slope between shore and hinterland" (Pethick 1984, 192).

The integrated, dynamic nature of sub-aerial and sub-aqueous processes on coastal slopes appears to have presented a formidable task to geomorphologists, for no complete quantitative study of the total system has yet appeared. In part, this is likely due to the difficulties which face any quantitative slope study, but also results from the combination of two quite distinct branches of geomorphology. Authors dealing with hillslopes rarely mention the special coastal case, while conversely, works on coastlines normally discuss sub-aerial processes in a few words. Trenhaile (1987), and Sunamura (1992), however, made steps to bridging this gap amidst their research into rock cliffs and coasts. Another useful overview of the subject is provided by Bromhead (1992), who often discussed the stability of slopes using examples from the south coast of England and Wales. Together, these author's works appear to be the most useful and comprehensive descriptions of coastal slope form and process. The following section provides a brief overview of the interaction, processes and factors which influence the stability of slopes within a coastal context.

2.5 - Factors Influencing Coastal Slope Failures

Carson and Kirkby (1972) suggested that slopes range between those which are i) Transport-Limited, where the rate at which weathered material is removed from the slope is slower than the rate of supply by weathering processes, and ii) Weathering-Limited, where the transport processes are sufficiently effective to remove all debris supplied by weathering. Viles and Spencer (1995) and May (1977) applied the processes of weathering and transport to the dynamics of coastal slopes. These can be summarized as follows:

> 1) **Weathering and Subaerial Processes** - which produce deposits of rock, soil and debris at the foot of the slope and reduce its upper slope
>
> 2) **Marine or Subaqueous Processes** - which are responsible for the removal of debris, the erosion of the cliff-foot, and the lowering of the foreshore

A popular temptation and mis-conception is to ascribe coastal slope processes entirely to the action of the sea (Sunamura 1992). This is not so, and instead it is a combination of sub-aerial and marine processes which create the distinctive coastal slopes (Pethick 1984). Figure 2.3 provides a graphical summary of some of the major terrestrial and subaqueous factors which influence the stability of coastal slopes. This figure also indicates several ways in which humans can contribute to bluff instability, and

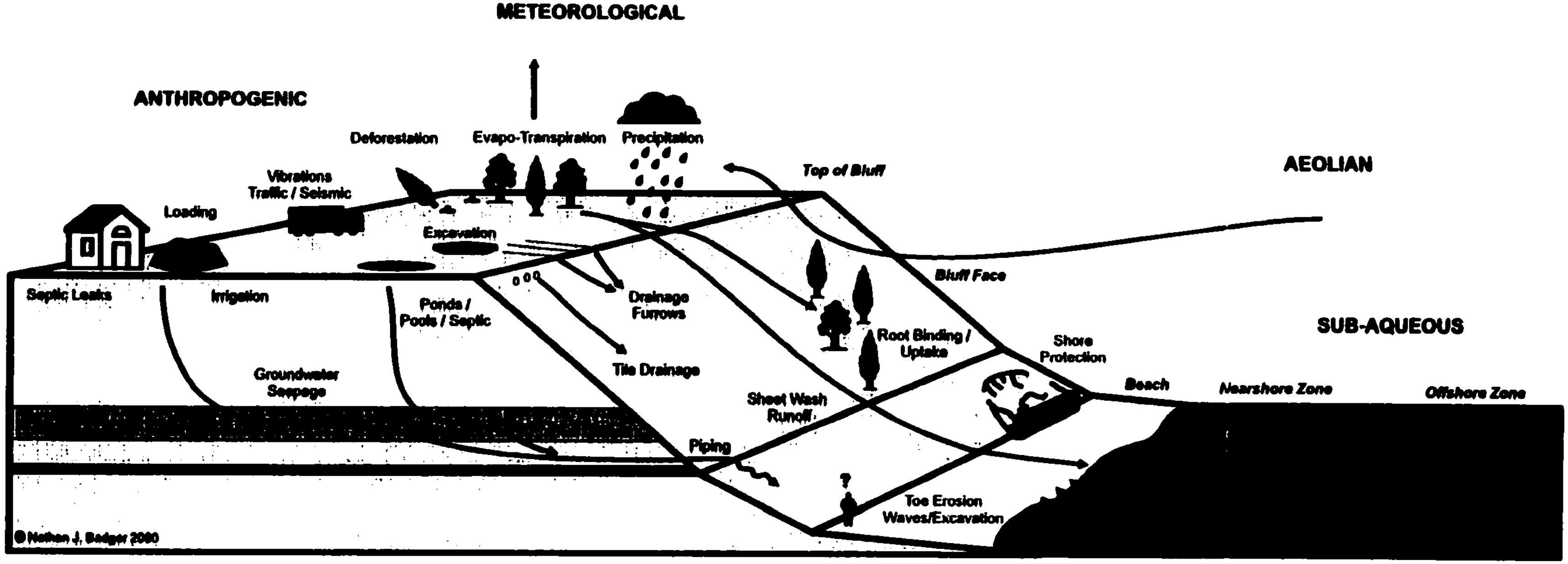


Figure 2.3: Anthropogenic, Meteorological, Aeolian and Sub-Aqueous factors which affect slope stability. Longshore currents are formed by waves striking the beach at an angle. Nearshore and offshore zones are noted. Sand is transported alongshore by the currents and in a zigzag fashion by wave uprush and backwash. Ice jams, waves, and high water levels can erode the stabilizing effect of the bluff toe (modified from Carter et al. 1989, OMNR 1994, TL and AS 1998).

is meant to summarize and display many of the processes and factors discussed throughout this chapter. All the features associated with inland slope failures, including similar range of environmental trigger mechanisms, are to be found at the coast, where the occurrence of slope failures is greatly influenced by the lithology, geologic structure, and geotechnical properties of the cliff-forming material (Grainger and Kalaugher 1988). Temporal factors, such as rain events or earthquakes, are also important, in addition to spatial factors. For example, Plant and Griggs (1991) discussed the effects of the Loma Prieta earthquake on coastal bluff failures near San Francisco, California.

In the absence of frequent climatic or tectonic trigger mechanisms for coastal failures, some researchers suggested that marine erosion, particularly of the nearshore platform and downcutting of the nearshore, are the long-term causes of the majority of coastal slope failures (Davidson-Arnott 1998, Grainger and Kalaugher 1988, Hutchinson 1986, Boyd 1981). When waves erode the base of the slope, the slope becomes unstable due to the increase in slope angle or in slope stress caused by basal erosion (Sunamura 1992). Table 2.3 summarizes a number of the dominant marine processes which act to erode the base of the cliff and transport the resulting sediment away (Clark 1979, May 1977). Marine processes can, in turn, be affected by a host of factors which include sea level change, storm waves, force of waves at the slope base, fetch, seiche, offshore relief, amount and effectiveness of cliff-foot protection (natural and human-made), and the strength of the materials which form the lower portion of the slope (Gibb 1981, May 1977, Sunamura 1992). A detailed description of marine nearshore processes is beyond the scope of this paper. For excellent overviews of coastal processes, including coastal currents, sediment transport, wave energy, and nearshore erosion, the reader is referred to works by Pethick (1984), Carter (1989), Viles and Spencer (1995), and Zenkovich (1967). Where relevant, a number of marine processes are also discussed in further detail when the GIS study site for this research is described in Chapter Five.

Table 2.3: Marine processes which influence cliff or bluff erosion, and the transport of eroded sediment (after Clark 1979, May 1977, Pethick 1984).

1. **Corrosion** - chemical (calcareous solution) weathering by salt water
2. **Attrition** - breakdown of debris formed by erosion
3. **Hydraulic action** - pressure variations by waves causing block removal
4. **Quarrying** - wave action pulls away loose rock
5. **Abrasion** - mechanical weathering whereby wave induced currents move sand and shingle against the cliff-face
6. **Bio-erosion** - includes smoothing of rock by browsing invertebrates and, fish and chemical action due to exudates from organisms.
7. **Transportation** - movement of material away from their origin through marine currents, including longshore currents in the nearshore zone, and shore normal, or offshore currents which carry material lakeward.

Very generally, marine slopes are considered to be a special case of slope development in which the removal of weathered material at the slope base is especially efficient (Young 1972), much like the effect of rivers on stream banks (Brabb 1989a). The nature of slope failures at the coast is, therefore, typically retrogressive. In many cases the capability of the marine processes to remove slope debris at the slope base is much greater than the rate of supply. Rock, debris, or soil displaced by falls, slides and flows is usually removed quickly by the sea and cannot provide stability, support, or protection at the base of the slope (Grainger and Kalaugher 1988). The slope will retreat parallel to itself, and the actual profile will depend on the structure and lithology of the slope (Pethick 1984, Viles and Spencer 1995). Resistant and homogenous materials produce the steepest slope faces and rates of slope retreat usually range from nearly zero to many metres per year. The combination of resistant rock, such as quartzite, and low to modest wave energy produces no measurable retreat. The more common range of cliff retreat is from about a millimetre per year in resistant homogenous rocks, to a metre or two per year on soft shales or the glacial materials of bluffs (Davis 1994).

Alternatively, where wave energy at the slope base is minimal, and the sub-aerial weathering processes are dominant, the supply of debris will exceed the capacity for removal, and the debris material builds up into a talus slope, or a seaward extension of the beach. In this case, the existence of a steep slope face is probably short-lived (Carson and Kirkby 1972, Davis 1994). As the talus builds up, it progressively protects the host rock whose profile develops a parabolic shape, which evolves from a vertical slope face to an angle matching the angle of repose of the talus. The actual form of the slope depends on the relative rate of supply of debris to its removal (Pethick 1984). Both of these outcomes are, however, simplistic, and on many coastal cliffs 'weathering-limited' and 'transport-limited' processes both operate and interact with one another (Viles and Spencer 1995). The result of these processes is both gradual erosion (hours, days, years) and rapid failure of the bluff or cliff material (seconds, minutes). Often it is difficult to separate gradual from rapid erosion and failure (Boyd 1981), but the difference is significant in the speed of the movement, and the impact of the material on objects within the path of movement. The difference is particularly important when human well-being is involved.

2.5.1 - Human Influence on Coastal Slope Failures

In addition to the many physical processes that act on coastal slopes, the actions of humans must also be considered (Emery and Kuhn 1982). In what he described as the "the rush to the shore", Pilkey et al. (1989, 1) regarded the intense, post World War Two development of coastal areas a major phenomena making coastal land loss and other risks an immediate concern for society. The coast serves as a lure to large numbers of people who seek recreation and relaxation, as well as industries dependant on the import of materials from overseas, the export of home produce, or the extraction of resources from the sea (White 1978). People at the shore, both permanent residents and visitors, need to be fed, housed, entertained, and often employed. The pressures exerted by humans at the coast emanates from these needs (Beatley et al. 1994).

Many of the anthropogenic factors which affect inland slope failures also affect coastal slope failures. Contributions may be minor, as in the erosion of slope faces by human shoes, or major, as in the creation of failures due to slope undercuts by construction sites (Pethick 1984). They may also include variations in the ground water table through septic leaks and irrigation, or channelization of urban or agricultural drains to slope faces (Sunamura 1992). Bird (1994) suggested that another important cause of slope failures along rocky coasts is human activity through fossil hunting, and Sunamura

(1992) and May (1977) discussed the destabilizing effects of vegetation removal when humans trample along cliff top paths. In some cases, these paths developed into deep gullies (up to one metre) which ultimately channel water to the slope face. The popularity of many coastal regions means that while there is pressure to develop locally, there is also encouragement to keep neighbouring areas accessible so that cliff-top paths and the beaches at the cliff base may be enjoyed (Grainger and Kalaugher 1988). Often these recreation or suburban residential areas are located in areas not protected from erosion, or in areas where erosion is severe due to updrift engineering projects.

Aside from these examples, many human actions "strongly affect the .... distribution of sediment already in the beach system," particularly through the disruption of natural longshore currents (Pilkey et al. 1989, 1). Engineering projects are largely responsible for this action. Harbour works, seawalls, groins, offshore breakwaters, jetties (Pilkey et al. 1989), dam construction on rivers, and beach mining (Sunamura 1992), create unintentional reductions in downdrift beach volume (Sunamura 1992). May (1977) noted that much of the coastline of southern England is now protected by these defence works. Although these structures are sometimes capable of arresting or slowing beach and bluff erosion if built properly, and at great expense (Viles and Spencer 1995, Sunamura 1992, McGowan et al. 1988), their effects are usually short-term, and in many cases these exacerbate erosion through the removal of sand from the nearshore zone (Pethick 1984). Instead, a wide beach in front of the cliff is the best natural wave-energy absorber to protect the shore (Sunamura 1992). A reduction in the volume of beach sediments decreases beach width and lowers beach level, which allows storm waves to reach the cliff and to intensify the force of assault when sand is mobilized and hurled on the cliff face. When beach material is removed or depleted, severe cliff erosion is likely to occur (Pilkey et al. 1989). In some cases, this reduction of beach sediment is countered by a further engineering project and intentional activity to halt cliff erosion is manifested through the building of a wide, artificially nourished beach in front of the cliff (Sunamura 1992). Other projects attempt to drain water from the bluffs, or redirect seepage through massive, subterranean drainage schemes (Viles and Spencer 1995).

Several summary notes can be made from the preceding discussion of coastal bluffs and cliffs. Firstly, it is apparent that coastal bluffs and cliffs are a widespread phenomenon along global coasts. The stability of these slopes is affected not only by terrestrial process, as with inland slopes, but also marine or subaqueous processes. In the wake of increased coastal development, coastal slope failures present a serious threat to human well-being, and efforts must be made to reduce their hazards and risks. In light of this problem, the last section of this chapter clarifies and discusses the terms 'hazard' and 'risk' in relation to coastal slopes and human activities.

2.6 - Slope Failure as Hazard

2.6.1 - Hazards, Risks, and Related Terminology

Unfortunately, 'hazard' and other related terms, such as risk, vulnerability, and disaster, are often confused, vague or misused throughout the literature. In order to clarify the purpose, objectives, methods and findings of the research in this paper, it is important that each of these terms be clearly defined. Thus, this section clarifies important 'hazard' terms and approaches to hazards research which bear relevance within this paper.

The term 'hazard' is often used to describe phenomena, usually physical agents, in the natural environment which pose a threat to human well-being (Hewitt 1983, Smith 1992). However, although hazards described as objective agents are necessary, "they are not sufficient conditions for damage or to initiate a disaster" (Hewitt 1997, 25). Strictly speaking, a hazard does not exist unless humans, their possessions and their activities are involved (McCall 1992). Whether natural or human in origin (landslides and tsunami, verses chemical spills and riots), a hazard directly relates to human life and property. Thus, 'hazard' is used in this paper to define 'a potential event or phenomenon where humans expose themselves and increase their vulnerability to natural environmental processes to the detriment of human well-being'. This definition stresses both the natural and human aspect of a hazard. It also implies that there are two important elements to a hazard event, including: i) the probability of, or susceptibility to, the event occurring, and ii) the degree to which the event disrupts human well-being, or the 'severity' of the event. Figure 2.4 describes the theoretical relationship between the probability/susceptibility of a hazard, and the severity of a hazard.

Clearly, the severity and probability of a hazard will operate at varying scales, either quantitatively or qualitatively. Susceptibility or probability can range from zero to certainty (low to high). In the same respects, severity can also range from low to high, and since severity, theoretically, is always capable of reaching a higher level of

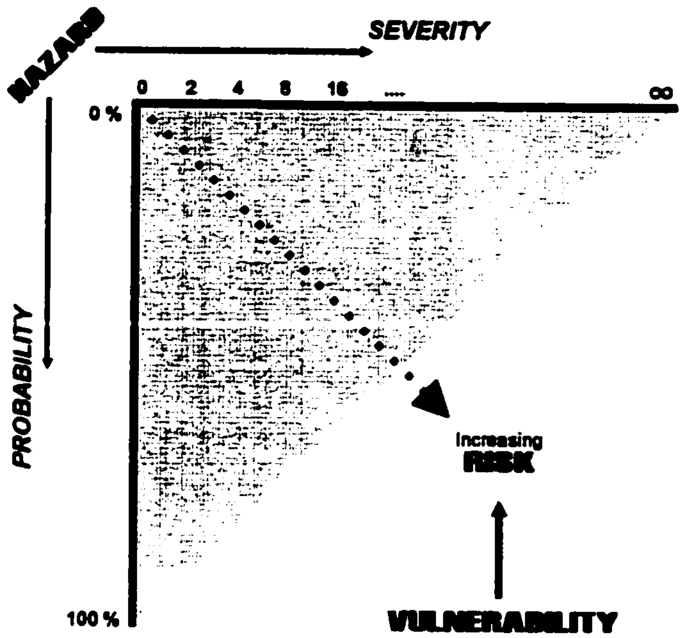


Figure 2.4: Theoretical relationships between hazard event, severity, probability, vulnerabilty and risk (modified from Smith 1992).

magnitude, Figure 2.4 depicts this axis as having an exponential scale. Keep in mind, however, that severity and susceptibility/probability, are not always evaluated in the same manner, and are likely to change from country to country, society to society. The relative magnitude of both probability/susceptibility and severity will depend largely on the values and culture of the society at risk, in addition to the way in which the hazard is perceived, the frequency of the event, and the actual hazard process itself (Hansen A. 1984). In other words, what may be considered a disaster along the bluffs of Lake Erie, may be considered a routine event on the shores of a different country. Generally speaking, however, threats and related examples in the list below are perceived as ranging from low to high severity within the context of western society (Hansen A. 1984, Smith 1992):

1) **Hazards to the Environment**	- loss of flora, fauna, and natural amenities, pollution
2) **Hazards to Material Goods**	- structural damage, damage to vehicles, machines, land or crop loss, economic
3) **Hazards to People**	- death, injury, disease, stress

While damage to goods and the environment can be extremely costly in economic and social terms, western society normally accepts that a direct threat to life is the most serious hazard faced by humans (Smith 1992), and the above list is therefore used as the basis for evaluating 'severity' throughout this research.

Disaster is often portrayed through literature as being indiscriminate, where death or survival is a matter of luck, or where humans are passive, pathetic, or weak victims (Hewitt 1995). Careful investigation shows, rather, discriminate patterns of harm as a function of social geography, land uses, built environments, and social or cultural factors (Hewitt 1995, 1997). These issues are commonly summarized in hazards research through use of the term 'vulnerability'. In its most correct usage, vulnerability refers to "attributes of persons, or activities and aspects of a community that can serve to increase damage from given dangers" (Hewitt 1997). Though literature tends to stress the 'exposure' aspect of vulnerability, Hewitt (6 Nov. 1999) suggested that there are instead four important factors which influence vulnerability. These factors are listed below with examples, and will be discussed throughout the paper, particularly in Chapter Six. Since one of the objectives of this study is to provide people with information about coastal slope hazards, item number four is of special interest. Figure 2.4 illustrates how vulnerability, in a theoretical sense, combines with the severity and probability of a hazard to increase the degree of risk.

1) Exposure	- Located in a slope failure zone (ie. land use)
2) Weakness of Human Element	- Physical (eg. not able to run from a slope failure, or dodge a debris fall) - Structural (eg. poorly constructed building, seawall, drainage system)
3) Available Resources	- Made available to persons/society to respond or cope (eg. emergency crews, insurance)
4) Protection	- From society (eg. forecasts, access to information/education, warning signs)

Unfortunately, the term 'risk' is often taken as synonymous with a hazard event, the probability/susceptibility of a hazard event, or only the severity of the event. Instead, risk describes the relationship between all of the concepts discussed above. Although used in different senses, and with different stresses in the literature, risk is a broad term which envelops a wide range of issues, and is culturally or socially constructed (Hewitt 1997). It seeks to evaluate the interplay between various aspects of a hazard, including the probability/susceptibility of an event occurring, and the severity of its impact on human well-being. Risk, in particular, considers and evaluates the human conditions that contribute to danger, and therefore takes into account vulnerability (Hewitt 1997, Hansen A. 1984). As noted previously, Figure 2.4 describes this theoretical relationship. For example, if the natural characteristics of a bluff make it highly susceptibility to failure, and failure of the bluff is potentially life threatening, risk is assessed as being very high. Should the individual or structure located in the path of the hazard be vulnerable in any sense, the risk may be assessed even higher. Though risk is often described in qualitative terms (ie. low, medium, high), variations of Equation 2.1 (after Jones 1992, Varnes 1984) are also used to calculate the degree of risk quantitatively. This equation forms the basis of many GIS slope failure risk assessments, including one used later in this paper.

$$\boldsymbol{Rs} = \boldsymbol{E}(\boldsymbol{H} \times \boldsymbol{V}) \tag{2.1}$$

Where,
Rs = specific risk (ie. not relative, or a comparison to other areas)
E = elements at risk quantified (eg. $, #'s)
H = probability of, or susceptibility to, hazard occurrence
V = vulnerability as a proportion of the total 'E'

As a final note, several terms are also used to describe the realization of a hazard event, including disaster and catastrophe. 'Disaster', and in extreme cases, 'catastrophe', are terms used to describe events where diverse damages and a collapse of the social fabric or its safety measures occur (Hewitt 1997). Since coastal slope failures are not always associated with this degree of severity, the term 'damaging event' is also used in this paper to describe events of a lesser severity than a disaster.

2.6.2 - Slope Failures as Hazard and Risk

Slope failures, whether inland or coastal, represent an important group of environmental hazards (Smith 1992). The diversity of causes and types of slope failures, as discussed earlier, is equally matched by their spectrum in size and frequency, and the subsequent range of hazards and risks which they present. This spectrum ranges from the nuisance of having a fence slowly pulled apart by soil creep, to the very high-magnitude events which can have disastrous impacts on society (Jones 1992). While a fast-moving mudslide is more likely to be a direct threat to life than is creep, both pose an indirect threat through structural damage or destruction (Hansen A. 1984).

Surprisingly, however, slope failures continue to be under-recognised, under-estimated and not particularly feared as a major hazard. This is particularly true in a coastal context, as evidenced in Chapter Three. Jones (1992) attributed this to "human perception of a phenomenon that is diverse in character and ubiquitous in occurrence, but rarely disastrous, so that impacts are frequent, small-scale and undramatic." Individual slope failures (unless associated with other hazards such as earthquakes, storms) rarely cause sufficiently large death-tolls or economic costs to claim enough media, sensationalised, political or managerial attention. However, it is the cumulative effect of these numerous, small-to-medium sized slope movements that is often overlooked, and which is rarely appreciated (Jones 1992). Research indicates that slope failures, both inland and coastal, have caused more property and economic loss, and greater loss of human lives than any other single geological hazard (Varnes 1984). Slope failures are also the most frequent of geologic hazards, and have the largest geographic distribution (Varnes 1984, Lopez and Zinck 1991).

In their global summary of the extent and economic significance of slope failures, Brabb and Harrod (Brabb 1989b) suggest that slope failures are largely predictable and preventable using current technology and necessary land planning. In many instances of slope failure, "a little knowledge of geology, along with appropriate preventative action, could have averted destruction" (Plummer and McGeary 1993, 181). Indeed, the need to reverse the upward trend of such losses, and the belief that the technologies exist to reduce human and property losses from hazards (such as slope failures), led to the passage of a United Nation's resolution in December 1987 designating the 1990s as an International Decade for Natural Disaster Reduction (IDNDR) (Press 1989). IDNDR encourages the use of monitoring and technology to help reduce levels of risk and hazard (Hewitt 1995). Likewise, this thesis aims to provide information, obtained through technology, that will help reduce the vulnerability of humans to coastal slope failures. The use of GIS as part of this research does not in any way imply that technology is the only way in which hazards or risk can be mitigated. Instead, it suggests that GIS, and other related technology can be used as a tool to provide information that highlights the human aspect of hazard and risk. This information should be used to alter human activities, which in most cases, is the root cause of the hazard, and is fundamental to any hazards research (Hewitt 1983).

With these thoughts in mind, the following chapter takes a closer look at global and local examples of bluff and cliff research from the literature, in addition to the risks associated with these events, and their influence on human well-being.

CHAPTER THREE

Coastal Slope Failures
Hazards and Risks at a Global and Local Level

> *"It was a classic confrontation between developers who thought their project would help a city grow, and environmentalists who wanted to preserve the coastline: in the end, the issues were decided by Nature."* W. Sayre and P. Komar (1988)

3.0 - Coastal Slope Failures in a Global and Local Context

The coast is many things to many people, and our perspective on it ranges widely depending on where and how we live, work, and recreate. Often defined as the dynamic interface between air, land and sea (Carter 1988, Viles and Spencer 1995), the coastal zone varies in width and usually changes with time. As a whole, it represents a broad spectrum of environments for the people and natural fauna and flora that inhabit it.

In the last one and a half centuries, the coast has become an area with a very high concentration of human habitation and employment (Barnes 1977). Unfortunately, human presence does not meld well with the highly dynamic nature of the coast, and in some instances the combination proves disastrous. Urban infrastructure and human lives are often lured to locate in the very path of land subsidence, beach erosion, wave attack, floods, tsunami, hurricanes, and other powerful coastal phenomena (White 1978).

Slope failures are another serious coastal hazard. Chapter Three builds on Chapter Two's discussion of coastal slope failures, hazards, and risks, to examine the extent to which these events exist and have been researched along the world's coasts. Several tables summarize research and reports discovered in the literature, including the nature and location of the event, contributory human and physical factors, damages, and attempts to mitigate the hazards and risks. The structure of this chapter is telescopic, in that the first portion of the chapter discusses coastal slope failures in a broad global context, while the second half focusses on their occurrence along the Great Lakes, and in particular, Lake Erie. Chapter Three is an integral part of this thesis, as it highlights the extent to which coastal slope failures threaten human well-being at a global scale, as well as the lack of research and attempts to mitigate these hazards. Together, this information justifies and guides the research and application of GIS to coastal slope failure mitigation, as discussed in Chapters Four through Five.

3.1 - Coastal Slope Failures: Hazard, Risk and Mitigation in a Global Context

In their discussion of sea cliffs, Emery and Kuhn (1982) noted that coastal slope failures are a global issue, and yet, their physical nature, attendant risks, and methods of mitigation are rarely discussed or compared between regions. This section examines coastal slope failures from a global perspective as evidence of the severity of the problem through its wide-ranging geography. It should be noted that much of the literature tends to discuss bluff failures in terms of long-term erosion, and it is often difficult to separate these accounts from rapid failures. This chapter attempts to focus on reports where rapid, large-scale failures occurred, have been researched, and are a threat to human well-being. Although the cumulative effect of long-term erosion is often as costly as large, rapid, failures, and gradual erosion is often accompanied by episodic, large-scale failures (Griggs 1994), this paper maintains the position that large, rapid, failures present a greater risk to humans due to their speed, mass, and potential impact. It is also important to note that this chapter focusses almost entirely on literature available within the public domain. Unpublished government and consultant documents were not examined, though they would undoubtedly provide a wealth of data and information for future research.

A broad overview of coastal slope failures is provided by Sunamura (1992) and Viles and Spencer (1995) using a number of examples from around the world. Sunamura (1992) focussed on a discussion of physical factors and engineered solutions, and tended to ignore the human risks, while Viles and Spencer (1995) discussed similar strategies, but helped to balance the picture by noting the use of management plans and policies as an alternative approach to hazard mitigation. Although his book is oriented towards slope failures in general, Bromhead (1992) provided an excellent discussion of large-scale coastal slope failures. His discourse is unique, in that many examples are taken from the south coast of England and Wales, and examples often include a review of human risks and anthropogenic factors in slope instability. Two other sources lend to a broad discussion of coastal slope failure hazards. Bird and Rosengren (1987) reported on the difficulty in mitigating risk of coastal slope failures due to the varied values of shoreline owners and the cost of legal battles, while May (1977) provided a unique discussion of earth cliffs and their failures from an ecological management perspective.

Despite these limited overviews, however, information tends to be rather scattered in various reports. Table 3.1 summarizes twenty-one of these reports from around the world, excluding occurrences along the Great Lakes, which will be dealt with later in this chapter. Information in the table was obtained directly from journal articles, newspaper articles, reports, and several books. Information regarding coastal slope failures is categorized by its location, date, spatial extent, slope material, type of failure, human and physical factors which contributed to the event, the severity or consequences of the event, and finally, efforts made to mitigate future failures.

What is particularly striking is the recency of these reports. The majority were compiled within the past decade, while the remainder, with the exception of one, fit into the past two decades. This is assumed to be the result of increased population pressure, affluence, development at the coast, a growing awareness of coastal and slope failure dynamics, and perhaps, a growing recognition that humans contribute to these hazards, and are increasingly affected by them. Another striking observation is the global extent of coastal slope failure hazards. Literature makes it clear that this problem exists beyond the scope of Lake Erie and the Great Lakes, and that risks vary widely in their nature.

The majority of reported events occurred along the coasts of the United Kingdom, the United States, New Zealand, and Australia. The exception to this is the occurrence of slope failures along the Black Sea and Bosporus coasts of Turkey (Onalp 1988).

Table 3.1: Global inventory of coastal slope failures, their severity, and other human implications

LOCATION	DATE	EXTENT OF EROSION/ DAMAGE	MATERIAL: CONSOLIDATED UNCONSOLIDATED	TYPE OF FAILURE	PHYSICAL FACTORS	HUMAN FACTORS	DAMAGE	MITIGATION DIRECT / INDIRECT	REPORT
AUSTRALIA (West) ***Cowarump National Park, Perth***	1996	· localised event	Consolidated	Fall	· cliff collapse	school class visiting base of cliff and surf beach	· 4 adults, 5 children killed	Not Stated	Reuters Information Service 1996
AUSTRALIA (South) ***Beaumaris Cliffs, Philip Bay, Melbourne***	1990	· localized event, but also scattered along 2km	Consolidated · stratified sandstone	Fall	· widening of joint planes by tree root penetration · seaward dip of bedding planes, intersecting vertical joints	· father and 3yr old son sitting at bluff base · minimal hazard perception · possible ground vibrations from overhead highway traffic · failure to erect warning signs in a known hazard area	· 3 year old boy killed	Indirect · large number of warning signs posted · fences installed at slope top and base in certain segments · controversial legal battles over hazard vs natural science area	Bird 1994
AUSTRALIA (East) ***London Bridge, Victoria***	1990	· localised event	Consolidated	Fall	· arch collapse	· 2 adults walked seaward across natural arch	· 2 people stranded on seaward extent of arch, near miss of death	Not Stated	Bird 1994
ENGLAND (South) ***Folkestone Warren***	1915 to 1950 · one large in 1915	· many failures	Consolidated/ Unconsolidated · thick bed of chalk over impermeable Gault Clay and Folkestone Sand beds	Rotational Slides · large, deep seated	· material and stratigraphy · water seepage	· construction of a harbour breakwater with progressive extensions · blocked downdrift movement of shingle and depleted beach sediment · undercutting and over-steepening of slopes by wave attack	· Folkestone Rail Line and train derailment	Direct · weighting and protection of slip toe with concrete · drainage works to reduce ground-water pressure	Goudie 1993, Sunamura 1992
ENGLAND (South) ***Barton-on-Sea***	1959 to Present	· many, sometimes multiple failures along 1,500m of coast	Consolidated/ Unconsolidated ·brick earth, gravels, Barton sand/silt, Barton clay, sandbeds	Slides, Falls, Flows	· water seepage, toe erosion, material/stratigraphy, geomorphology · shore orientation	· shore protection blocked downdrift movement of sediment, depleted beach sediment · failled timber groynes and revetments	· redential areas threatened	Direct · beach nourishment · artificial rock headlands · water drainage · reinstallation of groynes	Fleming and Summers (1986)
ENGLAND (South-East) ***Downderry, Cornwall***	1959 to Present	· many failures over 2km of shoreline · some up to 10m from bluff edge	Consolidated/ Unconsolidated · sand, clay, slate · poorly sorted, but partially stratified	Rotational Slides, Flows	· sea level rises · trigger events such as rain · ground water seepage · cliff undercutting by storms, waves · frost fracturing	· shore protection blocked downdrift sediment · over-loading of cliff top by house extensions, continued development · roof drains, soakaways, channelling · general disregard for active erosion	· cliff top gardens lost, destruction of houses, property loss ·road damage	Direct / Indirect · toe protection through rubble, gabions, concrete, mason walls · relocation, planning policies · vegetation of slopes	Coard et al. (1987)
ENGLAND (South) ***Lulworth Cove***	1977	· localized event, hundreds of tonnes of material	Consolidated/ Unconsolidated · rock, shale, clay	Fall	· heavy rainfall	school class doing a fossil dig	· 2 students, 1 teacher killed	Indirect · signs posted prior to event · subsequent attempts to illegalize fossil mining on Dover Cliffs	Bird 1994

LOCATION	DATE	EXTENT OF EROSION/ DAMAGE	MATERIAL (C) (U) CONSOLIDATED UNCONSOLIDATED	TYPE OF FAILURE	PHYSICAL FACTORS	HUMAN FACTORS	DAMAGE	MITIGATION DIRECT/INDIRECT	REPORT
ENGLAND (East) *Covehithe*	1990	· localized event	Not Stated	Fall	· cliff edge collapse	· mother and 7 yr old son crawling along cliff edge	· mother and 7 year old son trapped at bluff base, near death	Not Stated	Bird 1994
ENGLAND (South) *Ventnor, Isle of Wight*	Ongoing · one large in 1960-61	· many small and large below a 1.5km by 12km failure scarp	Consolidated/ Unconsolidated · Gault Clay, underlain by sandstones and overlain by sandstones and chalk	Falls · along rear scarp Rotational Slides · multiple below scarp	· material and stratigraphy · seaward dip of strata · high annual average rain	· failed harbour construction disrupted littoral currents and sediment supply · town built on an extensive complex of ancient landslides	· property, roads, buildings, utilities · cumulative damage 1960-1980 approx 1.5 million pounds	Direct / Indirect · surficial, non-geotechnical assessments, installation of subsurface movement monitoring devises · hazard zoning with relative probability based on geology, lithology, previous movement	Chandler and Hutchinson 1984
ENGLAND (North) *Devon, north coast*	Ongoing	· many spread along 50km	Consolidated · slate cliffs	Falls and Slides	· bedding joints, planes and faults in the slope material	· development of slope top · recreational areas at slope top and base	· degradation and loss of land, properties, footpaths, amenities · threat to lighthouse · threat to humans at slope base	Direct / Indirect · relocation of lighthouse · hazard ranking for slope top and base with recession rate, estimated recurrence of events, photo maps and cliff profiles	Grainger and Kalaugher 1988
NEW ZEALAND (North) *Waiapu County, North Island*	Ongoing	· many failures of variable size · one 520kmsq.	Consolidated · dominated by sandstone, claystone, siltstone sequences · occasional volcanic pumice and igneous outcrops	Slides, Flows	· severe waves through episodic storms · tectonic uplift of Pacific/Indian Plate · formation of updrift forelands from increase in river sediment · reactivation of old failures	· construction of coastal highways and railways · construction of seawalls disrupting nearshore sediment climate and currents · deforestation along coastal rivers	· threat to Waiapu County infrastructure, 3 towns	Indirect · 100 year hazard zones on planning photomaps · planning schemes, policies, ordinances · building permit refusals	Gibb 1981
NEW ZEALAND (North) *Western Wellington, North Island*	Ongoing · many large events in 1976	· many failures along 10km	Unconsolidated · largely sands and gravels	Slides	· growth of an updrift cuspate foreland · severe episodic storm waves	· construction of seawall disrupting nearshore sediment climate and currents · development on edge of large foredune · construction of coastal highway blocked supply of gravel which protected slope bases	· property loss up to houses · destruction of 1 house and 30 others threatened · destruction of previous seawalls	Direct / Indirect · rebuilt seawall · recommended setbacks or relocation · recommended beach nourishment programs	Gibb 1978
NEW ZEALAND, N *Waitemata Harbour*	Ongoing	· many failures along approx 60km	Consolidated/ Unconsolidated · soft, alternating sandstone and siltstone flysch deposits · topped by layer of silty clay	Falls and Translational Slides	· regularly spaced joints and blocks · fault and bedding planes · low to high seaward dip of rock	· population pressures along coast · development on slope top ·	· undermined foundations, houses, decks and pools · frequent close calls to humans at slope base	Direct / Indirect · hazard zone maps · setbacks up to 23ft based on geology · designated walkways on slope top	Moon and Healy 1994

LOCATION	DATE	EXTENT OF EROSION/ DAMAGE	MATERIAL (C) (U) CONSOLIDATED UNCONSOLIDATED	TYPE OF FAILURE	PHYSICAL FACTORS	HUMAN FACTORS	DAMAGE	MITIGATION DIRECT/INDIRECT	REPORT
TURKEY (NorthEast) ***Bosphorus and Black Sea Coast***	Ongoing	· many small and large failures	Consolidated/ Unconsolidated · western half is sedimentary, eastern and northeastern is volcanic rock · both areas overlain by thick gravel, sands and clays	Falls and Translational or Rotational Slides	· excessive pore/joint water pressure · thickening over burden · reactivation of old failures · intense rain events · sub-tropical weathering climate	· slope toe cuts for 1960s highway construction · slope deforestation	· social and economic disruption in heavily populated and cultivated area	Direct / Indirect · geotechnical studies at selected sites	Onalp 1988
UNITED STATES (West) ***Puget Sound and Seattle, Washington***	1972	· many failures along perimeter of Puget Sound	Unconsolidated · glacial deposits of Vashion tills and Esperance Sand beds over Lawton Clay beds, and vice versa	Rotational Slides · deep and shallow	· slope material and lithology · high annual rainfall, intense episodic rain events · rise in water table · increase in infiltration capacity through soil frost and loosened soil structure · aquiclude redirects percolated water · upward fluid pressure of water trapped between aquicludes · slope base erosion by waves	· diversion of drainage water onto slopes, hillside excavation, artificial fill over impermeable deposits · failure of retaining walls	· millions of dollars to public and private property, buildings and homes	Direct / Indirect · geologic and geotechnical assessments	Dunne and Leopold 1978, Tubbs 1974
UNITED STATES (West) ***Jump-Off Joe headland, Newport, Oregon***	1982 to 1986	· large, localised complex on headland	Consolidated/ Unconsolidated · weak mudstones and siltstones overlain by sand, silts and clays	Translational Slides	· steep seaward dip of slope material · high water table and groundwater seepage	· burst underground drain · development on slope	· demolition of condominium	Indirect · legal battles and headland hazard zones · revocation of geologist's license	Viles and Spencer 1995, Sayre and Komar 1988
UNITED STATES (West) ***San Francisco to Monterey Bay, California***	1989	· many failures along 240kms	Consolidated/ Unconsolidated · weak sedimentary rock and weakly consolidated Pleistocene dune sands	Falls, Translational Slides, Sand Flows	· Loma Prieta earthquake, magnitude 7.1 Richter Scale	· development at slope top · beach mining removes sediment supply and beach protection · mis-perception of hazard and geologic dynamics of the area	· six apartments and three homes demolished · 1person killed on the beach	Indirect · relocation of houses, demolition of some · abandonment of oceanfront streets	Griggs 1994, Plant and Griggs 1991
UNITED STATES (West) ***San Diego County, California***	Ongoing	· many small and large failures along 150kms	Consolidated/ Unconsolidated · consolidated rock to the north and unconsolidated alluvium to south	Falls, Slides and Flows	· intense rain and storm waves · geology, lithology · natural adjustments in littoral currents and sediment supply	· agricultural, residential and storm drains cause gullies · rise in water table from irrigation of lawns and agriculture · added slope weight from water and development · coastal highway and rail construction	· roads, rail, houses and recreation areas · beach access stairs and routes · cultural items (churches), commercial (restaurants)	Direct · beach nourishment · shore armour by old cars, rip-rap, concrete · slope faces sprayed with gunnite	Kuhn and Shepard 1984

LOCATION	DATE	EXTENT OF EROSION/ DAMAGE	MATERIAL (C) (U) CONSOLIDATED UNCONSOLIDATED	TYPE OF FAILURE	PHYSICAL FACTORS	HUMAN FACTORS	DAMAGE	MITIGATION DIRECT/INDIRECT	REPORT
UNITED STATES (West) ***State of California***	Ongoing	· many failures along entire coast · serious and concentrated in the south	Consolidated/ Unconsolidated · varies widely · mainly sedimentary rock and unconsolidated material in central and south areas	Falls, Slides and Flows	· seismic shaking · tectonic uplift · active fault zones within km of entire coast · high annual rainfall and intense episodic rain events · storm wave attacks · upslope failures	· dams on coastal rivers cause sediment depletion · jetties, breakwaters, seawalls affect beach and sediment supply and remove protection to back beach, bluffs and cliffs · irrigation of lawns and non-native vegetation on slope tops · culverts, storm drains on slope top and face cause gullies and failures · mis-perception of hazard by local residents and immigrants · intense population and development along coast, especially in south · uncoordinated, varied development policies and plans	· various reports of economic and property loss, human loss of life	Direct / Indirect · geologic reports and general investigations · attempts to establish setbacks	Griggs 1994
UNITED STATES (East) ***Upper Chesapeake Bay, Maryland***	Ongoing	· many small and large failures along perimeter of Chesapeake Bay	Unconsolidated · weakly consolidated sedimentary units of gravels to clays	Translational and Rotational Slides, Falls	· water currents through wave attack, seiche, fetch, and tides · percolation of rain, snow and ice meltwater · aquiclude barriers prevent downward percolation · piping and seepage at slope face remove decrease slope stability and remove slope sediments	· boat wakes · runoff affected by unbroken, planted, or plowed slope top · percolation increased through plowing	· hundreds of acres of agricultural land at bluff top	Direct / Indirect · sprayed concrete on slope faces · construction of sea walls · water drainage through pumps and wells · fallow buffer strips at slope edge to catch water · allow natural erosion	Palmer 1973
WALES (South) ***Llantwit Major, Bristol Channel***	Ongoing	· many small failures	Consolidated · alternating beds of relatively weak shale and strong limestone	Falls	· high wave energy at slope base · strong longshore currents remove beach material · material and stratigraphy	· recreation areas at slope base and top · weakened rock faces by blasting · flawed plans to lessen hazard through blasting	· close calls on human life at recreation areas	Direct / Indirect · blasting of rock faces in unstable areas · protection of slope base with blasted material · recent geotechnical assessments	Williams and Williams 1988

NOTES and LIST OF ABBREVIATIONS;

Consolidated - refers to cohesive, rock-like material, such as granite, chalk and slate, in addition to cohesive soils such as clay and till
Unconsolidated - refers to largely uncohesive materials such as sand and gravels

Those in the United Kingdom are found along the south and east coasts where material is typically unconsolidated, cliffs are steepened by quick toe removal from high energy waves, and population pressures are high. Hutchinson (1986) also reported on the importance of nearshore platform erosion on the failure and stability of London Clay cliffs at several coastal sites in England. Those failures reported from New Zealand are typically along the North Island and threaten property and houses, while those in Australia are typically a threat to human life, rather than economic and property loss. In the United States, coastal slope failures can be seen as a problem along the entirety of the west coast, from Puget Sound, Washington, to San Diego, California. The intense population pressure, seismic and tectonic climate, as well as flash rain storms, are assumed to produce ideal conditions for slope failure hazards along the west coast of the United States.

The geographical scale of coastal slope failures is reflected in the equally wide variety of slope failure sizes and materials. The extent of these hazards ranges from very small, localized events to very large failures. A number of reports discussed slope failure hazards in the context of large areas and numerous occurrences (eg. Bird 1994, Griggs 1994). Slope material can be broadly categorized as either consolidated or unconsolidated, and in combination with lithology, greatly influences the type of slope failure (fall, slide or flow). A wide variety of physical factors are also evident as a result of the broad spectrum of terrestrial, climatic and marine environments in which coastal slope failures are shown to occur. Human activity (eg. recreation, residential, industrial) is also variable, but evidently plays a major role in influencing coastal slope failures, and increasing vulnerability. Table 3.1 also documents failures very broadly by the material of the slope as either unconsolidated (glacial material) or consolidated (rock), and the human and physical factors believed to increase vulnerability to the event or events.

Finally, each event is also described in terms of its severity, as well as any attempts to either directly or indirectly mitigate future occurrences of slope failure. Mitigation of future hazards is evidently accomplished through a variety of techniques, which can be broadly categorized as either direct or indirect. Table 3.1 would suggest that direct initiatives (engineered solutions, shore protection, geotechnical) are commonly used when infrastructure is at risk, while indirect methods are used when human lives are at stake. These usually include restrictions on human access to 'risky' portions of the coastal zone. Indirect initiatives also include posting of warning signs, erection of fences, plans and policies, hazard maps and zones, or other management schemes designed to lessen the risk or prompt more detailed, geotechnical, engineering-type assessments. In some cases, nations have appointed governing bodies that are responsible for both direct and indirect management of coastlines. England, for example, has established the Coast Protection Act in 1949. This Act requires "Coastal Protection Authorities to manage the coastline and this involves the design of new protection works, the maintenance of existing works and the control of unprotected sections of coast" (McGowan et al. 1988, 1201).

An interesting aspect of the reports listed in Table 3.1 is the lack of discussion or emphasis on human risks. These are often mentioned as side comments, with engineering, and geotechnical assessments being the focus of the reports. Bird (1994) provided the only comprehensive summary of coastal failure hazards in terms of human risk of life. He discussed a number of instances where individuals were killed in Australia and England by cliff failures, in addition to methods used to mitigate this risk. Subsequent to several coastal slope tragedies in Australia, Bird (1994) predicted a large number of future legal battles over the responsibility for such disasters, and the benefits or non-benefits of 'zoning-off' areas that are frequently sites of scientific, recreational and scenic interest (Bird 1994). According to Bird (1994), the nature of coastal slopes, and the fall-out from coastal slope hazards and disasters, is a difficult problem that faces geologists, "for geological research and training requires the availability of field sites on coastal cliffs [sic] where geological formations are exposed and can be studied" (Bird 1994, 309).

In the end, however, Bird (1994) concluded that it may be necessary to exclude people (geologists, biologists, and the general public) from areas they may wish to visit, but that "there is also a need to provide information and education to improve public perception of coastal cliff hazards, and thus diminish the risk of accidents" (Bird 1994, 309). His report and recommendations expose the issue like few other authors have, and could not have been more timely. Two years subsequent to the publication of his 1994 report, nine children and adults were killed by a cliff fall (Table 3.1) in a natural park south of Perth Australia (Reuters Information Service 1996).

One of the more popular indirect means of dealing with coastal slope failures is the production of hazard maps, as recommended by White (1978) in his summary of natural hazard management in the coastal zone. Chandler and Hutchinson (1984), Gibb

(1981), and Moon and Healy (1994) all made use of various mapping techniques that depict hazard in an effort to mitigate future occurrences or severity of coastal slope failures. Grainger and Kalaugher (1988) discussed in more detail the construction of simple hazard zone maps for the Devon coast from evidence of previous slope failures and calculations of cliff top recession rates. Many of these maps could be improved in value by including humans into the analysis, so that maps depicted zones of risk, rather than just hazard.

These maps could also be improved through the use of computer analysis and GIS. Though most of these studies were conducted when computers were expensive, slow, and non-user-friendly, McGowan et al. (1988) suggested that a computer data base would help in the analysis of coastal slope failures through the storage of information from site investigation, and analytical tools. Grainger and Kalaugher (1988) also made indirect reference to the beneficial use of computers when they referred to the more quantitative techniques that had been conducted by Carrara in Italy in the early 1980s (eg. Carrara et al. 1995). Dunne and Leopold (1978) also discussed the use of computer generated hazard zone maps by Tubbs (1974) in his analysis of coastal slope failures in the Seattle, Mercer Island, and Puget Sound region. Though computers and GIS may assist and improve these instances of coastal mapping, Grainger and Kalaugher (1988) concluded, as stressed even in this paper, that mapping techniques do not eliminate the need for more detailed studies and should, instead, provide the impetus for future investigations.

3.2 - Coastal Slope Failures and the Great Lakes

The previous section highlighted twenty-one investigations and tragedies which occurred along coastal bluffs around the globe. Of all places, however, the most detailed work on erosion and failure in tills and other clayey diamictons, is that carried out on the shores of the Great Lakes, particularly during the 1970s and 1980s (Hutchinson 1986). The purpose of the next two sections of this chapter, is to review and discuss the general characteristics of Great Lakes coastal bluffs, their associated risks, and recent efforts to research and manage them. This review helps to highlight areas where future research is required, particularly in light of the study presented later in this paper.

3.2.1 - The Nature of the Great Lakes Bluffs

With 17,000km of shoreline (USEPA and EC 1995), Lakes Superior, Michigan, Huron, Erie and Ontario form the eastern border between Canada and the United States, and are the world's largest system of surface fresh water in the world (USEPA and EC 1995). The basin is also home to about 33 million people, including about one tenth of the total United States population and over one quarter of Canada's population (USEPA and EC 1995). In 1992 and 1993, the International Joint Commission (IJC) estimated that 40% of the Canadian Great Lakes shoreline is occupied by residential, commercial, and industrial development, including more than 100,000 residential settlements (IJC 1992, 1993). Seventeen metropolitan areas with populations over 50,000 are located within the Lake Erie basin alone (USEPA and EC 1995). Like much of the world's coastlines, population, encroachment, and development exacerbate the physical problem of bluff erosion and failure along the Great Lakes (Carter et al. 1987).

The physical nature of the Great Lakes shoreline is a significant factor in assessing the nature of bluff failure and erosion in the basin. A series of Quaternary ice lobes and larger ice sheets are believed to have carved out the present basin during the Wisconsin continental glaciation between 10,000 and 1,000,000 years ago. These events were responsible for the layers of glacial sediments which now cover the region and make up a large portion of the shorelines (Ashworth 1986, Chapman and Putnam 1984, and Karrow and Calkin 1985a, 1985b). Approximately 7,500km of the Great Lakes shoreline is composed of bluffs made up of unconsolidated, yet largely cohesive glacial material (GLBC 1977). This material is often described as glacial drift and includes glacial tills and glaciolacustrine sands, silts and clays which were eroded, transported, and deposited by the advance and retreat of the glaciers (EC and OMNR 1975, GLBC 1977).

Figure 3.1 depicts the erodible and non-erodible sections of shoreline along the Great Lakes. Unconsolidated material forms the bluffs of Lakes Michigan, Erie and Ontario, and the south shores of Lakes Huron and Superior, while bedrock outcrops form the north shore of Lakes Superior and Huron (GLBC 1977). This map does not include smaller variations along the shoreline, and instead, is provided only as a general reference to illustrate the extent to which Great Lakes shorelines are composed of cohesive and non-cohesive soils or rock (including some areas of limestone), versus cohesive, consolidated rock (eg. Canadian Shield to the north). High erodible bluffs exist on all five lakes, but are most prevalent along Lake Michigan and Lake Erie. In some cases,

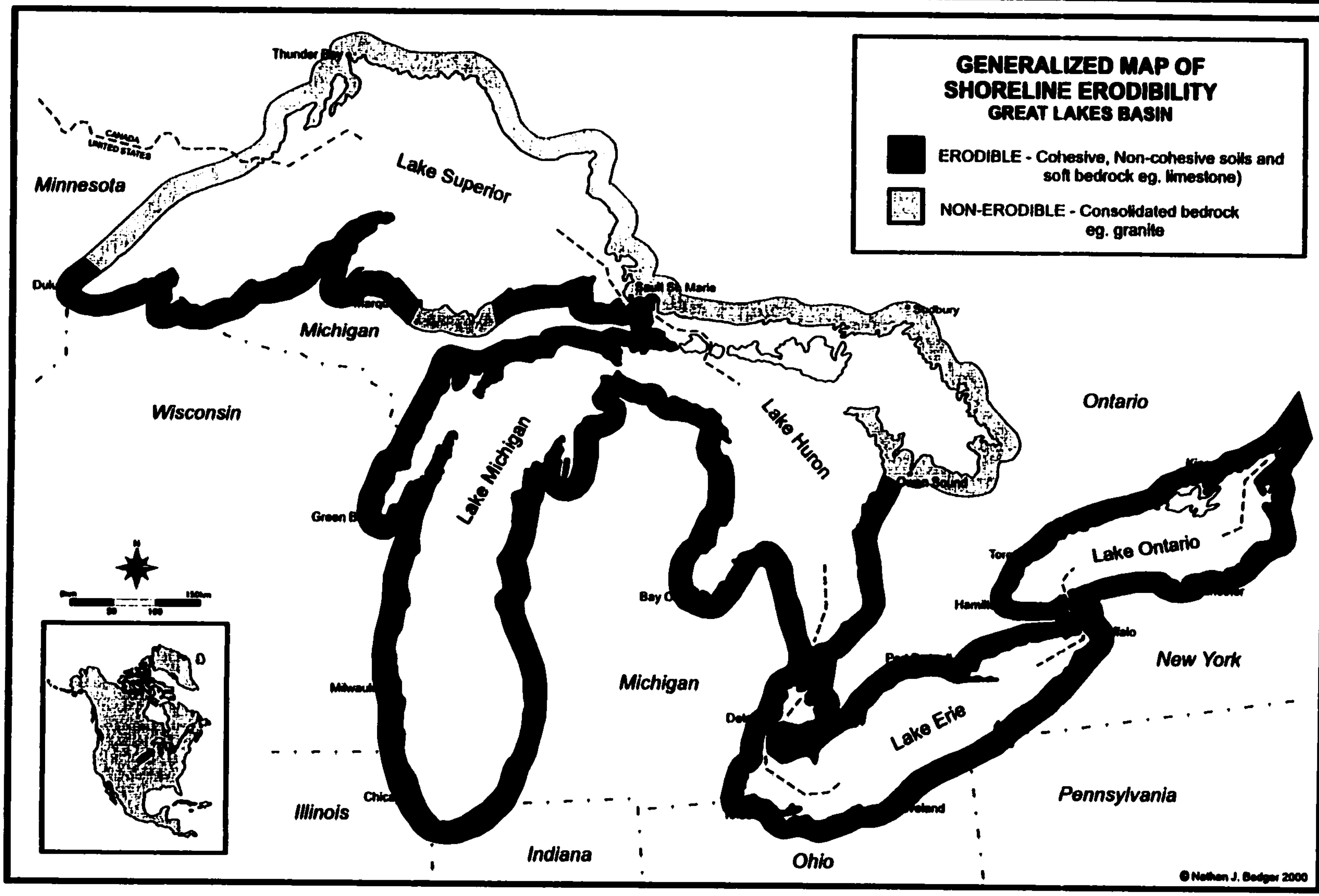


Figure 3.1: Erodible and non-erodible sections of the Great Lakes shoreline, Canada and United States (modified from GLBC 1977).

their morphology may reach slopes of a vertical nature, or heights over 85m such as those at Scarborough on Lake Ontario (EC and OMNR 1975, GLBC 1977, Eyles and Hincenbergs 1986).

A wide array of physical factors make it difficult to understand and mitigate the bluff problem. Most sources attribute the long-term recession (>20yrs) and dynamics of the bluffs to marine-related processes (Davidson-Arnott and Ollerhead 1995, Davidson-Arnott and Langham 1995, Kamphuis 1986, Quigley and Gelinas 1976), while terrestrial processes are believed to control short-term erosion through episodic events such as bluff failures (Davidson-Arnott 1998). These marine and sub-aerial processes cut into the glacial material at the shore and are similar to those which act on the cliffs and bluffs of ocean coasts. The shores of the Great Lakes are not subject to the same magnitude of wave energy that the ocean storms and swells produce, but wave induced toe erosion is very effective during severe short-term events, such as storms and seiches, where lake levels can be raised by over 2 metres (Bird 1985). This action is further intensified during long-term lake level fluctuations (Bird 1985).

Isostatic rebound continues to raise coastlines within the north-east portion of the basin along Lakes Huron, Ontario, and especially Lake Erie (Bird 1985). The resulting tilt of shoreline materials affects bluff erosion in various ways through decreases in shear strength along natural shear planes, seepage, and ground water movement (Bird 1985). Wind also has a strong indirect and direct influence on beach dynamics through its control of the wave climate, and increases in aeolian sediment transport to beaches, dunes and bluffs. Finally, shore or lake cover ice during the winter can protect the shore from wave erosion, while local ice jams during spring break-up can scour sections of the beach, bluffs and nearshore (OMNR 1994, Saulesleja 1986). Together, these marine and terrestrial processes produce thousands of slope failures annually along the Great Lakes, some of them with volumes in excess of 200,000 m^3 (Cruden et al. 1989).

3.2.2 - Hazards, Risks, and Difficulties with Mitigation

Amidst the dense population of the Great Lakes, bluff failures frequently represent large costs through loss of urban or agricultural land and property. Failures are also a risk to human life. Since bluff erosion often provides littoral nourishment for the development of beaches, this process can, in itself, play an effective role at drawing larger numbers of people to hazardous areas of the coasts (Cruden et al. 1989). It is no surprise that the shores of the Great Lakes have, therefore, drawn an increasing amount of attention and research from planners and engineers concerned with the stability of the bluffs (Bosscher et al. 1988). The continued need for bluff research and hazard management was recently evidenced through the near-death of a young Guelph girl during a sand dune collapse on the shore of Georgian Bay, near Midland, Ontario (Canadian Press 1999, Ferris 1999).

Direct and indirect intervention have both been used to manage bluff erosion problems on the Great Lakes. Engineered protection devices and other shoreline structures have been constructed along each of the Lakes through both public and private initiatives (Davidson-Arnott and Kreutzwiser 1985). While some were successful (eg. Quigley et al. 1974), most were only effective over short periods of time and tended to increase downdrift shore erosion (Davidson-Arnott and Kreutzwiser 1985). Shoreline structures also provide a false sense of security or protection, and are, therefore, responsible for an increase in shoreline encroachment (Kreutzwiser 1982).

Several sources discuss bluff failure mitigation initiatives which failed or simply increased shore erosion. Carter et al. (1987) described the installation of groynes near Painesville Ohio, where bluff recession was halted in the groyne area, but accelerated in downdrift areas at a rate of over 3m/yr. Davidson-Arnott and Keizer (1982) reported on the short term protection provided by an expansive length of seawalls and groynes along a cohesive shore at Stoney Creek, Lake Ontario. According to the report, only 18% of the sea walls could survive 10 years in an undamaged state after construction, and the proportion of survival became null in 30 years (Davidson-Arnott and Keizer 1982). Ironically, the Special Studies Branch of the North Central Division of the Corps of Engineers summarized in 1973 what has long been known about engineered constructions along the Great Lakes shoreline:

> "Millions of dollars of private funds are being spent to repair severely damaged property, construct new protective works, or relocate homes .... In most cases this construction will fail because of inadequate planning and design. Millions of dollars in property damages will be recorded" (Buddecke 1973, 15).

A second alternative to mitigating Great Lakes bluff hazards is through Indirect initiatives, including management plans and land use policies. Unfortunately, comprehensive, integrated management plans along the Great Lakes shores are rare or non-existent, especially in the case of Canada (Cruden et al. 1989, Lawrence 1995b). Efforts are often hampered by the complex nature of the shoreline. Since the shorelines vary greatly in their composition, it is difficult to prescribe general treatments to bluff failure (GLBC 1977), and localized plans are likely of greater value. In general, the physical aspects, solutions, and management plans require a multidisciplinary approach and knowledge base, supported by costly, site specific, and time consuming geotechnical and hydraulic studies (Cruden et al. 1995, Edil and Vallejo 1980).

Great Lakes bluff management plans are also hampered by complex jurisdictional arrangements and Canada's failure to develop a national shoreline management policy. Hildebrand (1989) discussed Canada's shoreline management policy problems and contrasted them with the efficiency and effectiveness of the Coastal Zone Management Plan established in the United States through Coastal Management Act in 1972. In the United States, management of the shoreline is carried out in a coordinated fashion by cooperative state and federal programs, whereby states have the power to legalize and enforce Coastal Zone Management laws and plans (Hildebrand 1989). In Canada, the Ontario Ministry of Natural Resources (OMNR) has typically been the lead agency for shoreline management (Cruden et al. 1989), but no exhaustive management plan exists, and most planning and control structures have been implemented within a vacuum. Apart from Hildebrand (1989), Canada's shoreline management problems are also addressed by Harrison and Parkes (1983), Davidson-Arnott (1985), Kreutzwiser (1988), Lawrence (1995a, 1995b, 1995c), and Lawrence and Nelson (1992).

3.2.3 - Water Levels and Progress with Bluff Research and Management

Despite the problems with Great Lakes shoreline management plans and coordinated efforts to study shoreline processes, some positive steps have been taken over the past three decades towards a more comprehensive plan, and a better understanding of the bluff dynamics and hazards. These changes are slow, but are important (Lawrence 1995c). To a large degree, this progress is a response to fluctuations in the Great Lakes water levels. Severe property loss and damage incurred during high levels has: **i)** heightened an awareness of bluff erosion hazards, **ii)** demonstrated the need for formulation of management policies to reduce coastal risks, and, **iii)** prompted an interest in the physical erosion of the bluffs and their dynamics. These effects are touched on within the remainder of this section, and Sections 3.2.3, and 3.2.4.

One hundred and fifty years of records indicate that Great Lakes water level changes are natural variations (Moulton and Cuthbert 1987), and that intervals can vary widely and erratically over a number of years (Buddecke 1973). Although these fluctuations are not a new phenomena, high lake water levels did not manifest themselves as an 'issue' until the past 40 years while shoreline development increased (Chieruzzi and Baker 1958). During the high water levels of 1952-1953, 1972-1973 and 1985-1986, billions of dollars of damage (Keillor 1990) were incurred when low-lying, flood-prone areas were inevitably inundated by high water levels. Beach sediments and coastal bluffs suffered increased erosion, and property and land was damaged or destroyed during peak water levels, storms and other intensified lake level events (Davidson-Arnott 1985, Moulton and Cuthbert 1987).

During the 1985-1986 high levels, an important article was published by Davidson-Arnott (1985) which identified the human aspect of the water level 'hazard' through shoreline encroachment. Kreutzwiser recently echoed this root cause when he stated that "a portion of the increase in damage must be attributed to increasing encroachment" (Kreutzwiser 1988, 146). Elsewhere, Kreutzwiser (1982, 1987) also noted a lack of proper planning, continued development in 100yr erosion zones, and failure to recognize or regard the implications of fluctuating water levels. Many aspects of the high water level events are described in reports, not otherwise mentioned, such as: Centre for the Great Lakes (1988), Chenoweth (1974), Day et al. (1977), Day and Fraser (1979), Fraser et al. (1977), Great Lakes Commission 1987, Kreutzwiser (1988), Needham and Nelson (1979), Rasid et al. (1989, 1992), Misener and Daniels (1982), and Lawrence and Nelson (1994).

Unfortunately, public attention and many of the reports and studies which stemmed from the high water events focussed on the role which high water levels played in the erosion and inundation of beaches, flood-prone or low-lying coastal areas. The effects of lake levels on coastal bluffs are often ignored, or only dealt with in a cursory manner. This is disturbing, particularly when shore bluffs are equally desirable areas for development, are equally as hazardous, and suffer the same, if not greater increases in erosion during high water levels (Lawrence 1995b, Rasid et al. 1989, USACE 3 Jun. 1999a). Edil and Vallejo (1980), Quigley and Di Nardo (1980), and Quigley and Gelinas

(1976) all discuss the physical effects of water levels on bluff erosion, many of which are detailed later in Chapter Five.

In spite of the dominant emphasis of attention and research stemming from high lake levels, it is important to recognize that lake levels have played an important role in initiating coastal bluff research. Management plans and bluff initiatives for the Great Lakes shoreline in Ontario can be linked to crisis responses during high water and related storm events (Lawrence 1995b). Several reports have recommended the construction and use of coastal zone management and land-use plans through the aid of government institutions (Foulds 1977, Keillor 1990), and since 1985, the demand for a comprehensive, legally binding, holistic, and integrated shoreline hazard management program has been particularly strong in Ontario (Davidson-Arnott 1985, Kreutzwiser 1992, Lawrence 1995b, Lawrence and Nelson 1992). The following section discusses several of the large-scale studies which have stemmed from Great Lake water levels.

3.2.4 - Large Scale Shoreline Studies and Bluff Research

Within the past three decades a number of large-scale projects have been implemented by governmental and non-governmental organizations to investigate Great Lakes water levels and shoreline erosion. American, Canadian and joint initiatives are detailed and evaluated by Lawrence (1995a, 1995b, 1995c), and to a lesser degree, the Great Lakes Shoreline Management Guide (FOC, EC, and OMNR 1981) and Kreutzwiser (1987). Several of these studies have contributed to the management and understanding of the bluff failures and erosion. It is useful to review these studies in order to guide and contextualize the GIS research described later in this paper.

For the sake of brevity, and in keeping with the Lake Erie focus of this paper, large-scale projects are only discussed in terms of Canadian initiatives. Table 3.2 summarizes the projects most relevant to shoreline bluff research. For each project, the lead institution is noted, as well as the general time period of the research. The purpose and results are then described briefly, and a statement is made about the importance and contribution of this research to an understanding of bluff processes, the hazards and risks of bluff failures, and their management. Finally, major reports associated with the projects are listed, in addition to any relevant supporting documentation. The reader is referred to these publications for further information about each project.

The high water levels of 1972-1973 sparked several key studies including the Great Lakes Shore Damage Survey (GLSDS), a Shoreline Public Awareness Program, the Great Lakes Shoreline Management Guide, and the Canada-Ontario Great Lakes Monitoring Program (Boyd 1981, FOC, EC, OMNR 1981, Lawrence 1995b). Together, these studies sparked bluff research and heightened awareness of bluff hazards, particularly in relation to water level fluctuations.

Following high water levels in 1985-1986, the Ontario Shoreline Management Review Committee recommended stronger provincial action related to shore hazard planning and land uses affected by water level fluctuations, flooding, erosion, and subsequent damages (Lawrence 1995b). Several initiatives were proposed to address the hazard-prevention interests of the provincial shoreline management program.

Table 3.2: Large-scale projects and studies which contributed to bluff research on the Canadian Great Lakes shoreline

PROJECT	INSTITUTION and DATES	DESCRIPTION of PROJECT (Purpose, Results)	CONTRIBUTION TO BLUFF RESEARCH	PROJECT REPORTS and SUPPORTING DOCUMENTATION
Canada-Ontario Great Lakes Shoreline Damage Survey (GLSDS)	EC and OMNR (1973-1974)	· detail the extent and severity of the 1972-73 water level damages, survey shore characteristics from Port Severn Lk. Huron to Gananoque Lk. Ontario · provide recommendations to formulate shore management plans and policies · resulted in a report and atlas (1:10,000 with 1973 air photos, contours, recession/accretion histograms, shore damage, land ownership, land value, land use, physical shore characteristics, damage to shore protection	· first general discussion of bluff erosion problem, human and physical factors of erosion, spatial, quantitative summaries of recession	• Preliminary Task Force Report (TFASEI 1973) • Technical Report (EC and OMNR 1975) • Great Lakes Coastal Zone Atlas (EC and OMNR 1975)
Shoreline Public Awareness Program	Federal-Provincial Coordinating Task Force (-1974-1981)	· directed follow-up programs to implement recommendations in the GLSDS · purpose was, in part, to provide public shoreline awareness programs and publication of several pamphlets to inform the public and reduce the damage · prompted the Shoreline Management Guides noted below	· publications showed an awareness of general shore hazards, role of vegetation in slope stability, nature of bluff erosion, engineered solutions, and role of humans in bluff failure	• Pamphlets/Publications Included: (FOC, EC, and OMNR 1981), (FEC 1974), (FEC and OMNR 1974), (FOC and OMNR 1979), (GLBC 1977)
Great Lakes Shoreline Management Guide	FOC, EC and OMNR (-1974-1981)	· Guide made available to shoreline managers (municipalities, CAs, Ministries) to describe physical shore processes, environmental concerns, systems approach to shore management (physical, biological, socio-economic), shore management · purpose was to provide plans, background information, studies, recommendations to enable development and implementation of comprehensive shore management policies, and reduction of flood and erosion hazards	· examined shoreline erosion and hazards from a holistic perspective and included the bluffs · heightened awareness of bluffs · recommendations never acted upon	• Great Lakes Shoreline Management Guide (FOC, EC and OMNR 1981)
Canada-Ontario Great Lakes Monitoring Program	FOC (1973-1980)	· measured and monitored bluff and beach processes using ground and aerial surveys at 162 stations Port Severn Lk. Huron to Gananoque Lk. Ontario · shore profiles, bluff recession rates, volume of erosion/accretion	· monumental contribution · separate attention given to bluff processes, erosion, rates, composition, modes of failure, management consideration	• Final Report - Canada-Ontario Great Lakes Monitoring Program (Boyd 1981)
Great Lakes - St. Lawrence River Flood and Erosion Policy Statement	OMNR (1994)	· comprehensive overview of Great Lakes shore dynamics, suggested solutions to hazards and erosion, including direct and indirect methods · emphasis is on engineered / geotechnical investigations and solutions, but management schemes, and hazard land zoning are also discussed · included portions of OMNR's Geotech. Principles for Stable Slopes (details slope dynamics, instability factors, temporal/spatial distribution, identification and classification, stability analysis, mitigation methods · no legal status to date, but incorporated into revised Ontario Planning Act with Bill 163 1994-1995	· most detailed, quantitative summary of shoreline slope processes to date · focuses on geotechnical solutions, but expands on possible setback policies, management schemes · solutions to reduce hazard, losses · recommends computer stability analysis, modelling	• Implementation Guidelines, and Technical Guidelines (OMNR 1994) • Geotechnical Principles for Stable Slopes (TL and AS 1998) • Comprehensive Set of Policy Statements (OMNR 1994) • Discussion of Tech. Guidelines, Policies: (McKeen 1992), (McKeen 1995), (Kolberg 1995), (Sullivan 1995)
Shore Sediment and Littoral Cell Definition Study	OMNR (1988)	· coastal engineering studies which mapped and defined sediment budgets (volumes and erosion rates), as well as the nature, direction and cells of littoral currents · supplemented by wave climate data base study · purpose was to support CAs in developing SMPs	· examined the role of bluff erosion in sediment supply · role of currents and nearshore processes in bluff stability, erosion	• Littoral Cell Definition and Sediment Budget for Ontario's Great Lakes - Final Report (F.J. Reinders 1988)
Great Lakes Shoreline Management Plans (SMPs)	CAs and OMNR (1989 to present)	· to be designed by local CAs and OMNR to minimize danger to, and property damage from, flooding, erosion, and associated shoreline hazards · to ensure shoreline development adequately addresses flooding and erosion hazards through public and private management and development alternatives, including prevention, protection, emergency response, public information, environment and monitoring	· allowed bluff studies to be conducted at a local level, and with the level of detail required · CAs and public prompted to become familiar with physical and human aspects of bluff failures	• Guidelines for Developing Shoreline Management Plans (OMNR 1997) • SMPs examples include: Long Point Region Conservation Authority (PA, TA, PWA 1989), Ausable Bayfield Conservation Authority (ABCA 1994)

These included the establishment of a new Provincial Shoreline Management Policy to be declared under the Ontario Planning Act, active government participation in land-use plan input and review, delineation of shoreline flooding and erosion hazards, development of information databases, preparation of Shoreline Management Programs, training and technical development of staff, liaison with other agencies, and public education (Lawrence 1995c).

Several of these recommendations and initiatives have been the focus of shoreline projects in Ontario over the past decade. In 1989, Conservation Authorities (CA) or OMNR districts were designated as the implementing agencies to begin development of Great Lakes Shoreline Management Plans (SMP), as detailed by OMNR (1987), and Lawrence (1995a, 1995 b, 1995c). To aid in their development, two large-scale coastal engineering studies commenced to examine sediment budgets and littoral cell definitions (completed by F.J. Reinders 1988), and to build a wave climate database for the Great Lakes (Lawrence 1995b). SMPs provided opportunity for CAs to develop goals to minimize hazards and risks at the shoreline through public information, monitoring, appropriate planning, and access to previously unavailable maps, data, and funding through provincial ministries. Unfortunately, the majority of SMPs have limited legal status, because the regulatory controls for provincial land-use planning are held, at most locations, by municipalities and Official Township Plans.

Following the SMPs, work began in 1990 on a new Great Lakes-St. Lawrence River Flood and Erosion Policy Statement. A draft version of the policy was prepared, with the stated objectives of reducing risks to life and property and to encourage a coordinated approach in the wise use and management of lands susceptible to Great Lakes flooding and/or erosion (Lawrence 1995c). The policy aimed to clarify the shoreline hazards definition and establish provincial guidelines for determining and applying regulatory flood and erosion standards along the Great Lakes shoreline (OMNR 1994). Two draft documents accompanied the draft policy statement, including Implementation Guidelines and Technical Guidelines for the Great Lakes-St. Lawrence River System (TGGLSLS). Included within the TGGLSLS was a chapter on slope stability which was later released by the OMNR (TL and AS 1995) as a guide to the Geotechnical Principles for Stable Slopes (GPSS).

Internal review of the policy continued from 1990 to 1993, and it was anticipated that the policy statement would be developed and included in the final recommendations and planning documents of the 1991 Sewell Commission on Planning and Development Reform in Ontario. However, with the release of the provincial government's response to the Commission in 1993, and subsequent revisions to the Planning Act with Bill 163 in 1994-1995, the Great Lakes shoreline flooding and erosion hazard policy statement has, instead, been incorporated into a Comprehensive Policy Statement (Ontario Ministry of Municipal Affairs 1994) on natural heritage, environmental protection and hazards. This turn of events has left the very future of Great Lakes shoreline Management in Ontario in doubt (Lawrence 1995b).

Great Lakes shoreline management is, therefore, currently directed, albeit rather loosely, by the Comprehensive Policy Statement and the revised Ontario Planning Act. The TGGLSLS has since been completed in hopes that it will be reconsidered and incorporated more wholly into shore management policies in a future political environment. Although the TGGLSLS (OMNR 1998) and GPSS (TL and AS 1994) have a strong bias towards the use of engineered shore protection, the guidelines do provide the most useful, detailed, and quantitative summary of Great Lakes shoreline slope processes to date. These documents are a great aid to the development and application of SMPs which are capable of examining and accounting for more localized and site-specific variations in the shoreline (Lawrence 1995b).

3.2.5 - Small Scale Shoreline Studies and Bluff Research

In addition to the large-scale studies completed by federal and provincial agencies, there are a number of small-scale, bluff related, studies which have been produced within the past three decades by both governmental and non-governmental organizations. This section briefly reviews several smaller-scale studies conducted along the Great Lakes, and illustrates how they contributed to a growing understanding of the bluffs, how they heightened an awareness of their threat to human well-being, and what attempts have been made to manage bluff hazards and risks.

Table 3.3 summarizes fourteen reports which are organised by study location, the institution leading the study, and the date of the research. Reports on Lake Erie bluff research are excluded from this review, and are dealt with separately in Section 3.3. Table 3.3 also notes the major areas of research and the major findings for which discussion or data is provided in the research report. Within the 'research areas' column, a statement is made as to whether hazards, or risks to human well-being, were described

Table 3.3: Small-scale projects and studies which contributed to bluff research on the Canadian Great Lakes shoreline

STUDY LOCATION	LEAD INSTITUTION	DATE OF RESEARCH	RESEARCH AREAS	MAJOR FINDINGS	COMPUTER ANALYSIS	AUTHOR
LAKE SUPERIOR						
Wisconsin: **Minnesota border east to Bark River**	Various	1978 - 1979	GL, GT, MN, SM, HY Hazard	- geologic, geomorphologic, and geotechnical properties presented for reaches in study area - landslide hazard potential determined by reach - results from conventional stability analysis compared to those from probabilistic method - 5 hazard zones defined, based on the calculation of a 'stable slope inclination'	Slope Stability Analysis - Simplified Bishop Method	Schultz et al. (1984)
LAKES SUPERIOR and MICHIGAN						
Wisconsin: **Manitwoc County to Illinois border on L. Michigan, entire Superior shore**	Wisconsin Geological and Natural History Survey	1976	BC, CL, FF, GE, GL, GT, HY, MN, RR, SL, SM, VG Anthropogenic Hazard	- $15 million dollars damage/loss in property (houses, commercial, industrial) in 1972-1973, and $4.5 million in 1951/1952 - shoreline reaches and critical hazard areas in the study area are determined by a number of factors including recession rates, and Factor of Safety - Factor of Safety calculations represent most critical conditions that could affect slope stability - data assumptions, non-homogenous nature of the bluff material, and hydraulic factors can change the Safety Factor and are not accounted for in the analysis	No	Mickelson et al. (1977), Sterrett and Mickelson (1978)
LAKE MICHIGAN						
Illinois: **Winnetka to Waukegan**	Illinois Coastal Development Project	1976	RR, GL, WE, NS, HY, VE, MN, GL Anthropogenic Hazard	- bluff erosion widely distributed along the shore, but most severe damage is near urban centres - various factors contribute to the erosion - historical photos, maps and field examinations provide helpful info to determine recession rates and form bluff stabilization programs - lake levels important in erosion, but there is a lag before and after due to stabilization of the slope (naturally) and erosion of beach nearshore and toe when rising - groins are largely ineffective	No	Berg and Collinson (1976)
Wisconsin / Michigan: **Illinois state line to southern Door County - Indiana border to northern Leelanau County**	Various	1980	RR, SM, FF, HY, CL, BC, GL, SM Anthropogenic	- long term recession rates at 118 sites evaluated spatially, compared to shore zone characteristics - recession rates vary widely over 120 years - average values show recession rates similar on both sides, but values differ north to south - dune-oncompassed bluffs recede slower - groundwater seep, shore orientation, fetch, and protective structures influence recession rates - erosion will continue at metres per year unless protective devices are built, or lake levels lower	No	Buckler (1983), Buckler and Winters (1983)
Wisconsin: **Manitwoc County to Illinois border on L. Michigan**	University of Wisconsin, Madison	1974 - 1980	FF, SL, GT, HY	- data from Wisconsin study sites are extrapolated to the Great Lakes shoreline - coastal slopes change in reaction to many things, are complex, need to be understood better with better analytical tools - better tools must consider all of the factors - height, groundwater and unit weight of bluffs and material affect stability	Slope Stability Analysis - Simplified Bishop Method	Edil and Vallejo (1980)

Wisconsin; **Kenosha County to Kewaunee County**	University of Wisconsin, Madison	1974 - 1980	SL, GL, GT, HY, SM	· Factor of Safety not enough info with coastal bluffs · size and location of slipe circle and consequent evolutionary processes must be determined · unstable circle criterion applicable to steep/uncohesive slopes · usually predicts deeper slips · critical circle criterion is applicable to low angle or cohesive slopes, and predicts successive retrogressive shallow slumps · many hydraulic, geomorphic, geologic factors affect which failure occurs	Slope Stability Analysis - Simplified Bishop Method	Edil and Haas (1980)
Wisconsin: **Northern Milwaukee County**	University of Wisconsin, Madison	~1986 - 1988	GL, GT, BC, HY, RR	· probabilistic approach is effectively used to determine potential instability for areas with missing or poor quality data · data from probabilistic assessments of slip circle stability can be compared to data from conventional assessments · certain delineations of safety possible with probabilistic info which cannot be with conventional · hazard potential classifications can be applied to shore sections and used for the development of appropriate remedial measures and recommendations	Slope Stability Analysis - STABL	Bosscher et al. (1988)
LAKE ONTARIO						
New York; **L. Ontario shore in New York**	New York Sea Grant Institute / State University New York, Buffalo	1974-1976	GL, BC, RR, GT, NS	· historic recession rates measured at 250 sites for 99 year period · recession rates spatially variable due to bedrock outcrops, and clay content · many other nearshore and morphological features responsible for recession rates and failures · bluff failure and erosion occurs as discrete large-scale mass-movements	No	Calkin (1978), Calkin and Geier (1983)
Ontario: **Etobicoke Creek to Highland Creek**	Metropolitan Toronto and Region Conservation Authority	~1980	CL, GL, GE, MN, FF, HY, NS, SM Anthropogenic Hazard	· overview of the bluff erosion, failure hazards, and failure factors in each management area · direct and indirect management initiatives and future plans · details of a shoreline hazard and management policy, management program details · environmental implications of shore modification	No	MTRCA (1980)
Ontario: **Scarborough Bluffs**	University of Toronto, Scarborough	~1967-1969	BC, FF, CL, HY, RR, GL Anthropogenic Hazard	· overview of bluff erosion, failure factors, erosion verses recession · discussion of geology and stratigraphy, suspected influence of ground water · overview of air photo analysis, literature review and extensive field investigations · recognition of physical and human factors controlling toe erosion, particularly septic beds	No	Bird and Armstrong (1970)
Ontario: **Scarborough Bluffs**	York University	~1976 - 1978	VG, HY, SM, GL Hazard	· vegetation plays only a minor role in reducing or preventing erosion and recession · pioneer plants (eg. Coltsfool) are removed by slumping before succession can occur · woody vegetation indicative of more stable areas · vegetation can occur and progress to forested slopes in well-drained areas where toe is protected	No	Fowle et al. (1982)
Ontario: **Scarborough Bluffs**	University of Toronto, Scarborough	~1980	GL, MN, HY, SM, VG, RR Hazard	· failure and recession are closely related to subsurface water concentrations and resistance and permeability of materials · more information on the spatial and temporal variation of ground water is needed · hazard area strategies urgently needed · control structures must include water drainage · toe protection will only halt recession after years	No	Bryan and Price (1980)
Ontario: **Scarborough Bluffs**	University of Toronto, Scarborough	~1986	GL, HY, SM	· alternating layers of sandy fine-grained diamicts result in differential permeability · pipe structures develop where groundwater seepage is focussed by sand filled basins on the upper surface of the diamicts · scallops result from the collapse of pipes and focussed surface runoff · model is presented to rationalize the location of scallops along the bluffs in terms of glacial lake floor paleogeography and sediment distribution	No	Eyles and Hincenbergs (1986)

Ontario: **Scarborough Bluffs, Bluffer's Park**	Trent University	~1986	RR, HY, SM, GL Hazard	- different slope morphologies (and associated geology) exhibit different recession rates - this observation is complicated by short term data - slope morphology should be studied closely in future detailed recession rate calculations	No	Buttle and Von Bulow (1986)
Ontario: **Scarborough Bluffs, South Marine Drive**	Various	~1986	GL, GT, HY, MN Anthropogenic Hazard	- geological and groundwater conditions in this area are unique to the Scarborough Bluffs and result in shallow rotational slides - geological, groundwater conditions, and proposed stabilization measures are described - offshore dyke, foreshore platform, subdrainage system have been successfully completed to reduce a serious hazard in an intensely populated area	No	Parker et al. (1986)

NOTES and LIST OF ABBREVIATIONS:

~ - signifies an approximated date, no date provided in the report
BC - Beach Conditions (beach width, slope angle, beach material)
CL - Climate
FF - Failure Factors - (various)
GE - Gully Erosion
GL - Geology (bluff material, lithology, stratigraphy based on drill holes or bluff face)
GT - Geotechnical analysis (soil strength, stress, properties, density)
HY - Hydrology and Hydraulics (seepage, piezometric readings, ground water)
MN - Management and Control of Erosion (direct and indirect, past or future recommendations)
NS - Nearshore - (water levels, currents, nearshore sediment budgets)

RR - Recession Rate
SL - Slope Stability (profiles and calculations based on Bishops' Factor of Safety)
SM - Slope Morphology (height, slope angle, orientation)
VE - Volumetric Erosion
VG - Vegetation
WE - Wave Energy/Power

Hazard - mention made of threat or damage to property, buildings, or human life
Anthropogenic - human factors discussed as influences in shore bluff erosion

alongside the bluff problem. The final two columns of the table note whether computer analysis was used or described in the report, as well as the authors and date of the final published report.

As with the larger-scale reports, many of the small-scale reports can be seen as reactions to the high lake water levels during 1972-1973 and 1985-1986. The nature of most of these studies can be summarized as both qualitative and quantitative, local, geotechnical investigations and/or hazard zoning initiatives. Most of the reports generally make use of either geotechnical (slope stability analyses profiles, bore hole investigations, material stress capabilities, recession rates) or geological studies (stratigraphy, soil identification) and combined, they cover a large range of research areas, and report on a wide variety of findings. While Edil and Vallejo (1980), and Cruden et al. (1989) attempted to provide overviews of the bluff problem along the entirety of the Great Lakes, information within the reports is extrapolated from separate, site-specific studies on Lake Michigan, or Lake Erie.

Lake Huron and Lakes Superior have received the least amount of research and attention in terms of bluff studies. Lack of research along Huron is surprising, especially when the eastern shores of the Lake contain many miles of bluffed shoreline prone to high rates of erosion (GLBC 1977). This is likely due to the relatively low population along the shores of this Lake. Though not listed in the table, the only available reports which discussed the bluffs on Lake Huron were a Shoreline Management Plan compiled by the Ausable Bayfield Conservation Authority (1994) and examinations of the shoreline gullies by Burkard and Kostachuk (1995, 1997).

In contrast to the erodible shores of Huron, Lake Superior has likely received little attention because its northern shoreline is mostly composed of consolidated rock. Some of these northern stretches are, however, still capped by clay and silt glacial deposits and pose a concern to road construction and shoreline developments (Green et al. 1977, Rasid et al. 1989). On the other hand, the southern portions of Superior are composed of unconsolidated materials. In 1976 the Wisconsin Coastal Management Program (WCMP) sponsored a comprehensive geological overview of the shoreline bluffs (Mickelson et al. 1977) lining the state of Wisconsin, including portions of the south Lake Superior shore and a large section of Lake Michigan. Schultz et al. (1984) continued with these studies and performed geotechnical studies on the southwestern Superior shoreline and defined hazard zones by long-term stable slope inclinations. On the Wisconsin shores of Lake Michigan, the WCMP report was followed by geotechnical slope stability investigations at the University of Wisconsin in Madison by Edil and Haas (1980), and Edil and Vallejo (1980). A massive investigation into shore bluff recession rates over a 120 year period at 118 sites was conducted on the Wisconsin and Michigan shores in 1980 and is described by Buckler (1983), and Buckler and Winters (1983). Berg and Collinson (1976) also reported findings from preliminary studies on the bluffs and the effects of shoreline protection structures along the Illinois shore of Lake Michigan.

High water levels in 1985-1986 resulted in further geotechnical bluff assessments on Lake Michigan shores, once again by University of Wisconsin in Madison. Bosscher et al. (1988) contrasted and compared the use of probabilistic and conventional methods of determining potential hazard areas within northern Milwaukee County using a computer software package called STABL.

A number of small-scale studies were also conducted along the shores of Lakes Ontario and Erie after the 1972-1973 high water levels. Calkin (1978) and Calkin and Geier (1983) summarized a geologic inventory completed along the New York shores of these two lakes. However, much of the work on Lake Ontario, has focussed on the bluffs to the east and west of Toronto as early as 1967 (Bird and Armstrong 1970). In 1980 the Metropolitan Toronto and Region Conservation Authority (MTRCA) released a shoreline management program that discussed the shore bluff between Etobicoke Creek and Highland Creek. Further reports focussed on the Scarborough bluffs where bluff failure and recession is a severe problem (eg. Bryan and Price 1980, Eyles and Hincenbergs 1986, Fowle et al. 1982, Buttle and Von Bulow 1986). After a series of geotechnical studies, shoreline revetments were built along sections where erosion most threatened Scarborough bluff top developments, as reported by Parker et al. (1986). In addition to these studies, Lake Ontario has also been the focus of several studies designed to determine the effect of nearshore erosion on bluff recession rates. Studies by Davidson-Arnott (1986), Davidson-Arnott and Ollerhead (1995), and Davidson-Arnott and Langham (1995) are not listed in Table 3.3, but the effect of nearshore processes on the bluffs is important to note and understand. Research conducted between Burlington and St. Catharines has determined that vertical lowering of the near shore profile is an important control in bluff recession and that the two are in dynamic equilibrium.

A number of studies have, therefore, been conducted on the bluffs of Michigan, Ontario, and to a lesser degree Huron and Superior. Although the hazards and hazard zoning is mentioned from time to time, most of the emphasis has been placed on understanding the geotechnical and geologic nature of the bluffs. In some cases this has even been attempted through the use of computer programs to assess slope stability through variations of deterministic slip circle analyses (eg. Edil and Haas 1980, Schultz et al. 1984, Bosscher et al. 1988). In no cases, however was GIS reported to have been used to examine or map shoreline slope failures.

3.3 - Coastal Slope Failures and Lake Erie

The previous section of this chapter has highlighted several examples of bluff research along the Great Lakes shoreline. These examples illustrated the lack of focus on the human risks, as well as the limited use of computers in the zonation or analysis of coastal bluff failures. As Lake Erie merits its own separate discussion, this section focusses attention on bluff research which has been conducted along the American, and in particular, the Canadian shore of this Great Lake.

3.3.1 - Lake Erie Bluff Research, Hazards and Mitigation

Lake Erie forms a natural border to south-western Ontario, and the states of Michigan, Ohio, Pennsylvania and New York (Figure 3.1). In general, it exhibits similarities with much of the Great Lakes shore in terms of bluff erosion, hazards, glacial history, population pressures, and even management problems. Though the number of bluff studies are by no means towering, Lake Erie's bluffs have been the prime focus of most Great Lake bluff studies, of which many contributed a wealth of knowledge to the understanding of global coastal slopes and their dynamics (Hutchinson 1986).

Table 3.4 summarizes some of the major studies conducted along the Lake Erie shore, both in Canada, and the United States. The provinces or states referred to within this table can be located on Figure 3.1. Carter et al. (1987) provided a comprehensive, yet generalized overview of the entire Lake Erie shore erosion issue. Though geared towards the issue of lake level flooding, the book discussed several topics which related to the bluffs, including the human and physical history of the Lake, the nature of the bluffs, a discussion of physical and human factors which contribute to erosion and failure, and shore protection (Carter et al. 1987).

Perhaps the earliest study to focus directly on the bluffs was completed by Chieruzzi and Baker (1958) in Perry Township Park near Painesville Ohio. This study was no doubt initiated as a result of the 1951-1952 high lake water levels, and provided a comprehensive overview of the factors responsible for the failures using geotechnical and geological surveys, in light of years of shoreline damage and threats to inland developments and valuable orchard and agricultural lands along much of the entirety of the Ohio shoreline (Chieruzzi and Baker 1958). Studies along the American shoreline are not evident again until the early 1980s where Calkin (1978), and Geier and Calkin (1983) reported on the bluffs of New York state, and Knuth (1983) reported on recession rate studies from Pennsylvania.

Table 3.4: Lake Erie inventory of bluff erosion and failure studies

STUDY LOCATION	INSTITUTION	DATE OF RESEARCH	RESEARCH AREAS	MAJOR FINDINGS	COMPUTER ANALYSIS	AUTHOR
CANADA and USA						
Shore of Lake Erie	National Audubon Society	~1987	GL, NS, SM, CL, GE, WE, MN, BC, FF, HY, RR Anthropogenic Hazard	- broad overview of the entire Lake Erie shore, including many physical and human aspects influencing its dynamics - bluff erosion and failure factors - stresses the negative human influence on erosion and need for better indirect management - maps rank shoreline hazards based on recession rates, flood potential, beach width, and protection	No	Carter et al. (1987)
OHIO STATE						
Perry Township Park	University of Ohio, Columbus	~1957 - 1958	RR, GL, CL, NS, HY, GT, MN, BC, FF, WE Anthropogenic Hazard	- overview of bluff erosion problem on Great Lakes and south Erie shore - detailed investigation of bluff stability, erosion control, and management - seepage, rain, ice, waves play a major role in stability - remediation works best if it is regional, and not site-specific due to coastal dynamics - recession and failure can be halted through toe protection, beach development and stable slope development	No	Chieruzzi and Baker (1958)
PENNSYLVANIA STATE						
Ohio State Line to New York State Line	Commonwealth of Pennsylvania Coastal Zone Management Program	1974 - 1982	RR, NS, BC, MN Anthropogenic Hazard	- short (1yr) and long-term (8yr) recession rates are presented on a one km grid along the shoreline - information will support the Bluff Recession and Setback Act which help reduce community risk to bluff recession eg. Erie Pennsylvania	Bluff Crest Digitization	Knuth (1983)
NEW YORK STATE						
Hamburg to Pennsylvania State Line	New York Sea Grant Institute / State University New York, Buffalo	1974 - 1983	GL, RR, VE, WE, FF, BC, CL, MN Anthropogenic Hazard	- recession rates vary over time and space - recession rates are lower than Ontario and other States due to protective action of bedrock bluffs (shale) and protective structures - volumetric erosion and stratigraphy is spatially variable and due to a number of factors - information will be used to plan and manage shore recession, hazards, and risks	No	Calkin (1978), Calkin and Geier (1983), Geier and Calkin (1983)

ONTARIO						
Leamington to Colchester	Essex Region Conservation Authority / Ministry of Natural Resources	-1974 - 1976	GL, FF, SL, GT, NS, RR Hazard	- overview of bluff recession given for area in addition to many factors which contribute - erosion of bluff toe by failure (clay) or undermining (sand) from wave action is the prime reason - recession rates and slope stability calculated and profiled - results from Pigeon Bay and Colchester are compared	No	Kilgour et al. (1976)
Peacock Point to Detroit River	UWO	-1971	FF, MN, GL, WE Anthropogenic	- summary of erosion problems, processes and many factors - human factors play an important role in bluff erosion - limitations of erosion control structures - case studies in management from Point Pelee, Harbours, and Long Point - management must assess the entire coast as an ecosystem	No	Caldwell (1971)
Rondeau to Long Point	UWO	-1964 - 1975	FF, RR, SM, WE Anthropogenic	- three main morphological types of failures - lake levels and wave energy important factors in variable recession rates - comparison to London Clay cliffs, south and east England - tile drainage can initiate erosion and gully formation	No	Quigley and Gelinas (1976)
Patrick Point, Iona, Pt. Stanley and Port Bruce	UWO	1964 - 1976	HY, GT, WE, CL, RR, FF, NS, SL	- detailed description of site processes - differential recession rates between sites - failure is cyclical and based on complex terrestrial and marine factors, especially lake levels - four basic types of cyclic failure identified	No	Quigley et al. (1977) Quigley et al. (1978)
Port Bruce	UWO	1964 - 1977	FF, RR, GL, GT, SL, SM, VE	- failure, volumetric erosion, and slope angle is cyclical, about 7 to 25yrs - failure cycles are the result of softening during low lake levels, and toe erosion during high lake levels and storm events - 4 morphological failure types are identified	No	Quigley and Tutt (1968), Quigley and DiNardo (1980)
Port Bruce and Colchester	UWO	-1964 - 1978	SM, SL, RR, VE, MN	- short-term mapping of shoreline geomorphology usually overlook the short term bluff cycles and spatial and temporal variation of other factors - strip maps of shore geology, long-term geotechnical data are very useful - positive relationship between wave energy and recession rates at Port Bruce, but not Colchester, relationship still a matter of conjecture - hydraulic and geotechnical factors vary from region to region and play different roles at each site	No	Quigley and Zeman (1980)
Port Burwell to Long Point	NWRI	-1978	RR, ST, WE, SM, GE, BC Anthropogenic Hazard	- north shore of Erie has highest recession rates of Great Lakes - bluff erosion affected by shore orientation - apart from Port Burwell jetty, the shore suffers erosion from purely natural processes - future studies are needed to determine individual influence of terrestrial and aquatic variables	No	Zeman (1978)
Port Burwell to Clear Creek	NWRI	1978 - 1983	CL, WE, GL, NS, SM Anthropogenic Hazard	- long history of human activity in region - erosion of this cohesive coast is complex - different coastal process models are needed to predict cohesive shore erosion and the behaviour of beach materials on cohesive coastlines - coastal structure interactions may be slightly different than previously understood on the Great Lakes	No	Philpott (1983, 1986)

Port Burwell to Long Point	NWRI	~1978	RR, SM, NS, WE, CL Anthropogenic	· nearshore barriers only affect sand shores · recession rates vary over time and space · errors of precision and accuracy associated with recession rate calculations · a linear relationship exists between wave energy and recession rate · effect of nearshore sand deposits is essential to understand jetty effect	No	Dick and Zeman (1983)
Pointe Aux Pins to Long Point	NWRI	~1986	RR, FF, WE, NS	· foreshore erosion is the controlling factor of bluff erosion and is a function of wave energy and foreshore geotechnical properties · wave action is insufficient to erode the hard glacial till of the study site, and instead, granular sediments act as an abrasive to cause erosion	No	Kamphuis (1986)
Port Glasgow to Clear Creek	NWRI	1978 - 1987	NS, GL, SM, VE Anthropogenic	· nearshore sediment budget calculated based on stratigraphic nearshore sediment distribution and bluff stratigraphy · harbour structures have only a short term effect (8yrs) · very low downdrift accumulation rate in the study area (1%) · bluff erosion accounts for 89% of the sediment supply	No	Rukavina and Zeman (1987)
Port Burwell and Port Granby (Lk. Ontario)	NWRI	~1988 - 1990	HY, GT	· seepage is a major contributing factor to erosion of non-homogenous bluff material along the Great Lakes · traditional Limit Equilibrium Methods are replaced by Finite Element Seepage Analysis Methods to accurately assess the Factor of Safety in bluffs with seepage · design and effectiveness of dewatering remedial measures can be easily assessed in Finite Element Seepage Analysis Methods	Finite Element Seepage Analysis - PC-SEEP	Zeman (1990)
Nanticoke to Port Bruce	OGS	~1973 - 1983	GL, FF, SM, GE, MN	· variable bluff composition and stratigraphy between Port Bruce and Nanticoke is given an comprehensive review, and is mapped · materials affect outline of shoreline, seepage, profiles, stability, erosion · complex erosion factors and processes · this information should be incorporated into shore erosion protection and management studies · various types of failures are identified in addition to discussion on gully erosion and formation · glacial history of the region	No	Barnett (1983a, 1983b, 1987, 1990), Barnett, OGS, OMNR (1983), Barnett, Bajc, Sando (1983), Barnett, Sando, Bajc (1983)

NOTES and LIST OF ABBREVIATIONS:

~ - signifies an approximated date, no date provided in the report
BC - Beach Conditions (beach width, slope angle, beach material)
CL - Climate
FF - Failure Factors - (various)
GE - Gully Erosion
GL - Geology (bluff material, lithology, stratigraphy based on drill holes or bluff face)
GT - Geotechnical analysis (soil strength, stress, properties, density)
HY - Hydrology and Hydraulics (seepage, piezometric readings, ground water)
MN - Management and Control of Erosion (direct and indirect, past or future recommendations)
NS - Nearshore - (water levels, currents, nearshore sediment budgets)

RR - Recession Rate
SL - Slope Stability (profiles and calculations based on Bishops' Factor of Safety)
SM - Slope Morphology (height, slope angle, orientation)
VE - Volumetric Erosion
VG - Vegetation
WE - Wave Energy/Power

Hazard - mention made of threat or damage to property, buildings, or human life
Anthropogenic - human factors discussed as influences in shore bluff erosion

On the Canadian side of the lake, studies have been completed by four main centres, including the Essex Region Conservation Authority, University of Western Ontario (UWO), the National Water Research Institute (NWRI), and the Ontario Geological Society (OGS). The first of these studies was by Essex Region Conservation Authority along the western Lake Erie shore between Leamington and Colchester after the 1972-1973 high water levels. This study provided an overview of the nature of the bluff dynamics and measured recession rates and slope stability through geotechnical analysis.

The final three sets of studies describe bluff research along the north central shore of Lake Erie, generally between Erieau in the west to Long Point in the east. In this section, bluff erosion is particularly pronounced and long term rates range from 0.2 to 4.9 metres per year (Boyd 1981). One of these sets of studies has been compiled by UWO. In 1971, Caldwell (1971) provided one of the first general, holistic, overviews of the Lake Erie north shore region in light of increasing shoreline development and population growth. This holistic examination included a discussion of such topics as transportation, recreation, agriculture, industry, and the physical nature of the shoreline, among others. A major focus of the report was bluff erosion along the shoreline, including sub-aerial and marine factors of the erosion and failure, and its implications for future development and land use planing.

UWO was also the source of several geological and geotechnical studies on the bluffs as early as 1964, but largely after the 1972-1973 high water levels. In 1968 Quigley and Tutt (1968) analysed the massive erosion and landsliding taking place near

Port Bruce. They estimated that the bluffs had receded up to 10 miles over the past 10,000 years, and predict that continued recession would greatly affect shoreline developments along Erie's north shore. Later, Quigley and Gelinas (1976) provided a qualitative summary of the mechanics and three major morphological types of bluff retreat using bluffs at four study sites. They also compared Lake Erie bluffs with those of London Clay in England, as described by Hutchinson (1986). Quigley et al. (1976, 1978) continued their investigation of the bluffs from a quantitative perspective and outlined the complexity of bluff retreat mechanisms and bluff processes. Their reports proposed that the different types of retreat are largely 'cyclic' and they described this phenomena as a reaction to lake water levels and various terrestrial processes. Further studies by Quigley and his colleagues focussed on research stations near Port Burwell and Port Bruce. 'Cyclic' instability, recession rates, volumetric erosion and results from other geotechnical studies at Port Burwell were also compared to results at Colchester (Quigley and Zeman 1980) and Port Bruce (Quigley et al. 1978). Another study (Quigley and Di Nardo 1980) reviewed factors which contributed to bluff instability at Port Bruce, and examined the stability of the bluffs through geotechnical slip circles.

A third set of studies was conducted by the NWRI at the Canada Centre for Inland Waters (CCIW) in Burlington. Most of this research occurred in response to a $30 million legal claim filed against the Canadian government in 1978 (Philpott 1986). Shore owners east of Port Burwell alleged that the Port Burwell breakwater was responsible for shore erosion, and subsequent damage to property and loss of land. In 1985, the Canadian Government finally ruled against the shore owners' claims, after which, several reports were published by Philpott to summarize the studies conducted during the investigation (eg. Philpott 1983, 1986).

Zeman (1978) also summarized research that had been conducted in the disputed area prior to the litigation claim. These exploratory studies gathered data on recession rates, wave power energy, gully formation, and preliminary information on shore stratigraphy, morphology, and slope failure factors. This summary also recommended that further sub-aerial and aquatic studies be initiated in order to understand processes better, especially the role of the Port Burwell harbour breakwater amidst a plethora of natural causes (Zeman 1978). A report by Dick and Zeman (1983) discussed the difficulty of assessing recession rates due to spatial and temporal variability and the accuracy of methods such as photo maps and charts. Kamphuis (1986) summarized the relationship of wave energy with bluff recession and noted that abrasion by sediment load is chiefly responsible for toe erosion along the bluffs. A further study examined the nearshore sediment budget in the claim area based on calculations using stratigraphic nearshore sediment distribution and bluff stratigraphy (Rukavina and Zeman 1987). Zeman (1990) later assessed data from the study area and at Port Granby to examine the possibility of using computer generated limit equilibrium models to determine slope stability of the shoreline's non-homogenous bluffs, and to assess slope drainage works as a means of reducing seepage and groundwater effects on bluff failure.

A final set of investigations focussed on the terrestrial side of the north-central Lake Erie shoreline. During the 1980s, the OGS initiated an extensive geologic examination of the bluff faces between Port Bruce and Nanticoke, as reported by Barnett

(1983a, 1983b, 1987, 1990), Barnett, OGS and OMNR (1983), Barnett, Bajc and Sando (1983), Barnett, Sando and Bajc (1983). Information from these reports included the description, recording and analysis of the bluff stratigraphy and materials, in addition to an interpretation of the regions' glacial history, and factors responsible for gully and bluff erosion. These studies later contributed to an important OGS map on the Quaternary Geology of Southern Ontario (Barnett, Henry and Babuin 1991).

3.4 - Great Lakes and Lake Erie Bluffs: Implications for Future Research

Together with human encroachment at the shoreline, coastal slope failures are a serious hazard. This chapter has illustrated several important aspects of coastal slope failures which together, justify the need for further research into the dynamics, management and especially, the mitigation of bluff hazards and risks. An extensive literature review has evidenced the global nature of the bluff hazard. Worldwide reports have also described a wide array of human risks and bluff tragedies at the shoreline, in addition to numerous research projects, and attempts to mitigate the hazard through management plans, policies, and a host of engineered initiatives. Despite these efforts, there are a number of common and important problems with bluff hazard research.

Many of the gaps in coastal bluff studies are evidenced along the Great Lakes, and in particular, Lake Erie, where research, management and the nature of bluff failures mirror those of an international context. Extensive geotechnical studies have examined the terrestrial and marine nature of the bluffs, and recent management plans have discussed the bluff erosion problem, so that a great deal of information has now been collected, and the dynamics of the bluffs are relatively well understood. This information should now be analysed and applied to the mitigation of bluff hazards along the Great Lakes shoreline. Unfortunately, most studies and management schemes along the Erie and Great Lakes shore are applied to the inundation, damages, and hazards of lake levels in low-lying, flood-prone areas. Efforts need to focus more solely on the bluffs, and the threats which they pose to human well-being through rapid, large-scale bluff failures. Literature suggests that these events pose a serious threat to both property and human life (eg. Bird 1984, Bender and Lawson 1994, Reuters Information Service 1996, Ferris 1999). Work on the bluffs is also site-specific, reactive rather than pro-active (Kreutzwiser 1992, Schultz et al. 1984, Bosscher et al. 1988), and focussed on individual aspects of the marine or terrestrial environments. In order to understand and mange the bluffs effectively, a holistic investigation is necessary which incorporates both human and physical factors.

At present, the lack of a comprehensive, effective shoreline management policy in Ontario and Canada makes shoreline management difficult. In lieu of this problem, and in lieu of the fact that this situation may exist for some time, it is important that bluff management not wait for future tragedies to occur before measures are finally taken to reduce risks. A proactive approach should be taken to immediately make use of available data. Together, the TGGLSLS and GPSS provide a useful, standardized, guide to assessing, and managing bluff hazards along the Canadian Great Lakes, even without a provincial shoreline policy. Since the provincial government provides the CAs with authority to formulate localized SMPs, access to governmental data, and encouragement to use modern research technology (Lawrence 1995c), it seems advantageous for the CAs to develop bluff hazard management plans and analyses at a local, yet regional level. Through the guidance of the TGGLSLS and GPSS, this could be accomplished through useful computerized tools such as Geographic Information Systems.

Several sources were noted throughout the chapter as having used computers to analyse coastal slopes. Others have simply recommended hazard zone mapping and use of GIS to mitigate coastal risks (eg. Monmonier 1987, Grainger and Kalaugher 1988). The ability of a GIS to accommodate multivariate, regional data, and its ability to store, update and effectively present results, makes it an ideal tool with which to analyse the multidisciplinary, ever-changing environment of coastal bluffs. As a prelude to the GIS application presented in Chapters Five through Seven, Chapter Four first examines the benefits and methods of GIS applications in slope stability analysis.

CHAPTER FOUR

Hazard and Risk Mapping with GIS: An Aid to Slope Failure Mitigation

"Crime, of course, is but one of many hazards for which risk varies from place to place. Wouldn't it be helpful to have no-go, no-build, or no-live maps for all kinds of nasty surprises?" M. Monmonier (1997)

4.0 - Mitigating Slope Failures Hazards and Risk through GIS

The previous three chapters briefly summarized the nature of coastal slope failures, their hazards and risks in both a local and global context. Losses due to coastal and inland slope failures are increasing as residences, highways, recreational developments, and major structures spread into unstable regions. This spread is often occurring so rapidly "that it outstrips the capabilities of existing engineering services for detailed stability analyses on a site by site basis" (Dunne and Leopold 1978, 573). For these reasons, the potential failure of hillslopes is rarely considered in most development, even in areas prone to slope failures. To counteract this trend, and perhaps to reduce landslide damage if the information is used by planners, efforts are now being made to map the susceptibility of slopes to failure (Dunne and Leopold 1978). This technique usually involves mapping slope failures, and/or factors which contribute to slope failure, such as slope inclination, geology and hydrology. Susceptibility can then be combined, or overlaid, with some indication of the potential threat to human well-being to produce risk maps.

The purpose of Chapter Four is to briefly summarize how computers, and particularly GIS, are increasingly useful tools in assessing slope stability. Although previous research has focussed almost exclusively on inland slope failures, the methods and techniques are just as valuable in the reduction of risk at the coastline. Several major approaches to slope stability assessment are discussed first, followed by a brief summary of the benefits and methods of GIS in slope assessments, and finally, a review of several GIS and 'indirect' coastal hazard mapping applications. Ultimately, this summary will help to clarify and justify the methods of research described in the following chapters of the paper, as well as the context and contribution of this research paper amidst other contemporary slope stability analyses.

4.1 - Engineering and Geomorphological Approaches

Over the past decade and a half, several sources have made an effort to summarize the major methods used to estimate slope instability. Doornkamp (1989) and Bonham-Carter (1994) contributed general overviews of computerized mapping in the earth science field, while Hansen (Hansen A. 1984), Hearn and Fulton (1987), Fulton (1987), Cooke and Doornkamp (1990), and Jones (1992) provided excellent summaries of mapping, computers and GIS more specific to slope investigations. Carrara is another major literary contributor to this field. Several key reports provide a useful overview of slope stability analysis, particularly in light of his own research in Italy (eg. Carrara et al. 1991, Carrara et al. 1995, Carrara and Guzetti 1995). The most effective, thorough, and up to date summary of computerized slope analysis is, however, a recent article by Soeters and Van Westen (1996) amidst a large, comprehensive report on landslides by Turner and Schuster (1996). Together with Hansen (Hansen A. 1984), these authors catalogued and discussed different examples and methods of slope stability analysis. Using their combined suggestions, slope stability investigations can be described, very generally as either i) Engineering Approaches; or, ii) Geomorphological Approaches.

Figure 4.1 summarizes the two major slope investigation techniques, in addition to their relevant 'sub-approaches'. This chart also indicates whether or not the approaches are amenable to either manual or GIS/computer methods of investigation. Though this chart tends to imply that each method is independent of another, there is often overlap or interaction between each technique. For example, Engineering approaches often draw on regional information generated within Geomorphic Approaches, and frequently make use of site specific deterministic models, which are often associated with Geomorphic Techniques.

With the *Engineering Approach* (non-mapping) the engineer is largely interested in the stability of the individual site or slope on which they are working. Data derived from geotechnical investigations can be substituted into conventional empirical and deterministic slope stability computer models in order to determine the factor of safety of

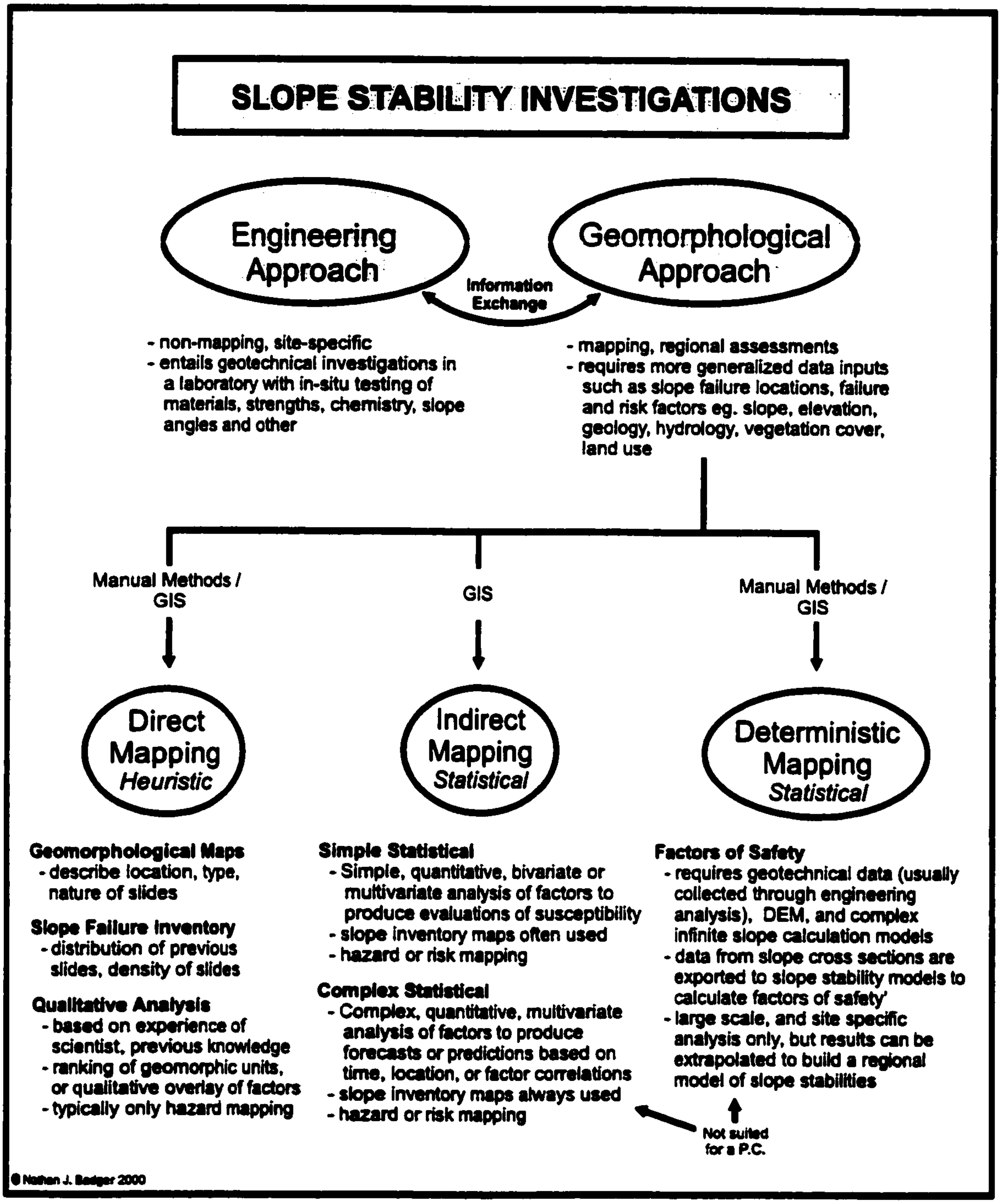


Figure 4.1: Classification of major approaches to slope stability investigations. The chart summarizes the main points of each method, and indicates whether the approach is amenable to manual and/or GIS techniques. Some overlap and interdependency exists between classes.

the slope in question (Soeters and Van Westen 1996). Some of these tests are described by Graham (1984), including the stability coefficients of Bishop, Janbu, and Morgenstern.

Geomorphological Approaches to slope assessment have also evolved to counter the time, costs, and intensity of large scale surveys associated with the Engineering approaches. These techniques aim to delineate the most hazardous or risky areas in a region, so that detailed engineering investigations can, subsequently, be concentrated in areas where it is most required (Hansen A. 1984). This process of delineation is often termed 'hazard zonation', where assesments attempt to determine the spatial variability of slope stability (Carrara et al., 1995). In contrast to the engineering approach, regional map construction plays an important part in displaying and disseminating information (Hansen A. 1984). In turn, however, geomorphological assessments are often used to direct and aid engineering approaches (Hansen A. 1984).

The Geomorphological Approach, as described by Soeters and Van Westen (1996), can be achieved using three significantly different techniques, including: i) Direct Mapping; ii) Indirect Mapping, and iii) Deterministic Mapping. Each of these approaches are summarized in Figure 4.1. For detailed descriptions of these methods, the reader is referred to research by Hansen (Hansen A. 1984), Jones (1992), Carrara et al. (1995), and Soeters and Van Westen (1996).

Direct mapping focusses on the analysis of the landforms and identification of previous and present failure locations from which to extrapolate assessments of slope stability to the rest of the study area. In essence, this approach identifies the *effects* of natural and human induced processes on the landscape (Hansen A. 1984), and may include slope failure inventory maps, and geomorphological maps (Jones 1992).

Indirect mapping and *Deterministic mapping* require the identification, collection and mapping of data which pertains to the factors and mechanisms of slope failure (Jones 1992). These approaches focus on the *causes* of slope failure or damage, and aim to identify the controlling parameters of the slope failure system and to construct models which simulate this system, in order to predict favourable or unfavourable conditions (Hansen A. 1984). Indirect techniques that focus on the probability, or likelihood of the event are often termed 'susceptibility' or 'probability maps', while indirect techniques which involve the assessment of the potential losses that may be incurred by society through hazardous impacts, are distinctly different in theme, and are generally referred to as 'risk maps' (Hansen A. 1984). Either way, the construction of these maps can be accomplished at various levels, including both qualitative or quantitative, and bivariate or multivariate analysis (Figure 4.1).

During the 1980s the use of GIS for slope instability mapping increased sharply because of the availability of user-friendly software and faster Personal Computers (PC). Over the past decade, research on slope stability zonation appeared at an increasing rate within the literature, and will doubtless continue to do so. Despite the growing number of reports of GIS use in slope stability analysis, in addition to the wide range of applications and locations, analyses appear focussed on inland slope hazards and risks, and no GIS slope stability studies were discovered for coastal applications.

Many case studies presented in the literature are semi-direct, where quantitative data (eg. slope inclination, elevation) is converted to qualitative data, in the form of hazard classes, and then overlaid to determine a rating of hazard or risk. This approach is used by Kawakami and Saito (1984) in the mountains of northern Japan, and by Mora and Vahrson (1994) in central Costa Rica. Reading (1993) also approached slope stability analysis in Greece, with the additional weighting of factors in order to account for their differential contribution to slope instability.

In the case of complex, statistical analysis, techniques often rely on knowledge of previous occurrences, or evidence of past failures, together with instability factors, to arrive at a judgment as to the likelihood or potential of future events (Carrara et al. 1995, Hansen A. 1994). These approaches also make use of discriminant, conditional or regression analysis to enrich their assessment. Recent examples of multivariate statistical analysis using GIS and logistic regression are presented by Carrara and his team from Italy (eg. Carrara 1983, Carrara et al. 1991, Carrara et al. 1995). The statistical model is 'built up', or calibrated in a 'training area' where the spatial distribution of landslides is (or should be) well known. In the next step, the model is extended to the entire study area, or 'target area' on the basis of the assumption that the factors that cause slope failure in the target area, are the same as those in the training area. These factors may include geology, stratigraphy, vegetation cover, aspects of hydrology, and even land use in the case of risk maps (Carrara et al. 1995, Navarro and Wohl 1994).

A number of examples of indirect mapping, particularly statistical, are reported in the literature. Rowbotham and Dudycha (1998) used multivariate, logistic regression on geomorphometric units in the Phewa Tal watershed of Nepal, while similar studies were also performed by Gupta and Joshi (1990) in the Ramganga Catchment of the Himalayas, and by Atkinson and Massari (1998) in the Italian Appenines. Another example of multivariate analysis of landsliding using GIS was presented by Bernknopf et al. (1988), who applied multiple regression analysis to a data set using presence or absence of slope failures as the dependent variable and the factors as independent variables. Among a large number of other examples, other indirect techniques utilized Monte Carlo simulations, logistic regression, discriminant analysis, bivariate analysis, and other multivariate analyses, as evidenced in work by Brabb (1995), Shu-Quiang and Unwin (1992), Naranjo et al. (1994), Thein et al. (1995), Mark and Ellen (1995) and Davis and Keller (1997), Fernandez et al. (1999). Navarro and Wohl (1994) present an especially interesting study where indirect GIS techniques are applied to the urban foothill area of Medellin, Columbia to assess risk of slope failure. Various physical factors were first combined to determine slope failure susceptibility, and then overlaid with land use vulnerability for the final risk maps, which were then presented to urban planners.

Deterministic models (Figure 4.1) require geologic conditions to be fairly homogenous, landslide types simple, and complex mathematical models available with which to evaluate stability factors through hydrological and geological slope stability models. Several cross sections are usually taken through one or more slopes, and the 'stability' of the slope/slopes extrapolated to a regional scale (Soeters and Van Westen 1996). Chapter Three of this paper noted several examples of the use of deterministic models used to examine the stability of bluffs along the Great Lakes (eg. Shultz et al.

1984, Edil and Vallejo 1980, Bosscher et al. 1988, Zeman 1990). Complex combinations of deterministic slope stability models, GIS software packages, and Digital Terrain or Elevation Models (DTM and DEM), are also recently reported in literature for assessments in civil engineering in Columbia (Van Westen and Terlien 1996), groundwater and hydrological considerations in Columbia and Costa Rica (Terlien et al. 1995), timber harvesting in Washington (Miller and Sias 1998), and for analysis of the problematic Leda Clays near Montreal, Canada (Tabba 1984), and, simple landslide analysis in Vorarlberg, Western Austria (Van Asch et al. 1993).

As a final note with regard to slope stability investigations, 'probability' or even 'susceptibility' of slope failure, should not be confused with the exact time of a slope's failure. On a regional scale, the temporal dimensions of slope failure are essentially a function of triggering mechanisms such as extreme rainfall, or earthquakes (Rowbotham 1995). In spite of an increased understanding of the dynamics of slope systems and factors contributing to slope instability, the timing of such triggers is not readily linked to a model of spatial instability. Instead, forecasting and prediction of slope failure timing is complex (Hansen A. 1984). Thus, most of the current, regional, hazard and risk maps are not usually able to predict when, or even exactly where failures are most likely to occur (Carrara et al. 1995).

4.2 - Geographical Information Systems

Great strides have recently been made in the field of land stability assessment, especially with respect to the range and accuracy of slope failure hazard assessments

(Jones 1992). The identification and delimitation of hazard or risk zones undoubtedly provides an extremely valuable framework for decision-makers (Naranjo et al. 1994). The aid of computers and GIS in this process is regarded as being highly advantageous (Hansen A. (1984), and may provide a spring-board for a rapid increase in investigations (Carrara et al. 1995, Naranjo et al. 1994).

Although a lengthy discussion of GIS is beyond the scope of this thesis, it is helpful to understand, in summary form, both the advantages and disadvantages of using a GIS in slope investigation methods. Section 4.3.2 discusses several limitations to GIS, while this section summarizes several of its advantages. For detailed discussions of GIS, the reader is referred to general texts such as those by Burroughs and McDonnell (1998), Aronoff (1989), Obermeyer and Pinto (1994), or Bonham-Carter (1994).

Very simply, GIS are computer based systems that are used for the collection, storage, manipulation and analysis of georeferenced objects, phenomena and spatial and non-spatial or attribute data, where geographic location is an important characteristic or critical to the analysis (Obermeyer and Pinto 1994). A GIS must provide the following four sets of capabilities to handle georeferenced data: **i)** input **ii)** data management (data storage and retrieval), **iii)** manipulation and analysis, and **iv)** output (Aronoff 1989). Table 4.1 summarizes some of the advantages of GIS within slope stability analysis, particularly in terms of the four GIS components mentioned previously. Each of these will become clearer in the latter portion of this chapter, and in the case study presented later in this paper.

Table 4.1: Advantages of GIS applications in slope stability analysis

Advantages of GIS Applications in Slope Stability Analysis
• Data input is flexible ... both method and source: eg. digitizer, scanner, mouse, keyboard, photos, remote sensed images, text and graphic files • Interactive display, mistakes undone easy • Handles and stores large amounts of data • Single database • Database easily updated or adjusted • Georeferencing to a single, common base map • Export and import of data is possible • Interplay with wide variety of GIS related software and hardware • Powerful spatial analysis • Quality, accuracy, flexibility and ease of output eg. text, maps, tables, 3D, 2D, digital file, screen image, hard copy • Cost-effective at a local planning level

Perhaps most important of all advantages listed in Table 4.1 is the powerful spatial analytic capabilities of the GIS, which distinguish it from other types of information systems or manual methods of slope stability investigations. The analysis of complex, multiple spatial and non-spatial data sets in an integrated manner forms the major part of a GIS's capabilities, particularly in slope stability analysis (Aronoff 1989, Carrara et al. 1995, Coppock 1995, Reading 1993). One particularly powerful spatial function of most GIS is overlay analysis, which enables the user to combine the attributes of one map layer with another according to a user-specified logic in order to produce derivative map output showing relationships between the phenomena of both map layers" (Bonham-Carter 1994). The following section builds on the spatial analysis capabilities of a GIS and discusses the dominant approach to computerized slope stability assessments.

4.3 - GIS and Slope Stability Analysis

Many methods and techniques are proposed to evaluate the landslide hazard and to produce maps portraying its spatial distribution (landslide hazard zonation). A number of these, including those which involve GIS, were discussed in Section 4.1. At present, there is no agreement on either the methods, or even the scope of producing hazard maps (Carrara et al. 1995). The following sections discuss the dominant approach to slope stability analysis, in addition to some of the limitations and errors which can accompany GIS analyses.

4.3.1 - Construction of Terrain Units and Overlay Analysis

Despite the conflicting views, the mess of terminology, and the methods of describing and organizing hazards maps, most of the methods proposed are founded upon a single conceptual model. This requires, when possible, to first map the landslides over a target region, or a subset of it (training area), and further, to identify and map a series of geological and morphological factors which are directly or indirectly correlated with slope instability (Carrara et al. 1995). The spatial variation and correlative magnitude of the factors is then estimated and applied to the demarcation and zonation of 'susceptibility' and 'risk'. Zonation refers to the division of the land surface into homogenous areas or domains and their ranking according to degrees of actual/potential hazard caused by slope failures (Carrara et al. 1992).

Slope failure factors may be obtained from field work or readily available digital or hard copy maps (Carrara et al. 1995), from DEMs (Burroughs and McDonnell 1998, Rowbotham 1995, Niemann and Howes 1992), or even from remotely sensed image (both satellite and aerial photography), as described by Crozier (1984), Van Westen (1993), and Mantovani et al. (1996). Whatever the case may be, hazard zonation requires a detailed knowledge of the processes that are, or have been active in the slope area (Van Westen 1993, Hansen A. 1984). This should be addressed through literature reviews, field work, map research, and other background studies (Hansen A. 1984, Varnes 1984, Turner and Schuster 1996), or data bank inventories, as reviewed in studies such as Dikau et al. (1996), and Collotta et al. (1988) and Carrara et al. (1995).

The model then requires both an estimate of the relative contribution of these factors (individually and collectively) in generating slope failures, and finally the classification of the land surface into domains of different hazard degree through various techniques which assess the relationship between slope failures and the contributing factors. This model is based on the well-known and widely applied, uniformitarian principle "the past and present are keys to the future" (Varnes 1984, Hart 1986), and implies that slope failures in the future will be more likely to occur under those conditions which led to past and present instability (Carrara et al. 1991, 1995, Hansen A. 1984). In order to build up the hazard model, investigators may use heuristic (index) or statistical approaches (probabilistic)(Carrara et al. 1991, 1995, Hansen A. 1984), and even weight the various factor maps (Soeters and Van Westen 1996).

Most hazard assessment techniques operate by the manipulation or combination of one or more environmental factors. One feature common to nearly all of the factors is spatial variability, and the measurement and cartographic representation of these factors. In natural environments, the interrelations between materials, forms, and processes result in morphological boundaries which frequently reflect geomorphological and geological differences. Thus, it is widely accepted that the ideal sampling unit with which to measure environmental factors is the homogenous geomorphological unit (Carrara et al. 1995, Hansen A. 1984). Geomorphological units may be obtained in a pre-ready or digitized map format, or may require construction through the combination of several separate geohomogenous data layers.

The chief concern with data describing geohomogenous units is its transfer from hard copy sources (such as maps) to a digital format. This step is critical as it determines the functionality of the data later in analysis. Thus, geohomogenous units can be simplified in several ways, each of which may allow automated data encoding, storage, analysis and final map production stages in a GIS. This is usually accomplished by organizing data from geohomogenous units into 'terrain-units' (or mapping unit or homogenous domain), including either polygons or geometric units, such as grids (Hansen A. 1984). Terrain units are useful as the final hazard zonations can be quickly updated if new data are added, either in the form of additions to existing factor maps (for example as new landslide deposits are recognized) or even as new factor-maps are produced (Hansen A. 1984). By definition, the terrain-unit must be mappable at effective cost and time over the entire region through criteria which are as objective as possible. When this is accomplished, all the subsequent analyses will refer to and treat each terrain-unit as a spatially homogeneous domain in terms of both instability factor characteristics and landslide hazard degree. In each case, a terrain-unit is necessary in order to generate a data-base of the environmental data needed to describe a given process or phenomenon, and to build up a predictive or explanatory model of the spatial or temporal distribution of such a phenomenon (Carrara et al. 1995).

Various methods are proposed to define the terrain-units for environmental factors (Meijerink 1988). Computer amenable data can take the form of a either polygons or grid units, to which are applied spatial coordinate or reference systems and attribute values. Figure 4.2 describes a sample list of parameters that might be mapped, and various processes involved in representing and analysing the geohomogenous units in a GIS environment. The first method relies on the fact that geohomogenous, irregularly shaped units can be simplified from paper maps into *polygons*, wherein vertices are joined by straight lines (Figure 4.2). Maps can be encoded using a coordinate digitizer with the degree of complexity of the polygons being modified to suit accuracy and data storage requirements. In large areas or multivariate studies, the small loss of boundary definition is offset by the greater speed of analysis. Factor-maps composed of polygonal units can

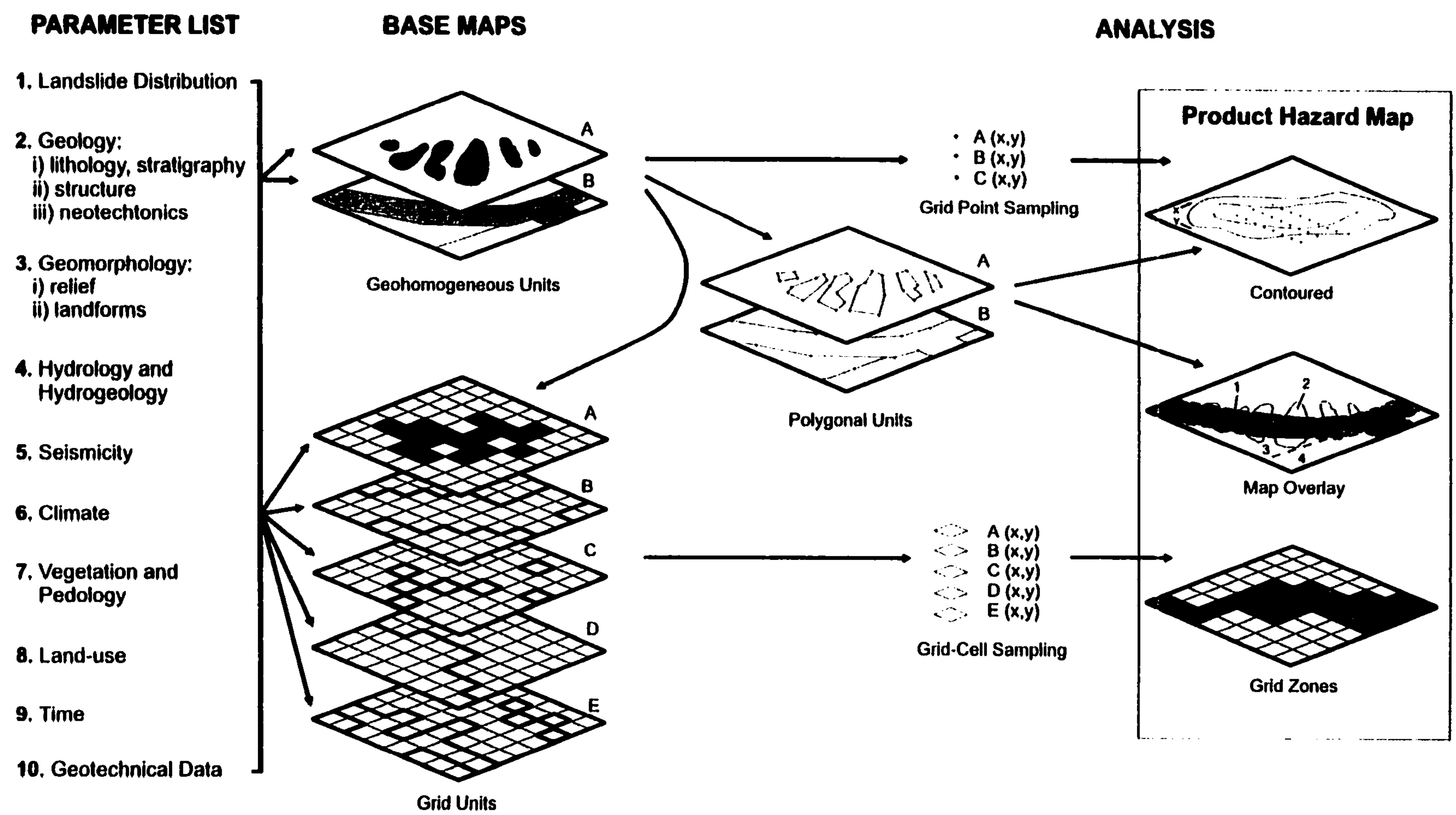


Figure 4.2: Slope stability overlay analysis. Sample parameters, modes of data collection, presentation, and analytical techniques are illustrated for the most common approaches (modified from Hansen A. 1984).

by analysed by superimposition or 'overlay' (Hansen A. 1984). As noted in Section 4.2, this method fully exploits the most basic function of a GIS (Carrara et al. 1995).

A map overlay implies that each slope-instability factor has been sub-divided into a few significant classes, all of which will be stored into a single map or layer. By sequentially overlaying all the layers, homogenous domains are singled out whose number, size and nature are strictly dependant on the criteria used in classifying the input factors. Chung et al. (1995) refer to these domains as Unique Condition Units (UCU). Although some claim the technique to be fully objective, it being the result of an automated overlay algorithm, its main weakness refers to the inherent subjectivity in factor classification. Additionally, by overlapping more than 5-7 maps, thousands of small, statistically meaningless, domains can be generated. Regardless of these limitations, this approach has a very important advantage, namely, it can be applied in those situations where it is conceptually or operationally difficult or impossible to pre-define a physically-based terrain-unit or domain (Carrara et al. 1995). In addition, several GIS packages (eg. Idrisi) offer analytical modules to group, rank or otherwise assess the characteristics of the many UCUs which may arise through overlay (Eastman 1997).

A second method used to define terrain-units is the use of regular, well-defined *geometric sampling units* without any direct environmental significance (Figure 4.2). Although the use of geometric sampling schemes may result in the further loss of detail and boundary definition, this method has several advantages. Firstly, since all factor maps have common spatial divisions, the problem of parameter boundary variability does not arise (with the exception of mixed pixels). Secondly, the methodology becomes readily amenable to automation (Hansen A. 1984).

Geometric sampling can be accomplished through automated or manual grid point and grid cell sampling. In the case of *grid point* sampling, computers can calculate which polygon contains a given point by comparison with the boundary lines. From a comparison of the same point on each factor-map, factor groupings or numerical totals, and hence final hazard classifications, can be rapidly evaluated. This process is repeated with a regular point-spacing, with quantitative results being contoured and qualitative results being grouped into hazard zones (Hansen A. 1984).

Alternatively *grid cells* may be generated. Grid cell sampling has a number of supporters among raster-based GIS users (Bernknopf et al. 1988) and implies the division of the study region into grid-cells of given size which become the terrain-unit of reference. Each cell will then be assigned a value for each factor taken into consideration (Hansen A. 1984). The advantages and limitations of the technique are well-known. Owing to the matrix format of the data, computer processing and manipulation is fast and algorithmically simple (Aronoff 1989), and since data are regularly distributed in space, sampling constraints in statistical analysis are relaxed (Carrara et al. 1995).

Traditionally, investigators used quite large (100m x 100m) or very large (1km x 1km) grid cells, so wide regions could be covered with a relatively small number (in the range of 1,000 to 10,000) of cells, each one treated as a case or sampling unit in the statistical processing and analysis (Carrara et al. 1995, Hansen 1984, Soeters and Van Westen 1996). Since, grid-cell limits do not bear any relation to the geological, geomorphological or other environmental boundaries, many investigators argued that the approach was relatively inaccurate and aesthetically unacceptable. As computer technology developed in terms of data entry devices (raster scanners) and mass-storage capacity, there has been a tendency to use smaller and smaller grid-cells (ie. 30m x 30m up to 10m x 10m). In this way, spatial inaccuracy reduced itself, but to cover even a small sample area (ie.100km^2), an overwhelming number of grid-units is required, which leads to "unmanageable problems of both CPU time and numerical instability when data [has] to be processed by complex statistical techniques (Carrara et al. 1995)". Choice of grid cell size, and issues of data space and management are therefore important considerations with this method (Hansen A. 1984).

A third, and developing method with which to define terrain units is based on the partition of a region into sub-basins or *main slope-units*. Depending on the type of instability to be investigated, the terrain-unit may correspond either to the sub-basin or to the main slope-unit. Since a clear physical relationship exists between slope failures and the fundamental morphological elements of a hilly or mountain region, namely drainage and divide lines, the technique seems most appropriate for landslide hazard assessment. One limitation is the difficulty in manually identifying sub-basin boundaries. Since it is virtually impossible to consistently draw divide lines on topographic maps covering large regions, an automated procedure is required. Many techniques for automatically generating drainage-divide networks are available on the market (Burroughs and McDonnell 1998). Carrara et al. (1995) reported, however, that few provide reliable and accurate results. Regardless of the algorithmic complexity and inaccuracies of these techniques, the main conceptual and operational potentials and pitfalls of the slope-unit approach are the significant reduction in landslide mapping errors and problems in selecting the average size of the slope-unit, respectively (Carrara et al. 1995).

4.3.2 - Limitations and Errors with GIS

Throughout the discussion of GIS applications in slope stability analysis, advantages and limitations of these methods have been noted briefly. Section 4.3 has noted several of the advantages, while disadvantages include availability and capability of software and hardware, scale or resolution of the data, data loss through geohomogenous unit boundary definitions or sampling methods, and many others. The limitations and possible errors through GIS are important to note and be aware of before conducting a GIS analysis. Despite its analytical capabilities and cost and time efficiency, the power and accuracy of a GIS relies heavily on the knowledge of those who collect the data, manage and manipulate it, in addition to their wants, goals, and values. Failure to consider these at any step in a GIS analysis can make the procedure "a theoretical exercise instead of a practical tool. Or worse yet, the analysis results may be misleading (Aronoff 1989)."

Several limitations and concerns related to GIS in slope hazard assessments are summarized by Coppock (1995), and Carrara et al. (1992). Coppock notes five general limitations, including **i)** the availability of appropriate data, **ii)** the tendency for errors to trail through the data from step to step (ie. cumulative errors), **iii)** the need for a broad and solid understanding understand of the hazard and the physical processes, which is often multidisciplinary, iv) limited functionality of some GIS software and hardware, and, v) ability to meet the needs of the user (Coppock 1995). Coppock expanded on his points and observed that no software is currently ideal for incorporating the fourth dimension, that is time, into hazard assessments. The ability of the assessment to meet the needs of the user are often complicated by difficulties in communicating the end product and support by agencies and infrastructure to put the information into action.

Carrara et al. (1992) have also echoed many of Coppock's points. The difficulties of tracking errors through successive steps in slope failure analysis is highlighted as a particular concern, in addition to the inadequate knowledge of the relationship between causal environmental factors and slope failures. Overall, Carrara et al. (1992) concluded that deterministic, geomorphic, and statistical methods are all error-prone and uncertainty in hazard zonation ranges from intermediate, to high. Error, in most cases, cannot readily be 'tracked', and a quantitative estimate of the magnitude of error is possible only for the statistical methods.

Carrara et al. (1992) also pointed out that the inclusion of 'risk' into slope analysis is neither conceptually nor operationally simple. In the literature, risk related to slope failures has been examined, but rarely evaluated (Carrara et al. 1992). The final section of this chapter looks briefly at previous attempts to assess coastal hazards and risks using GIS or computerized mapping analyses, including coastal slope hazards.

4.4 - GIS and Coastal Slope Failures: A Useful Tool for Mitigating Risk

The diffusion of GIS technology opens up a range of new possibilities for hazard mitigation and disaster management (Alexander 1995). Among many others, Cendrero (1989), and Monmonier (1997) suggested that maps and hazard modelling are an effective way of representing coastal hazards and mitigating risks. According to Monmonier:

> "Acceptance of cartographic simulation and risk assessment as normal and necessary may prove as monumental a turning point in public administration as the acceptance centuries ago of boundary maps, without which land ownership, taxation, and zoning would be impossible" (Monmonier 1997, 295).

Despite the apparent usefulness of GIS in coastal slope analysis, only one example could be found in the literature. This work was performed by researchers from University of Washington on Mercer Island, Seattle, and is only briefly described by Dunne and Leopold (1978). Research is assumed to have been completed by Tubbs (1974), but is poorly sourced, and no supporting documentation could be obtained for this study.

Apart from this possible study, all of the reports discussed inland slope applications (eg. Carrara et al. 1995, Reading 1993, Small 1992), or assessments of other coastal hazards, such as flooding and storms. Chapter Three noted the use of several computer applications along the bluffs of the Great Lakes (eg. Edil and Vallejo 1980). These were, however, largely deterministic applications without the use of indirect or heuristic, regional, hazard zonation maps. Geomorphic techniques, and simple hazard zonations are applied to the coasts of England and New Zealand through geomorphic surveys and aerial photography by Chandler and Hutchinson (1984), Kalaugher et al. (1987), Grainger and Kalaugher (1988), Moon and Healy (1994), and Gibb (1981).

Other applications have described the benefits of GIS as a means of inventory and display for various coastal attributes such as recession rates, environmentally significant areas, or general shore characteristics, shoreline changes, and aspects of flooding and erosion, as described for the Great Lakes by Moulton (1990), Coleman et al. (1989), Law (1990), Lawrence (1995c), Stewart et al. (1997), and EC 8 Nov. (1998), for Central America by Thieler and Danforth (1994a, 1994b), and in England by Clark et al. (1990). Several statistical techniques have also been applied to determine slope instability factors along coasts in the United Kingdom, but without the use of GIS or mapping techniques (eg. Davies et al. 1998, Jones and Williams 1991).

Finally, GIS applications have also been used in several cases to determine hazards and risks to coastal storms (Monmonier 1997). In each of these cases, factors contributing to flooding, inundation and destruction are overlaid with geologic factors and human vulnerability to estimate the risk of failure. Hickey et al. (1997) described the effectiveness of this technique for Jekyll Island, Georgia, while Johnson and Sales (1994) have recently applied this to the prediction of location and potential hazards of shoreline erosion along Lake Superior, Minnesota.

Despite the application of these studies to coastal features other than bluff failures, their methods, and those discussed for indirect, inland slope techniques in Section 4.2, can be applied and used in the zonation of coastal slope hazards and risks. As noted in Section 4.3.1, grid cell terrain units are particularly useful for overlay of susceptibility and risk factors to create UCUs. Although polygon overlay would be the ideal method for an analysis of Lake Erie's north shore, grid cell overlay will be employed, and is described in further detail in Chapter Six. Unfortunately, ArcInfo was not available for the analysis, and other vector software packages, such as MapInfo or ArcView, are incapable of overlaying multiple criteria and producing a 'summary' value for polygonal UCUs. Although these packages were initially used to construct vector maps, the results of an overlay are only available as 'on-screen, visual' displays, and ArcView cannot perform analysis on floating point data. Instead, the procedure is best performed in a raster package such as Idrisi. The large-scale data available for the analysis (1:10,000) was also amenable to the grid overlay technique without substantial data loss. Main slope units are better suited to inland slope analysis within drainage basins, while grid point sampling generalizes the data, and is time inefficient.

Chapters One through Four highlighted the nature, global and local extent of coastal slope hazards and risks. GIS and computers are evidently a useful tool in the analysis and mitigation of these risks through zonation techniques (Hearn and Fulton 1987). This information can be readily output in the form of maps, which can be used to help plan shoreline development, educate the public, or locate areas where warnings should be posted as to the risks. The following three chapters discuss the application of GIS and slope stability analysis to a reach of bluffs on the Great Lakes, as a method of reducing human risks.

CHAPTER FIVE

GIS Analysis of Lake Erie's North Shore: Study Reach, GIS and Data Issues

"There, ... where the coastline shoulders out into the sea, you search the landscape for its difficult splendour. There are sudden gullies and domes littered with glacial boulders in a jagged equipoise. The glacier's nosing wedge dishevelled all the hillsides and the stones seem sprinkled by a child." E. Ormsby (1992)

5.1 - GIS Analysis of Lake Erie's Bluffs

The previous chapters of this paper have introduced the issue and dynamics of coastal slope failure, particularly along the Great Lakes and Lake Erie. Chapter Four also discussed the useful role that computers and GIS can play in providing information to aid in risk mitigation. Figure 5.1 shows where information from the previous chapters fits the major conceptual steps taken to complete this research. In short, the discussion and literature review contained within Chapters One through Four helps to justify the research contained within these latter three chapters, and show how this research contributes to other studies currently being conducted. This information also helps to direct the steps and methods used in this research.

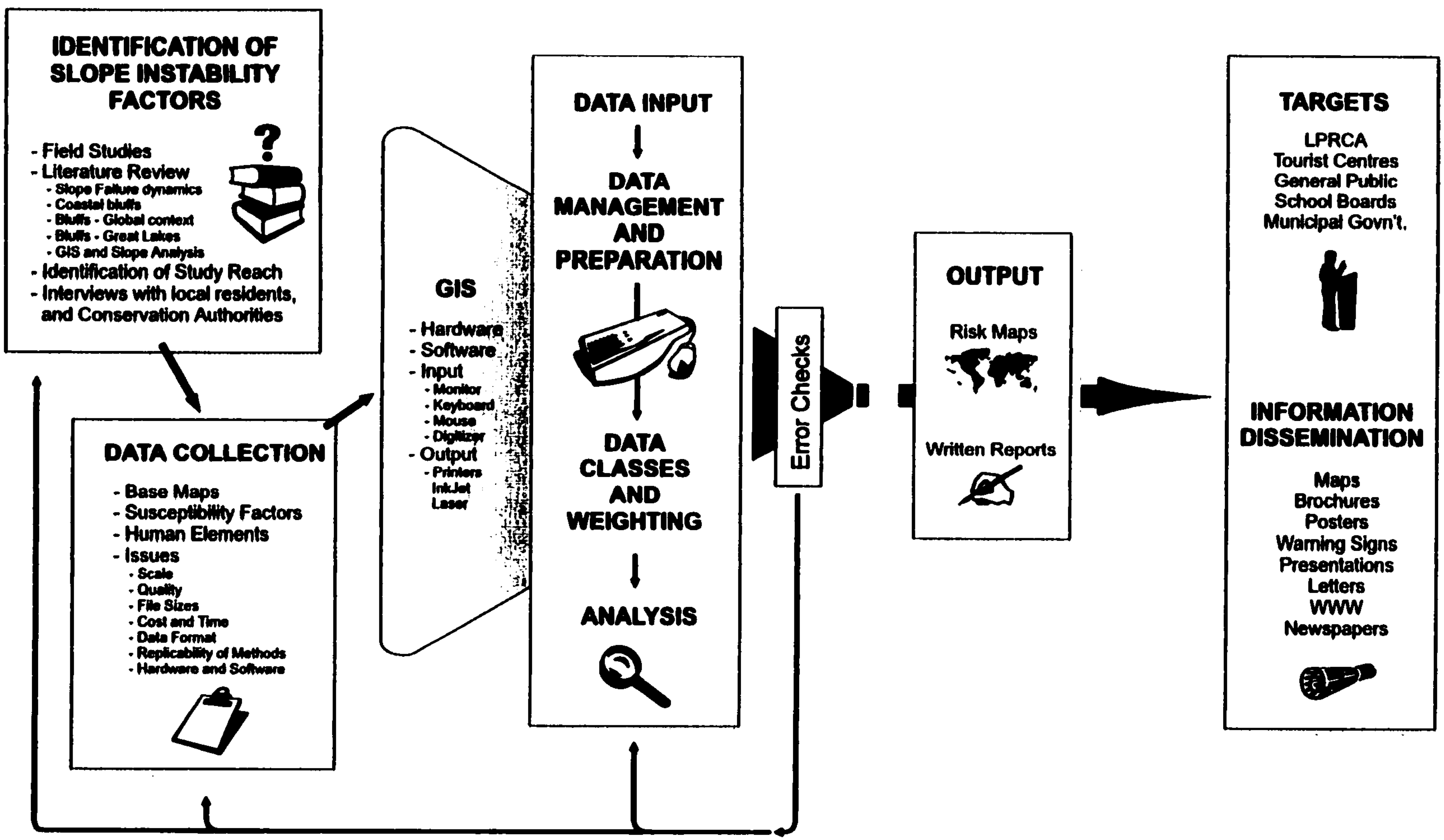


Figure 5.1: Conceptual model of the research methods used for the study, particularly the GIS analysis and presentation of results.

With this critical foundation, Chapter Five then focusses on the methods of the study, including study reach determination, description of the human and physical components of the study area and their association with slope failures and risk, identification of instability factors along the study reach, hardware and software restrictions, collection of data, input and management of data in a GIS, and the analysis and presentation of the data. Chapter Six follows with a discussion of the analysis and results of the GIS analysis, and Chapter Seven completes the paper with recommendations and conclusions.

5.2 - The Study Reach

Over two thousand kilometres of the shores of the Great Lakes are erodible clayey or sandy soils (Cruden et. al. 1989). Shorelines eroded in this glacial drift are, generally, steep bluffs that extend for many kilometres. Due to the large expanse of these bluffs, it was necessary to conduct this exploratory study using a shorter section of the shoreline. Although the shore and bluffs of Lake Huron or Ontario were viable options, a study reach was sought along the north shore of Lake Erie due to its proximity to the University, and a prior familiarity of the study area and shoreline by myself and my advisor Dr. Mary-Louise Byrne, of Wilfrid Laurier University, Waterloo, Ontario.

5.2.1 - Determination of the Study Reach

Each of Erie's north shore Conservation Authorities were contacted by phone and asked several questions to help determine whether their jurisdiction would be suitable for an exploratory study, and whether they had information that may aid in the study. Questions pertained to whether or not studies had been conducted on the shoreline or bluffs in their region, how recent information was, what format and quality of data was available, whether or not data would be amenable for a GIS analysis, and to what extent they were willing to assist with such a study.

After several weeks of phone calls, and an interview with Bill Baskerville (Baskerville 1997), Head of Planning and Technical Services for Long Point Region Conservation Authority (LPRCA), it was decided that a portion of their jurisdiction contained a reach of shore that would be suitable for an exploratory GIS study. The study reach is located along the north-central shore of Lake Erie in Ontario, Canada. Figure 5.2 displays the study site, which stretches roughly 24km east from Big Otter Creek, near the village of Port Burwell, to the Hahn Marsh, which forms the western edge of the Long Point World Biosphere. The National Topographic Series (NTS) map of which contains the study reach and surrounding study area is 40I/10, Port Burwell. Draw a line east and west of here and it will touch Rome and northern California (Bemrose 1995). The study area is bounded roughly by longitudes 80°33'E to 80°49'E and latitudes 42°34'N to 42°40'N. The corresponding Universal Transverse Mercator (UTM) coordinates are roughly 515,000m E to 538,000m E, and 4,713,000m N to 4,722,000m N.

The study area is managed by the LPRCA (head office in Simcoe), by the Aylmer District Office of the OMNR, and is located within the political boundaries of Bayham and Norfolk townships. Bayham township forms the western portion of the study area, and is contained within the Municipality of Elgin County, while Norfolk and South

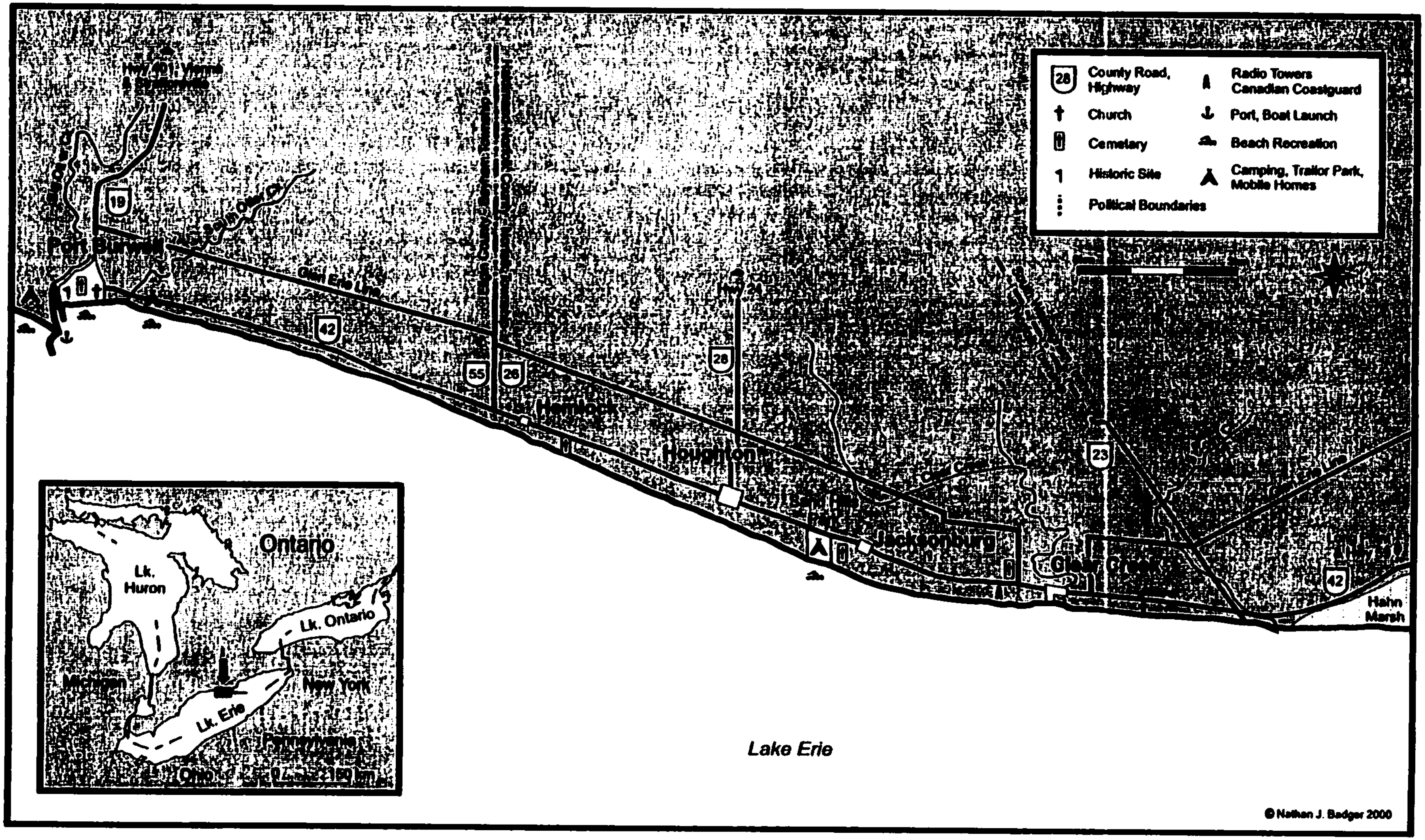


Figure 5.2: Port Burwell to Hahn Marsh, Long Point - location of the study reach on Lake Erie's north-central shore, Ontario Canada

Walsingham townships form the central and eastern portions of the study area respectively, and are located within the Municipality of Haldimand-Norfolk Region (Figure 5.2). Both municipalities are responsible for formulating Official Township Landuse Plans which determine where, how, and which development can occur within the township (Beatty 1999, Jonkers 1999, OMMAH 2000). This includes shore development and hazard land designation, where development cannot occur, unless a review of the land use zoning is accepted through a successful application to the township. Shoreline protection is monitored jointly between the township and the OMNR (Baskerville 16 Dec. 1999). In drafting and administering their Official Plans, these townships must adhere to provincial laws set forth in the Comprehensive Policy Statement, as introduced in 1994 (OMMAH 2000, OMMA 1994).

While familiarity and proximity were advantages to choosing this study reach, several more important reasons also prompted this choice. One important reason was that human and physical features of the bluffs and shoreline within the area are similar to reaches of shoreline bluffs found elsewhere along the Great Lakes. The length of the study site (approximately 25km) also ensured that it contained enough spatial variability with which to perform a rich analysis. Literature, and recent field trips to the shores of Lakes Huron, Ontario, and other sections of Lake Erie indicated that the height, material and factors influencing bluff stability were fairly similar, while field work and communications with the LPRCA also suggested that development continues to increase within the study area, alongside population growth (Baskerville 1997). The results and methods of this study will therefore be beneficial and applicable outside the study area.

Another reason for choosing the site was the availability of data and information for the study area. Within the past two decades a number of large, formal studies were conducted in and around the area, including a Shoreline Management Plan (LPRSMP) completed by the LPRCA (PA, TA and PWA 1989), a detailed study of the Quaternary stratigraphy and Sedimentology by Barnett (eg. Barnett 1987), and information compiled as a result of the Port Burwell shore erosion damage claim study (eg. Philpott 1986). In addition to these larger studies, a number of journal articles report on research that has been conducted in the area, as discussed in the previous literature review. Studies of a broader scope on the entire Great Lakes shoreline were also available and included, as discussed partially in Chapter Three, the Shore Damage Survey and Coastal Zone Atlas (EC and OMNR 1975, EC and OMNR 1976), the Canadian Great Lakes Coastal Zone Database (EC 8 Nov. 1998, Gillespie 16 Mar. 1993), Great Lakes Erosion Monitoring Program 1973-1980 (Boyd 1981), Littoral Cell Definition and Sediment Budget (F.J. Reinders 1988), the Environmental Sensitivity Atlas (EC 1994) and a draft version of the Great Lakes St. Lawrence Technical Guidelines (OMNR 1994).

In addition, confirmation was received from the LPRCA that Ontario Base Maps (OBM) and NTS maps had been compiled for the region in 1997. Video tapes of the shore had also been filmed by LPRCA, and several sets of air photos had been compiled in the region since the 1950s. Combined, all of these sources provided helpful background and information about the study area, and led to a host of other sources of information, including data, maps, reports, journal articles and reports that could be used for the study.

Finally, this site was chosen because it contains a section of shore where bluff failures and human activities resulted in damage to, or loss of property, as well as the deaths and near deaths of a number of individuals. During an initial visit to the study reach in June of 1997, large sections of the shoreline were observed in various stages of failure and erosion, and were evidently responsible for damage or loss of nearby buildings, services and property. More importantly, in August of 1994, the seriousness of the bluff hazard was finally realized in the collapse of a portion of bluff on six young boys just outside the borders of Sand Hills Park (Bender and Lawson 1994, Daniszewski 1994). While playing on the beach beneath the bluffs, a large section of sand slid off of an underlying clay layer, killing four of the boys through traumatic asphyxia (Edwards 1994). Dr. Mary-Louise Byrne, Wilfrid Laurier University, Waterloo, was asked to comment on the cause of the accident (Edwards 1994, Ganley 1994) and her familiarity with the hazard and slope failure dynamics would prove helpful during the research. News of the tragedy soon prompted reports of similar accidents along this reach of shore, including the broken knee of a young girl in 1993 (Daniszewski 1994), and the near-death burial of three boys during a similar collapse near the park in 1975 (Humphreys 1998).

As a result of the 1994 tragedy, a Corner's Inquest was requested and various recommendations were made to reduce the risk of future coastal slope failures within the region (Freeman et al. 1995). Field work, accident reports, and an untold number of similar unreported tragedies, also indicated that the region of shore between Big Otter Creek and the Hahn Marsh posed a high risk to human well-being and merited investigation as a means of reducing the risk. This study stems from this understanding, and it is hoped that it will contribute to this end.

5.2.2 - Physical and Human Components of the Study Reach

This paper has stressed the human and physical components of slope failure factors, hazards and risks. It is important to understand that both physical and human factors must be present before a shoreline slope failure constitutes a hazard. Sub-aqueous, aeolian, and terrestrial factors work together to cause slope failures, but humans can also contribute to pre-existing physical conditions to increase instability. Without human presence, a natural event is not a hazard to humans. The severity of a hazard is therefore gauged by the degree to which humans are affected by hazard events. In the case of the study area between Long Point and Port Burwell, human and physical attributes join to characterize this stretch of shoreline and to determine the location, probability, severity and risk of bluff failures.

The following two sections of this chapter outline some of the dominant physical and human components of the study area. Where appropriate, the influence of physical and human components are described in terms of their contribution to the stability or instability of the bluffs. Human aspects are also discussed in terms of their vulnerability to the hazard, and the degree to which they determine the severity of a potential bluff failure. This discussion is intended to tie together the literature review from previous chapters, information gleaned during field work, and the rationale for including certain factors in the final GIS analysis.

5.2.3 - Physical Components of the Study Reach

The physical components of the study area can be discussed under six broad headings, including, Geology, Shore Aspect and Orientation, Climate, Recession Rate, Drainage, and Vegetation. By discussing each of these, it becomes readily apparent how intertwined and complex each of these is in the failure of the north shore bluffs (Barnett 1990, Quigley and Gelinas 1976). In general, the bluffs in the study areas exhibit four major modes of failure which are similar to those found in study sites west of the area by Quigley et al. (eg. Quigley and DiNardo 1980, Quigley and Gelinas 1976). These include: **i)** ongoing sheet erosion and small flows in response to rainfall, surficial seepage and wind, **ii)** frequent, small rotational, bluff-top or bluff toe failures extending + or - 3m back from the front of the slide **iii)** less frequent, very large, deep-seated rotational slides extending many metres (over 30m) back from the bluff edge, and **iv)** smaller-scale topples and translational slides from tension cracks and fractures in more cohesive sediments, such as clays.

Very generally, field work determined that sand flows and rotational slides were evident in the area of Sand Hills Park where aeolian forces piled large dunes of sand along the bluff edge. Large and small rotational slides were found in the western portions of the study reach (between Little Otter Ck. and Houghton), while topples and small rotational slides were discovered in the eastern portions, east of Jacksonburg. Of all four types of slides found in the study area, large rotational slides are believed to present the greatest risk to humans due to their large expanse, the force of their mass, the speed of their movement, and the long distance which they can travel. During field work, rotational slides were found to have travelled up to20m from the base of the bluffs, across the beach and into Lake Erie. Figures 5.3a-l are pictures of the study site, the bluffs, human presence, and other important features which are noted throughout this chapter.

5.2.3.1 - Geologic History, Geology and Stratigraphy

The geologic history, geology and stratigraphy is a vitally important aspect of the study reach, and in understanding the dynamics of the bluff failures. This information is well documented by authors such as Barnett (1983b, 1985, 1987), Chapman and Putman (1984), Calkin and Feenstra (1985), and Karrow and Calkin (1985a, 1985b). Their research summarizes the numerous advances and retreats of Pleistocene glaciers which sorted and/or dumped various types of materials in the Lake Erie basin (Caldwell et al. 1971). This glacial till and unconsolidated material now forms 45% of Erie's north shore (Burns 1985).

Quaternary glacial deposits and features dominate the study area, and were deposited during the Late Wisconsin age, approximately 14,800 to 12,300 radiocarbon years before present. These sediments record a fluctuating eastward recession of the Erie Ice Lobe margin during the Port Bruce Stadial, Mackinaw Interstadial and subsequent Port Huron Stadial (Barnett, OGS and OMNR 1983). During the ice-advances (stadials), the Erie Lobe of the continental glacier entered the northeastern end of the Lake Erie basin and spread southwestward down the basin following the natural orientation of Lake Erie (Barnett, Sando and Bajc 1983). During the northeastward retreat of the ice margin (interstadial), water levels in the Erie basin fell, leaving behind the distinctive shore

Figure 5.3a: Bluffs start low in the east between Hahn Marsh and Long Point Creek. Beaches are wider, and vegetation often covers the bluff faces. A sunken barge (horizon) provides a natural groyne. Proposed location of Captain's Cove Marina.

Figure 5.3b: Bluffs rise west of Long Point Creek. Tile drain (bottom) evidences agriculture fields above the bluffs.

Figure 5.3c: Large gully, slides, rotational slides (left), and sand/silt flows (right) near Houghton.

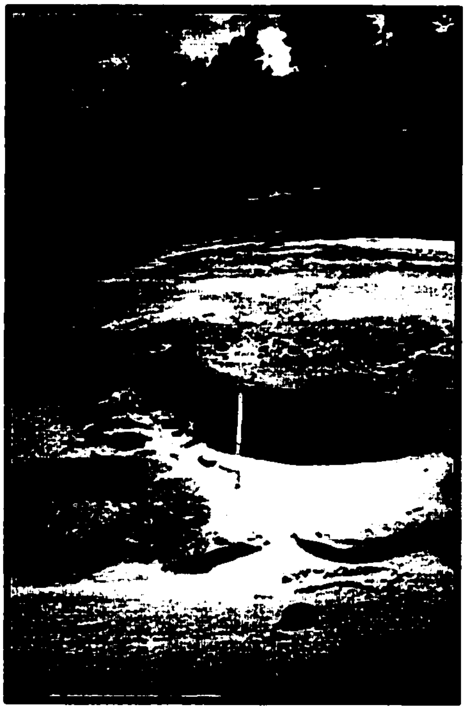


Figure 5.3d: 'Danger' sign within Sand Hills Park. Notice seepage failures at the clay-sand interface near the beach, and stratigraphy above.

Figure 5.3e: Steep bluffs east of Little Otter Creek. A clay base is overlain by silt and sand. Topples are evident, in addition to the clay remains of former failures in the lake.

Figure 5.3f: Large bluffs, in the central portion of the study site near Houghton. Notice stratigraphy, bluff terraces, wider beach, rotational slides, debris, and mix of sand over clay.

Figure 5.3g: Large sand flow at Sand Hills Park. Notice stratigraphy and small beach. Aeolian sand has been piled above the Norfolk Sand Plain which is evident in the middle of the flow back scarp.

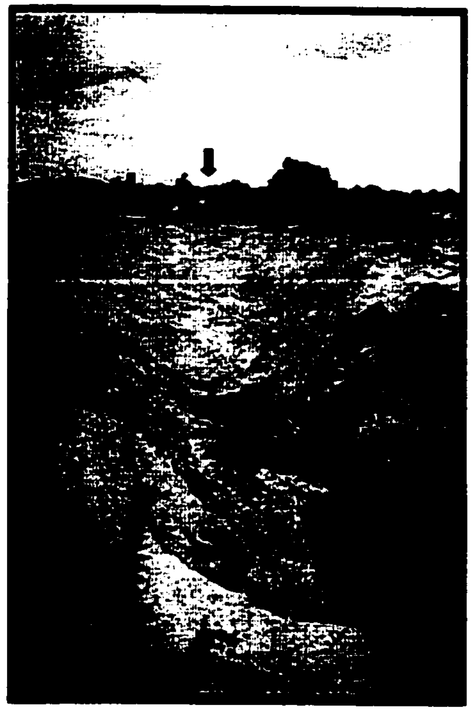


Figure 5.3h: Large gully formation just east of Port Burwell. Arrows point to the truck on Road 42 just beyond the gully edge, in addition to houses on the far side of the road.

Figure 5.3i: Large bluffs, in the east-central portion of the study site near Hemlock. Notice stratigraphy, and seepage between sand and clay layers. Piping failures are also evident, along with rotational slides and flows.

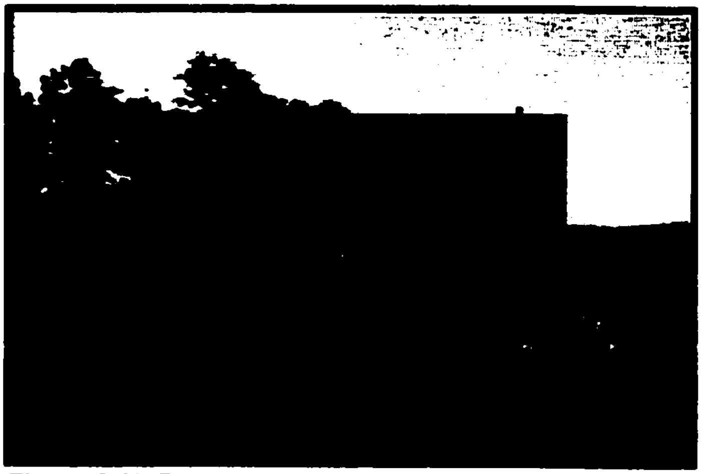


Figure 5.3j: Property between Road 42, and the bluff edge. Several months later '50' was spray-painted over with '48' (approximately).

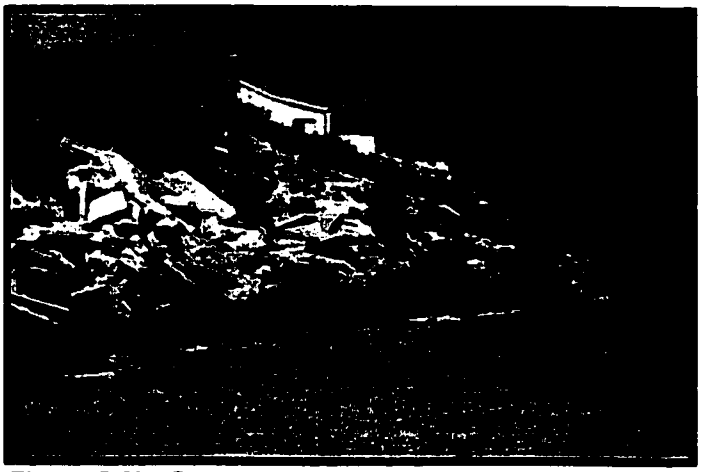


Figure 5.3k: Concrete and rubble shore protection for cottages adjacent to the Hahn Marsh.

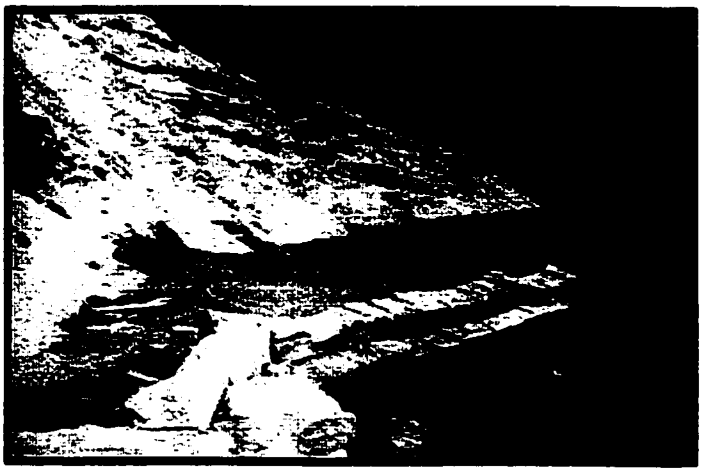


Figure 5.3l: Several sets of concrete-block groynes established at Sand Hills Park.

bluffs. The current datum level of Lake Erie is defined as 173.5masl by the 1985 International Great Lakes Datum (USACE 3 Jun. 1999b, USACE 10 Sep. 1999b). The bluffs rise in height from lake level (173.5masl) at Big Otter Creek, to 16.5m (190masl) near Little Otter Creek, and then level off at around 26.5m (200masl) just east of this point. Further east, past the central portion of the study area, the bluffs peak at over 51.5m (225masl) within Sand Hills Park. Here, aeolian processes nurture a large, cliff-top dune which rises almost 30m above the surrounding plane (Barnett 1987). To the east of the Park, the bluffs then drop in height again from about 26.5m (200masl) to just under 6.5m (180masl) when they reach Clear Creek and the Hahn Marsh.

Large, ice-contact, glacier-fed lakes, including Lakes Whittlesey and Warren, fronted the Erie Lobe ice margin during de-glaciation and allowed for the deposition of both glacial and glaciolacustrine sediments (Barnett, OGS and OMNR 1983). The major type of glacial sediment in the study area is till. Glacial till is a sediment that has been transported and deposited by or from the glacier ice, with little or no sorting by water and is usually a very poorly sorted mixture consisting of a variety of grain sizes and of rocks and minerals (Dreimanis 1982, as cf. Barnett, OGS and OMNR 1983).

Glaciolacustrine sediments are sediments deposited in lakes bordering a glacier, and are usually stratified because water was the major transporting medium (Dreimanis 1982, as cf. Barnett, OGS and OMNR 1983). Most of the stratified sediments in the study area entered Lakes Warren and Whittlesey by way of a large proglacial stream from the north, and whose delta spread westward from the receding ice-marginal zone of the glacier (Barnett, OGS and OMNR 1983, Chapman and Putnam 1984). Chapman and

Putnam (1984) included this area in their Norfolk Sand Plain physiographic region, which they suggested is part of a gently sloping fan-shaped plain, whose apex occurs in the vicinity of Brantford to the north. Sedimentation was dominated by quasi, or near-continuous density underflows that resulted in the deposition of a sequence of thick rhythmites (Barnett 1987).

The geologic composition and stratigraphy of the bluffs varies widely from east to west, and has been the focus of a great deal of work by Barnett as part of a PhD at University of Waterloo, and research with the OGS. A correlative cross-section of the geology and stratigraphy of the study area has been compiled by Barnett (1987), and is featured, in part, as Figure 5.4. This figure will also be referred to later in the chapter when the construction of a digital geologic/stratigraphic data layer is discussed. Overlying the Marcellus bedrock Formation of the Devonian age (Barnett, OGS and OMNR 1983), is a thick blanket of Quaternary sediments. Maps produced by Barnett in the early 1980s indicated that these sediments reach over 100m depth in the study area (Barnett, Bajc and Sando 1983) drift thickness map. A map published by Barnett in 1983 provides a useful written and graphic summary of the region's Quaternary Geology (Barnett, OGS and OMNR 1983).

Quaternary sediments in the region include over-lapping sequences of two major glacial tills (Wentworth and Port Stanley Tills) which are preserved as massive diamicton layers (Barnett 1987). In the context of glacigenic sediments, Hambrey (1994) defined diamicton as a non-sorted, unconsolidated, terrigenous sediment deposited by glacial action, and containing a wide range of particle sizes. These diamicton layers are

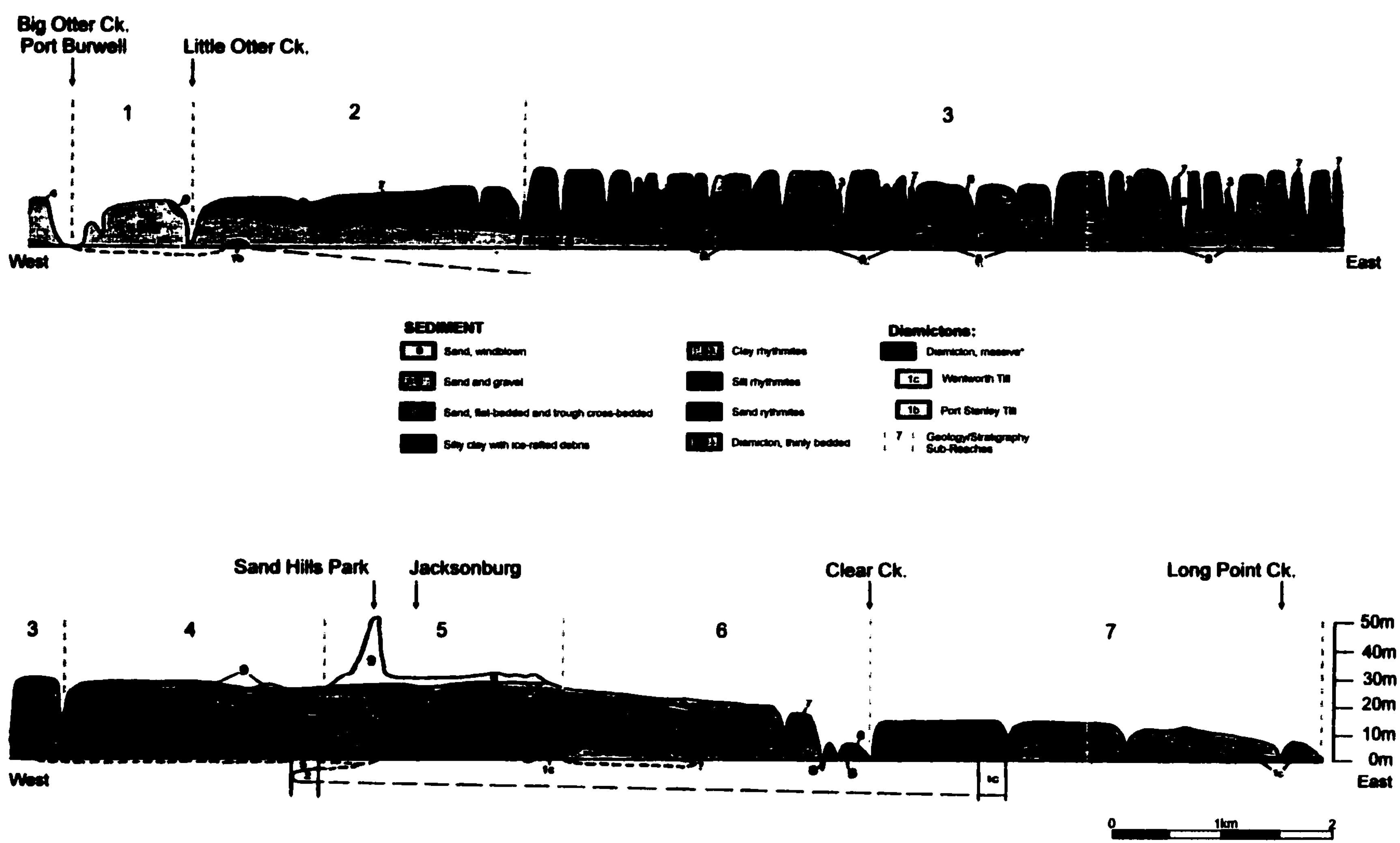


Figure 5.4: Correlative geology and stratigraphy of the shore bluffs within the study reach, Big Otter Creek to the Hahn Marsh. Geologic/stratigraphic sub-reaches are also denoted (pink line) and discussed later in the chapter (modified from Barnett 1987).

separated and individually overlain by deltaic bottomset sands and glaciolacustrine silts and clays. Sediments in the bluffs generally become older and coarser toward the west and upwards through the bluff in the direction of glacier recession (Barnett 1983b). East of Port Burwell to the Sand Hills, the Port Stanley Till is overlain by highly contorted laminated silts and clays with abundant ice-rafted debris. This unit in turn is overlain by well-laminated silts and clays which grade upwards into a coarsening-upwards sequence of cyclically-bedded glaciolacustrine clays and silts, to fine and medium grained sands. These sequences are capped in places by trough-bedded sands. As a whole, the sequences represent a regional shallowing of a large proglacial lake which occupied the western portion of the Erie basin and record the recession and oscillations of the glacier during the later stages of the Port Bruce stadial, and into the Mackinaw Interstadial (Barnett 1987). In several places, detrital organic material has been found in the upper cap, as evidenced by pieces of calcified and fossilized wood discovered during field work. Aeolian sand in the form of cliff-top dunes also caps the eastern half of this bluff segment (Barnett 1987).

Between Jacksonburg and the eastern end of the study area, the relatively resistant Wentworth Till is exposed in the lake bluffs. This portion of shoreline also presents a cross section through the Galt Moraine which marks the farthest westward extent of the glacial advance that deposited the Wentworth Till (Barnett 1987). Near Jacksonburg, numerous glacially-derived sediment flows are present along the western flank of the moraine and inter-finger with glaciolacustrine sands which are the main component of the bluffs to the west of this point. At the far eastern end of the bluff segment, the hummocky nature of the moraine is preserved in the shore bluffs with silts infilling the depressions and the entire sequence capped by glaciolacustrine clays (Barnett 1983b).

The geology and stratigraphy of the bluffs play a very significant role in controlling factors which contribute to bluff instability in the study area. Barnett (1983b) provided a long list of these factors, including groundwater dynamics (discussed in more detail later) and bluff morphology (eg. slope and elevation). Throughout the reach, the inclination of the bluffs ranges from around 0 to 90°, and is largely dependant upon the angle of repose of the various materials. Quigley and DiNardo (1980) discussed typical slope angles calculated for bluffs just west of the study reach. These match well with those discovered during field work in this study reach, where terrestrial and sub-aqueous processes are very similar. Of particular note is the stepped bluff profiles which occur in the central portion of the study reach where sands and silts overly materials with higher clay content. The angle of repose for the sands and silt is much lower than that of the clay material in the middle portion of the bluff. The base of the bluff is often covered with material that has eroded or failed from the top or middle of the bluff, and tends to form an angle of repose just slightly higher than the top of the bluff, so that the entire bluff profile forms an 'S' shape. Aside from the angle of repose which materials are able to maintain, the average inclination of the bluffs is also affected by the natural variations in lake water levels (Quigley and DiNardo 1980, Quigley et al. 1978).

A further morphologic factor which affects slope instability is elevation. Crozier (1986) and Zaruba (1982) noted that the height of the bluffs is an important contributor to failure susceptibility. In general, the higher the bluff feature, the greater the stresses that are likely to occur within the bluff, and the greater the potential severity of bluff instability (Crozier 1986). Height is particularly important in the case of cohesive soils, such as clays and silts, where it positively influences the formation of deep-seated rotational slides (Crozier 1986). Carson and Kirkby (1972) discussed methods of calculating the weight of material, and the subsequent instability of bluffs over a potential shear plane.

5.2.3.2 - Drainage and Groundwater

Surface drainage and groundwater is an another important physical aspect of the shoreline, particularly because of its role in bluff stability. The lake plain is deeply dissected by four major water courses which drain into Lake Erie. The largest of these courses is Big Otter Creek which flows almost directly from the north, flanks the western side of Port Burwell, and provides the first natural harbour west of Long Point. The second largest water course is Little Otter Creek which drains into Erie from the northeast, approximately 1km east of Big Otter Creek where it flanks the eastern side of Port Burwell. No major water courses drain into Lake Erie for almost 17km east of Little Otter Creek until Clear Creek, which drains roughly from the northwest through the hamlet of Clear Creek. Approximately 4km east of Clear Creek, Long Point Creek, the smallest of the 4 major water courses, drains towards Lake Erie from a northwest direction.

Numerous gullies are also a characteristic 'drainage' feature of the shoreline. Burkard and Kostaschuk (1995, 1997) noted the incision of similar gullies along the eastern shore of Lake Huron. Gullies within the Lake Erie study site appear frequently along the western portion of the study region between Little Otter Creek and the hamlet of Houghton. The types of gullies vary throughout the study area and are affected by groundwater, geology, stratigraphy (Barnett 1987, 1990, Boyd 1981), deforestation, and alterations to bluff top drainage patterns (Burkard and Kostachuk 1995, 1997). Large amphitheatre-shaped gullies occur east of Port Burwell where silt and sand rhythmites are overlain by a more permeable sandy sediment (Zeman 1978). Groundwater seepage and piping of the silt and very fine sand portions of the rhythmites contribute greatly to erosion during their rapid formation (Barnett 1990). In areas of till or complex stratigraphy, such as between Jacksonburg and the Hahn Marsh, gullies and creeks are often steep-walled, and 'v' shaped (Barnett 1990). During the period of this research, two unusually large gullies formed along the shore just west of Regional Road 55/26. In both cases, the gullies eroded inland over 185m and seriously threaten the existence of Road 42, one nearby house, and other infrastructural services which parallel the road. Both gullies are the focus of ongoing engineering projects which are attempting to prevent further erosion.

Aside from the gullies, groundwater also has an important destabilizing effect on the bluffs in the central and western portion of the study area through piping. Barnett (1987) noted that the stratigraphy and geology of the study area dips slightly toward the shoreline, and so groundwater naturally moves to the bluff edge. Here piping and groundwater seepage occurred along the finer inter-beds within sequences where finer sediment dominate. Piping moves small grained sediments through the glacial drift towards the bluff edge, effectively undermining the bluff (Barnett 1983a, 1987, Zeman 1990). Groundwater seepage also has the effect of 'greasing' the zone between permeable and impermeable sediment beds. Water over-saturates the very fine silts and sands, decreases their cohesive strength and creates a highly unstable shear plane where overlying material is able to 'slide off' less permeable layers below. This phenomena also contributes to the formation of large rotational slides, and is believed to be responsible for the deaths of the 4 boys near Sand Hills Park in 1994. For further details on the role of ground water on soil stability and seepage, the reader is referred to works by such authors as Dunne and Leopold (1978), Vukovic and Pusic (1992), Zaruba (1982), and Selby (1993).

5.2.3.3 - Aspect and Orientation

In general, the shoreline of the study reach is oriented roughly north-northwest to south-southeast, in contrast to the long, southwest-northeast orientation of Lake Erie. Along the study reach, there are however, noticeable differences in the shore orientation. The far west end is oriented west to east from Big Otter Creek to Little Otter Creek, then north-northwest to south-southeast for about 15.5km all the way to just east of Jacksonburg, where reach orientation changes abruptly again to west-east for another 7.5km up to the Hahn Marsh. The northwest to southwest orientation of the shore means that the general aspect of the bluffs is southwest. Since the predominant wind direction is from the southwest, the bluffs within the study region receive wind, rain, and wave energy almost directly head on. It is important to note that the orientation of the shoreline is greatly affected by the properties, and stratigraphy of the materials within the shore bluffs and foreshore area. The promontory just east of Jacksonburg is one example of this, where the bluffs and foreshore are composed predominantly of more resistant and cohesive Wentworth Till (Barnett 1990). Boyd (1981) noted that this shoreline promontory is a semi-headland, and acts as a groyne to reduce downdrift erosion.

5.2.3.4 - Climate and Weather

In addition to geology, climate and weather are two very important physical attributes of the study area and are an important factors affecting bluff stability. The effects of groundwater and lake level are controlled in part by the availability of precipitation. Chapman and Putnam (1984) noted that this particular region receives greater than average rainfall than the rest of southern Ontario, and this was substantiated by data from nearby climate stations at London and Simcoe where average annual rainfall is 938mm and 955mm respectively, compared to that of Hamilton and Windsor at 890 and 901 (EC 1999). Weather in the region is also highly variable and can bring large storms accompanied by intense and prolonged rainfall (Burns 1985). The correlation of rain events with a subsequent increase in the number and magnitude of bluff failures was noted several times during interviews with shoreline residents (eg. Allenson 1998). High amounts of rain were also received during the days just prior to the 1994 Sand Hills Park tragedy (Edwards 1994). During the spring and fall, melt and rainwater is particularly abundant and is believed responsible for saturating the bluffs and for an increase in bluff failures (Baskerville 1997).

5.2.3.5 - Wave Energy and Lake Water Levels

Perhaps the most important impact that climate and weather have on the physical nature of the study area are their role in influencing wave energy. Wave energy is controlled by wind velocity, direction, duration and fetch (Gelinas and Quigley 1973), and its effect is influenced by shoreline profile and orientation, shoreline material, lake levels, and short term lake events such as seiche, and storm surge (Davidson-Arnott 1989, Gelinas and Quigley 1973). In turn, wave energy plays an important role in the littoral drift of sediments, shoreline recession rate, toe erosion, and ultimately the erosion and stability of the bluffs (Caldwell et al. 1971). This relationship was supported by Gelinas and Quigley (1973) during a study of Erie's north-central shore from Rondeau to Long Point. A linear correlation was found to exist between long-term erosion rates and wave energy available at the shore, with the exception of the study reach east of Port Burwell, where erosion was discovered to be faster (Gelinas and Quigley 1973). The relationship between waves and recession rates of cohesive bluff shorelines is also explained in physical terms as a function of wave-foreshore interactions, as detailed by Kamphuis during the Port Burwell litigation (Kamphuis 1986).

Mean wind direction for the study area is from the west and southwest during Spring, Fall and Winter, and then dominantly from the southwest during Summer (Philpott 1986). As such, winds frequently blow along Lake Erie's southwest-northeast axis and fetch is capable of reaching several hundred kilometres before winds reach the study area. These conditions also allow some of the highest wave energy on Lake Erie to directly hit the central portion of the study area from the southwest (Philpott 1986). The shoreline just south of Port Burwell offers the best exposure to wave attack in the entire north-central portion of Lake Erie and likewise experiences very high rates of erosion (Gelinas and Quigley 1973). At the same time, even if all the water in Lake Erie was drained, erosion of the shore bluffs would still continue. Many of the forces that act to chemically and mechanically weather the bluff face would continue to loosen and transport soil particles from the bluffs (Boyd 1981).

Lake levels amplify the effect of wave energy on the study shoreline, and on the stability of the bluffs. The water level of the lake is constantly changing due to long term hydrologic changes in the Great Lakes basin, and short term storm events (USACE 3 Jun. 1999a). Over longer periods of time, Erie water levels move in a non-regular cycle between years of high and low water levels (Quigley and Gelinas 1976, USACE 10 Sep. 1999a, 1999b). During high lake levels, slope faces are steepened, altering the slope failure mechanisms from a slow, flattening process controlled by effective stresses, to a short-term, toe failure mechanism controlled primarily by geometry and undrained shear strength (Quigley and Gelinas 1976). Waves break near the shoreline, protective beaches associated with low water level are washed away, and very active bluff erosion occurs due to limited dissipation of wave energy, and heightened ability of nearshore currents to increase their load of eroded silts and clays, which stabilize the bluff toe (Davidson-Arnott 1989).

When lake levels are low, much less bluff erosion occurs. However, extensive offshore erosion occurs within the breaker zone, thus deepening the water. Subsequent rises in water level are then accompanied by waves which break directly against the bluffs

(Davidson-Arnott 1989). The cyclic mode of flat and steep bluff profiles has also been linked to lake levels and wave energy through research by Quigley et al. from Port Bruce to Colchester (eg. Quigley et al. 1977, Quigley and Di Nardo 1980). Bluff profiles were found to flatten and exhibit deep-seated rotational slides at several north shore sites shortly after water levels dropped and shore bluff sediments softened. Although influenced by the physical characteristics of the shore sediments, steep bluff profiles were also characteristic of high water levels, and represented high rates of toe erosion through available wave energy. Bluff profiles also exhibit a stepped profile due to the differential erosion and failure of different bluff sediments (Barnett 1990).

Short term lake level changes can also adversely affect the stability of the bluffs, especially when superimposed on high lake water levels (Gelinas and Quigley 1973). Frequent storm events during the spring, summer and fall increase the normal wave energy available at the coastline, and are responsible for set-up and seiche which move waves closer to the toe of the bluffs. The effect of storms is most pronounced in their ability to increase wave energy along the shoreline, or at the bluff base, leading to increased erosion (Gelinas and Quigley 1973).

During the winter, wave energy and littoral currents only play a minor role in bluff and shore erosion because of ice cover. However, ice cover has the ability to gouge, and erode the toe of the bluffs especially when ice is pushed against the shore during winter storms and late winter and spring thaws (Carter et al. 1987). The erosive action of ice was evidenced during a March 1999 visit to the study reach, where large ice rafts were discovered pushed up against the bluffs, underneath sediment from the overhanging bluffs. Median Ice Cover is usually established along the study area from the second week of January until mid to late March (Saulesleja 1986), the bluffs are potentially subject to the erosive capabilities of the ice for up to three months of each year.

5.2.3.6 - Littoral Drift

Prevailing southwesterly winds also generate eastward littoral currents in the study reach. The term littoral drift is used to define a shoreline reach (littoral cell) within which there is an uninterrupted net longshore sediment transport in one direction (longshore currents), with boundaries across which there is little or no exchange of sediment with adjacent cells (Davidson-Arnott 1989). The study reach is believed to form a sub-littoral cell within a larger littoral cell which stretches from the western limit of Port Glasgow, to the tip of Long Point (F.J. Reinders 1988, Philpott 1986). Sediment, derived primarily from nearshore and shore bluff erosion within the study reach, is transported in rapid fashion from west to east across the study area, eventually accumulating at Long Point (St. Jacques and Rukavina 1973). High sediment loads were evident in the study area by the permanent discolouration of the water during field trips to the study area during ice-free months of the year.

Wind, storm events, shore orientation and sub-aerial bluff erosion process all influence the movement of sediment through a littoral cell, such as the one associated with the study reach (Davidson-Arnott 1989). Between all these variables, a natural equilibrium develops between the steepness of the nearshore profile and the rate of erosion. When sediment supply does not meet the potential sediment transport rate, the littoral cell has a negative balance, erosion rates are high, nearshore profiles are generally steeper due to the high erosion rates, beach size is generally smaller, and consequently, more wave energy is available at the bluff toe (Davidson-Arnott 1989). A negative sediment balance is believed to characterize the study reach between Port Burwell and Long Point (Davidson-Arnott 1989). This situation is exemplified by the study area, and the sediment budget is therefore felt to be a very important long-term controlling factor of the high recession rates experienced along the study reach (Davidson-Arnott 1989, F.J. Reinders 1988). Longshore and offshore transport, in addition to littoral drift and cell sediment budgets, are discussed in detail for the study area by F.J. Reinders (1988). Ashworth (1986) and Boyd (1981) touched on some of these processes for the Great Lakes in general.

5.2.3.7 - Recession Rate

Recession rate can be defined as the rate at which the general profile of the bluffs moves inland. This is most often calculated by comparing the location of the bluff edge or another definable point, at intervals along the shoreline over a certain number of years (Boyd 1981). Since lake level fluctuations rise and fall over a 10 to 20 year period, it is important that recession rates be measured over a long period of time (at least 20 years) in order to smooth out short-term variations (Dick and Zeman 1983, Gelinas and Quigley 1973). Long and short term studies determined that shoreline recession rates peak at close to 5 metres per year along certain sections of the study reach, representing the highest and most persistent erosion rates along the entire north shore of Lake Erie (Carter et al. 1987, Geomatics Inc. and Davidson-Arnott 1992, Philpott 1986, Zeman 1978). In fact, comparative charts constructed by Sunamura (1983, 1992) indicated that the study area contains some of the highest recession rates in the world.

Clearly, these rates are affected by a large number of factors, as evidenced in the previous discussion. It should, however, be noted that recession rates must be approached with some caution. Kuhn and Shepard (1983) note that sea-cliff and bluff retreat is episodic, site-specific, and strongly related to the meteorological conditions, geology, and sub-aqueous processes. Unfortunately, it is difficult to obtain data or research which allows these events to be accounted for. Episodic events, site-specific failures and shore retreats were evidenced many times within the study site, and it is felt that the best method of reducing this problem is through the evaluation of long-term recession rate records which help to 'smooth-out' these temporal and spatial variations.

Despite these cautions, however, long-term recession rates provide an extremely useful indication of the susceptibility of shoreline bluffs to gradual and rapid failure of the bluffs, and as a measurement, are an excellent indicator of the effects of a large number of sub-aqueous and climatic factors eroding a particular reach of shore.

5.2.4 - Human Components of the Study Reach

5.2.4.1 - Population

Human components, as with physical, are important aspects of the study area, in that they determine the severity of shoreline hazards, and also influence bluff stability. Population is centred in the village of Port Burwell in Bayham Township, but has also collected at a number of smaller centres within Norfolk Township along County Road 42 including (in an eastward direction): Hemlock, Houghton, Jacksonburg, and Clear Creek. In addition to these centres, many individual dwellings are located rurally along Road 42 and the connecting Concessions and Lines. From a quantitative perspective, data from Statistics Canada (Statistics Canada 1974, 1999a, 1999b) indicates that population has experienced a long term increase in the study area, as well as a recent short term jump. This is clearly exhibited in the village of Port Burwell where population rose from 726 in 1976 to 883 in 1991, and then jumped by 15.9% between 1991 and 1996 to 1,230. This increase is far above the provincial population increase of 6.6% for the same period of time. As a whole, population in Bayham township increased from 3,584 in 1951, to 4,309 in 1991, after which it jumped by 9.6% to 4,721 in 1996. Norfolk township has increased from a population of 11,528 in 1976, to 11,804 in 1991, after which it jumped by 6.7% to 12,590 in 1996.

Townships surrounding Bayham and Norfolk also exhibited population increases within the past decade, albeit at a slower rate. For example, the township of Malahide (just west of Bayham) and Delhi (just east of Norfolk) underwent a population increase closer to 4.5% between 1991 and 1996. The city of London, less than an hour north of the area, is the largest city in the region and also experienced a 4.5% population increase. Nearby Tillsonburg experienced a 9.9% jump in population to 13,211, and is located only 25km north of the study reach. While investigating the study area during field trips, a number of visitors within Port Burwell and nearby beach areas identified themselves as residents of the London region, and it is assumed that the city is an important source of tourists and vacationers for the study area. The general increase in population within the study reach and surrounding region is indicative of an increase in settlement in areas close to the Lake Erie and the Great Lakes shoreline, and most surely indicative of increasing demand for the use of the shoreline's services, natural amenities and recreational developments (Carter et al. 1987, Quigley and Zeman 1980).

5.2.4.2 - Transportation

While Lake Erie provides an important means of access to the study area, road access to the shore area is facilitated by a robust network of roads and highways. Port Burwell is the 'hub' of transportation and communication in the area. It is connected to nearby Highway 401 and the towns of Vienna and Straffordville to the north by Highway 19. Until recently, the village and port was also connected to Straffordville by a spur of the Canadian Pacific Railway. Port Burwell also contains the first major port and marina west of Long Point. County Road 42, (also know as Lake Front Rd. or Road 42) provides a primary road connection between the hamlets noted above, and is generally located anywhere from 50 to 600m from the edge of the bluff. Due to the close proximity of this road to the bluff edge, LPRSMP has recommended that plans be undertaken to relocate Road 42 to Glen Erie Line which is the first Line north of County Road 42 (PA, TA and PWA 1989). Here, a hard and soft topped Line parallels Road 42 approximately 1km north of the lakeshore road, while Highways 23, 24 (to the north), 59 and 3 connect to nearby centres, such as Port Rowan, Long Point, Walsingham, Tillsonburg, Simcoe, Port Bruce, and Port Stanley. Road relocation, due to bluff failures, has already been implemented in nearby Port Bruce (Quigley and Tutt 1968).

5.2.4.3 - Residential Development and Other Infrastructure

Scattered along Road 42, Glenn Erie Line, and its adjoining concessions and regional roads are numerous houses, and farms, in addition to several small pockets of cottages, at times located within 5 to 10 metres of the bluff edge. Chapman and Putnam (1984) believed that a number of physical attributes in the region encouraged population and settlement since a decline after the First World War. These include different agricultural techniques and increased prosperity of the sandy soils, and different crops (eg. tobacco, soybeans, fruits and vegetables, and recently ginseng). The land has also allowed ease of excavation, accessibility of ground and lake water, porous soil which permits the operation of septic tanks, not to mention the close proximity of Lake Erie's recreational areas (Chapman and Putnam 1984).

Residential developments are not only at risk to damage and destruction through bluff failures, but often contribute to bluff instability through water contributions (septic leakage, lawn watering, stream diversions, swimming pools, pond construction). Bluff development can also increase shear stresses through added weight of buildings, excavations vibrations from heavy machinery. Bluff development also requires that services be provided in the region, and most of these closely parallel Road 42. Infrastructural services such as water lines, telephone and hydro lines, and in the town of

Port Burwell, gas lines, all border the road and are costly if damaged by bluff failures. Near the east end of the study reach, the Canadian Coastguard has erected two Remote Marine Radio Towers between Road 42 and the bluff.

5.2.4.4 - Land Use

Apart from Port Burwell and smaller centres, land use in the study area is primarily rural with agriculture being the primary land use and source of income. Tourism and commercial fishing centred around Lake Erie and light service industries situated in Port Burwell are additional sources of income (Barnett 1987; PA, TA and PWA 1989). The north shore of Lake Erie, as evidenced in the study area, is prime agricultural land and is intensively farmed with cash crops such as tobacco, corn, and soybean. In addition, there are a number of small vineyards and peach and apple orchards. Although most of the land has been cleared between the shoreline and the first Concession, small woodlots and patches of trees and shrubs have been left, often dividing property lots and lining the edge of the bluffs. The eastern end of the study reach between Jacksonburg and Clear Creek is more noticeably wooded between Road 42 and the bluff. This section is underlain by the undulating surface of the Galt Moraine, dissected by Clear Creek and its tributaries, and as such some of this area is largely unsuitable for farming.

Field work indicated that land use is an important factor in the stability of the bluffs, particularly in terms of vegetation removal, and drainage particularly between the shoreline and Road 42. Although preliminary investigations conducted on the

Scarborough Bluffs years ago suggested vegetation plays no role in slope stability (Fowle 1982), several sources suggest otherwise, such as TL and AS (1998), Mickelson et al. (1977), Viles and Spencer (1995). May (1977), and GLBC (1977), made similar arguments, and even suggested that the public be encouraged to vegetate coastal slope property, as a means of reducing rill, gully, and sheet erosion. In many cases, soil erosion and bluff erosion is amplified by clearing forest cover along the shore, failure to leave buffer strips along the bluff edge, and by leaving the land bare after harvest during winter and spring (Burns 1985). This action causes sheet erosion towards the bluff edge, and reduces the ability of vegetation to bind the bluff material together or intercept ground water through root networks.

Transpiration is also an important method of removing water from the bluffs, that may be potentially destabilizing. Vegetation is particularly important in stabilizing the bluff faces and is evidenced along the reach, and at several locations just outside the study reach to the east and west. To the west, inside Iroquois beach, a fillet beach has formed in front of the bluffs behind the Port Burwell breakwater, and slopes have stabilized with mature vegetation. Bluffs to the east are protected by Hahn Marsh and have also stabilized with mature vegetation. The document Geotechnical Principles for Stable Slopes (GPSS) produced for the Ontario Government summarizes many ways in which vegetation stabilizes slopes, including the reinforcement of soil through root systems, removal of water from the soil, reduction of flow velocity, and the reduction of frost penetration (TL and AS 1998). Field studies also indicated that certain vegetation types may be useful in identifying the presence of recent slope failures. For example, Coltsfoot

(*Tussilago farfara L.*) was often found in recent bluff slides, as soon as several weeks after movement (Allenson 1998). The usefulness of this species in stabilizing bluff faces, and in the identification of recent earth movement is also noted by Hendrickson (1998) for Gros Morne National Park, Newfoundland, and May (1977) along the English coast.

Agricultural practises along the shore bluff tend towards draining water off the edge of the bluff, since this is the natural water flow direction in most cases. Drainage furrows and drainage tiles are often observed channelling water towards the bluff edge where gullies develop and bluff stability is greatly decreased (Caldwell et al. 1971). In many cases, irrigation is also provided in agricultural land along the bluffs, which in itself is a large input to groundwater along the bluffs. Palmer (1973) discussed a similar problem along the bluffs which line Chesapeake Bay, Maryland.

5.2.4.5 - Recreation Areas

Recreational land use also exists along the study area. Parks and beach areas are important centres of human activity along the shore bluff and beaches, and are also areas where the severity of slope failures is probably highest due to the inherent vulnerability of peoples very lives to bluff instability and erosion dynamics. The very nature of recreational and relaxation areas also provides a false sense of security against hazards, and a mental focus that is usually distracted from the hazardous dynamics of the bluffs. Recreational attractions include Port Burwell Public Beach beside the Big Otter Creek jetties, privately run Erie View Trailer Park just west of South Otter Creek, and Sand Hills Park just west of Jacksonburg. Erie View Trailer Park provides beach access down to the bluff, and contains at least 10 seasonal trailer sites, and a further 15 mobile homes of which some are located within 5m of the bluff edge year round. Sand Hills Park, which boasts 'Ontario's largest pile of sand', is the study area's busiest recreational attraction. Situated atop a large sand dune, the park contains 350 campsites, access to a small beach at the base of the bluffs, and departure points for paragliding (Sand Hills Park Farm 5 Aug. 1999) throughout the Spring, Summer and early Fall. The park, and nearby shore areas, are also the location of several bluff failure accidents, as discussed earlier.

5.2.4.6 - Historical and Cultural Elements

Related to recreational areas are several historical and cultural features in the study area which attract human presence, are of cultural value, but are also subjected to damage and destruction through bluff failures and erosion. Heritage and items of cultural value were noted during field work and include several cemetery lots dating back to the 1800s along Road 42. Many of the cemeteries in the study area contain relatives of people still living in the area. Many of these were buried between the war of 1812 and the early 1800s, not to mention the uncle, aunt and other relatives of the inventor Thomas B. Edison. Several cemeteries also contained stones which dated individuals buried very recently, or within the last century. Museums and particularly cemeteries, are regarded as valuable heritage and cultural items (OMCCR 5 Aug. 1999). The study reach also contains a turn-of-the-century Anglican church designated as a Provincial heritage site in Port Burwell, The Port Burwell Marine and Historical Museum (Ontario Museum

Association 5 Aug. 1999), and the Port Burwell Lighthouse (Carter et al. 9 Aug. 1999) which is toted as Canada's first wooden lighthouse and the first light to shine over Lake Erie. These attract people to the study area, and are potentially at risk to sudden loss or damage through bluff failures.

Another cultural aspect of the study area is brought to light through native archaeological remains. Although official archaeological sites were not discovered in the region, native archaeological items were found at Sand Hills Park (Sand Hills Park Farm 5 Aug. 1999), and several official archaeological sites were unearthed by the University of Western Ontario along the bluffs west of the study reach. The nature of these sites is discussed by Quigley et al. (1983), where a preliminary archaeological survey of East Elgin County, between Port Stanley and Port Bruce, has identified prehistoric Indian sites along the shore bluffs believed to be occupied 7000 B.C. to 1500 A.D. These sites were described as being at risk to shore bluff erosion and were predicted to be fully removed by the year 2000 (Quigley and Haynes 1983). Such loss is deemed an important loss of cultural and historical information.

5.2.4.7 - Shore Protection

Shore protection provides evidence of human development and engineering attempts in the region. It also has positive and negative affects, as noted by Carter (1988), and Davidson-Arnott and Keizer (1982). Generally, however, shore protection can have site-specific, short-term, positive effects if constructed properly. Quigley et al. (1977) reported on the successful installation of gabion groynes on Lake Huron, Ontario.

Although the shoreline in the study area has not been subjected to large amounts of hardening, a mix of concrete-block seawalls and rip-rap are installed east of the Port Burwell beach, at Sand Hills Park, and at a pocket of cottages immediately west of the Hahn Marsh. LPRSMP noted that the shore protection east of the Port Burwell harbour is providing some protection at the time, but is known to require reinforcing and improvement in several sections (PA, TA and PWA 1989). Shore protection at the Sand Hills park is relatively recent, and at present appears to be providing some protection, especially in the areas flanked by concrete blocks. During field work it was determined that the shoreline immediately up-drift of the protected portion of the Park had receded at least 20m further inland than the unprotected portion. The effect of this protection on areas down-drift of the park are uncertain, but could lead to larger failures in future. Shore protection near the Hahn Marsh appears also to be providing some protection, but is in need of future repairs and reinforcement. Hundreds of tires dot the shoreline of the study region as the result of an illegal and ineffective shore-stabilization project attempted by a resident east of South Otter Creek several years ago (Baskerville 1997).

Perhaps the most obvious shore protection in the study region is the breakwater at Port Burwell. Started in 1834, the Port Burwell harbour jetty was extended to an 8m water depth in 1929, totalling 1,300m lakeward from the original shoreline (Philpott 1986, Zeman 1978). In 1978, the alleged negative impact of the breakwater on down-shore bluff erosion and sediment transport was the subject of a 30million litigation by shoreline residents between Little Otter Creek and Long Point Creek. The litigation also prompted a great deal of research and study by a number of individuals and agencies for the Federal government. In 1985, the results of extensive research were released and a ruling was made in favour of the federal government. Research indicated that the breakwater had little long term effect on shoreline erosion, and was not starving the down-shore of sediment, or increasing erosion due to the large volume of littoral sediment that was already moving through an area of negative sediment budget (Davidson-Arnott 1989, Philpott 1986). In fact, reports by Philpott (1983, 1986) indicated that the breakwater may instead provide a noticeable reduction in shoreline recession in the area. Modelling of storm surge conditions indicated that the effect of the breakwater is to cause a local reduction of surge induced nearshore currents for a distance of 5 to 10km east of the harbour . Hydrodynamic studies also showed that the breakwater shelters the shore east of the harbour for a distance of about 3km. This is believed to be the principal reason for the local reduction of shore recession close to the east side of the Harbour (Philpott 1986).

5.2.4.8 - Future Development

Future development is an important human aspect of the study area, as it governs population growth, and the increase or decrease in human activity along the shoreline as well as various factors which influence the bluff stability. In the early 1970s, proposals arose to develop a Parkway along the length of the Lake Erie shoreline from Windsor to Niagara. Portions of this parkway were to replace Road 42 in the study area, as a means of providing a 'recreation corridor' along the north shore, providing access to the shore amenities, and stimulating recreational, commercial, residential and industrial development along the shoreline (Caldwell et al. 1971). Although the proposal is presumed to have fallen through, other investigations are underway to examine transportation routes along the study reach. In particular, Elgin County is currently investigating the long term implications of shoreline erosion on their ability to maintain Road 42 (Baskerville 1 Oct. 1999).

There is still recent evidence of development, population, and a demand for recreational facilities in the study region. During field work, and comparison with recent OBMs of the land south of Road 42, at least 25 buildings, new homes, or barns were discovered built in the region, most of which had been located between the Road and the shore bluff. The region has also received a recent proposal to develop a marina at the mouth of Long Point Creek on Lot 1 of Norfolk Township, immediately west of the Hahn Marsh (Baskerville 1997). A marina complex comprising of a marina, restaurant, hotel and a resort condominium development is proposed by a consortium of developers and a landowner. The marina is proposed as a means of providing boating access in the region. Since no boat facilities are provided on the south side of the Long Point Spit, the nearest facilities west of the spit are in Port Burwell, close to 25km away. The first proposal for Captain's Cove Marina was received in January of 1991 (Sandwell 1991), but was not accepted due to unresolved questions about the project's effect on present lakeshore processes (Sandwell 1992). A revised proposal was submitted in September of 1992 (Sandwell 1992), and although there has been no initial development in the area, the status of this proposal is unknown and the development project could still be alive (Baskerville 1 Oct. 1999).

5.3 - Data Availability and Analytical Restraints

Determining the study area, its human and physical components, as well as the nature of slope failures in this area were fundamental steps to performing a GIS slope stability analysis. These steps were parallelled by a search and collection of data which would describe such processes for use in a GIS analysis. While searching for this data, several important 'data-related' decisions and considerations had to be made. Many of these issues were noted in Chapter 4, including scale of the data, time, costs, and benefits of the research (Hansen 1984, Fulton 1987). The following sections discuss several of these, including the factors that would be used for the analysis, hardware and software considerations.

5.3.1 - Determining Slope Instability Factors

Due to the complexity of landslides, such as those within the study area, it is difficult to accurately assess all the factors that contribute to the instability of slopes, much less obtain the data reflecting their spatial or temporal distribution (Barnett 1990, Varnes 1984). Hutchinson (1986) noted that field studies are frequently bedevilled by the number of variables and their differing degrees of activity. These difficulties were evidenced during the investigation along Erie's north shore.

Many factors were believed to contribute to the slope failures of the bluff, but without geotechnical investigations, it was impossible to obtain and include data for these factors in a GIS analysis. For example, the spatial distribution of ground-water is believed to play an important part in the stability of the bluffs. However, without a detailed study, it is impossible to include some of this information in a regional analysis. The temporal distribution of ground water is also a major factor in bluff stability. Episodic event of heavy rains can quickly over-saturate certain stratigraphic layers and cause sudden failure (Zaruba 1982). The dynamics of such events are difficult to quantify and include in a regional GIS study (Carrara et al. 1985), and detailed temporal and spatial information is best obtained from site-specific, geotechnical investigations, which, while useful, also require large expenditures of money and time.

Due to these limitations, the goal of this study was, instead, to perform an exploratory, regional investigation of slope stability and risk through cost and time efficient mapping and analysis. These preliminary investigations are important, and can further aid in defining specific locations for more detailed geotechnical and site specific assessments (Hansen A. 1984).

Previous discussion has listed many factors believed to contribute to the instability of the bluffs. Identification of these factors was the first step towards building a database for the analysis (Carrara et al. 1995). Using this list of factors, the next step in the research was to determine whether data could be obtained for any of these factors and incorporated into a GIS analysis. After months of searching for data, and determining hardware and software restraints (discussed below), it was determined that the following data layers could be compiled for an analysis: Slope, Elevation, Geology and Stratigraphy, Vegetation, Recession Rate, Shoreline Protection, and Human Elements at risk within the study area. Together, these factors are believed to provide a comprehensive, regional view of the susceptibility to bluff failure.

5.3.2 - Hardware and Software Issues

Hardware and Software are the core components of a GIS (Aronoff 1989, Burroughs and McDonnell 1998), and as such, were key considerations at a very early stage of the research. The size, and format of the data necessarily had to be compatible with hardware and software available at Wilfrid Laurier University (WLU) and University of Waterloo (UW), in addition to my own personal familiarity with GIS. GIS hardware consisted of a Pentium II 350 Mghz. CPU with 128Mg RAM, 24x CD ROM, 8Gb HDD, and Windows '98 Operating System. Since many of the data files were very large, an Iomega 100Mb Zip drive, CD ROM writer, and 4Gb Network Drive were also used for data backups and transfers between UW and WLU. A keyboard, mouse, 4'x3' desk digitizer, Umax Astra 2400S and several printers, including an Hewlett Packard Inkjet 720, Hewlett Packard Laser 5M/5MP Postcript, and Epson Stylus 1520 Inkjet Printer, were used as input and output devices. GIS software included several packages including ArcInfo 7.2.1 (ESRI 1998a), ArcView 3.1 with 3D Analyst 1.0 and Spatial Analyst 1.1 extensions (ESRI 1998b), MapInfo 5.0 Professional (MapInfo Corporation 1998), and Idrisi for Windows 2.0 (Clark Labs 1997). Corel WordPerfect Suite 8 (Corel Corporation 1997a) and CorelDRAW 8.0 (Corel Corporation 1997b), and CorelPHOTOPAINT 8.0 (Corel Corporation 1997c) were also used in the compilation of the text and diagrams associated with the thesis. MapInfo is a basic mapping package for vector line work and simple analytical functions, while Idrisi is a raster based GIS package that provides complex analytical capabilities, particularly through overlay analysis and statistical assessments.

5.3.3 - Replicability of the Analysis by Conservation Authorities

One last consideration while collecting data for the analysis was its compatibility with current work by CAs. It is hoped that this work will be able to be replicated or incorporated into management and planning initiatives by local governing bodies such as the CAs, OMNR or the OMOEE. In order to do so, hardware, software, and data must be readily accessible and available to these bodies, in addition to a standard set of guidelines for choosing, using or analysing this data.

The Technical Guide: Great Lakes - St. Lawrence River Shoreline (TGGLSLS) (OMNR 1994) and Geotechnical Principles for Stable Slopes (GPSS) (TL and AS 1998) are both provincially produced documents and provide a helpful foundation for other CAs wishing to engage in this form of research. The final copy of the Tech Guideline has yet to be released or accepted as law by the province, but it is assumed that this will eventually be mandated by the provincial government as the basis for CAs management of the shoreline. Both documents are felt to be useful, standardized guidelines for estimating slope risk along the Great Lakes shoreline and effort has been made throughout this study to incorporate information from the guidelines, and to use their method of ranking slope stability. An unfinished chapter in the draft copy is devoted to Slope Stability, while the entirety of the GPSS (TL and AS 1998) is devoted to this topic and is very useful. The latter document also includes a chart with factors to be considered in ranking the stability of coastal slopes, in addition to a classification scheme for each variable. Four of the variables used in this study are included in this chart, including slope, elevation, vegetation cover, and stratigraphy. The suggested classification scheme, though modified slightly in some cases to fit a five tier classification.

In order that the Conservation Authorities and other governing bodies could replicate this research, an effort has also been made to use hardware and software that would be readily available to them. While searching for a study reach, and discussing GIS use with the CAs and Aylmer District OMNR office along the north shore, it was evident that ArcView (Baskerville 16 Dec. 1999), and in some cases ArcInfo (Kebbel 23 Feb. 1998) were currently used for presentation and analysis of data. Although much of the digitizing and data layer management was initially performed in MapInfo, ArcView is capable of performing the same job. Outside of these packages, ArcInfo was used to create Digital Elevation Models (DEM) and Idrisi was used to perform most of the overlay analysis and summary statistics. Without Idrisi, the same analysis could likely be performed in ArcInfo. Without Idrisi or ArcInfo, it may be difficult to duplicate the steps taken in this project. However, Idrisi is readily available for purchase at around $1,500 United States dollars (Clark Labs 10 Dec. 1999). In addition, it is speculated that upcoming versions of ArcView's 3D and Spatial Analyst extensions will be able to perform similar raster based analytical functions as Idrisi and ArcInfo.

Since data is a major issue with GIS analysis, it is important that all governing bodies have ready access to the information used in this study. Much of the information was obtained from OBMs, data available through CCIW and the OGS, and simple field work. All of which is readily accessible and inexpensive to the CAs. In some cases, this data is also available in digital form which saves time and costs (eg. OBMs).

5.4 - Data Sources and Acquisition

Perhaps the greatest hurdle in this research was the search for, and acquisition of data. Close to a year and a half was spent searching for information and data related to factors believed responsible for bluff failure. This research consisted of many phone calls, emails, interviews, and trips to various institutions. Several sources of data that were discovered could not be used due to their poor quality, or the time needed to obtain them, such as digital copies of the OBMs. Other sources of data were obtained, and although interesting and of a high quality, contained data that was not fully relevant to bluff stability research, was out of date, in an incompatible data or software format, or used classifications or scales of research that were not fully compatible with this study. These included the Great Lakes Coastal Zone Database which was in SPANS format (EC 8 Nov. 1998, Gillespie 16 Mar. 1998, Holland-Hibbert 25 Sep. 1998), Great Lakes Coastal Classification and Mapping Study (Geomatics Inc. and Davidson-Arnott 1992), the Environmental Sensitivity Atlas (EC 16 Oct. 1998, EC 1994), an uncompleted shoreline mapping and GIS program implemented by the Canada-Ontario Flood Damage Reduction Program in 1987 (Lawrence 1995c, EC 8 Nov. 1998), and the Great Lakes Shore Damage Survey Coastal Zone Atlas (EC and OMNR 1976). In the end, almost all of the data and information was obtained from field trips to the site, OBMs and NTS map sheets, work by Peter Barnett on the Geology and Stratigraphy of the Shoreline, and data compiled during the Port Burwell Litigation of 1978-1985. Though some of these sources are specific to the study reach near Port Burwell, much of the information is readily available to CAs. This does not discount the fact that CAs and other organizations may also have collected locally relevant data along other reaches of Lake Erie and the Great Lakes.

5.4.1 - Ontario Base Maps (OBMs)

In order to best describe the acquisition, and preparation of the slope instability data layers, each layer is discussed individually in Chapter Six. An initial section here, however, first describes use of OBMs and some of the basic steps taken to digitize them.

OBMs provided the best base maps for the study area, in addition to a host of other data layers, as described in the next chapter. Eleven OBMs spanned the study reach and were purchased from the OMNR through Technicom Consultants, Waterloo, Ontario. The identification numbers for each map are listed in the Bibliography (OMNR 1997). Each of the maps was produced in 1997, and based on the most recent air photographs of the region taken in 1985.

The OBMs were considered to be a critical acquisition for several reasons. Firstly, the maps contained information that could be used to compile several critical data layers including Elevation, Slope, Vegetation Cover, and various Human and Cultural Features such as roads, houses, and buildings. Secondly, the OBMs are produced at a scale of 1:10,000 which is a more than adequate scale considering Carrara et al. (1995) suggest that the coarsest resolution to be used in a GIS study of slope failure is 1:25,000. Soeters and Van Westen (1996) also discuss the scale of slope analysis and suggest that the scale used in this study is large scale, and maps can be used for site level investigation before the design phase of an engineering project. The OBMs were therefore used as 'base maps' for the study area, to which other data could be applied and mapped. Utilizing the same maps for several data layers, and digitizing them all in one session would also help reduce a number of errors including registration errors and non-standard errors which accompany information obtained and compiled from several sources.

OBMs were digitized using MapInfo Professional 5.0 and a 4'x3' digitizing tablet in the Geography and Environmental Studies Department at WLU. Although scanning the maps was an option, this method is not recommend (Aronoff 1989) due to locational errors, numerous concatenations, and a great deal of data clean-up and error corrections. Each of the maps was successfully registered using 4 control points to obtain a registration error under 0.025cm (ie. 2.5m on the ground [0.025cm x 1:10,000 maps scale = 2.5]) before relevant features were digitized. In order to utilize the borders of the OBM sheets and to provide some context for the actual study area, digitizing was extended a short distance east and west of the actual study reach to where the relevant OBMs ended (Figure 5.5). Bluffs along this extended area do not border Lake Erie, are largely protected from subaqueous processes, and generally quite stable, as evidenced by the mature vegetation which covers a large portion of these slopes (Barnett 1983b, 1987). The bluffs west of Big Otter Creek are protected by a fillet beach that has formed behind the Port Burwell breakwater. To the far east, the bluffs are protected by the Hahn Marsh.

Since the entirety of each OBM was not needed for the study, only a strip of land between the shoreline and Glenn Erie Line was digitized. This strip ranged from about 1.5 to 4km in width and generously contained any land that would be affected by the maximum 100yr erosion limit (ie. 529m). This figure is calculated using the maximum annual average recession rate in the study reach (5.29m/yr x 100yrs), as determined by Fleming (Fleming 1983 as cf. PA, TA and PWA 1989) during research for the Port Burwell Litigation case. Unfortunately the maximum rate is erroneously cited to be 4.5m/yr by Carter et al. (1987) and the LPRSMP (PA, TA and PWA 1989). Although all 10 OBMs did not collectively form a four-sided rectangle over the study area, it was advantageous to define the study area in this form, in order to create a Digital Terrain Model (DTM), and for ease of data imports and exports through Idrisi. Figure 5.5 shows how the OBM sheets were used to define the study area boundaries, and is a useful reference to discussion contained in the remainder of this chapter. Figure 5.5 also shows several geographic locators and the location of the study reach containing the data which would be analysed in Idrisi. Much of the area within the rectangle contains no digitized data, and two of the OBMs are dissected by the boundaries to reduce the size of data images. Figure 5.6 depicts a representative portion of the OBMs and the resulting digitized image in MapInfo.

Although hardcopy OBMs were used during this research, it should be noted that digital copies were also available for the study area. These were not used for several reasons. The chief reason was the tardiness in receiving these maps from the Aylmer District Office of the OMNR. From order date to the reception of the final map took close to 8 months, after which each map layer for each OBM (a total of 220 layers) had to be manually converted from ArcInfo export files (*.e00*) to ArcView shape files (*.shp*) (using ArcView's Import 71 utility) so files could be used with GIS software at WLU. Once these maps were received and converted, it was discovered that the 1st digit in the

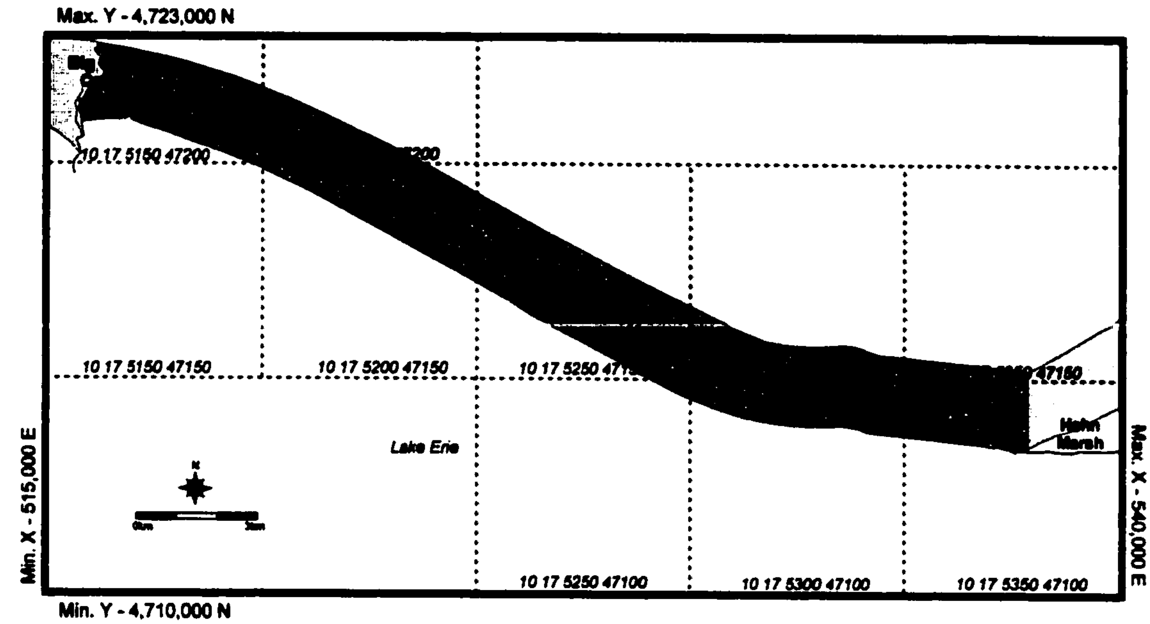


Figure 5.5: Location of the study reach and 529m recession setback in relation to the OBM sheets. Portions shaded light grey to the east, west and north of the study reach were only digitized in part, but not included in the final risk analysis. The min. and max. coordinates were used to define boundaries for the Idrisi raster images, and are noted on the diagram along with several geographic locators.

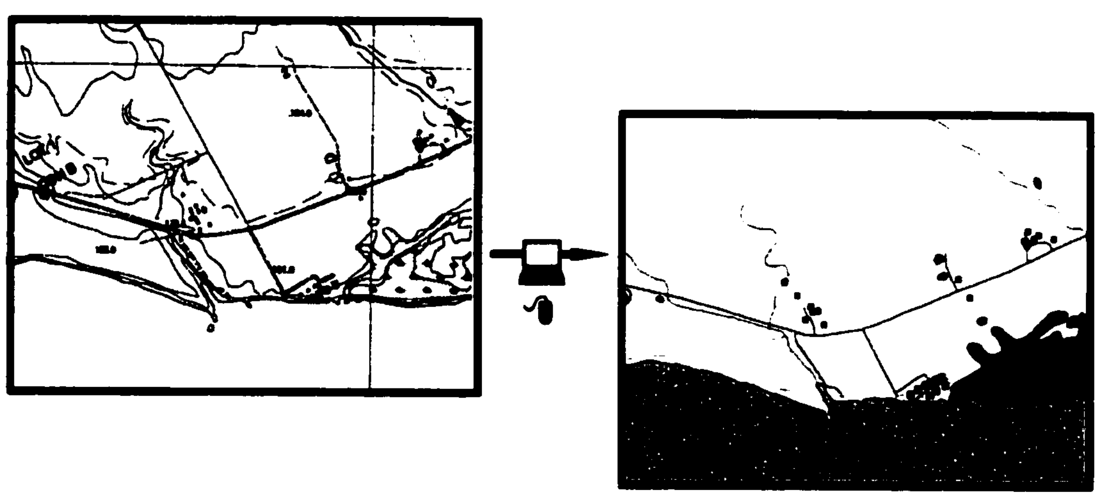


Figure 5.6: Sample section of an OBM, and the corresponding digitized image in MapInfo. Features in the sample include vegetation cover, Hahn Marsh, ponds, Clear Creek, roads, trails, buildings, elevation contours, and Lake Erie.

longitudinal coordinate (y coordinate) had been truncated by OMNR (eg. 4,720,000N was rendered 720,000N) and each of the 220 data layers would require extra processing using 'X,Y Shift' Avenue Script *(.ave)* to prevent maps from being located in the Caribbean. Due to the time required to convert these maps, missing data layers on certain OBM sheets (eg. buildings), and general time needed to clean them up, the OMNR digital maps were not used and those digitized from the hardcopy maps in MapInfo were maintained as the base maps for the research and analysis.

The digital maps received from the OMNR were, however, useful for calculating some form of error within the digitized maps. Several principal data layers (contours, roads, vegetation and buildings) from random OMNR digital map sheets were prepared and overlaid with my own digitized maps and the differences noted. In general, the maps display a surprising degree of reproductional accuracy. Positional differences certainly exist between many points, lines and polygons, but these only range from 0m to approximately 5m, and in rare instances, up to 8m. When one considers that the thickness of most lines on an OBM represent approximately 2.0 to 10m (eg. contours, roads), this is a fairly small amount of error. Many of these errors are assumed to be the result of map shrinkage and digitizing errors.

One noticeable difference between the OMNR digital maps and the digitized hardcopy OBMs, is that polygons for vegetation are consistently larger in their digitized format. This phenomena, which accounts for an average addition of 4m width to the sides of each polygon, appears to be due to the interpretation of the line symbol used to demarcate vegetation polygons on the hardcopy maps. Here, the vegetation polygons are formed by an undulating line (Figure 5.6), where the width of the wave accounts for about 4 to 5m. While maps were digitized, the perimeter of the outermost wave had been followed, apparently expanding the perimeter of the polygons from the OMNR digital maps. The ramifications of this difference are discussed later in the section which focusses on the creation of the vegetation data layer.

Another difference noticed in comparing the maps was a seemingly standardized locational shift between the two maps. In general, objects on the OMNR map sheets appeared to be shifted about 1.5 to 2m to the southeast of their matching counterparts on the digitized maps. No reason was determined for this, and due to the generally small and standardized nature of the error, this was not perceived to be a concern.

Comparison with the OMNR digital maps indicated that the digitized hardcopy OBMs were of a fairly high quality. Despite the apparent quality of the reproduction they undoubtedly contain errors of commission (digitization errors, errors producing hardcopy) and omission (undigitized objects), in addition to extraneous errors such as map deformation through shrinkage or expansion (Aronoff 1989, Burroughs and McDonnell 1998).

Many hours were spent attempting to minimize these errors. Several measures were taken to reduce errors of omission or commission. Upon the completion of each data layer, systematic visual checks were made to ensure that items had not been missed. Random checks were also made to ensure map sheets had not shifted on the digitizer by randomly retracing lines and polygons and comparing results. Where items had been missed, or errors made in the location of digitized points, lines and polygons, corrections were made. Various items (eg. contours, spot heights) were assigned elevation attribute values and errors were easily made while typing in the numeric values. In order to check for these errors, each spot height digitized directly from the OBM was double-checked. In addition, the MapInfo data tables (referred to as Browsers) were scanned for anomalous values, and Standard Query Language searches were made for values that could, but should not appear in the data tables. In order to reduce shrinkage or expansion, maps were digitized immediately after receiving them. Several steps were taken to reduce the effects of extraneous errors, including efforts to digitize the maps immediately after receiving them. In addition, some corrections were made to better 'edge match' adjacent OBM sheets. Occasionally, objects (particularly roads and vegetation polygons) which spanned the borders of two OBMs did not match well due either to errors in the original hardcopy OBMs, or slight variations in the registration errors between maps. In most cases these errors amounted to about 4 or 5 metres and the items were edge-matched as best as possible by adjusting the 'meeting-point' of the objects to the mid-point of the locational difference. Finally, it is important to note that several variations exist between the OBMs and the current study area. This is inevitable since the OBMs are based on information from 1985 air photos. Physical, human, and cultural information digitized from the OBMs is necessarily dated to 1985, and could not be updated through field work without a large amount of time.

Aside from errors of commission or omission, or extraneous errors, it is important to note that a digitized map is only as accurate as the scale of the source map from which it was digitized. For example, if a map is digitized from a source at 1:10,000, it may be plotted on screen and paper at 1:2,000 (or any scale!) using MapInfo or ArcView's 'zoom' features. However, the information is not accurate to 1:2,000, and is only accurate at the original scale of 1:10,000. Smaller features not visible on the 1:10,000 source map will not suddenly appear when the map is produced at 1:2,000. For this reason it is not recommended to produce a map at scales larger than that at which it was digitized (Boyd 1981), and 'analytical' maps for this study will not be printed or displayed at a scale less than the original of 1:10,000.

CHAPTER SIX

GIS Assessment of Lake Erie's North Shore: Data Collection, Preparation and Analysis

"A momentous adaptation of electronics and numerical analysis, hazard zone maps are a new cartographic genre, as distinct in appearance and function as property maps and navigation charts." M. Monmonier (1997)

6.0 - Introduction to the Research

This chapter describes the creation and preparation of seven main data layers used to evaluate failure susceptibility and risk. The discussion in this section is necessarily generalized, but is meant to capture some of the key decisions and steps taken to collect, prepare, input, manage, analyse, and present the data and results using a variety of desk top publishing software packages, and several GIS software packages including MapInfo, ArcInfo, Idrisi, and to a lesser degree, ArcView. Chapter 7 then focusses on a discussion of the methods and results, in addition to recommendations and conclusions from the study.

Overall, this chapter is structured such that each data layer involved with the analysis is individually discussed, and then briefly summarized using graphs, tables, and a map. Following the data layer descriptions, several sections discuss the methods and issues concerned with the overlay assessment of slope failure susceptibility, and risk. Where appropriate, discussion is made of the accuracy and potential errors associated with the methods. Although most data layers were originally digitized to the extent of the 100yr bluff erosion limit, discussion and analysis focusses on the land area within 20, 10, and 5yr recession setbacks from the bluff edge. The rationale for using these limits is discussed in Section 6.5 which details the creation of recession rate data layers.

For reference purposes throughout the chapter, Table 6.1 summarizes the major MapInfo data layers produced and used in the study, including the name of the data layer, metadata description of the layer, source of the data, and the format of the digitized data (ie. point, line, polygon). When specifically referred to throughout this chapter, data layers are italicized, and software utilities or commands are capitalized and italicized.

This research evidences the interplay which is necessary, and now possible, between various GIS and non-GIS software packages. The ability to transfer and convert map data from vector to raster format (ie. linework to grid) was particularly important. Although vector format was most amenable to the input and preparation of the maps in MapInfo, this data was best converted and analysed in a raster format within Idrisi. The software interplay necessary to prepare, analyse and present the data in this study is depicted in Figure 6.1. In addition, Figure 6.2a-d is a continuous flowchart which further details the methods of research. These flowcharts (Figures 6.1 and 6.2) should be used liberally as a reference while reading through this chapter, as they contain a great deal of methodological information regarding parameters, value judgments, software, commands, functions, and data layer names required to create the final risk maps.

Table 6.1: Metadata for all MapInfo map layers, including name of the layer, source of the data, general description of the layer, and the data format.

[illegible]	[illegible]	[illegible]	[illegible]
Geographic Locators			
Labels_printmap	- legend, OBM sheets, borders etc.	OBM	Text
Labels_contours	- contour interval elevations	OBM	Text
Labels_locators	- road names, towns, creeks, townships	OBM, NTS, Field Work	Text
Obm_mapsheets	- outline of OBM map sheet borders	OBM	Line
Initial	- rectangle which encloses the entire mapped study area - used to determine max. and min. coordinates of study area	OBM	Polygon
Physical Features			
Creeks_drains	- creeks, smaller-scale natural and human drains	OBM	Line
Lake_erie	- Lake Erie, Big Otter Creek, and Little Otter Creek to Road 42	OBM	Polygon
Ponds_dugouts	- natural ponds and human agricultural dugouts, reservoirs	OBM	Polygon
Vegetation	- forest stands, large hedgerows (does not include orchards)	OBM	Polygon
Wetland	- wetland areas, mainly Hahn Marsh of the Long Point Marsh	OBM	Polygon
Elevation and Slope			
Breakpoints	- elevation spot heights which help to interpolate and define breaks in slope, gullies, and creek beds - integer and real	OBM (Interpolated)	Point
Contours	- elevation contours at 5m intervals - several contours mark elevation between 5m intervals, as depicted on the OBMs - integer and real	OBM	Line
Shoreline	- elevation contour which marks the Lake Erie datum level at 173.5masl	OBM	Line

Shoreline_general	- *Shoreline* contour, with removal of east breakwater of Big Otter Ck. and sand bar just east of Port Burwell beach - used to form bottom boundary of polygons for *Recessrate10, 20 and 5, Geostrat*, and *Shore_protect*	OBM (Interpolated)	Line
Spotheights	- elevation spot heights from OBMs - integer and real	OBM	Point
Studysite_clippoly	- encloses the 'land side' of the mapped study area - used in ArcInfo as a clip polygon to prevent TIN DEM interpolation of Lake Erie, Big Otter and Little Otter Creek	OBM	Polygon
Human Elements at Risk			
Buildings_houses	- houses, large sheds, tobacco kilns, small greenhouses	OBM	Point
Buildings_other	- commercial/industrial buildings, barns, large greenhouses	OBM	Polygon
Comm_towers	- radio communication towers owned by Canada Coastguard	OBM	Point
Hist_cultural	- historical and cultural features, including churches, cemeteries, heritage and historical sites	Field Work, NTS, OBM	Polygon
Railway	- Canadian Pacific Railway spur from Straffordville	OBM	Line
Recreation	- recreation areas including picnic sites, trailor parks, camping areas, parks and public beaches	Field Work, NTS, OBM	Polygon
Roads	- hard surface and all-weather loose or stabilized surface roads and access roads (includes driveways)	OBM	Line
Shore_protect	- shoreline reaches/areas protected by groynes, seawalls, or riprap, interpolated inland to furthest extent of *Recessrate20*	Field Work	Polygon
Trails	- loose, unpaved surface, dry weather vehicle access trails	OBM	Line
Geology and Stratigraphy			
Geostrat	- classified reaches/areas of homogenous geology/ stratigraphy, extending from *Shoreline_general* inland to furthest extent of *Buffer_529*	P. Barnett (Interpolated)	Polygon
Geostrat_ demarcbarnett	- location of P. Barnett's geological/stratigraphical data collection sites - demarcation of geological/stratigraphical reaches along *Shoreline_general*, using mid-points between P. Barnett's data collection sites	P. Barnett (Interpolated)	Point
Shoreline Recession Rate			
Buffer_529	- digitally generated 100yr recession rate buffer calculated using the max. AARR value for the study reach - buffer stretches 529m inland from *edge_of_bluff.*	OBM (Interpolated)	Polygon
Edge_of_bluff	- interpolation of the edge of the bluffs/gullies within the study reach from Big Otter Creek to Hahn Marsh. Long ravines and creek valleys are cut off slightly up-stream	OBM (Interpolated)	Line

Recessrate10	- classified reaches/areas of similar AARR using CCIW classification, C. Fleming and Sandwell's data, and 10yr recession setback - unit boundaries defined by *Recessrate_demarcflem, Shoreline_general*, and *Recessrate10_buffer*	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate10_buffer	- digitally generated buffers for classified recession rate reaches, as defined in *Recessrate_demarcflem* - buffer calculated using 10yr recession setback from *Recessrate_eob*	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate20	- classified reaches/areas of similar AARR using CCIW classification, C. Fleming and Sandwell's data, and 20yr recession setback - unit boundaries defined by *Recessrate_demarcflem, Shoreline_general*, and *Recessrate20_buffer*	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate20_buffer	- digitally generated buffers for classified recession rate reaches, as defined in *Recessrate_demarcflem* - buffer calculated using 20yr recession setback from *Recessrate_eob*	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate5	- classified reaches/areas of similar AARR using CCIW classification, C. Fleming and Sandwell's data, and 5yr recession setback - unit boundaries defined by *Recessrate_demarcflem, Shoreline_general*, and *Recessrate5_buffer* - only the reach with the highest average recession rate along the study reach area is included in the layer	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate5_buffer	- digitally generated buffers for classified recession rate reaches, as defined in *Recessrate_demarcflem* - buffer calculated using 5yr recession setback from *Recessrate_eob* - only the reach with the highest average recession rate along the study reach area is calculated for the layer	C. Fleming, Sandwell, CCIW (Interpolated)	Polygon
Recessrate_ demarcflem	- demarcation of recession rate reaches along *Shoreline_general* - location of C. Fleming's AARR data collection sites - demarcation of recession reaches, classified by AARR, along *Shoreline_general*, using mid-points between C. Fleming's data collection sites	C. Fleming, Sandwell, CCIW (Interpolated)	Point
Recessrate_eob	- modified version of *Edge_of_bluff*, from which is generated *Recessrate_buffers 20, 10, and 5.* - *Edge_of_bluff* is segmented to define the limits of the *Recess_rate 20, 10, and 5yr* reaches, using *Recessrate_demarcflem* as a guide	C. Fleming, Sandwell, CCIW (Interpolated)	Line

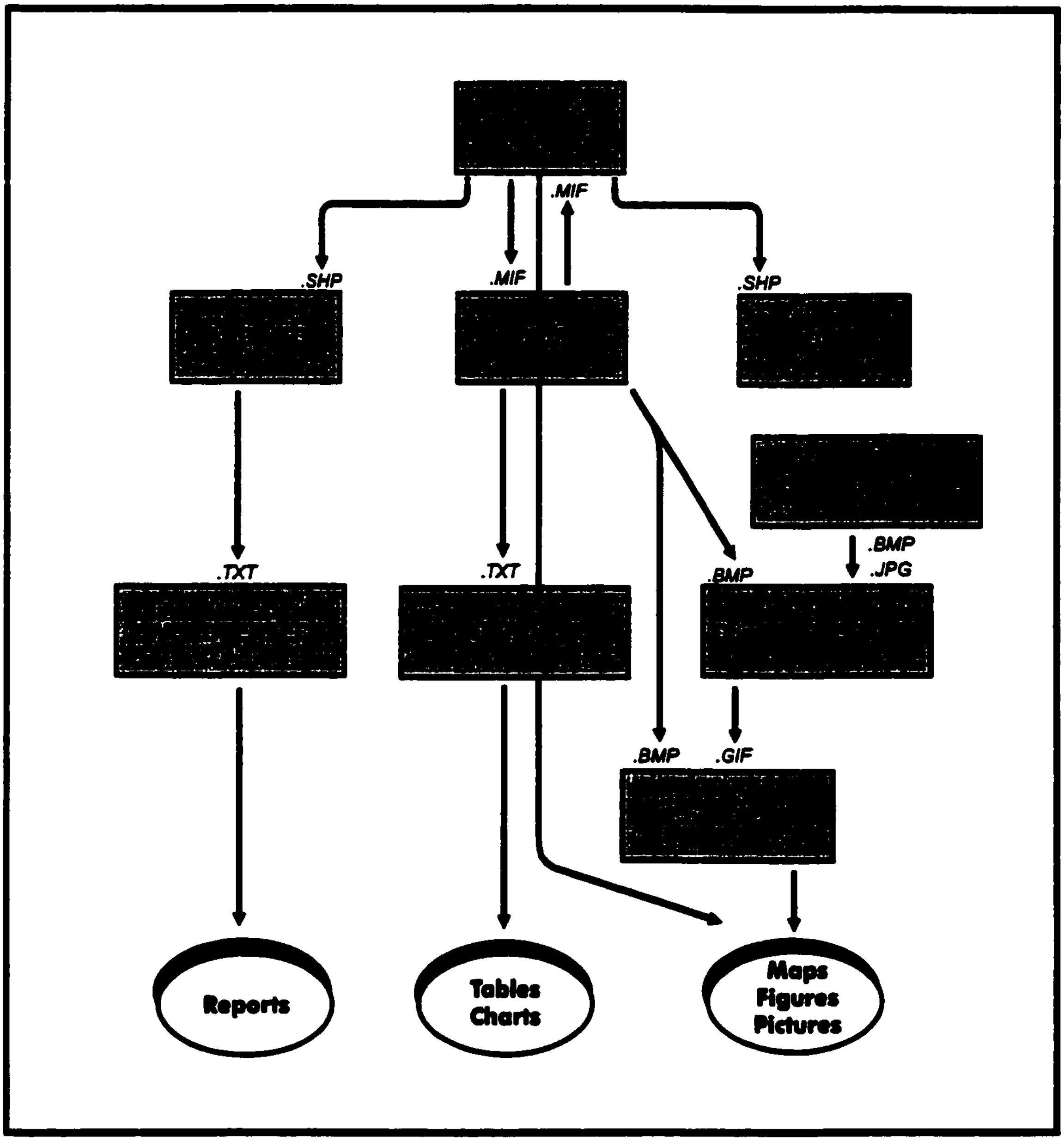


Figure 6.1: Flowchart showing a generalized view of the interplay between GIS and other software used for the input, management, analysis and presentation of data.

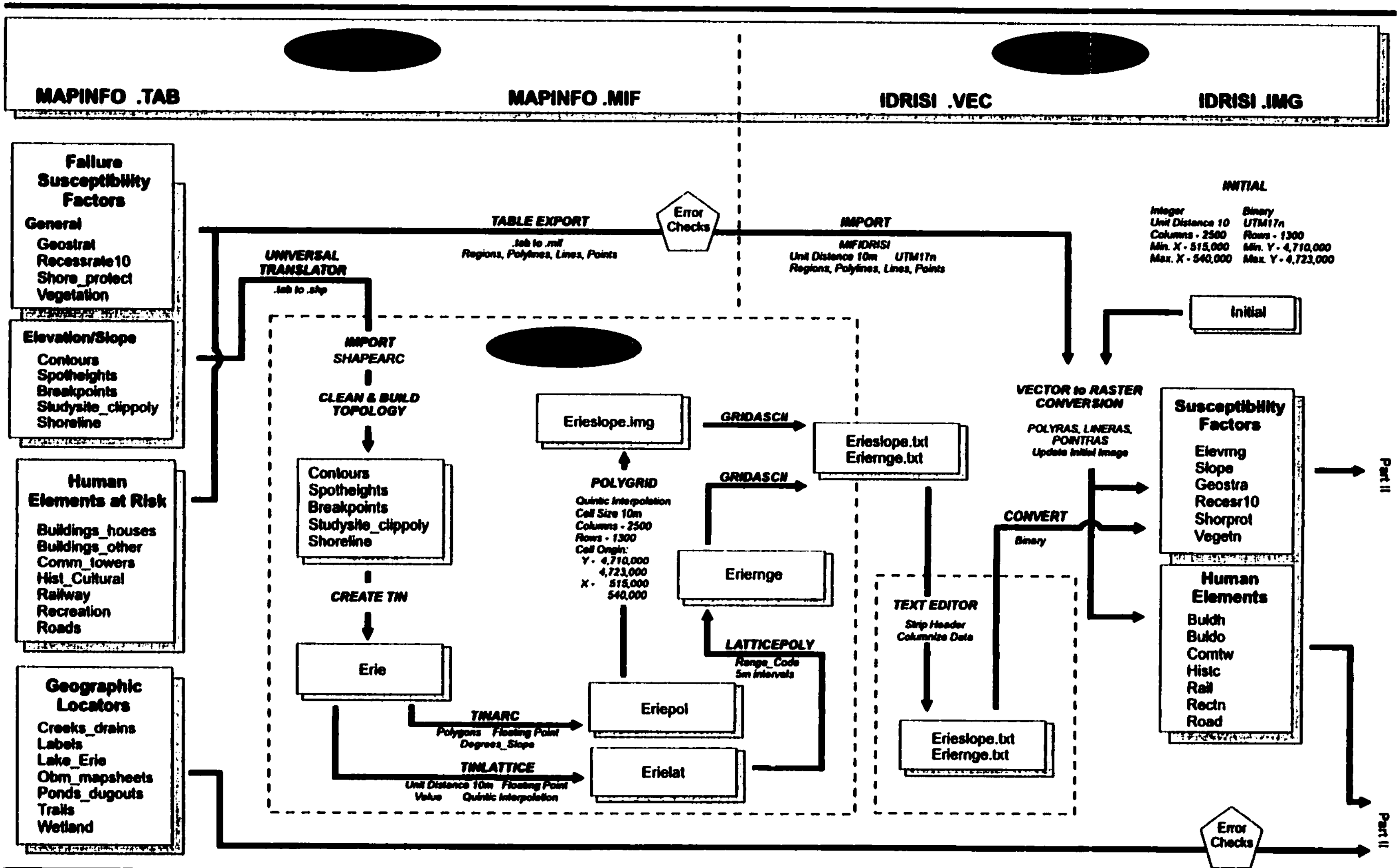


Figure 6.2a: Part I - Detailed flow diagram of data management, transformations, parameter inputs, and final analysis.

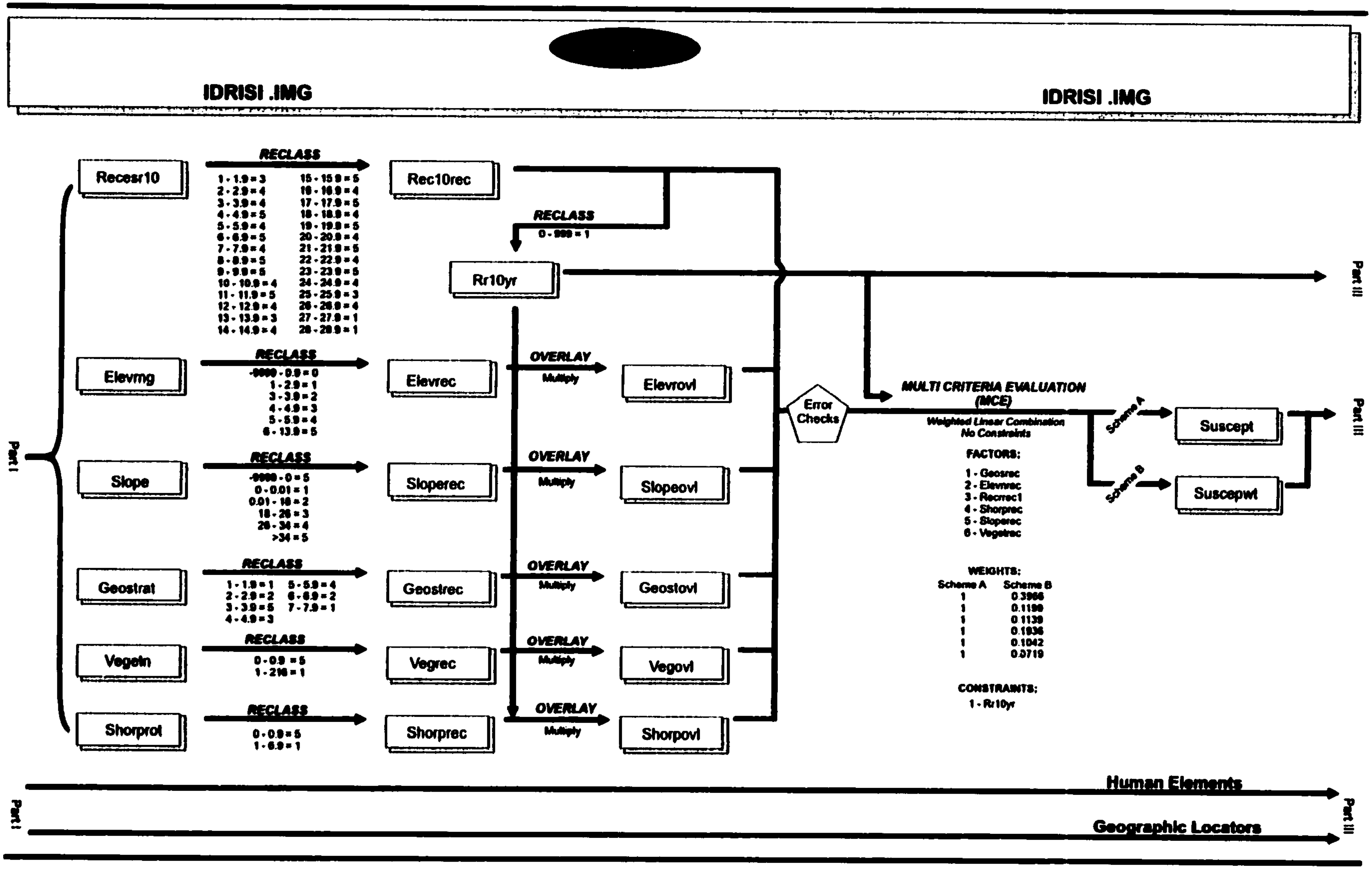


Figure 6.2b: Part II - Detailed flow diagram of data management, transformations, parameter inputs, and final analysis.

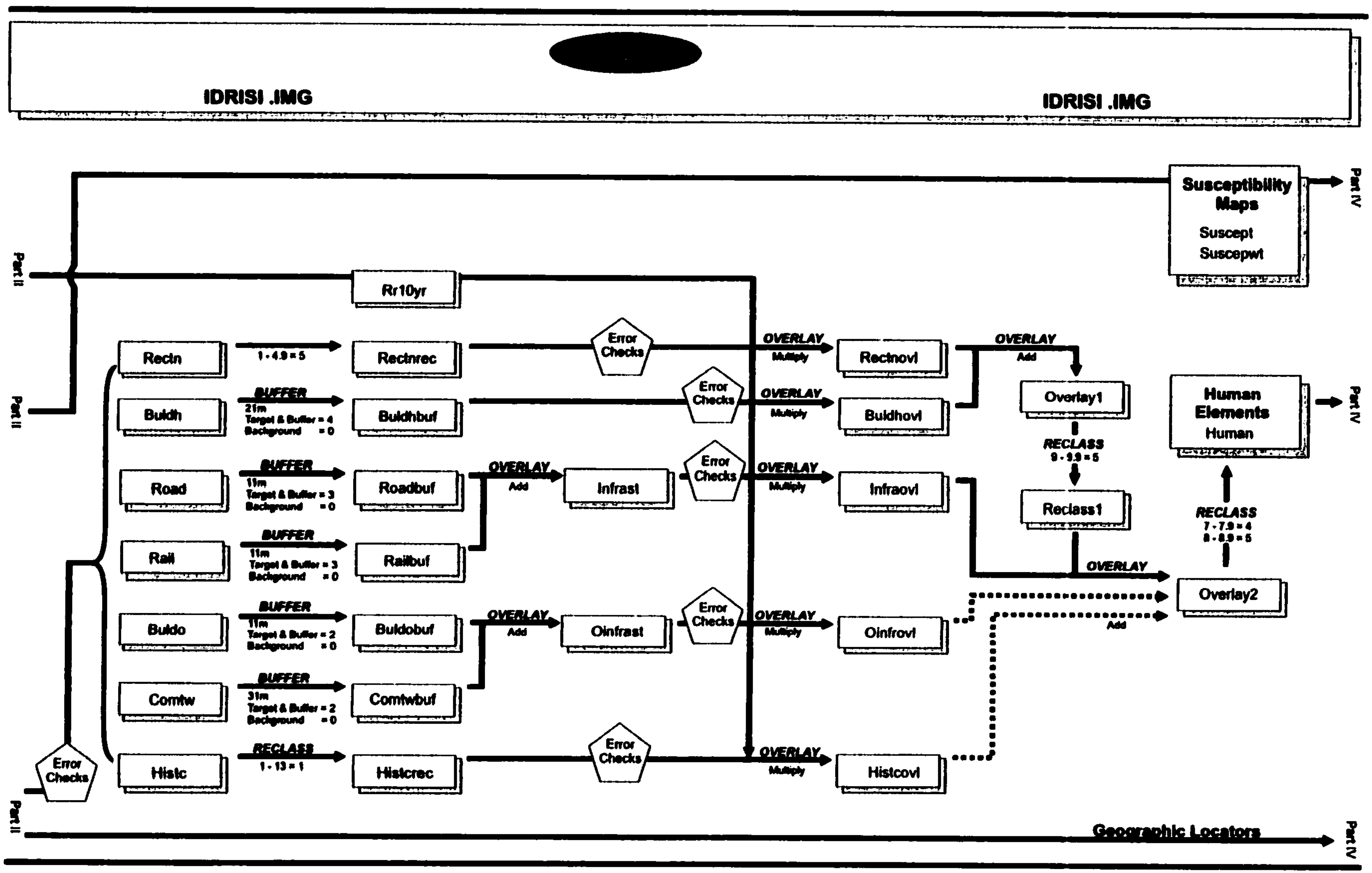


Figure 6.2c: Part III - Detailed flow diagram of data management, transformations, parameter inputs, and final analysis.

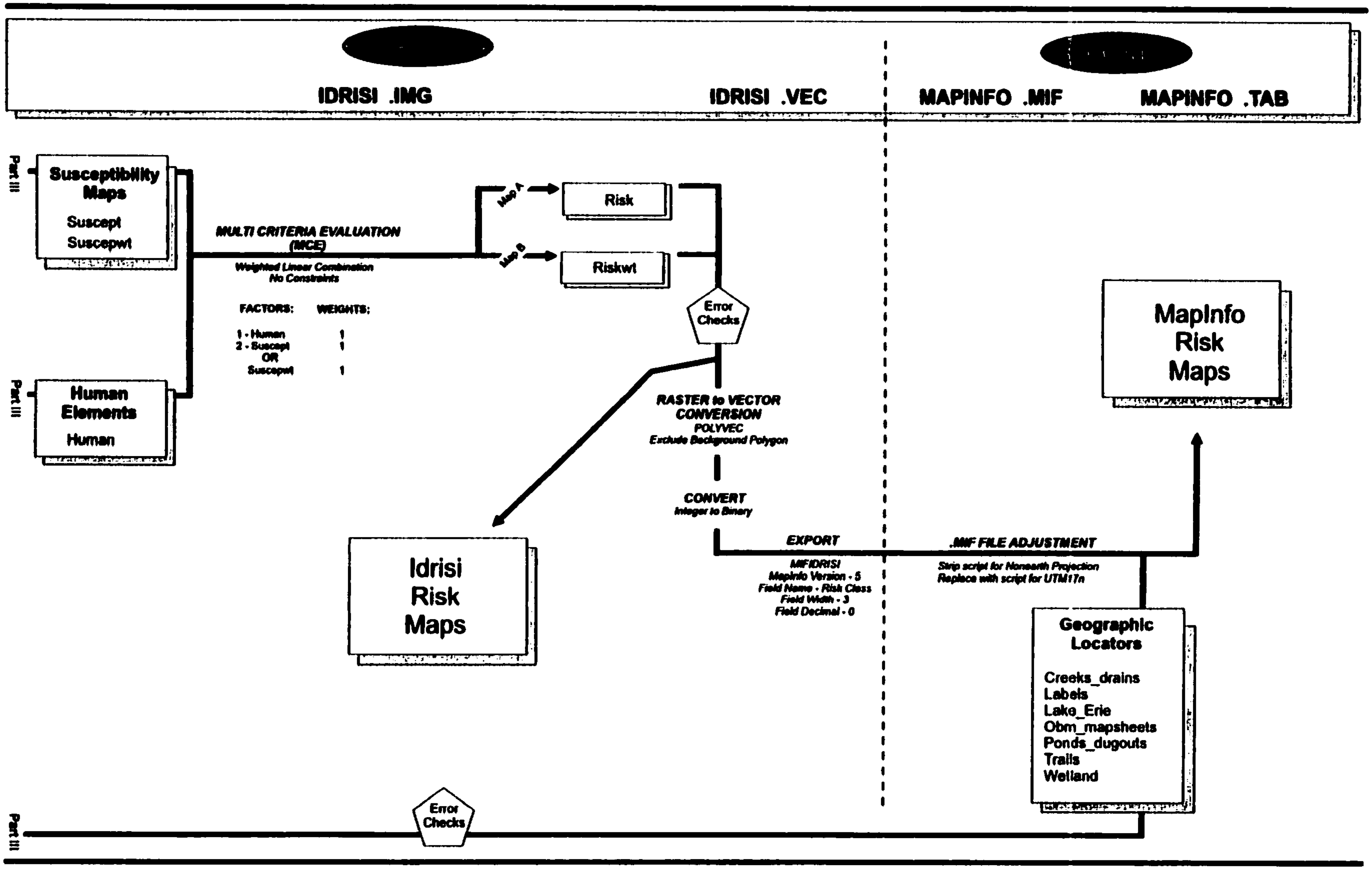


Figure 6.2d: Part IV - Detailed flow diagram of data management, transformations, parameter inputs, and final analysis.

6.1 - Basis for the GIS Research: Methods, Analysis and Presentation

Before describing the preparation and analysis of the data layers, it is important to note that several studies were used as the basis for some of the methods and techniques applied in this research. The first study concerns the use of GIS to develop a coastal risk assessment database for vulnerability to sea-level rise in the southeast United States. Although not related to slope stability analyses, Gornitz et al. (1994) constructed and combined 13 data layers (eg. elevation, geology, shore recession rates, hurricane frequency, mean hurricane surge) believed to influence the susceptibility of shoreline development to coastal erosion, permanent inundation, and episodic flooding events. By combining these layers, and weighting them according to their perceived importance, the correlation of factors helped determine high risk coastal reaches. The presentation of the studies's results, mirrored that of this research, in that they were summarized through a series of maps that would provide useful guidelines for the selection of areas needing more detailed investigation, in order to develop appropriate coastal management policies, prepare the public for future coastal hazards, and ultimately, reduce the risk of extreme coastal events (Gornitz et al. 1994).

Based on the discussion of slope stability analysis contained in Chapter Four, the study by Gornitz et al. (1994) could be classified as Simple Statistical, Indirect Mapping. Without the quantitative aspect of ranking and weighting the factor layers, their methods might otherwise be classified as Quantitative, Direct/Heuristic Mapping. The methods and research described in this chapter are very similar to that of Gornitz et al. (1994) and could, likewise, be classified as Indirect, Simple Statistical. Similarly, this research also performs the final analysis using raster overlay, and factor weighting. Though the study by Gornitz et al. (1994) was completed at a very small scale (1:2,000,000), their study provided a helpful reference while performing this slope stability research.

A second study by Reading (1993), performed in a remote area of southwest Greece, also helped as a guide to this research. Reading's paper described the methods used to derive maps of landslide susceptibility and to classify these regions according to their potential threat to human well-being. The research stressed the expediency and flexibility of using a GIS to analyse large amounts of disparate spatial data and to produce maps that were helpful for engineers and planners. Several factors believed responsible for slope failures were overlaid together to construct a map of slope failure susceptibility, including geology, drainage, elevation, and slope inclination, among others. Reading's (1993) study was helpful, in that it continued one step beyond that of Gornitz et al. (1994) to evaluate risk. Cultural and infrastructural features were mapped and each class weighted as to its perceived value to society. This map of human elements was then overlaid with the map of susceptibility to determine several small areas where landslides presented a potential risk to human activities.

Finally, a study by Small (1992) was also found useful while finishing this research. As part of a Master's thesis at Wilfrid Laurier University, Waterloo, Ontario, Small (1992) mapped risk of several environmental hazards (forest fire, landslide, flood, and avalanche) using a GIS overlay approach in Kananaskis County, Alberta, Canada. Work by Small (1992) could be considered Indirect Mapping using more Complex Statistical methods. The relationship between multiple hazards and various environmental factors (eg. vegetation, slope inclination, elevation, hydrology) was determined by cross-tabulations and calculations of ChiSquare coefficients. Each hazard was then weighted by the coefficients and overlaid with human elements to estimate risk. Although the study was not obtained until the end of this research, Small's study (Small 1992) emphasized the power of GIS in multivariate hazard and risk analyses, such as the one presented in this thesis. Small's report (1992) also echoes issues of error, accuracy, data sources, and presentation methods encountered, and later discussed, in this chapter.

Together, the research by Gornitz et al. (1994), Reading (1993), Small (1992), and several projects described in Chapter 4, Section 4.2, provided a useful guide and rationale for the methods and research described throughout this chapter. The benefits and limitations of this approach are touched on throughout this chapter, as well as in Chapter Seven. It is important to note that neither of these three studies included the dimension of time into their analysis. This research also excludes the temporal dimension of hazard and risk due to the complexity and difficulty of linking this with a GIS at a regional scale, using time efficient and cost-effective methods. Consequently, it should be noted that this research tends to approach the assessment of coastal bluff hazards and risks from a 'worst-case' scenario. The results of the analysis represent a 'snap-shot' in time, and different results could be obtained by performing the analysis at different times in the year, as elaborated upon in Chapter Seven, Section 7.1.4. The analysis of risk also assumes that failure events are rapid, rather than long-term, gradual, or slow failures, since rapid failures are believed to present the greatest threat to human well-being.

6.2 - Data Management and Preparation

6.2.1 - Elevation

Elevation is the first of seven data layers which will be discussed as part of the data and map preparation for the final risk assessment. The contribution of slope angle and elevation to landslides is well recognized and documented by many authors, such as Selby (1993), and Varnes (1984), and in technical documents such as the GPSS (TL and AS 1998), or the TGGLSLS (OMNR 1994). Although less emphasis is usually placed on slope angle than elevation, elevation is believed to be an important factor along the study reach due to its added weight and stresses on the bluff. Very generally, elevation increases the weight of a mass over the shear plane, increasing shear force and influencing instability (Zaruba 1982, Crozier 1986). The elevation of a bluff also affects the potential severity of a slope failure event. A bluff of 30m will carry and deform human property over a longer distance than a bluff of 3m. The amount of material involved in the failure of a bluff 30m high will also generate a greater threat to humans located at its base simply through sudden impact or depth of burial.

Of all seven data layers, elevation and slope took the longest to prepare and create. Continuous elevation data was obtained by generating a DTM, or DEM, of the study area from contour lines, spot heights and a large number of 'breakpoints'. OBMs depict elevation using contours at 5m intervals. In the case of the shoreline along the study reach, contour lines were occasionally included outside of the 5m interval to define the edge of the bluffs. In order to save a great deal of time while digitizing a 25km reach of shoreline at 30m elevation and 5m intervals, several shortcuts were necessarily taken.

Firstly, contour lines were only digitized as far back as the maximum 100yr erosion limit, except along Big Otter Creek where these were digitized to the first concession road north of Road 42, in order to surpass the northern extent of the town of Port Burwell. Carter et al. (1987) and PA, TA, and PWA (1989) cited the maximum average annual recession rate in the study reach to be 4.5m/year, when in reality, this has been calculated at 5.29m/yr by Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989). Using Fleming's calculation, this yields a maximum 100yr erosion limit of 529m. Due to the short-term objectives of this study, this was a decidedly generous area to accurately map for the analysis. This setback also provides enough information to create a DEM that accurately represents the topography of the bluffs and the region within an area that is of immediate threat to slope failures and shore erosion.

The second short-cut was to only digitize the top and bottom contours of the bluff, in addition to a contour which defined the level of Lake Erie at 173.5masl. This level, although mistyped as 174.5 in some OBMs, was determined by the 1985 Great Lakes Datum study (USACE 3 Jun. 1999b, USACE 10 Sep. 1999a). Big Otter Creek and the portion of Little Otter Creek south of Road 42 were both interpreted as being part of Lake Erie, and therefore included within this contour. In most cases, the bluffs are steep enough that contours between top and bottom only assist the DEM construction in a limited way. To ensure that a smooth transition was made between the beginning and ending of contour lines at the bluff edge, the contours were made to overlap for a distance of several hundred metres before being ended. In addition, the tail end of each elevation contour line was digitized through the study area until it had passed beyond the 100yr erosion limit. In this way, the elevation of the plain north of the bluffs was clearly defined by the contour lines. Since the land north of the bluffs is essentially a plain, few other contour lines entered the 100yr erosion limit. Those that did enter were also digitized to ensure the accuracy of the DEM close to the bluffs. In all, 47 contour lines were digitized, ranging from lake level at 173.5, to 225masl near the top of the sand dune in Sand Hills Park. The longest contour represents the interval for 175masl, stretches 34km by foot, and consists of 4,555 line segments. Even with the shortcuts, it is estimated that the total number of contour line segments for the study area is around 22,000.

During field work, it was noted that several physical changes had occurred within the study area since the OBMs had been created. For the most part, these included a general recession of the entire shoreline, and several new or enlarged gullies. Two particularly large gullies had formed on Lots 26 and 27 just west of County Road 26/55. Due to the time needed to map, and calculate these changes, physical changes were not included in the final elevation data layers.

Spot heights were also digitized to assist in the DEM creation. Approximately 315 spot heights were obtained from the OBMs within the 100yr erosion limit north of the bluffs. The location of the spot heights represent a random sample, and help to define slight topographic variations within the plain. A total of 23 interpolated spot heights were also placed outside of the 100yr limit to extend the DEM to the maximum boundaries of the mapped rectangle (Figure 5.5). Since this area is generally a level plain, and varies only between 198 and 203masl, all 23 spot heights were assigned an elevation of 200masl and placed every 3,000m along the edges of the OBMs (ie. 3 per map sheet side) to represent a regular sample.

In order to evaluate the ability of contour lines and spot heights to create an accurate DEM of the study area, contours and spot heights were brought into ArcView's 3D Analyst Extension by converting the MapInfo files (*.mif*) to ArcView shape files (*.shp*) using MapInfo's Universal Translator. The lines and points were analysed as mass points, and a test DEM of the study area was created as a Triangulated Irregular Network (TIN). A TIN is a vector data structure used to represent continuous data (eg. elevation and slope) by joining sample points through a network of tessellated triangles of irregular shape (Burroughs and McDonnell 1998).

The test DEM demonstrated that contour elevations and spot heights were insufficient to generate a detailed enough TIN of the study area. This was particularly the case in areas of complex topography such as creek beds, gullies, the shoreline, bridges, or wherever contour lines made high angled or elongated curves. In most of these cases the TIN would bridge the neck of sharp curves so that the inside of the curves were left as un-interpolated 'false plateaus', or 'padi terraces', as described by Burroughs and McDonnell (1998). A TIN has the advantage of being able to capture critical variations in areas of complex topology, such as the ridge crests, gullies, streamlines. and ravines found in the study reach (Aronoff 1989, Burroughs and McDonnell 1998)

To rectify this interpolation problem, approximately 1,617 additional spot heights were added to the study area to help define the topography and breaks in slope. To distinguish these from the original OBM spot heights, these points were created on a data layer called 'breakpoints'. Breakpoints were placed between existing contour lines to better define breaks and direction of slope using elevation values which represented missing contour lines, or intermediary values (eg. 170, 172.5, and 175masl). In some cases, breakpoints were necessary between the shoreline (173.5masl) and the first contour (175masl) and these points were assigned a value of 174.5masl. Points were also added where bridges crossed valleys in order to elevate roads and better define surrounding topography. The placement of all breakpoints was highly time-consuming, and was accomplished through visual interpolation and comparisons with the original OBMs. This process of adding points and testing new DEMs was undertaken 5 or 6 times until a DEM was finally created that eliminated major interpolation errors. The time and effort to eliminate minor interpolation errors was not worth the limited information that would be provided for the DEM construction.

Once a final TIN had been constructed for the region in 3D Analyst, it was assumed that the image could be saved as an ArcView shape file (*.shp*), converted to a raster grid in ArcView's Spatial Analyst Extension, and analysed in ArcInfo's Spatial Analyst. After several attempts to save the images as a shape file (*.shp*), in coordination with Dr. Dudycha from University of Waterloo, it was discovered that ArcView is not capable of saving floating (decimal) point values (ie. decimal elevations) as a shape file (*.shp*). Images with floating point values can only be displayed for visual interpretation on-screen.

In order to work around this problem, ArcInfo was used at University of Waterloo to generate TINs of the study area, and to convert them to grids of elevation and slope which could be analysed in the raster GIS software Idrisi. Dr. Dudycha's technical assistance and advice was instrumental during this process. Contours, spot heights, breakpoints and an additional 'clip polygon' which restricted TIN interpolation to the land portion of the study area, were all converted to shape files (*.shp*), imported into ArcInfo and used to build a TIN of the study area. Quintic interpolation was used to generate the DEM. This method of interpolation is ideal for maps with sparse data. Quintic interpolation places a curve surface over the triangle using the vertices of the surrounding triangles to smooth out the elevation surface (Dudycha 23 Nov. 1999). The DEM was then converted to both a polygon coverage from which to derive slope, and an ArcInfo Lattice (grid) of elevation. Slope values were extracted from the polygon coverage, saved as a separate polygon image, and then reconverted to a grid image using quintic interpolation. The elevation lattice was then reclassified into 13 elevation ranges using the values 173.5 through 230.0masl (Appendix A(i)), converted back to a polygon coverage, and then converted to a standardized grid applied to both the slope and elevation images.

Although it was originally hoped that grids could be created for the study area at a resolution of 1m, a test image of the study area using this resolution resulted in an image file size over 600Mb. Instead, a grid resolution of 10m was used, which itself resulted in a 6Mb file with 3,250,000 grid cells. A 10m resolution was felt to be an adequate median between file size and map detail. Each cell would readily represent the size of the smallest items (eg. houses) being mapped in the study area.

The ArcInfo grid files for slope and elevation were finally converted to ASCII

(*.txt*) files and prepared for import into Idrisi. Before Idrisi could import these files, the text (*.txt*) files needed to be 'altered' so that image header lines were stripped out (eg. map projection, min. and max. coordinates), and data values for each grid cell listed as a column, rather than a continuous line separated by spaces and hard returns. This process was to be automated through a C program written by Dr. Dudycha but was instead completed using the *SEARCH AND REPLACE* command in WordPerfect due to a malfunctioning server housing the C compiler at the time when this data was being processed. This process took close to two hours due to the enormous size of the files (75,000 lines long). Files were then imported into Idrisi and saved as Idrisi Image files (*.img*). Important decisions and options used to import, and create the Idrisi slope images are described in the flowchart in Figure 6.2.

Once in Idrisi, the elevation image was examined and determined to be representative of expected elevation values along the study reach. The only problem was that a small number of cells (approximately 4 per 3.0km) along the land-water interface were missing when compared to images generated directly in Idrisi. This data loss is believed to be the result of the TIN to grid data transformation within ArcInfo which, presumably, converts ArcInfo polygons to grids in a slightly different fashion than Idrisi's conversion of MapInfo polygons to a grid. This data loss on the slope images will not effect the final analysis in any significant manner, other than reducing the water-ward side of the recession setback, and analytical area by several hundred cells.

Elevation was originally classified into 13 ranges in ArcInfo. For the purpose of analysis, and as a means of compiling a scale which represented various degrees of failure susceptibility, this scale necessarily had to be reduced to a 5 tier classification. Once in Idrisi, the elevation data was reclassified to the scheme described in Table 6.2. It is difficult to classify bluff elevation by its susceptibility to failure, but the scheme is recommended (with slight modifications) within the GPSS (TL and AS 1998). By contacting the engineer behind the GPSS project (Tanos 1999), and a contact at University of Purdue, Indiana (Harbor 25 Nov. 1999), it was determined that the scheme is not empirically based. However, through personal field work, was felt to adequately represent the major ranges of height and failure susceptibility for the bluffs along the study reach. Important options and decisions made while creating the elevation image are detailed within the flowchart, Figure 6.2. Figure 6.3 is a graph which summarizes the classified image in terms of the total land area represented by the classified elevation values, within 20, 10, and 5yr recession setbacks from the bluff edge. Data tables for the unclassified and classified data are included as Appendix A(i) and A(ii). Figure 6.4 is the classified image of elevation's contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

Due to the difficulty in representing small grid cells using a graded colour scheme of one hue (ie. light to dark red), a cold to hot colour scheme was developed, and was applied to all the maps generated throughout the research. This scheme is self explanatory, even to the uninformed map reader, including planners, and the general public. High susceptibility, or risk is depicted using red, while low is represented by the coolest hue, blue.

Table 6.2: Elevation classification scheme (modified from TL and AS 1998).

Class	Elevation (metres)	Susceptibility to Failure	Explanation
5	< 16.5	Severe	Extremely high bluffs
4	11.51 - 16.5	Very High	Very high bluffs
3	6.51 - 11.5	High	High bluffs
2	1.51 - 6.5	Moderate	Moderately elevated bluffs
1	0.01 - 1.5	Low	Low bluffs
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

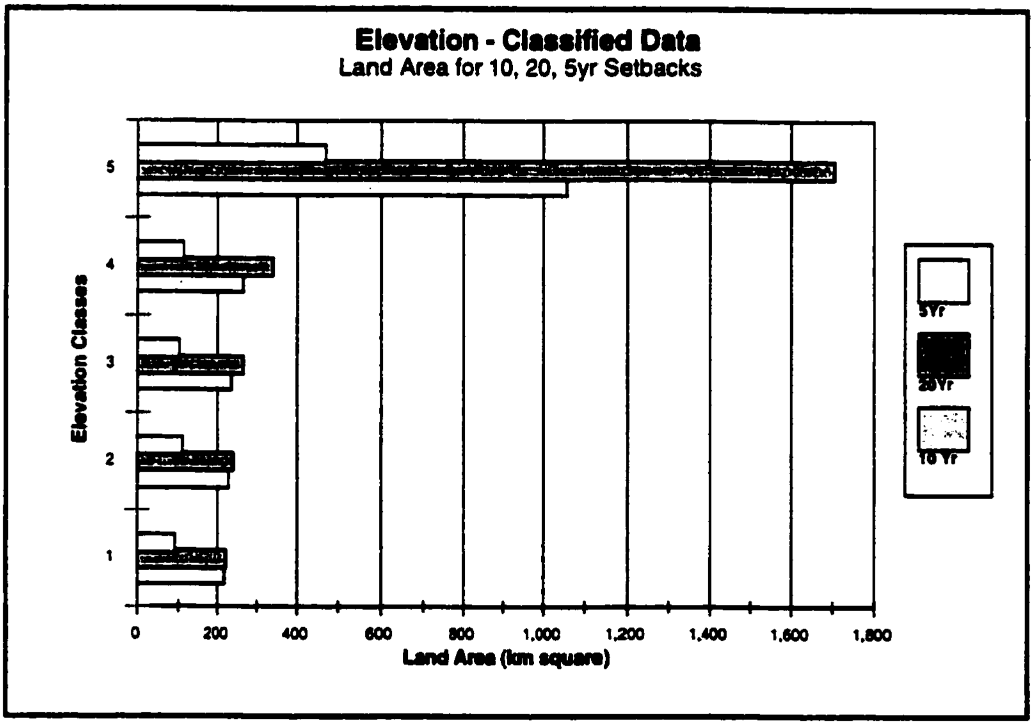


Figure 6.3: Elevation - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at $100m^2$ (10x10m).

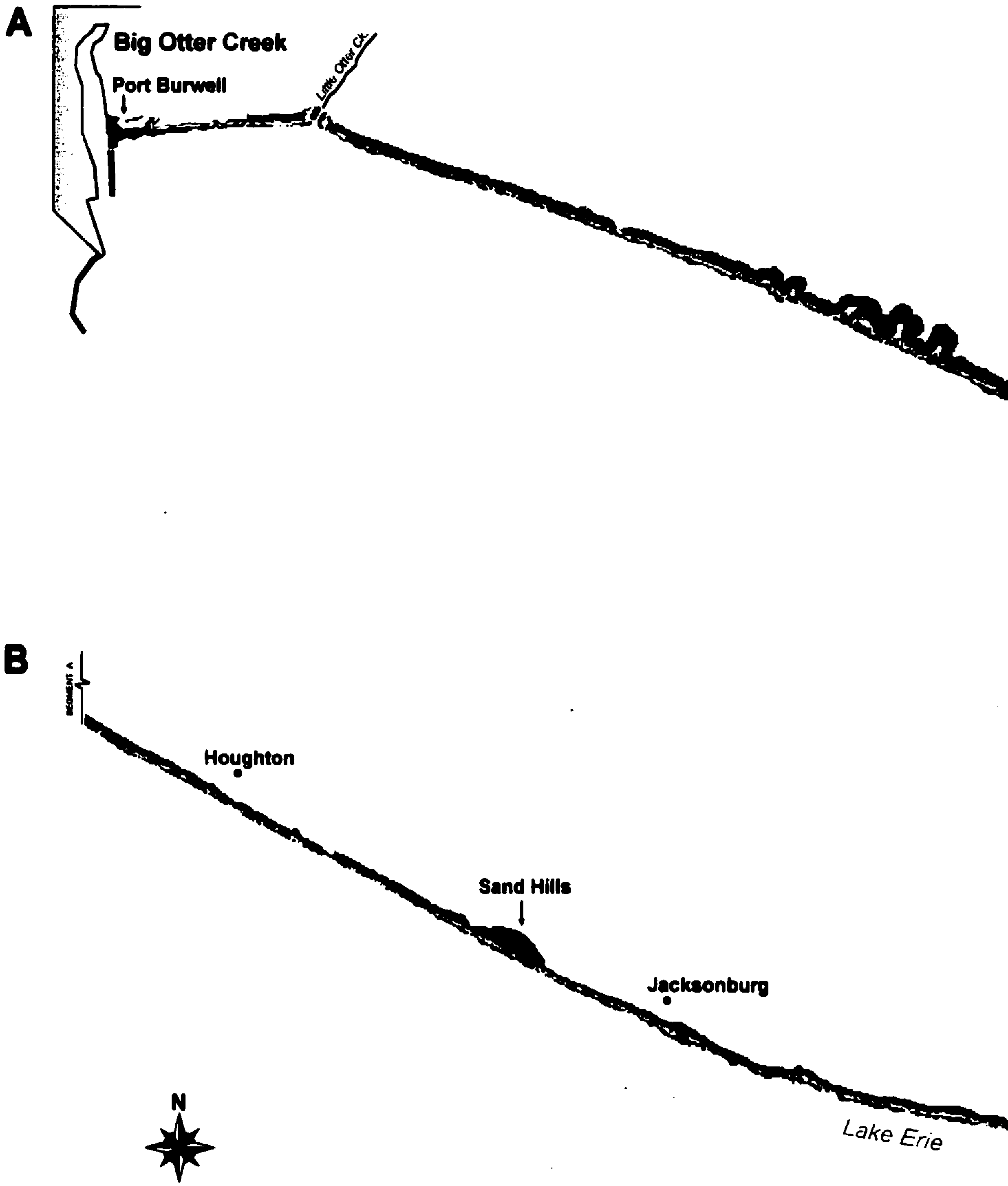
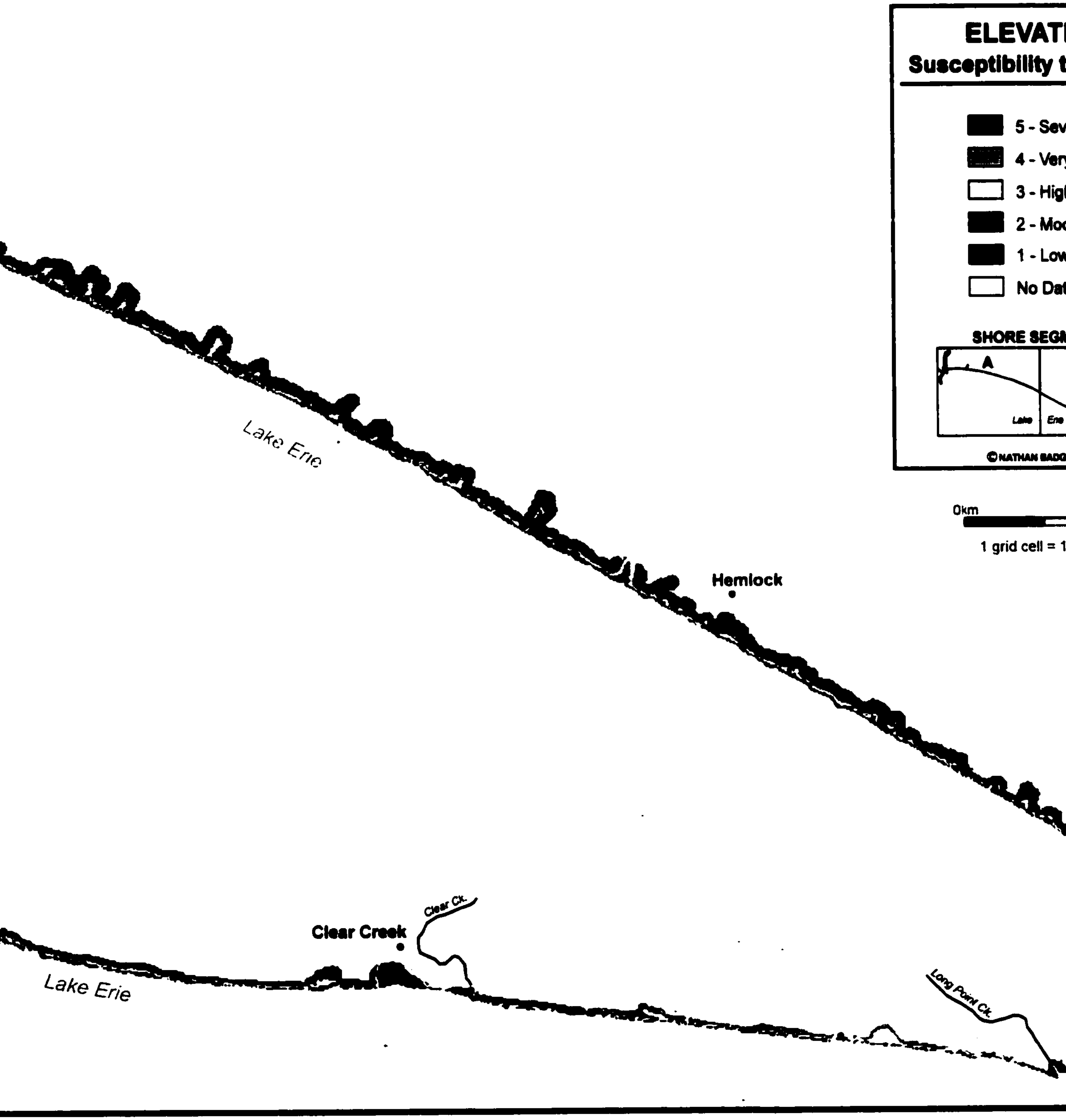
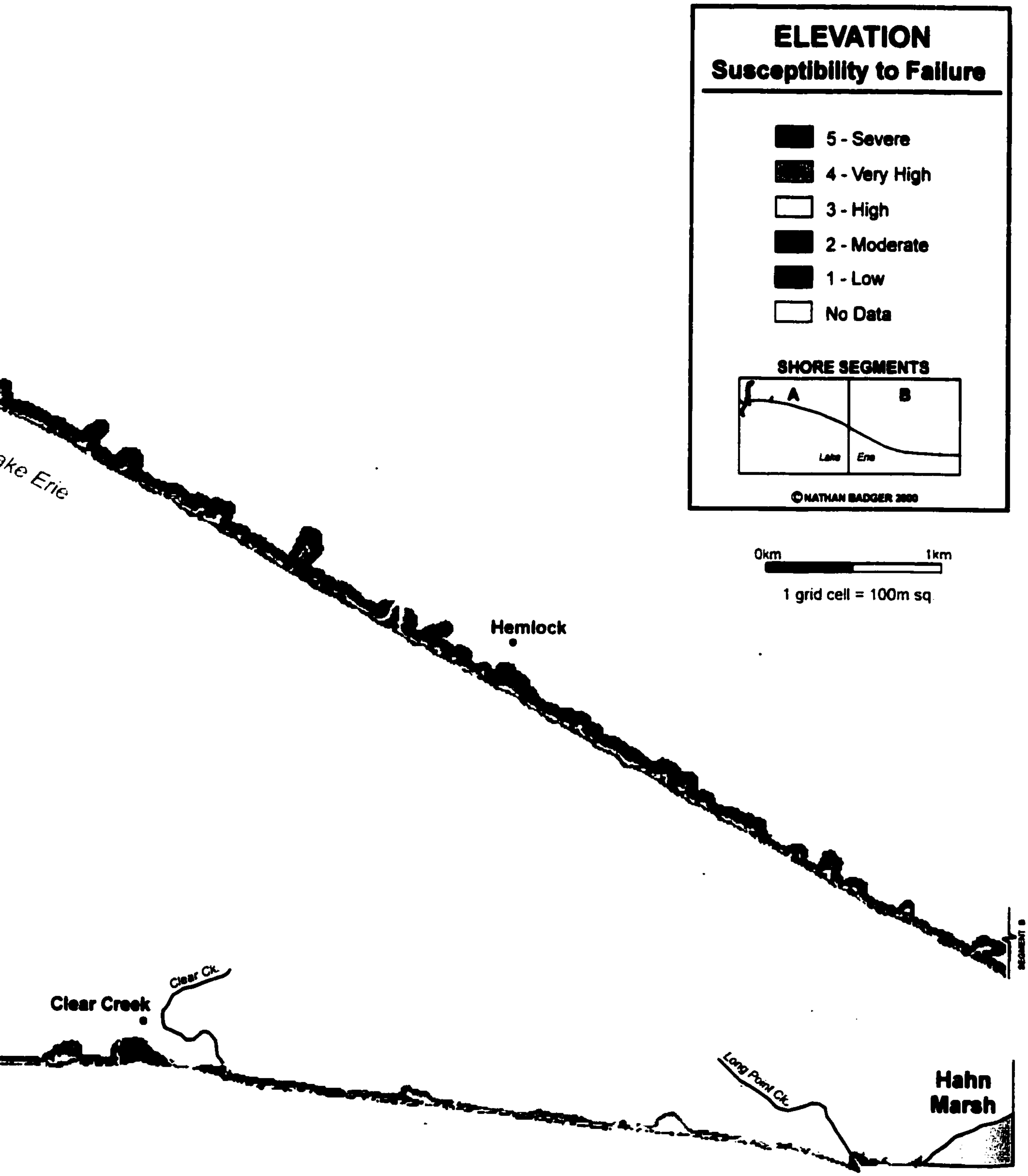


Figure 6.4: Shoreline elevation is used to classify the susceptibility of a 10 year recession
into CorelDraw and combined with several geographic locators.



10 year recession setback to failure. The Idrisi data layer was imported



to failure. The Idrisi data layer was imported

6.2.2 - Slope Inclination

The slope of a bluff or rise in elevation, is regarded as an important factor contributing to the stability of a slope. Selby (1983), Carson and Kirkby (1972) and Varnes (1984), discussed its importance, in addition to technical documents such as the GPSS (TL and AS 1998), and the TGGLSLS (OMNR 1994). Very generally, the steeper the slope, the larger the increase in shear force, and the tendency for the mass to slide along the shear plane.

Construction of a data layer depicting slope parallelled that of the data layer for elevation. Once a TIN had been created in ArcInfo for the study area, the TIN was converted to polygons for which were calculated and attributed slope inclination by degrees (among other attributes). Slope inclination values were extracted from this image, applied to an image with the same polygons, and converted to a standard grid. This grid was subsequently exported from ArcInfo as an ASCII text file *(.txt)*, and converted to an Idrisi-readable file format in like fashion as the elevation data layer so data could be imported into Idrisi and saved as an Idrisi Image file (*.img*). Important decisions and options used to import, and create the Idrisi slope images are described in the flowchart in Figure 6.2.

It is difficult to evaluate the accuracy of the Idrisi slope image, but a preliminary examination of the image indicates that values appear reasonable. High and low slope values exist where expected, and certain known features of the bluffs are evidenced through the slope data. For example, most of the bluffs have a steep, almost vertical face at their mid-point, often the result of a layer of clay. This vertical face appears in the slope images as pixels with a slope of 80°. As with the elevation images, the different methods of converting polygons to grids has resulted in data loss, including missing cells. This data loss on the slope images will not affect the final analysis in any significant manner, other than reducing the water-ward side of the recession setback, and analytical area by several hundred cells.

Slope values, excluding the image background in Idrisi, ranged from just over 0° to just under 90°, and necessarily had to be classified for further analysis. Table 6.3 describes the classification scheme used to reclass the raw values within Idrisi. This scheme is only slightly modified from one recommended within the GPSS (TL and AS 1998). Although these schemes are often based on geotechnical properties of the materials (Harbor 25 Nov. 1999) this scheme was determined to be unempirically based by Mike Tanos (Tanos 1999), the head engineer of the GPSS project (TL and AS 1998).

Table 6.3: Slope Inclination classification scheme (modified from TL, AS1998).

Class	Slope (degrees)	Susceptibility to Failure	Explanation
5	> 34	Severe	Extremely high slope inclination
4	26 - 33.9	Very High	Very high slope inclination
3	18 - 25.9	High	High slope inclination
2	0.01 - 17.9	Moderate	Low or moderate slope inclination
1	0	Low	No slope inclination
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

Unfortunately, no other scheme could be found, and it was decided that with modifications, this scheme followed the general breaks in data for slope inclination within the study reach. It displays an increasing susceptibility to slope failure with an increased angle of slope (TL and AS 1998). Important options and decisions made while creating the slope inclination image are detailed within the flowchart, Figure 6.2. Figure 6.5 is a graph which summarizes the classified image in terms of the total land area

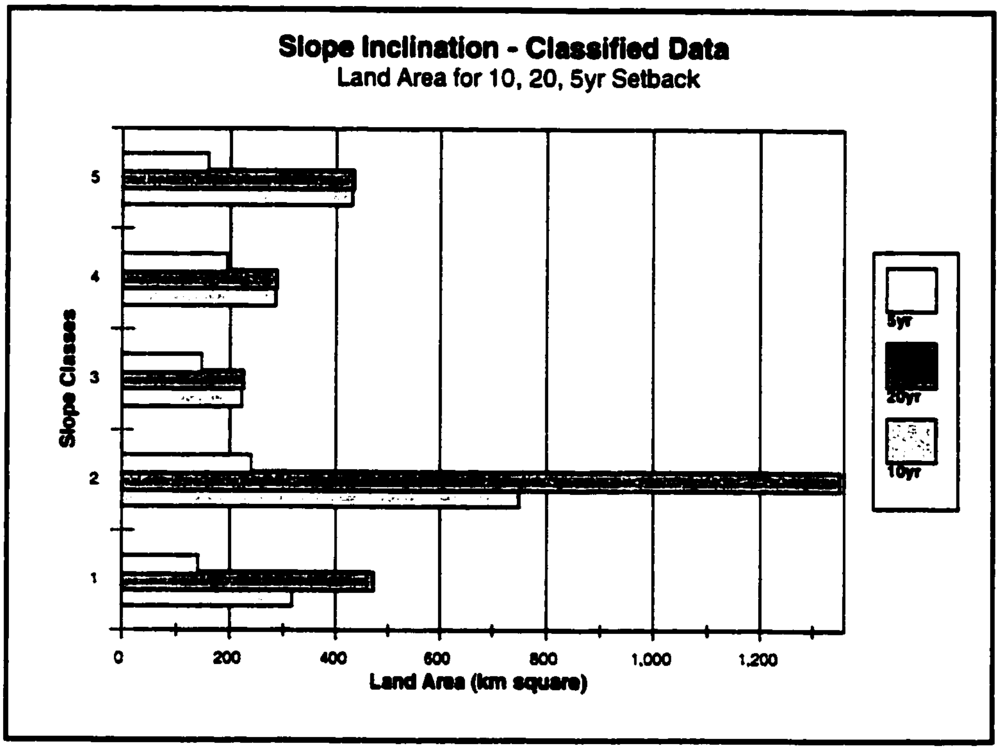


Figure 6.5: Slope Inclination - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at $100m^2$ (10x10m).

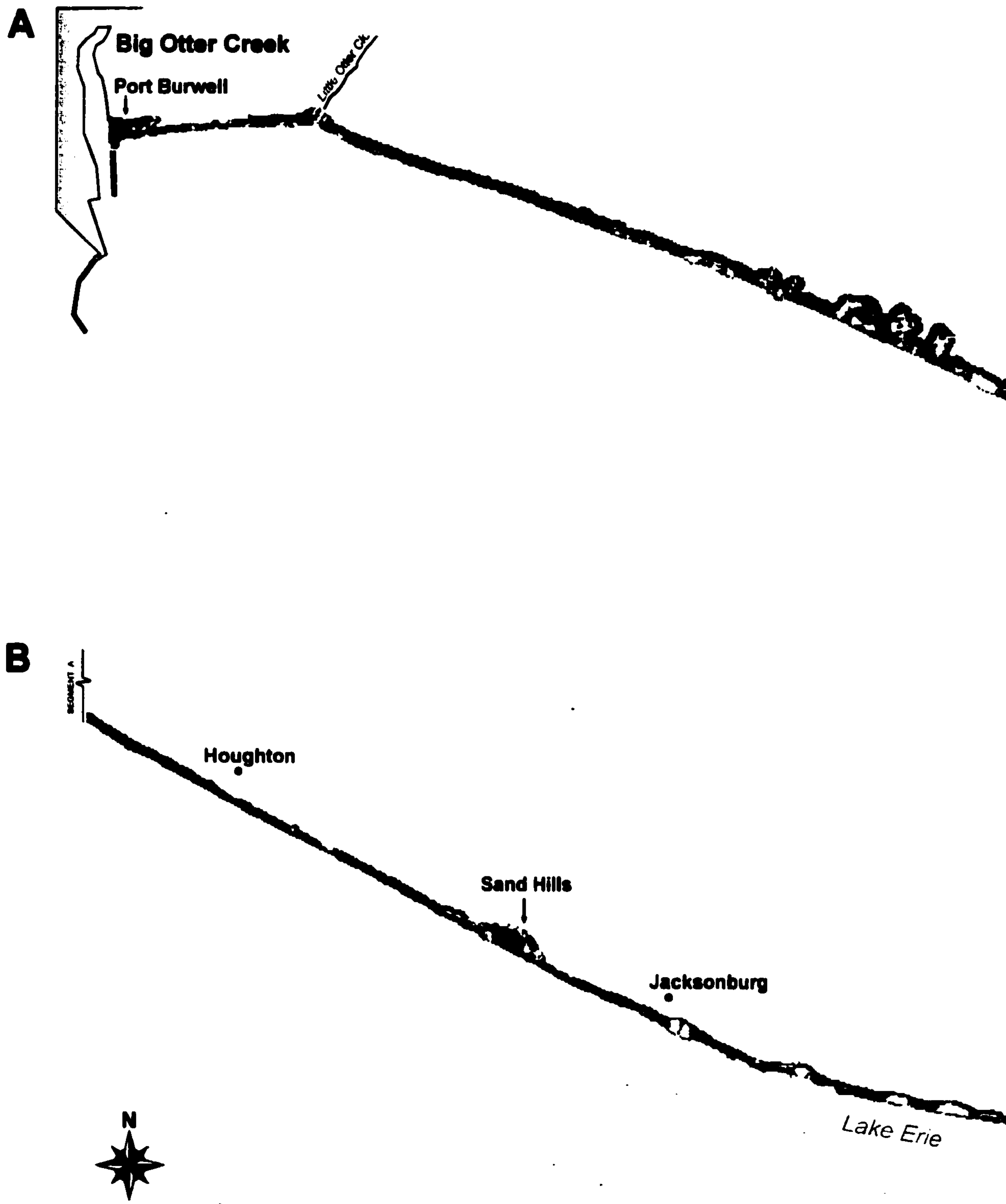
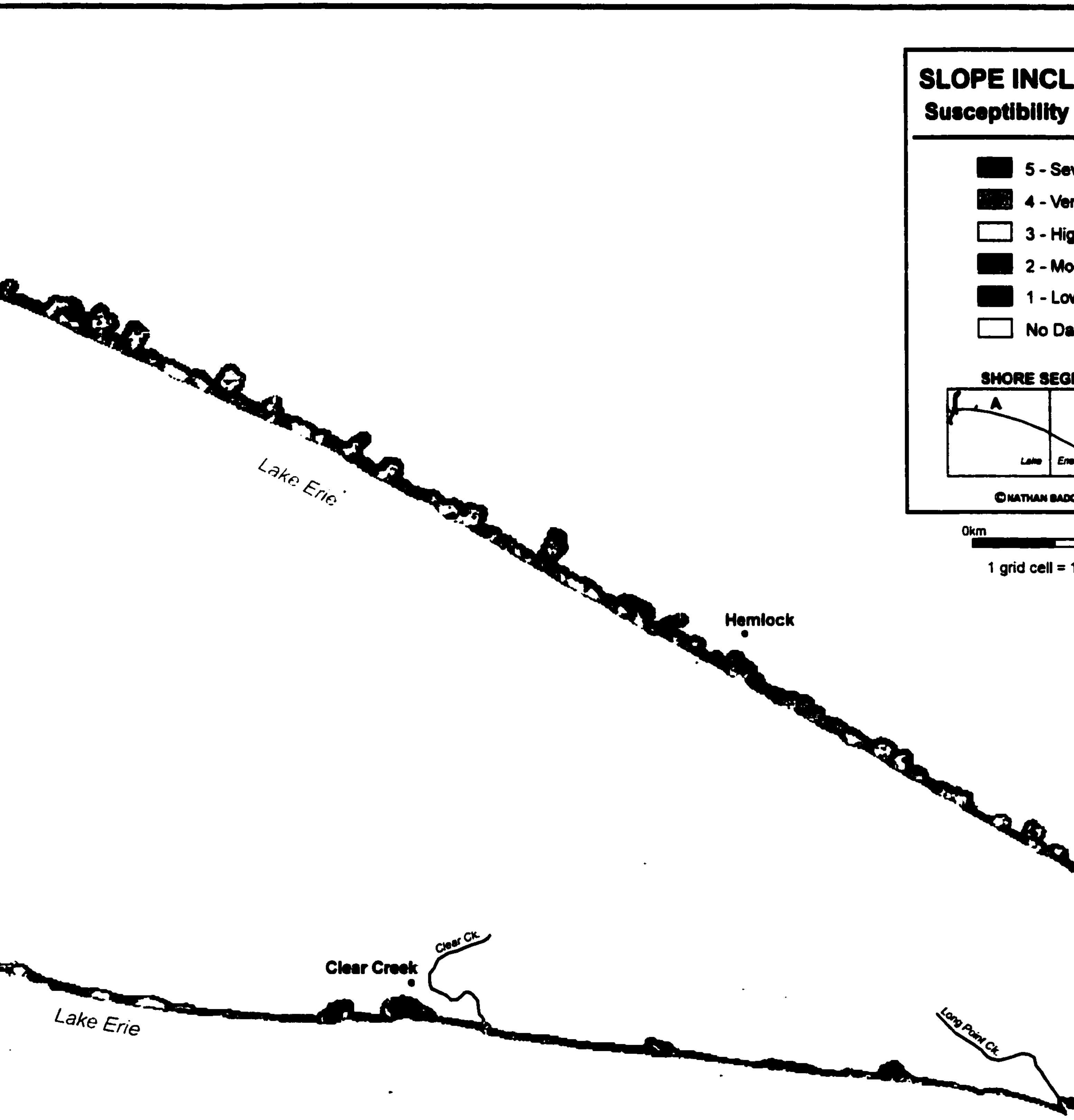
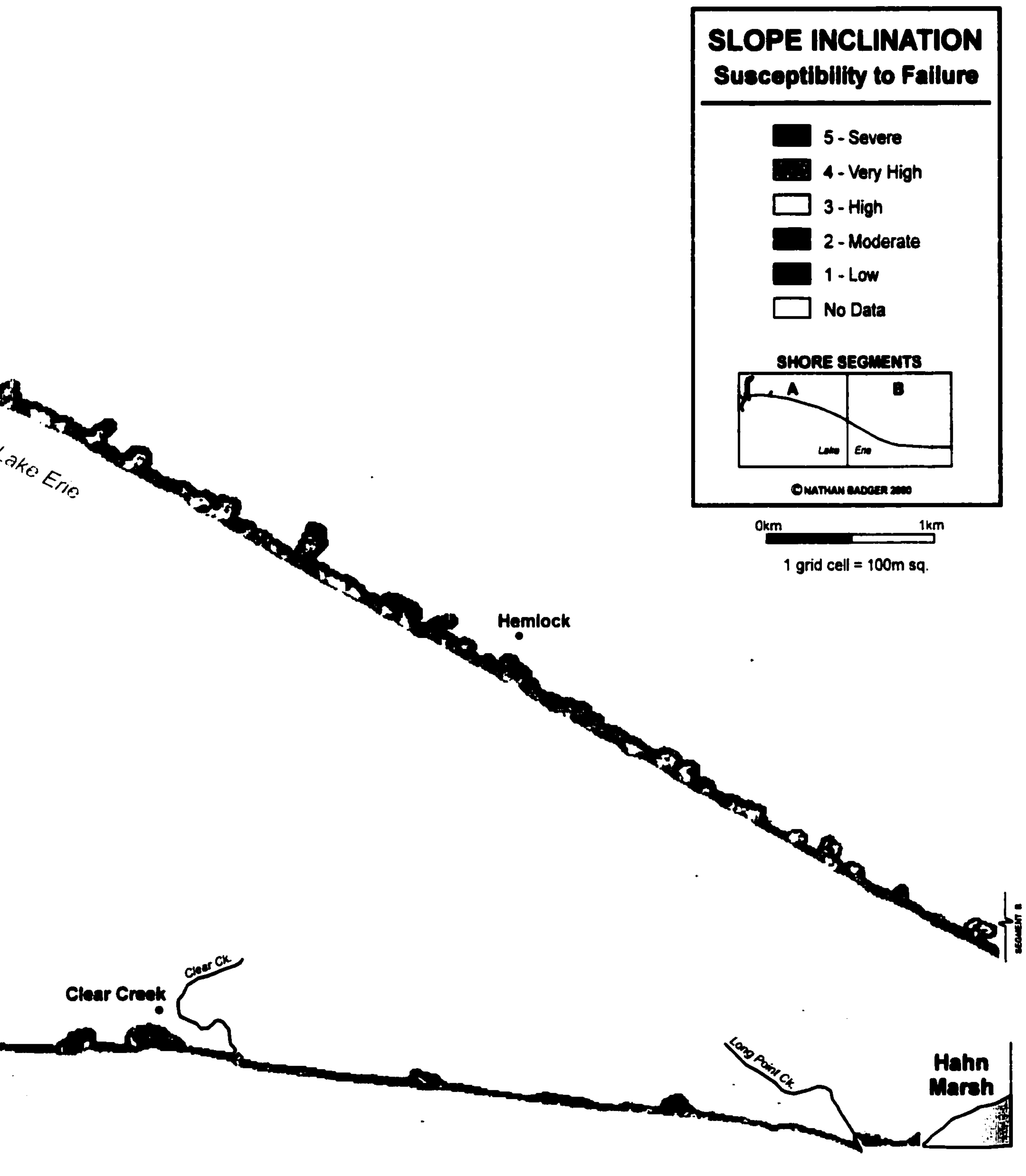


Figure 6.6: Shoreline slope inclination is used to classify the susceptibility of a 10 year rec
into CorelDraw and combined with several geographic locators.



bility of a 10 year recession setback to failure. The Idrisi data layer was imported



setback to failure. The Idrisi data layer was imported

represented by the classified slope inclination values, within 20, 10, and 5yr recession setbacks from the bluff edge. Data tables for the unclassified and classified data are included as Appendix A(iii) and A(iv). Figure 6.6 is the classified image of elevation's contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

6.2.3 - Geology and Stratigraphy

Slope geology and stratigraphy are recognized as important influences on the stability of slopes (eg. Varnes 1984, Selby 1993, Bromhead 1992), and are identified as major contributors to slope instability in the study reach by Barnett (1983b, 1987), Caldwell et al. (1971), Quigley et al. (1977), and Quigley and Zeman (1980). During the process of this research, field work has also indicated that geology and stratigraphy are perhaps the most important terrestrial controls of slope failure susceptibility along the bluffs.

Due to the three-dimensional nature of the Erie bluffs, the acquisition of stratigraphic and geologic information easily formatable for a GIS environment was, initially, a major difficulty. Geologic data has also been noted as a critical problem in other regional GIS landslide analyses (eg. Carrara et al.1995). However, maps and data depicting the quaternary geology and stratigraphy of the study reach were eventually obtained from a number of detailed studies conducted by Barnett (1983b, 1987).

In his PhD thesis, obtained from the Department of Earth Sciences at UW, Barnett (1987) provided a series of maps which depict the correlation of lake bluff sediments from Port Bruce, east to Port Ryerse (near Port Dover), including the study reach. One map is a cross-section which depicts the correlation of lake bluff sediments in the study reach at a scale of 1:40,000 (Barnett 1987). This map is included earlier in Chapter Five as Figure 5.4. Horizontal layers in the cross-section were colour coded and the section was then used to determine relatively homogenous sub-reaches of shoreline geology and stratigraphy along the study reach. Figure 5.4 depicts where the boundaries of these sub-reaches were placed, using a pink, dashed line. The demarcation of these boundaries was also aided through another set of Barnett's maps (Barnett 1987) which depict detailed stratigraphic and geologic cross-sections of the bluffs at 57 sample sites along the study reach. The sample sites and detailed cross-sections were superimposed by Barnett on a set of OBMs from the 1970s or 1980s at a scale of 1:10,000. This second set of maps allowed the boundaries of the sub-reaches to be more precisely determined by carefully examining changes in stratigraphic and geologic units within the sample site cross-sections. Using both sets of maps, the boundaries of the sub-reaches were demarcated at the mid-point between sample sites, and then digitized as a data layer in MapInfo, with which to create geology/stratigraphy polygons.

At the east and west ends of the study reach, sub-reaches could not be defined by determining midpoints between sample sites, and instead had to be interpolated. In the far east, the attribute value assigned to the last sample point was simply extended east to the beginning of the Hahn Marsh. In the west, the distance and difference in geology (according to the cross-section) between the western study boundary and the first sample point was too great to assign it one attribute value. Instead, the distance to the midpoint between the first and second sample was extended west from the first sample point. A separate geologic and stratigraphic division was then established between this reach and the western boundary of the study reach (Big Otter Creek). Due to the time span and shoreline recession which had occurred between the publication of Barnett's OBMs and the digitized 1997 OBMs, Barnett's sample sites (in addition to houses and roads!) were often located in the water, and were necessarily re-located to the shoreline by drawing a line perpendicular to the shoreline.

Once the study reach had been divided and classified based on its geologic and stratigraphic attributes, a digital data layer could be prepared to represent this information in MapInfo. Barnett (1987) noted that the flat plain above the bluffs dips slightly towards the shoreline (2.5m/km), but the geology and stratigraphy varies little over several kilometres as one travels inland from the bluffs. Using this assumption, geologic/stratigraphic divisions could be extrapolated back from the shore to the 100yr erosion limit, which was used to define the maximum limit of the other digitized OBM features. Using the geologic/stratigraphic demarcations along the shore as a guide, polygons were digitized along the study reach to represent this information. In one direction, polygons reached perpendicular back from the shoreline (ie. the contour for 173.5) to a 100yr erosion limit which was calculated from the bluff edge. In the other direction, polygons extended between the borders of adjacent geologic/stratigraphic polygon divisions.

In order to determine the exact limits of the 100yr erosion limit, a buffer had to be created back from a solid line demarcating the edge of the bluff (EOB). The EOB is the accepted mark from which to calculate recession rates and erosion distances (PA, TA, and PWA 1989, Boyd 1981) and was used by Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989) to calculate recession rates along the study reach during the Port Burwell Litigation. Since elevation contour lines are intermittent along the bluff edge, a new line was created that traced and joined the upper-most contour along the bluffs from one end of the study reach to the other (Big Otter Creek to Hahn Marsh). In cases where the bluff edge met long ravines or Little Otter Creek, the EOB contour was drawn across these features a short distance upstream to eliminate areas not of immediate concern in the context of shoreline bluff failures. At Sand Hills park, the EOB was drawn along the break-ridge of the sand dune. In the case of all gullies, the EOB was traced around their perimeter because their edges are believed to be just as unstable and hazardous as the bluff edges themselves. Barnett (1987) noted that though these gullies do not always recede or move inland at the same rate as the bluffs, they do continue to recede and can erode laterally for long periods of time. Lateral and perpendicular expansion up to 20m was evidenced for some gullies in the study reach during field trips over a three year period. Many gullies are already visibly threatening the stability of Road 42 and nearby houses, buildings and other infrastructure.

Using MapInfo's *OBJECT BUFFER* tool, a 529m buffer was created around the EOB, and saved as a polygon. The bottom of this polygon was then sliced off and replaced with a modified contour of the shoreline. This modified version excluded the east side of the Big Otter Creek breakwater, and a sand bar that had formed in front of Port Burwell beach. Both of these features were regarded to be extraneous shoreline items, and were not necessary for the analysis. The resulting polygon was then sliced up into 7 individual polygons using lines drawn perpendicular between the points demarcating the geologic/stratigraphic divisions, and the 529m erosion limit.

Each of the geologic/stratigraphic divisions were then classified to fit a 5 tier scale based on its perceived susceptibility to slope failure. This classification scheme is presented in Table 6.4. The rationale for these divisions was based upon the assumption that the geology and stratigraphy most susceptible to failure and hazardous to humans is where cohesive tills or rhythmites are overlain by less cohesive silts and sands. These geologic/stratigraphic conditions are believed responsible for the tragedy at the Sand Hills Park in 1994. This condition allows water to seep down through permeable layers to less permeable layers, where water then seeps out to the bluff edge along the shear plane, or over-saturates the over-lying bluff material just above the shear plane. Both instances often result in a rapid reduction of shear strength and eventually large or shallow rotational slides, translational slides, or gullies, where the less-cohesive material slides off the more cohesive materials. Areas where a variety of materials inter-finger each other, such as the section of Galt Moraine west of Jacksonburg, are deemed to be of moderate hazard due to intermittent and variable overlay of cohesive and non-cohesive materials which are also prone to slides through groundwater seepage and piping. Reaches of shore composed of fairly cohesive and homogenous materials, such as the Wentworth Till near Clear Creek, are deemed to be the relatively least susceptible areas to slope failure. Here, water is not as disposed to seepage along the bluff face, failures generally consist of small topples, and the bluffs are generally much more stable.

Table 6.4: Geology/stratigraphy susceptibility classification scheme.

Class	Geology / Stratigraphy	Susceptibility to Failure	Explanation
5	Sand, Sand Rhythmites over Silt, Clay Rhythmites	Severe	Geology/Stratigraphy disposed to a high incidence of seepage, perched water tables, rotational slides, gully formation
4	Mixed - Till, Diamicton, Sand, Sand Rhythmites	Very High	Geology/Stratigraphy disposed to similar characteristics as seen in Class 5, only to a slightly lesser degree
3	Sand over Sand Rhythmites	High	Geology/Stratigraphy disposed to some seepage, rotational slides
2	Sand over Silt, Clay Rhythmites or Sand over Diamicton	Moderate	Geology/Stratigraphy disposed to some seepage, infrequent slides
1	Clay Rhythmites, or Clay Rhythmites over Diamicton	Low	Geology/Stratigraphy not disposed to seepage, gully formation or rotational slides. Occasional translational slides.
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

Using the classification scheme, each geologic/stratigraphic polygon was assigned an attribute value (0 to 5) corresponding to its susceptibility to failure. The data layer containing the polygons was then converted from a MapInfo Table (*.tab*) to a MapInfo Interchange File (*.mif*), imported into Idrisi as a Vector file (*.vec*), and subsequently converted to a raster Idrisi image (*.img*). Important options and decisions made while creating the geology/stratigraphy image are detailed within the flowchart, Figure 6.2. Figure 6.7 is a graph which summarizes the classified image in terms of the total land area represented by the classified geology/stratigraphy values, within 20, 10, and 5yr recession setbacks from the bluff edge. The corresponding data table for the classified data is included as Appendix A(v). Figure 6.8 is the classified image of geologic and stratigraphic contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

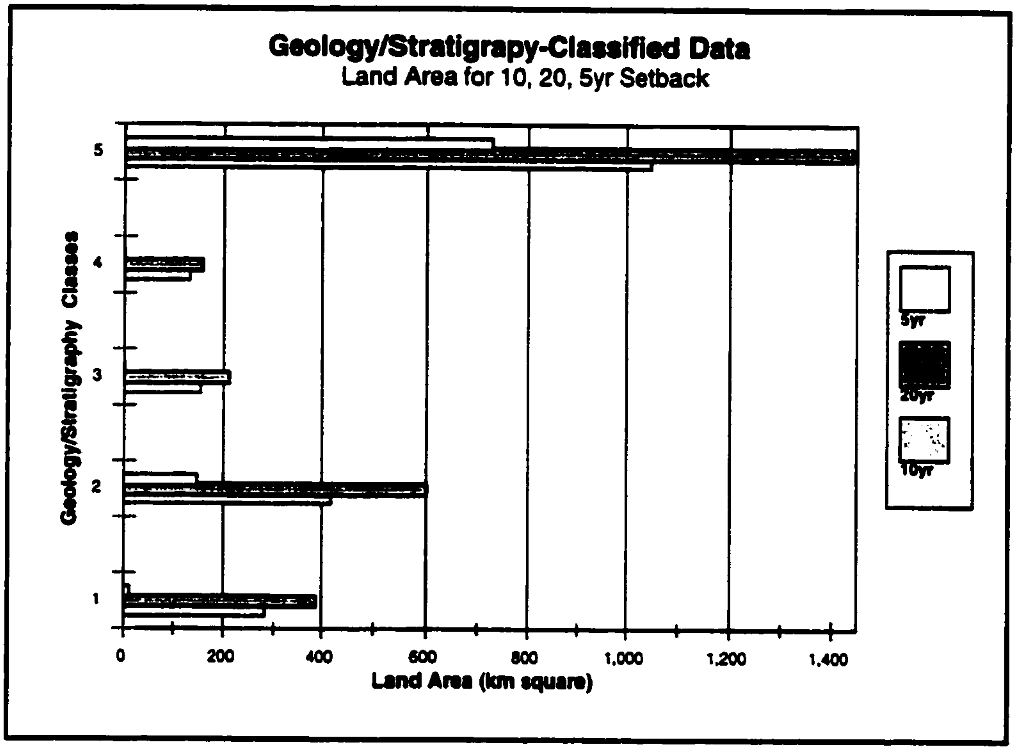


Figure 6.7: Geology and Stratigraphy - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at $100m^2$ (10x10m).

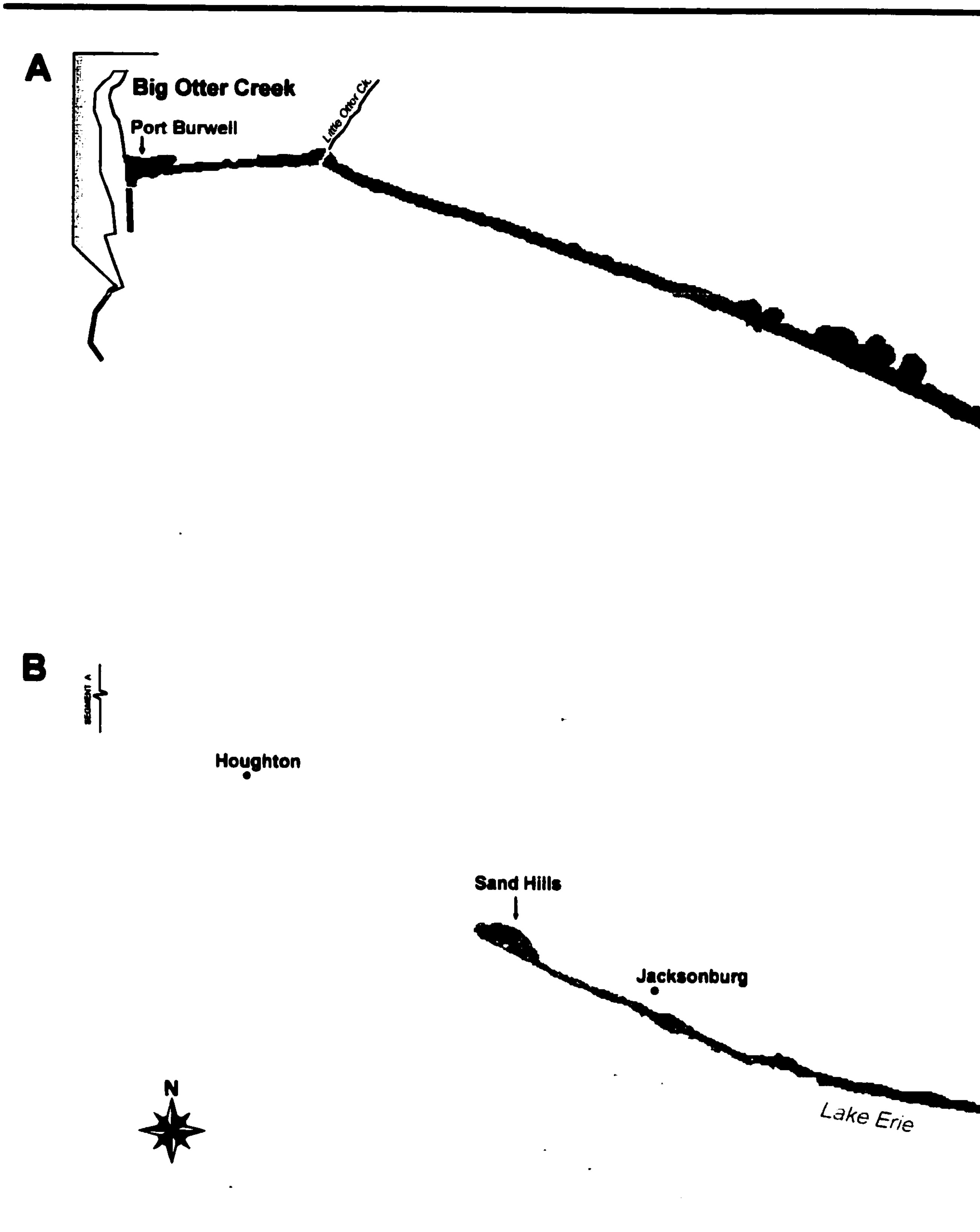
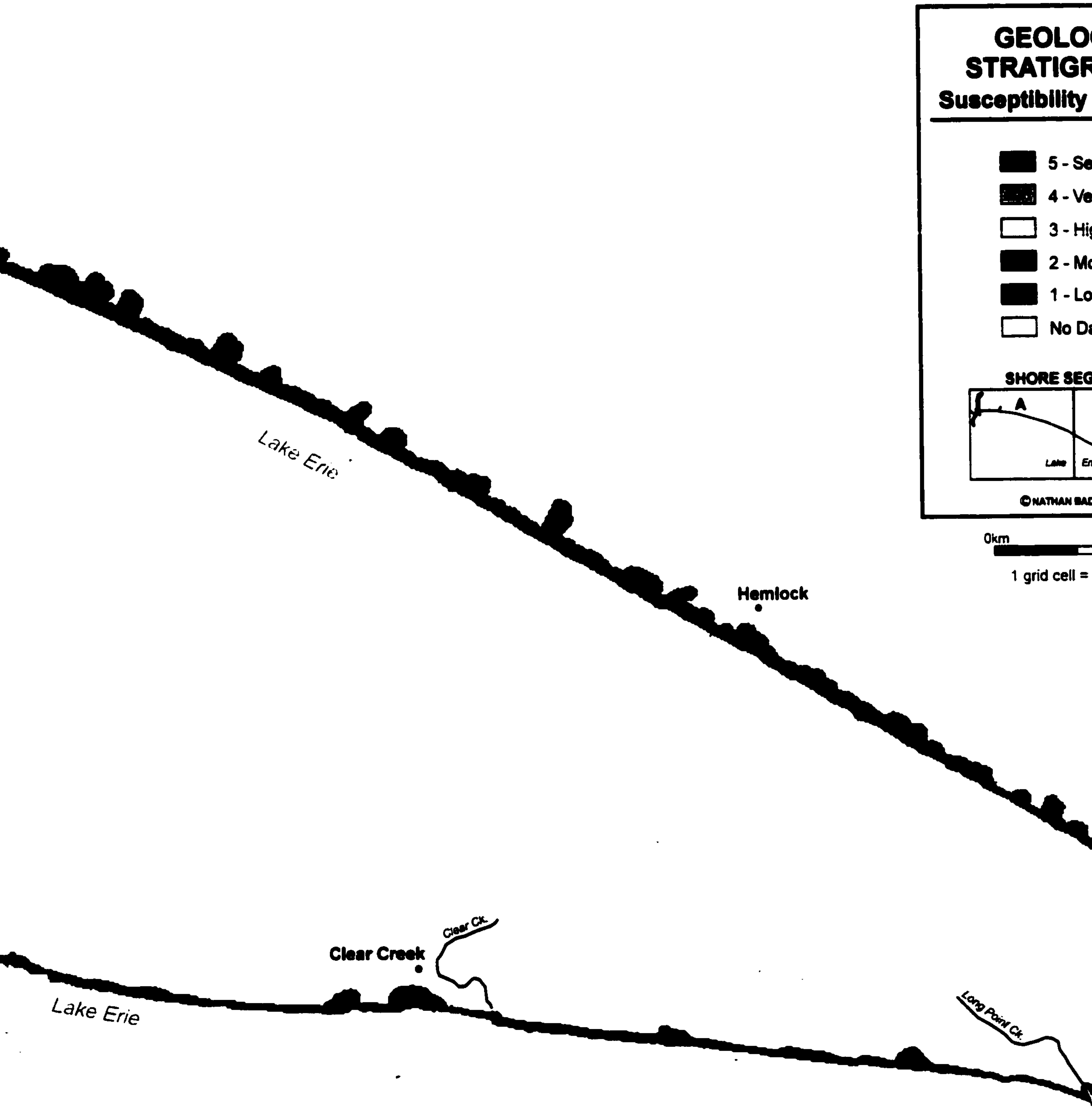
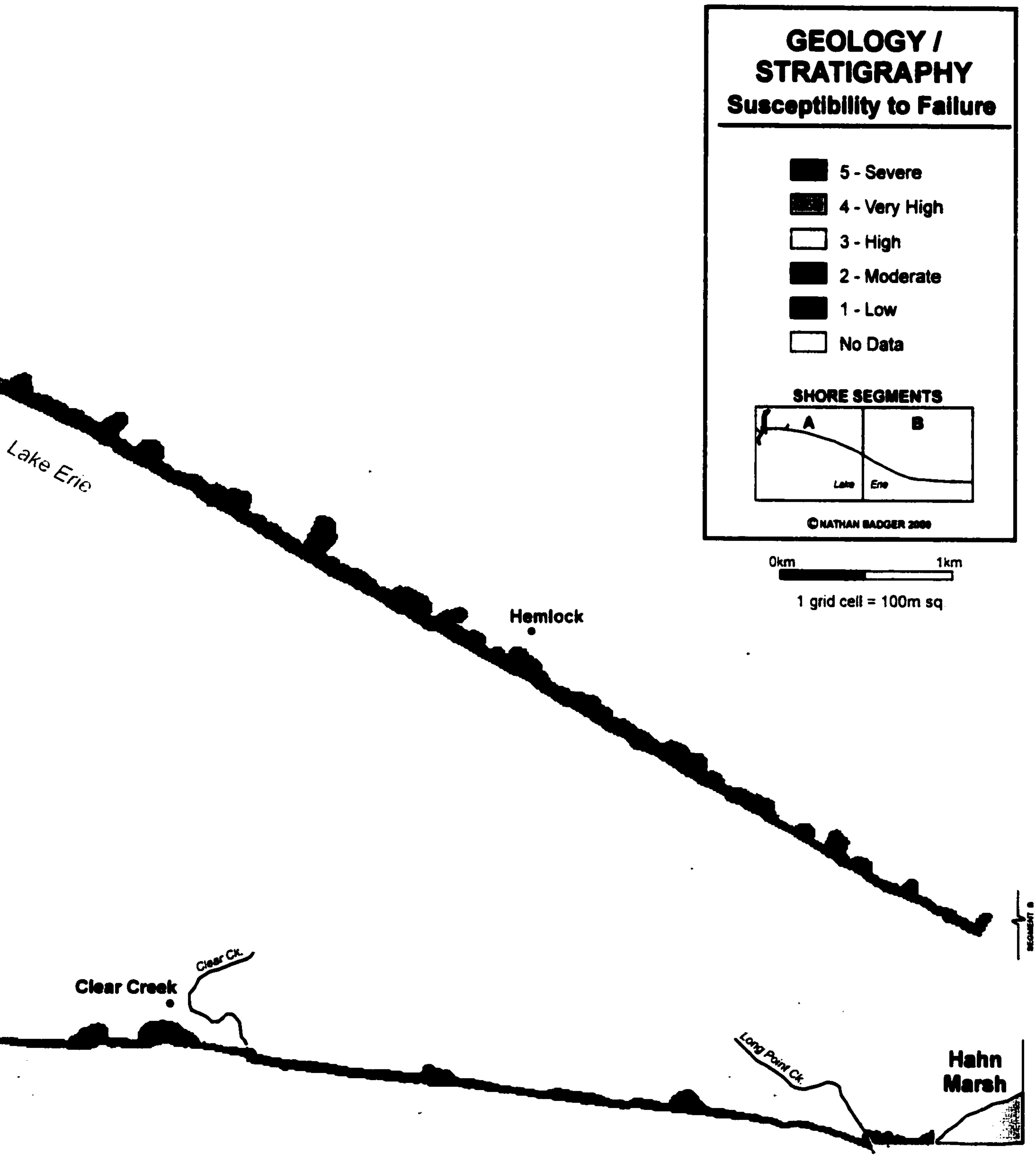


Figure 6.8: Shoreline geology and stratigraphy is used to classify the susceptibility of a 10
was imported into CorelDraw and combined with several geographic locators.



susceptibility of a 10 year recession setback to failure. The Idrisi data layer
cators.



recession setback to failure. The Idrisi data layer

6.2.4- Recession Rate

Coastal slopes are faced with a unique environment, where the toe of the bluff is threatened by subaqueous processes (Sunamura 1992, Davidson-Arnott 1989, Gelinas and Quigley 1973). Nearshore erosion, wave energy, water levels and littoral currents all affect the stability of the bluffs along the study reach. In turn these processes are controlled or influenced by wind direction, wind speed and duration, climate, and shore orientation and aspect. All these items are aptly summarized by the rate at which the shoreline recedes inland. Annual average recession rates (AARR) were therefore included in the analysis to reflect a large set of sub-aqueous and related influences on bluff stability.

The study reach is unique to the Great Lakes, in that it has been included in several important recession rate studies (Geomatics Inc. and Davidson-Arnott 1992, PA, TA, and PWA 1989). As part of the Great Lakes Erosion Monitoring Programme, Boyd (1981) calculated Annual Average Recession Rate (AARR) at 162 sites along the erodible portion of the Great Lakes, including 3 locations along the study reach. Due to the scale of this study, recession rate values were necessarily generalized along the study reach. In addition, the AARRs were calculated over a 7 year span, and therefore only reflect short-term averages, which do not accurately represent the long term variations and cycles of shoreline recession. Gelinas and Quigley (1976) recommend that recession rates be measured over a minimum of 20years in order to account for these variations. AARR were also calculated for the study reach (Pointe aux Pins to Long Point) by Fleming as part of the Port Burwell litigation claim. Since these values were calculated using air photographs between 1937 and 1975 at 100m intervals along the study reach, they represent long-term recession rates in the study reach much more accurately.

Unfortunately, Fleming's original report could not be obtained in time for the completion of this study, but is believed to be contained in archives in Toronto at the Ontario Regional Office of Public Works, along with a host of other reports produced during the Port Burwell Litigation (Kamphuis 25 Nov. 1998). For this reason, only vague information about his research methods are available (eg. Geomatics Inc. and Davidson Arnott 1992, Philpott 1986, PA, TA, and PWA 1989), and it is assumed that Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989) made his recession measurements at the edge of the bluff, rather than the shoreline. Although Fleming's report was unavailable, the LPRSMP has included 227 of his raw AARR values for the reach between Port Burwell and Long Point in the appendix of their Shoreline Management Plan (PA, TA, and PWA 1989). This information was a valuable source of data for this research.

Fleming's values were recently used in a Shoreline Classification and Mapping Study completed for CCIW and Environment Canada in 1992 (Geomatics Inc. and Davidson-Arnott 1992). CCIW's study was recently updated by Christian J. Stewart Consulting (1994) for the University of Virginia and USGS. Unfortunately, both studies classify and construct boundaries for recession rate reaches by averaging recession rate values over reaches of shore pre-defined by orientation, relief, and bluff and nearshore composition (Geomatics Inc. and Davidson-Arnott 1992). As a result, AARRs vary widely within their recession rate sub-reaches. Though these reports and digital data were readily acquired from CCIW, it was decided at a late stage in the data analysis that this 'pre-classified' data should not be used because AARR data would then be pre-correlated with reaches of geology/stratigraphy. In addition, AARRs were found to vary widely within each of CCIW's shoreline reaches.

To avoid these problems, 227 of Fleming's raw recession rate values, calculated along the study reach, were obtained from the LPRSMP appendix (PA, TA, and PWA 1989), and classified by natural variations in recession rates, rather than pre-defined reaches of shore orientation or composition. Classification was accomplished by using the scheme constructed for CCIW's Shoreline Mapping and Classification study. This scheme was created between Geomatics Inc. and Dr. Robyn Davidson-Arnott of the University of Guelph (Geomatics Inc. and Davidson-Arnott 1992), and was created to reflect a general assessment of natural variations in recession rates along the Great Lakes. Values within this scheme were also used to fit with a similar scheme used on the United States side of the Great Lakes (Davidson-Arnott Nov. 26 1999). The values used in the scheme were found to fit nicely with natural breaks and trends within Fleming's recession rate data, and after small modifications, the scheme was applied to AARR values along the study reach. Appendix B lists Fleming's raw values, in addition to the method used to classify it, and the location of sample sites. Table 6.5 describes the modified classification scheme. For the purpose of this study, Class 1 represents the amalgamation of three separate CCIW classes, including Accretion (<-0.1m/yr), Stable (-0.1 to 0.1), and Low (0.11 to 0.3).

Table 6.5: Recession rate classification scheme (modified from Geomatics Inc. and Davidson-Arnott 1992).

Class	Recession Rate (m/year)	Susceptibility	Explanation
5	>2.0	Severe	Severe rate of shoreline recession
4	1.21 - 2.0	Very High	Very high rate of shoreline recession
3	0.71 - 1.2	High	High rate of shoreline recession
2	0.31 - 0.7	Moderate	Moderate rate of shoreline recession
1	<0.31	Low	Low rate of recession, stable or accreting
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

Once classified, recession rate sub-reaches were then defined by joining adjacent sample site locations which fell into the same class. This process produced 26 separate sub-reaches, within which, the variability of recession rate values varied much less than along the sub-reaches constructed by CCIW. In order to calculate a recession rate setback for each sub-reach, a representative recession rate had to be evaluated for each sub-reach. This was accomplished by averaging all AARR values within each sub-reach as listed in Appendix B. Where sub-reaches contained sites with no data, these sites were not included in the calculation of the average value.

Several difficulties arose while using Fleming's data. Firstly, short sections of shoreline at the east and west ends of the study reach (210 and 870m respectively) did not contain recession rate sample sites with which to create recession sub-reaches. Recession rates had to be interpolated for these sections of shore, and several new sub-reaches constructed to represent them. For the eastern section, recession rates were interpolated based on adjacent sub-reach values and a familiarity of the shoreline through field work. In the end, it was decided to join this stretch of shore with the adjacent sub-reach to the west (sub-reach 1), which had an average recession rate of 1.2m/yr, (Class 3 - High). Interpolation for the western section was aided by recession rates estimated for the area within the Captain's Cove Development Project (Sandwell 1991, 1992). This section of shore was divided into 3 sections due to the small fillet beach which exists behind a sunken barge updrift of Long Point Creek. The first section was believed to have an average recession rate of just under 2.0m/yr (Class 4 - Very High), and it was therefore amalgamated with the adjacent sub-reach to the east as sub-reach 26. The second section (general region of the fillet beach) was assigned an average recession rate of 1.2m/yr (highest value for Class 3 - High) and represented sub-reach 27. The third sub-reach was assigned an average recession rate of 2.0m/yr (highest value for Class 4 - Very High), and represented sub-reach 28.

A further difficulty with using Fleming's data from the LPRSMP was that none of the sample locations were specifically georeferenced. Instead, each sample site is defined by a 'base chainage' distance in metres from an unknown starting location near Port Burwell. However, Lot Lines and other significant features along the study reach are also defined by a distance in base chainage, and could be located on the hardcopy and digitized OBMs. Using these fixed locations as benchmarks, the location of sample sites could be fairly accurately determined using MapInfo's *DISTANCE* tool, and the calculated differences in base chainage distance between sample sites in Fleming's data. While measuring the location of these sample sites, it was often noted that Fleming's measured distances in base chainage did not match with the measured distances calculated in MapInfo. These errors are believed to be the result of Fleming's use of air photos in measuring and locating sample sites. These errors, as applied to shoreline recession measurements, are discussed by Gelinas and Quigley (1973). In order to determine what effect these errors might have on analysis, an attempt was made to estimate this error by measuring the distance between 17 lot lines in MapInfo, and comparing these values to those listed by Fleming. Fleming's measurements varied from the MapInfo distances by -77m (- 0.125%) to +44m (0.066%). On average, Fleming's distances were less than MapInfo's measurements by -0.184%. Although this value is fairly small, individual boundaries for some subreaches will likely be shifted a small amount. This shift is not believed to have a dramatic affect on the final analysis.

As with the geology/stratigraphy data, polygons were then digitized for each recession sub-reach to represent the discrete point data as areal data. The bottom of the polygons for each sub-reach were drawn by tracing the generalized shoreline data layer. The sides of the polygons were constructed by extending a perpendicular line from the shoreline to the maximum extent of a 20, 10, and 5yr recession setback for each sub-reach. These buffers and setbacks were calculated for each reach by multiplying the average recession rate of each reach by a value of 20, 10, and 5yr. The resulting values are contained in Appendix B. These values were then used in MapInfo to generate separate recession buffers, back from the edge of the bluff, for each recession sub-reach. Recession polygons were completed by tracing the top of the buffers between the two sides. It should be noted that two reaches along the study reach contained AARRs which were positive. Since shore bluffs cannot accrete, or move lakeward, these values are felt to be either anomalous, errors, or accretion along the shore due to sandbar formation or the run-out of slope failure material into the lake. Should accretion be the case, such data would indicate that Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989) was measuring recession rates along the shoreline, rather than the bluff edge. Whatever the case, long-term accretion is not believed to occur at any location along the study reach, and these recession polygons were reassessed as having a recession rate of 0.30m/yr, which corresponds with the maximum recession rate value within Class 1 (Low). The anomalies in Fleming's data set highlight the potential problems associated with AARRs, where short term, temporal variations (such as rapid slope failures) are not accounted for, as noted in Chapter Five 5.2.3.7, and discussed later in Chapter Six.

The temporal recession periods (20, 10, and 5yr) were used for several reasons, and it is useful to diverge slightly at this point to explain why. Foremost of these reasons is their relatively short time spans, within which this analysis is believed to be most useful. Beyond a short-term time limit (eg. maximum of 20yrs) the factors, and controls on bluff failures along the study reach would need to be reevaluated, and are likely to take on different weights of importance, largely because nearshore erosion, is believed to be the major control on bluff erosion over the long-term (Davidson-Arnott 1998). Quigley and DiNardo (1980) note that a 20 year period represents the average full cycle of lake water levels and bluff instability modes along the Great Lakes.

These short time periods also represent single, or multiple terms within which Land Use Plans must be reviewed (OMMAH 2000). Under Section 26(1) of the Ontario

Planning Act, administered by the OMMAH, municipalities are required to hold a special public meeting, at least every five years, to determine the need for revisions to the Official Township Plan (OMMAH 2000). Regular reviews keep the Official Plan reflective of changing circumstances such as socio-economic, social, or environmental trends, cumulative impacts of development and new community needs and values (OMMAH 2000). In the case of shorelines, which are highly dynamic and ever-changing, regular reviews also allow for modifications which account for changes in hazard lands due to the landward recession of the shoreline or bluffs. The dynamics of the shoreline ultimately affect the location of future development and its threat to present or previous development.

Finally, the results of the slope failure risk assessments are also seen as being useful, within these shore spans, as a short-terming planning tool. This tool could help to enrich the Official Town Plan as a resource with which to determine the risks of locating short-term or seasonal residences (eg. mobile homes), risks within certain recreation areas during summer months, or even in the relocation of infrastructure (eg. roads, water lines, hydro) which may need require attention in the short term.

Once polygons had been constructed, each was assigned a value representing its magnitude of recession from the classification scheme. The data layer was then converted from a MapInfo Table (*.tab*) to a MapInfo Interchange File (*.mif*), and imported and prepared in Idrisi in like manner as the data layer for geology/stratigraphy, as described in Section 6.4. Important options and decisions made while creating the recession rate image are detailed within the flowchart, Figure 6.2. Figure 6.9 is a graph which summarizes the classified image in terms of the total land area represented by the classified recession rate values, within 20, 10, and 5yr recession setbacks from the bluff edge. A data table for the classified data is included as Appendix A(vi), while the unclassified values are contained in Appendix B. Figure 6.10 is the classified image of recession rate's contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

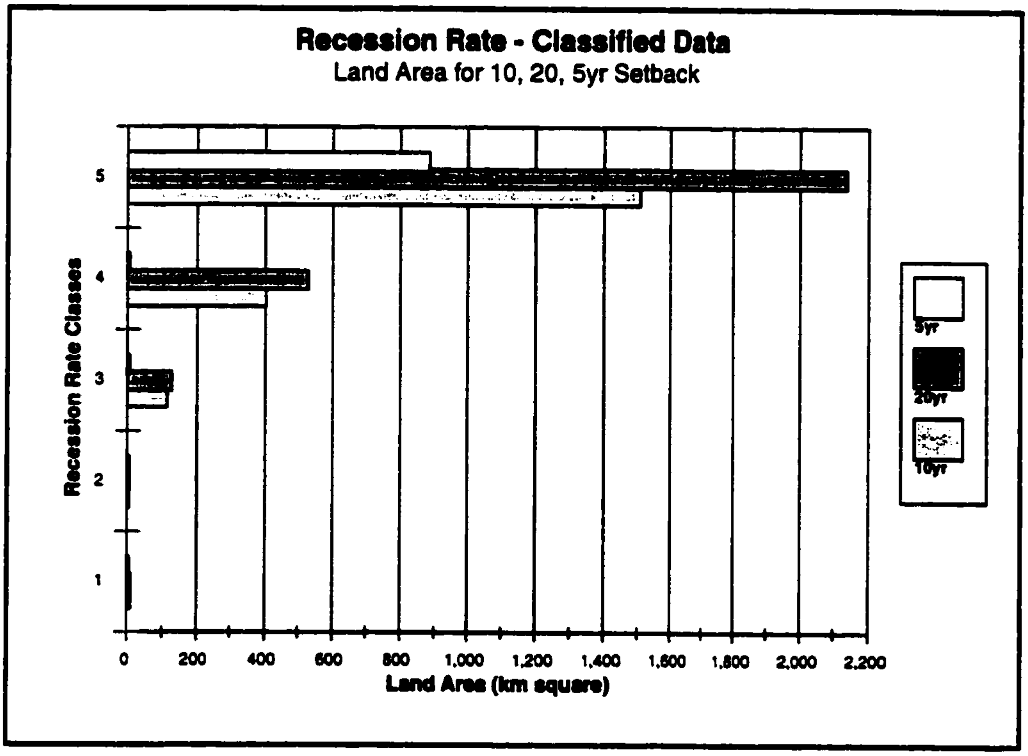


Figure 6.9: Recession Rate - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at 100m² (10x10m).

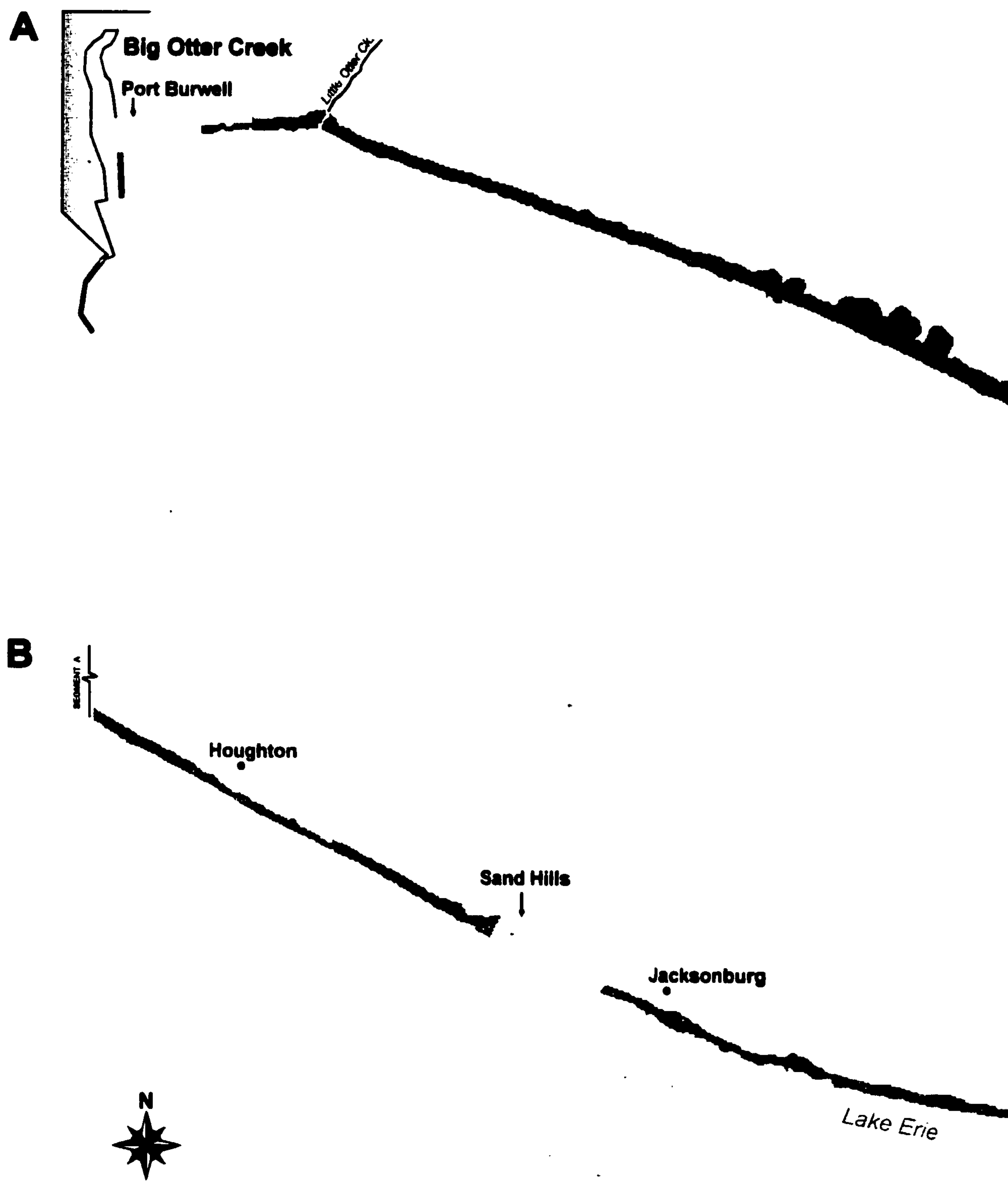
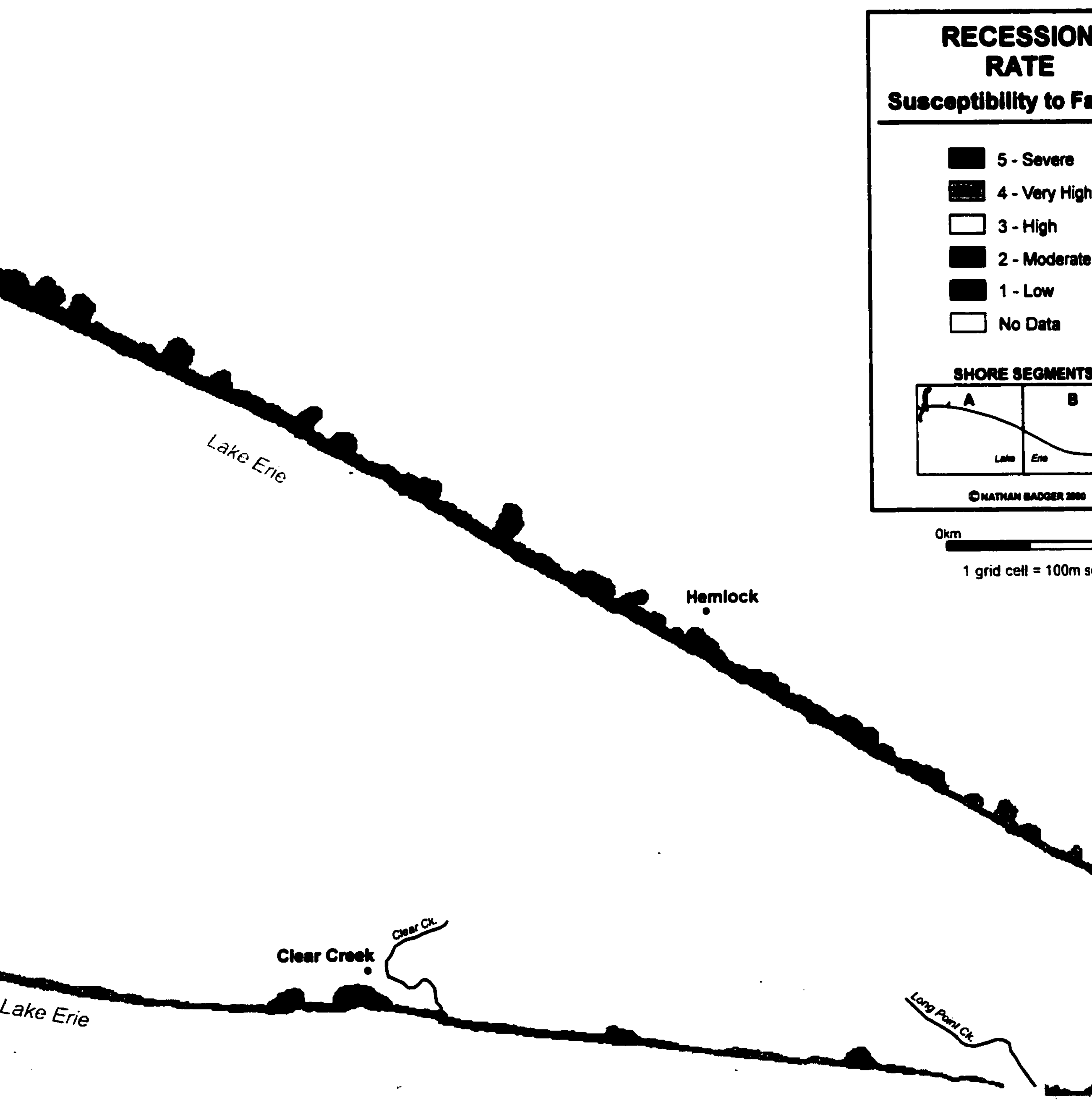
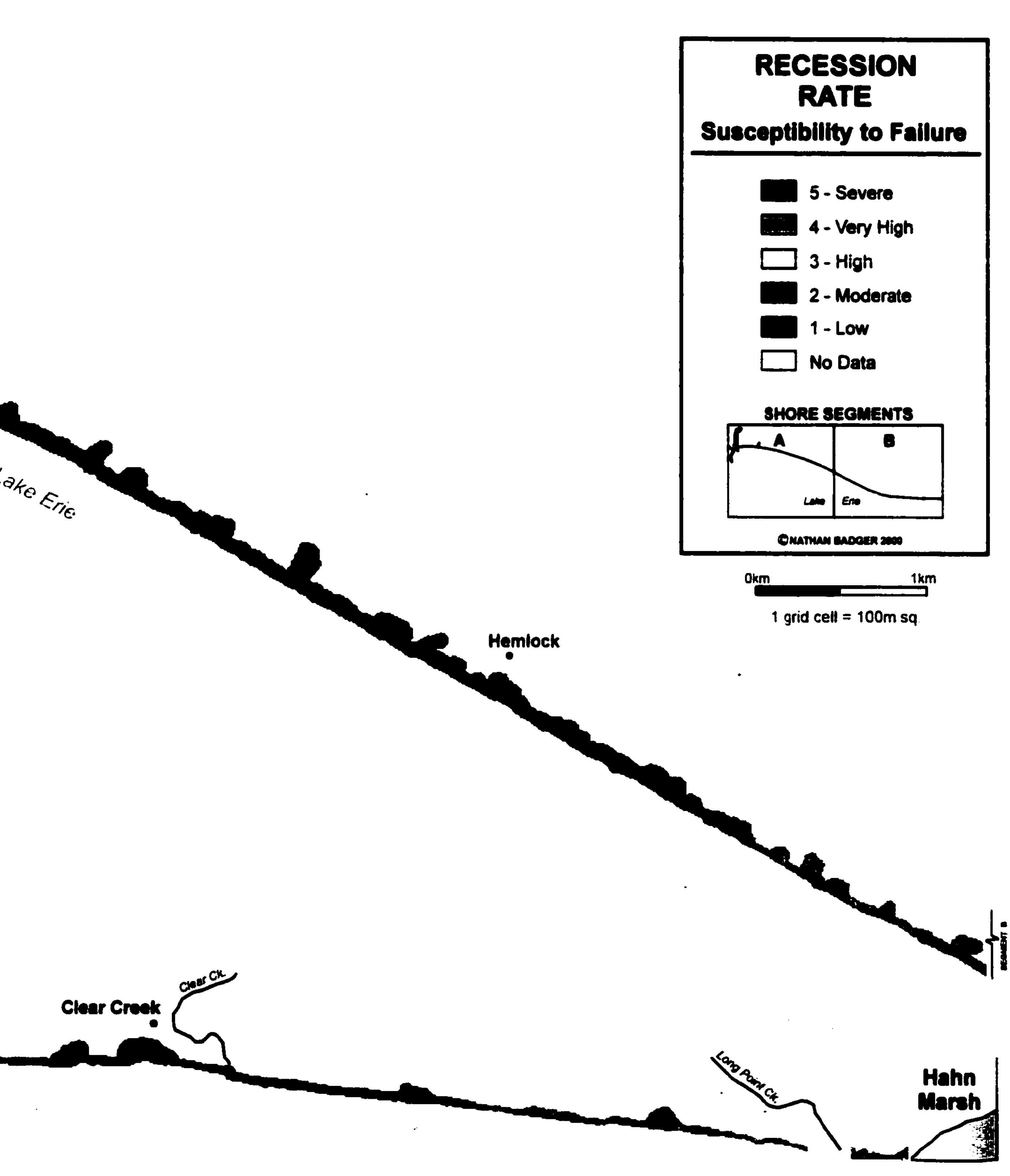


Figure 6.10: Shoreline recession rate (annual average) is used to classify the susceptibility
data layer was imported into CorelDraw and combined with several geographic locators.



ne susceptibility of a 10 year recession setback to failure. The Idrisi
nic locators.



0 year recession setback to failure. The Idrisi

6.2.5 - Vegetation Cover

Vegetation, as noted by Varnes (1984) and Selby (1993), plays an important contributory role in the stability of slopes. Although a small report by Fowle et al. (1982) suggested that vegetation cover on the Scarborough bluffs does not play a contributory role in bluff stability, various pamphlets (EC and ACAO 1995, GLBC 1977) produced by the provincial government, in addition to May (1977), Mickelson et al. (1977), the GPSS (TL and AS 1998), and the TGGLSLS (OMNR 1994) all suggest that vegetation can indeed aid in the stability of bluffs through interception of rain and groundwater and its cohesive force in holding slope material together through root systems. Even if vegetation does not play a major role, it does provide a strong indication of previous landslide activity by its presence or absence along the bluffs. Based on this observation, and the contributory role observed by others, vegetation cover will be included as a data layer in this study, and assumed to increase shear strength within the slope. For the purpose of analysis, areas covered by vegetation are assumed to be more stable and therefore less of a hazard than those areas not covered by vegetation.

Vegetation cover for the study reach was easily digitized from the OBMs. A total of 215 stands were digitized, the largest of which was 0.6376km^2 with a perimeter of 5.25km. Each vegetation stand is defined by the OBM legend as simply depicting areas of vegetation. Unfortunately, this is rather vague. However, several other symbols on the OBMs represent marsh and hedgerows, and therefore these stands are believed to represent major stands of thick, mature vegetation. This assumption was strengthened by comparing OBM vegetation stands to the equivalent stands mapped on the 1:25,000 and

1:50,000 NTS maps. Here, the same vegetation stands are defined as 'wooded areas', but excludes orchards and vineyards, which are present along the study reach. Such a definition would appear to indicate that the vegetation stands on the OBMs represent mature, forested areas, which incidently, are also believed to provide some of the greatest vegetative stability to a slope (Selby 1993).

A boolean classification (ie. 0 or 1) was all that was necessary for this data layer, since a particular area of shoreline was either vegetated, or unvegetated. The classification scheme in Table 6.6 summarizes the classification scheme for the vegetation data layer. Hence, no attribute values were applied to the vegetation stands in MapInfo, as vegetated areas were automatically assigned a value of 1 when imported by Idrisi. The data layer was converted from a MapInfo Table (*.tab*) to a MapInfo Interchange File (*.mif*), and imported into Idrisi in much the same manner at the geology/stratigraphy layers described earlier in the chapter.

Table 6.6: Vegetation cover classification scheme.

Class	Vegetation Cover	Susceptibility to Failure	Explanation
5	No Vegetation	Very High	Area not covered by vegetation
1	Vegetation	Low	Area covered by vegetation
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

As a final note in the discussion of the vegetation data layer, it is important to assess the effects of the enlarged vegetation polygons during the digitizing process, as noted earlier in the chapter. In summary, this error is believed to have a minimal effect on the total area of vegetation represented for the study error in the final Idrisi image. There is little doubt that the area is increased within MapInfo, but it is unlikely that the totality of this increase will accompany the data into Idrisi. When the polygons are converted to a 10m resolution grid, as they are imported to Idrisi, the interpolation method used to convert polygons to grid cells in assumedly only sensitive to measurements that equal half the size of the cell. In other words, in order for a cell to be assigned a value of 1, indicating presence of cover, the vegetation polygon must reach over 5m into the 10m grid cell. Since most of the polygons are only increased in size by an average of 4m a side, this is not believed to influence Idrisi to assign a large number more cells as being vegetation.

Important options and decisions made while creating the vegetation cover image are detailed within the flowchart, Figure 6.2. Figure 6.11 is a graph which summarizes the classified image in terms of the total land area represented by the classified vegetation cover values, within 20, 10, and 5yr recession setbacks from the bluff edge. A data table for the classified data is included as Appendix A(vii). Figure 6.12 is the classified image of vegetation cover's contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

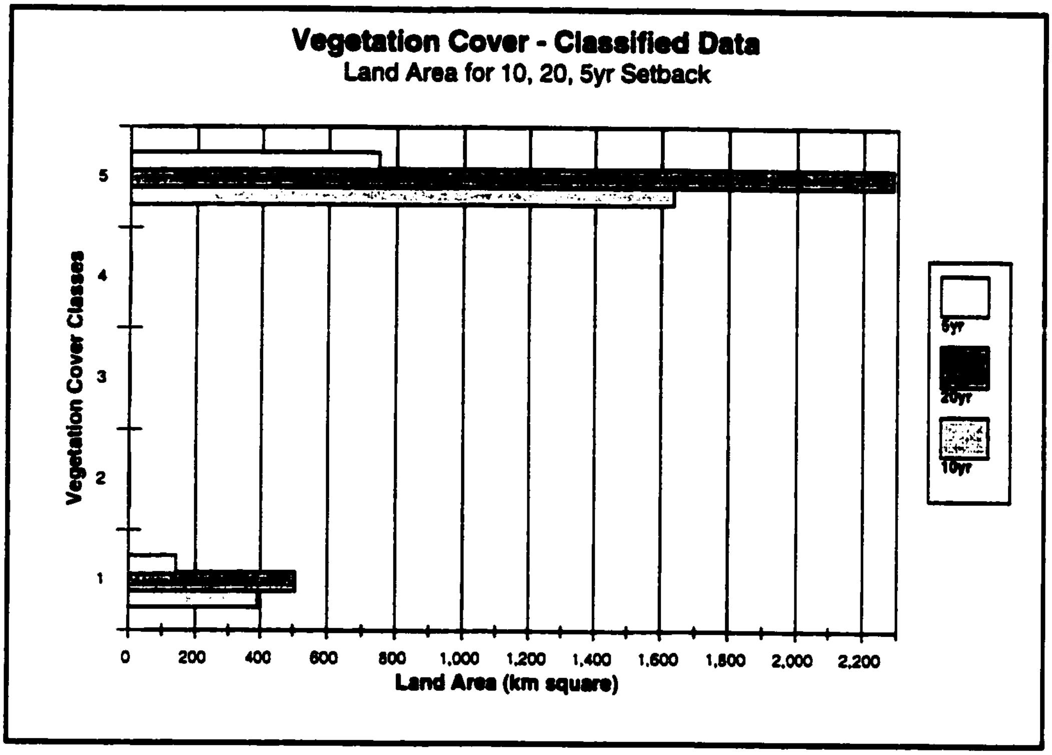


Figure 6.11: Vegetation Cover - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at 100m^2 (10x10m).

6.2.6 - Shore Protection

Shore protection is believed to have a mixed influence on the stability of shore bluffs, but is generally felt to provide at least short term stabilizing effects if protection is constructed properly (Carter et al. 1987, Zeman 1990). For example, Quigley et al. (1974) reported positive effects of shore protection along Lake Huron, Ontario. Davidson-Arnott and Keizer (1982) noted that 18% of all sea wall protection was in disrepair or destroyed within 10yrs along the shore of Lake Ontario, and none could

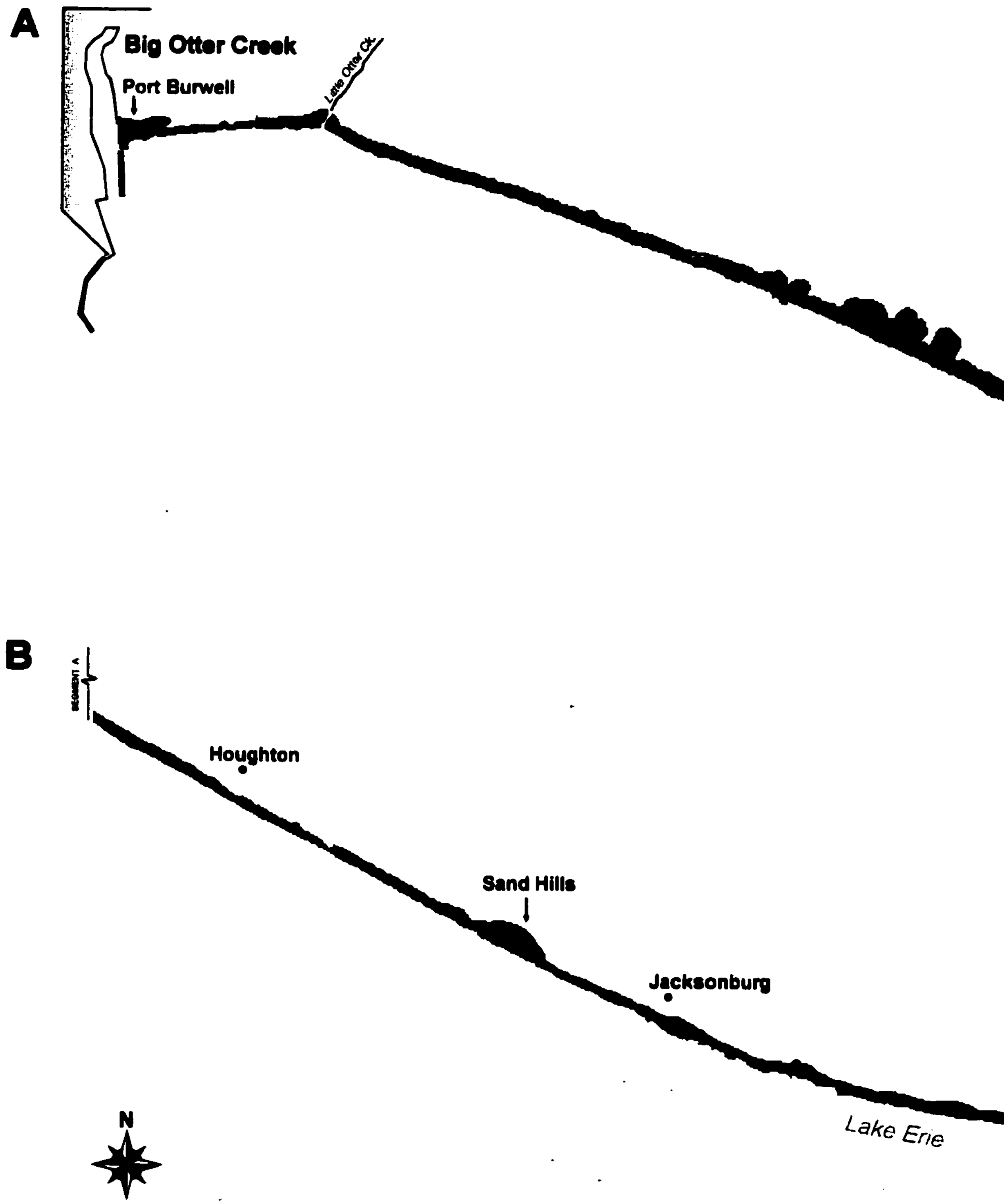
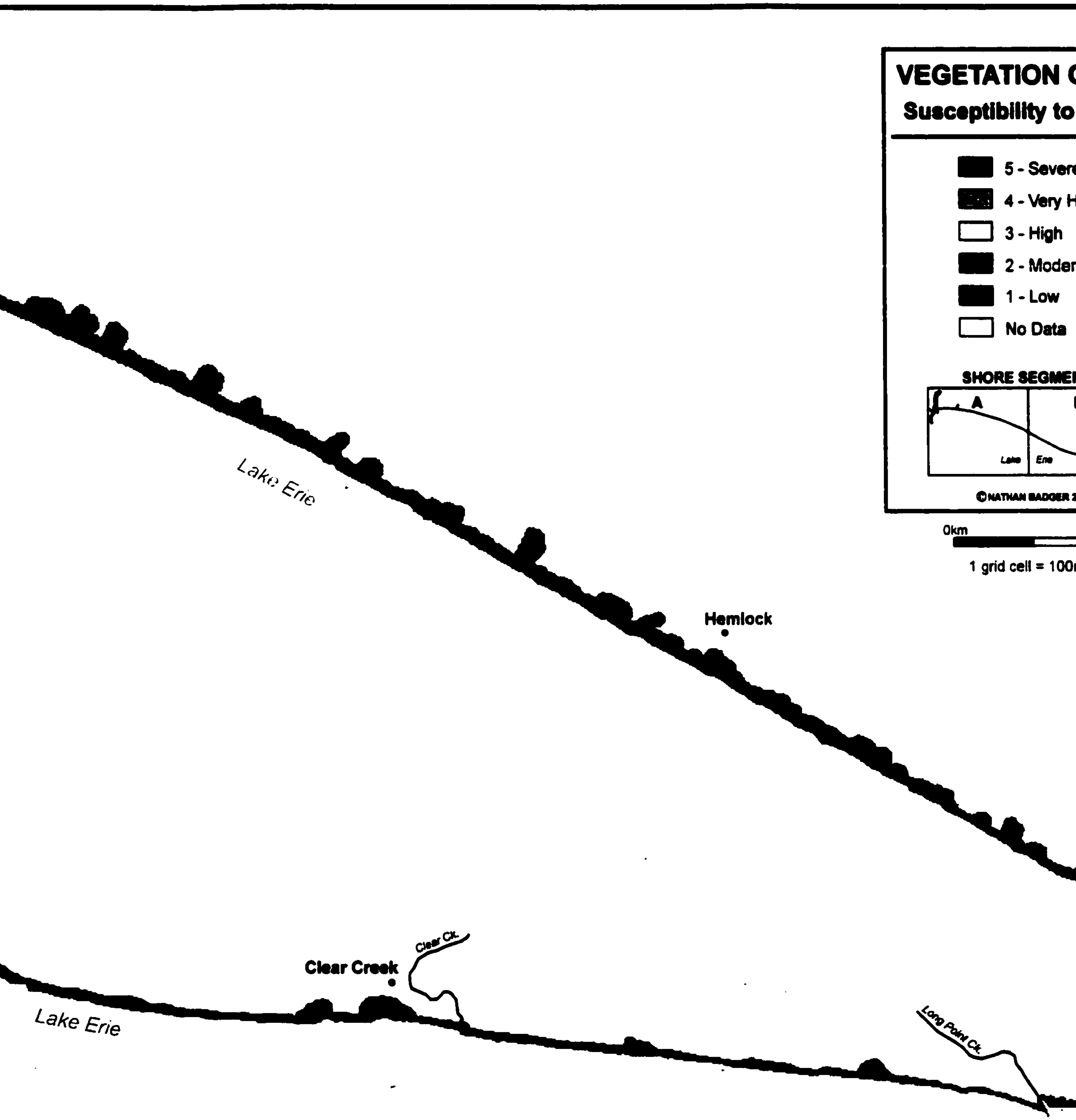
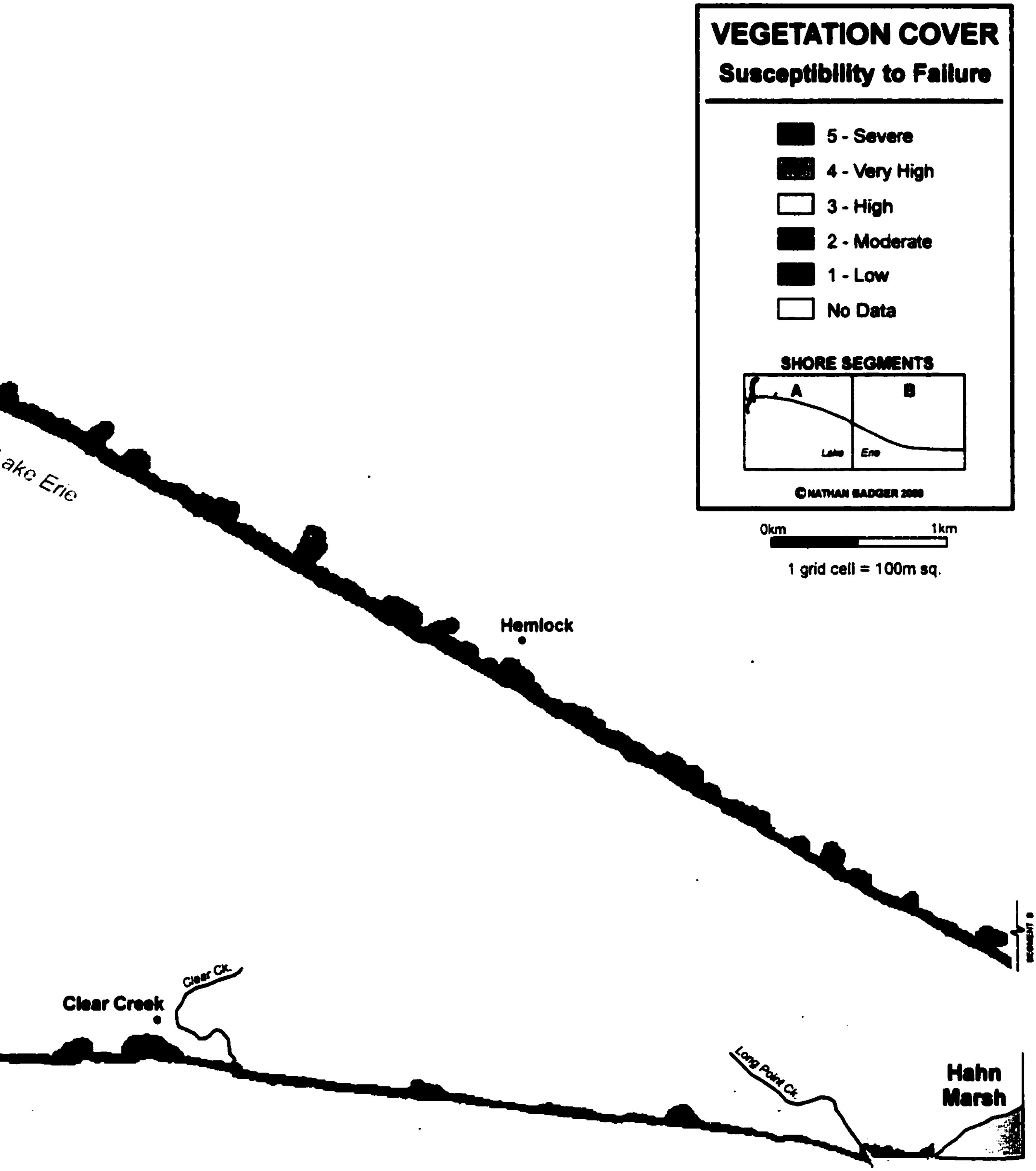


Figure 6.12: Shoreline vegetation cover (absence or presence) is used to classify the sus
The Idrisi data layer was imported into CorelDraw and combined with several geographic lo



o classify the susceptibility of a 10 year recession setback to failure.
eral geographic locators.



ty of a 10 year recession setback to failure.

withstand a 30 year period (Davidson-Arnott and Keizer 1982). While often difficult to measure within a short period of time, shore protection can also increase down-drift erosion depending on the littoral climate of the region (Carter et al. 1987).

The effects of shore protection are largely unstudied along the study reach, aside from the Port Burwell Litigation (Philpott 1983). However, during field work, shore protection appears to have contributed to temporary bluff stabilization along several sections of the study reach. This was evident east of the Port Burwell public beach, and along a short section of shore fronting cottages just west of the Hahn Marsh. This was most evident during field work at Sand Hills Park, where unprotected shoreline outside of the park has receded an additional 20m back from protected areas. In all three cases, shore protection appears to have provided some level of bluff stabilization and slowed the process of recession. The long term effects of this shore protection, and their short or long-term effect on down-drift erosion is unknown, would require large-scale investigations, and is therefore not considered in the analysis. Based on these observations and the positive short-term effects of shore protection noted in the literature, it was decided to include shore protection as a data layer in the analysis and assume its presence as a short-term stabilizing factor to the bluffs. The short-term effects also happen to fit well with the short-term planning tool which this research aims to provide.

OBMs do not map shore protection, and instead, this information had to be obtained through field work and information provided from the LPRCA (Baskerville 1997, PA, TA, and PWA 1989). Three sections of protected shore were discovered along the study reach, including a section of shore from the eastern limits of Port Burwell beach to Little Otter Creek, a section of shore in front of Sand Hills park, and a section of shore in front of cottages immediately west of the Hahn Marsh. The lateral extent of this protection was measured out during field work, and then demarcated on a new data layer in MapInfo using the Distance tool. As with the geology/stratigraphy, and recession rate data layers, linear data for each protected section of shoreline was then converted to areal polygons. The base of all 3 polygons was formed by tracing a line between the start and end points of the shore protection along the modified shoreline contour *(shoreline_general)*. Lines were then stretched perpendicular from these points inland to the furthest extent of the 20yr recession buffer. The polygons were then completed by tracing the 20yr buffer between the top of the two sides. Although the protection is assumed in the data to provide protection to the 20yr limit, this is assumed, and not necessarily the case. Beyond 20yrs it is assumed that present, unmentioned protection would be removed or damaged by shore recession processes.

As with vegetation, no attribute values were assigned to the shoreline protection polygons since the layer naturally represented a boolean classification. Table 6.7 describes the classification scheme used for this data layer, where shoreline protection is assumed to lessen the susceptibility of the bluffs to failure. The data layer was then converted from a MapInfo Table (*.tab*) to a MapInfo Interchange File (*.mif*), and imported and prepared for analysis in Idrisi. During this process, Idrisi automatically assigned an attribute value of '1' to areas of shore protection. Important options and decisions made while creating the shoreline protection image are detailed within the flowchart, Figure 6.2. Figure 6.13 is a graph which summarizes the classified image in terms of the total land area represented by the classified shoreline protection values, within 20, 10, and 5yr recession setbacks from the bluff edge. A data table for the classified data is included as Appendix A(viii). Figure 6.14 is the classified image of shoreline protection's contribution to bluff failure susceptibility. This image will be used in the final analysis of overall susceptibility.

Table 6.7: Shore protection susceptibility classification scheme.

Class	Shore Protection	Susceptibility to Failure	Explanation
5	No Protection	Very High	Area not fronted by shore protection
1	Protection	Low	Area fronted by shore protection
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

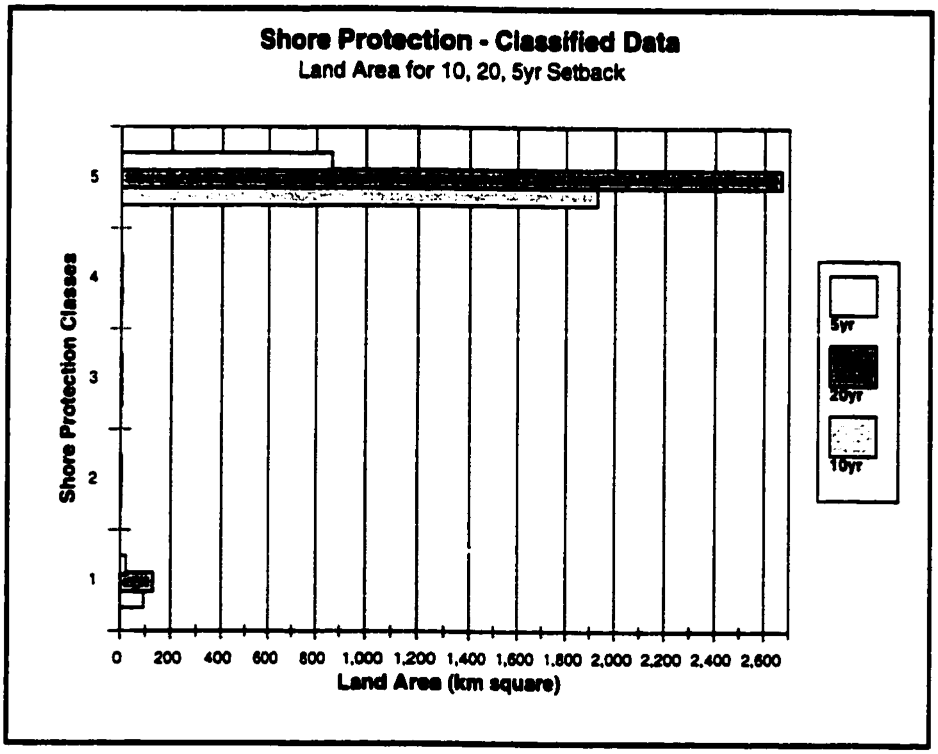


Figure 6.13: Shore Protection - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at 100m² (10x10m).

6.2.7 - Human Elements

The seventh and final layer included in the analysis depicts the location of human and cultural elements along the study reach. Without this information, an analysis of the previous six layers would simply provide an indication of where, and to what magnitude bluffs are most susceptible to failure using factors believed to contribute to slope instability. Through the inclusion of human and cultural items, one can evaluate the severity of a potential slope failure, in addition to the location, and general magnitude to

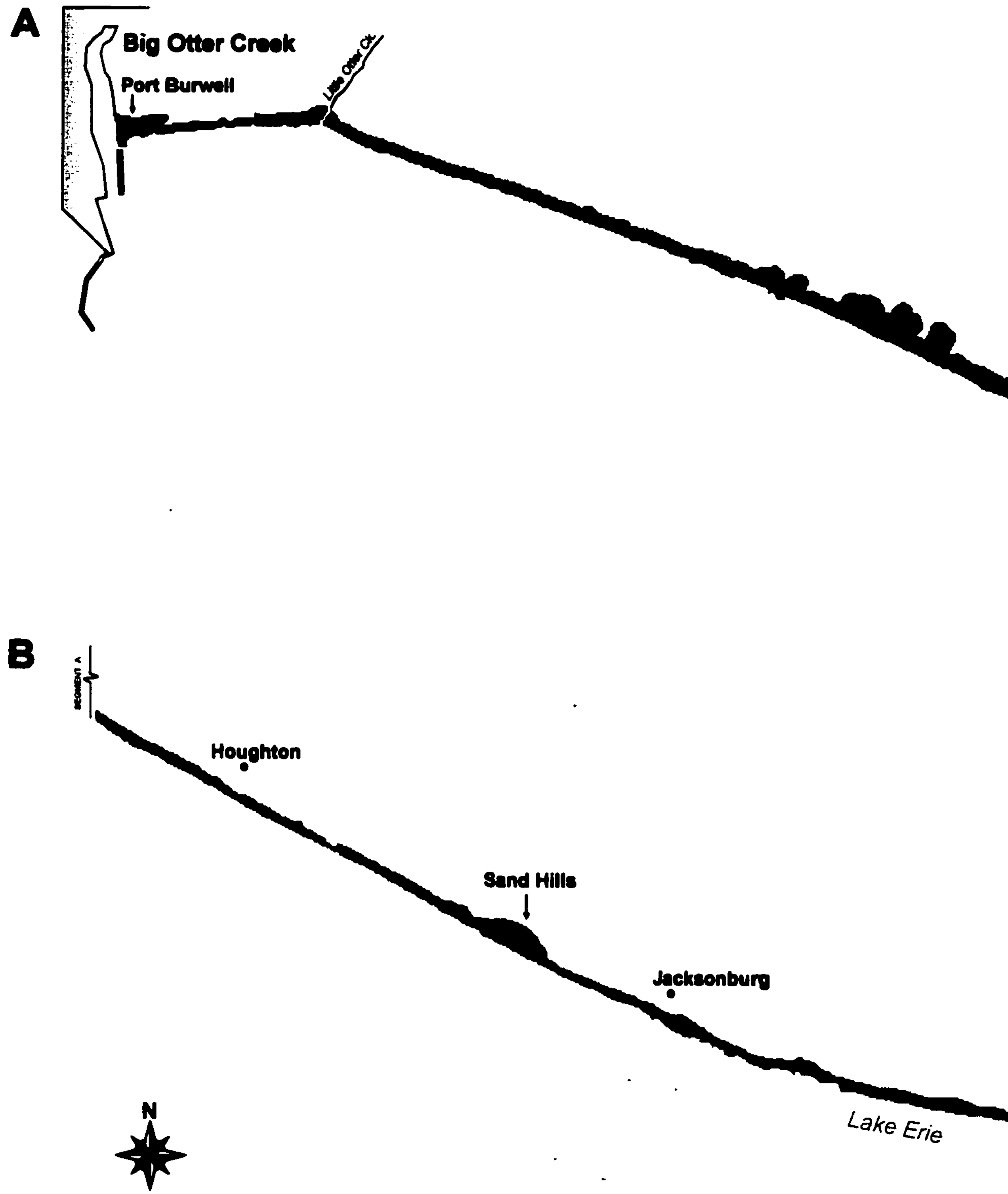
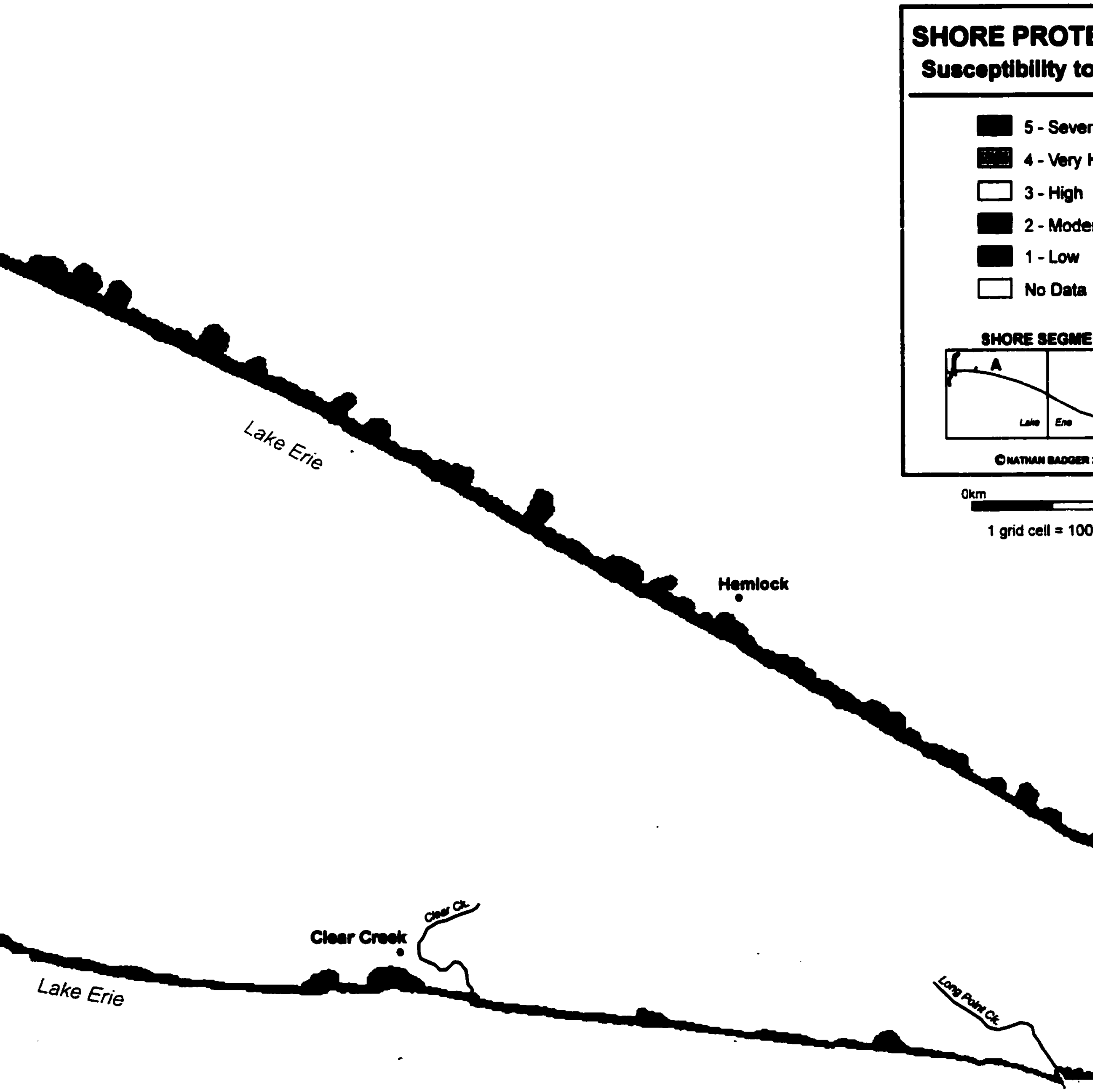
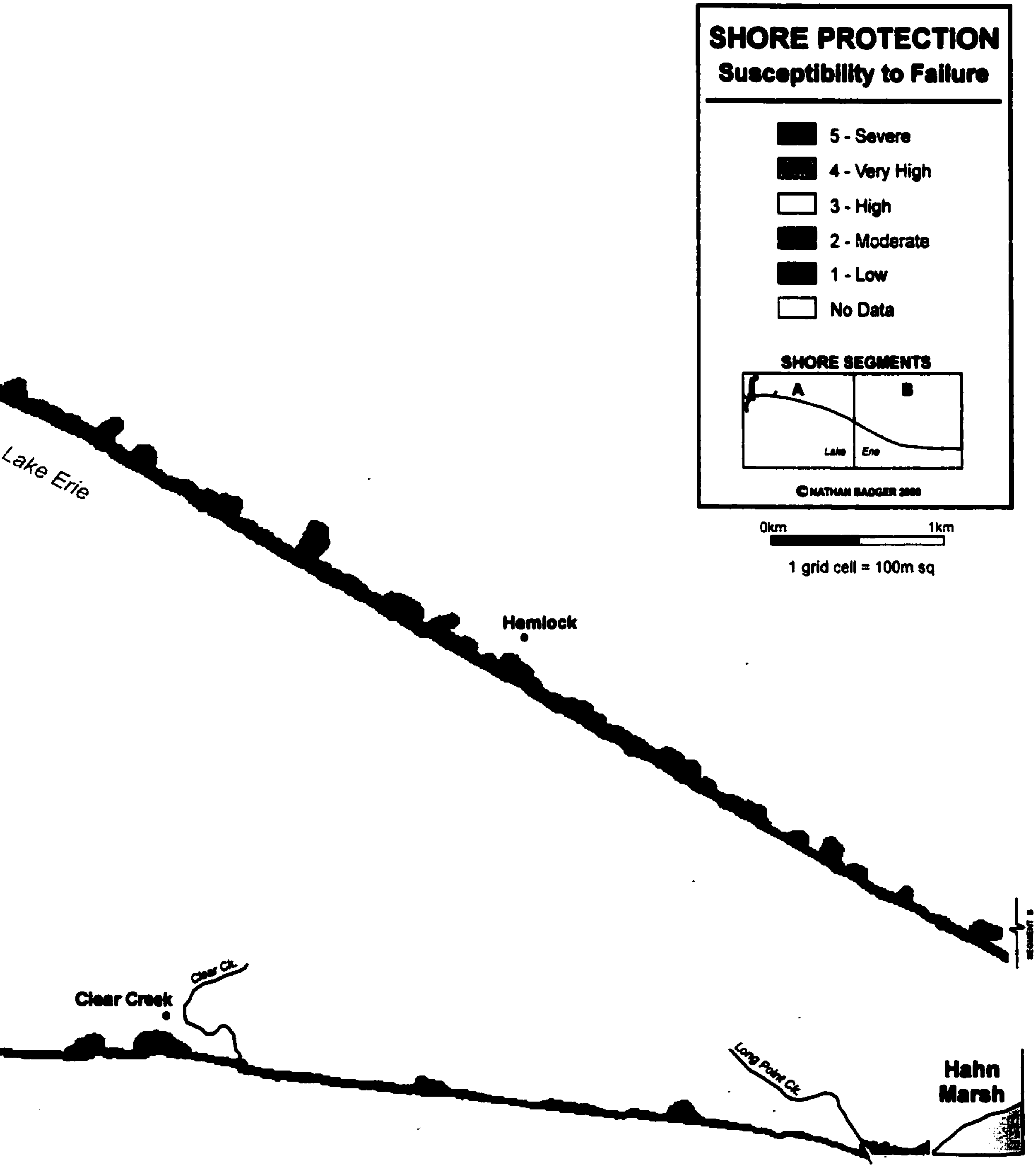


Figure 6.14: Shoreline protection (presence or absence) is used to classify the susceptibili
The Idrisi data layer was imported into CorelDraw and combined with several geographic lo



sify the susceptibility of a 10 year recession setback to failure.
veral geographic locators.



10 year recession setback to failure.

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which slope failures present a risk to human well-being (Hansen A. 1984). Figure 2.4 in Chapter Two illustrates the relationship between hazard failure susceptibility, failure severity, vulnerability, and the magnitude of risk. In summary, both the severity and the susceptibility of the hazard are required before risk can be calculated. It must also be noted that the assessment of risk varies based on the culture and values of the society performing the analysis.

A large variety of human or cultural items exist within the study area, but for the purpose of the analysis, these items were necessarily limited in scope to residential dwellings, other buildings, recreation areas, infrastructure such as roads, rail and communication towers, and finally, cultural or heritage items such as cemeteries, churches, historic sites, and museums. Although land is a further important loss of monetary value to humankind, time and information was not available to properly include this as part of the investigation.

Residential dwellings were included as a data layer because they contain personal possessions, are usually of high value, are generally surrounded by items of high worth (eg. cars) and are frequently the site of human presence. Other buildings, such as barns, large greenhouses, industrial and commercial sites were also included in the analysis as these sites often contain expensive items such as crops, merchandise, and farm machinery. Unfortunately, the OBMs do not clearly differentiate residential and non-residential dwellings by different symbols. Instead, point squares are used to define small buildings, and polygons are used to depict larger buildings at scale. During field work, the polygons were consistently verified as being non-residential buildings, yet the point buildings were occasionally discovered to represent buildings of house size, such as tobacco kilns, small sheds, or small greenhouses. This problem could not be corrected without a great deal of time and work and must be born in mind when interpreting the results of the risk analysis. A total of 1173 point buildings and 188 polygon buildings were digitized on separate layers so that each building type could be assigned a different attribute value during their conversion to Idrisi raster cells.

Most of the human element data was obtained from OBMs and NTS maps at a scale of 1:50,000 (40I/10 from 1986) and 1:25,000 (40I/10a,b,g,f from 1970 and 1971). NTS maps used in this research are cited in the Bibliography as DEMR (1970, 1971, 1976). This information was supplemented by tourist and information pamphlets or brochures picked up in the Township or Municipal offices, and several field trips which attempted to collect missing information, or to clarify and verify information on OBMs.

Recreation areas, such as beaches, camping grounds and parks were also included as a data layer. Though not depicted on the OBMs, the location of these areas were determined during field work and digitized as polygons. These regions were included because they are frequented by humans, and because they attract humans to the bluff edge, and the beach area below the bluffs. The severity of bluff failures in these areas is often high, as evidenced in the death of the four boys just outside Sand Hills Park. In total, three recreation areas were included in the data layer, including Port Burwell Beach, Erie View Campgrounds, and Sand Hills Park.

Infrastructure was also included as several data layers, including railway, roads, and the two Canadian Coastguard Radio Towers just west of Clear Creek. A total of 217 roads and 1.748km of railway were digitized, as these items provide important links to the study area for tourism, local inhabitants, commercial and industrial activity, and even services such as emergency vehicles. Roads in the study area are also closely parallelled by important services such as hydro and telephone lines. In the village of Port Burwell, the roads are also parallelled by water, sewage, and gas lines. The Coastguard Towers were also included as they are an important means of communication for Lake Erie boaters.

Finally, cultural and historic items were also digitized as several layers. These included 6 churches, 5 cemeteries, and 2 historic museums in Port Burwell. Though humans frequent these locations, they were included for their social value, as discussed earlier in the chapter. While the social value of these items is high, the value of human life is relatively much higher.

Aside from helping to determine risk, human presence can also play a direct role in influencing the stability of the bluffs within the study area (eg. ground water contributions, excavation, added weight). Although the emphasis of this research is not on their contributory role, as this is difficult to assess and map without further information, their contributory role should certainly be kept in mind throughout the analysis.

While constructing the human/cultural data layers through field work, several differences were noted between the OBM or NTS maps, and the current study area. Table 6.8 notes some of these changes, and indicates whether these items had been removed from the study area, or added through recent development. These changes are not surprising, since the 1997 OBMs had not been culture checked before production, and are based on information from 1985 air photos. NTS maps were inevitably somewhat out of date, since the 1:25,000 maps were published in 1970 and 1971 and the 1:50,000 were published in 1983. Due to the length of time required to update the cultural/human information through field work, and as a means of standardizing the digitized maps with their source, these changes were not made to the final human/cultural data layers.

Table 6.8: Changes to human elements within the Study Reach since the production of the OBMs in 1997, as noted during field work.

Item	Nature of the Change	Number of Items
Residences/ Buildings/ Greenhouses	Recently Built	32
Residences/ Buildings/ Greenhouses	Missing	3
Clear Creek Communication Towers	Missing	3
Port Burwell CPR Rail Spur	Missing	1

Once all the human and cultural elements had been digitized, they needed to be classified by their 'worth' or 'value' to humans. This rank would determine the severity of a slope failure event, should these items be damaged or destroyed (Smith 1992). For example, should a life be taken by a bluff failure, the severity of the failure would most surely be ranked as high. On the other hand, if items of cultural value were damaged or destroyed, the relative severity of the failure would be regarded as being much lower.

Table 6.9 describes the classification scheme which was applied to the human/cultural data. Note that some classes combine several data layers from the OBMs. For example, Class 3 includes data layers for both roads and railway, as both represent general transport infrastructure.

The data layer was then converted from a MapInfo Table (*.tab*) to a MapInfo Interchange File (*.mif*), and imported and prepared in Idrisi in like manner as the data layer for geology/stratigraphy. During this process, each layer was reclassified to fit the classification scheme described in Table 6.9. Where necessary, layers were combined through an Idrisi *OVERLAY* (eg. roads and railway for Class 3). Important options and decisions made while creating the human element images are detailed within the flowchart, Figure 6.2. Figure 6.15 is a graph which summarizes the classified image in terms of the total land area represented by the classified human elements, within 20, 10, and 5yr recession setbacks from the bluff edge. A data table for the classified data is included as Appendix A(ix). Figure 6.16 is the classified image of human elements at risk within the study area. This image describes the potential severity of a slope failure, in relation to human well-being, and will be overlaid with failure susceptibility in the final analysis to determine overall risk.

Table 6.9: Human elements and severity of failure classification scheme.

Class	Human Elements	Severity of Slope Failure	Explanation
5	Recreation Areas	Severe	- high probability of human presence - high vulnerability especially at beaches along base of bluffs - includes data from *(recreation areas)*
4	Residential	Very High	- high probability of human presence - high economic value, offers health/safety - high value of material goods and water contributions (pool, septic, irrigation) located nearby - includes data from *(buldings_houses)*
3	Infrastructure	High	- items concerned with infrastructure including communication, transportation, and residential services - gas, electrical, water, phone, sewage services also located close to road - includes data from *(roads)* and *(railway)*
2	Other Infrastructure	Moderate	- items associated with expensive machinery, crops, animals, commercial or industrial activities - barns, industrial/commercial sites, coastguard communication radios - includes data from *(buildings_other)* and *(comm_towers)*
1	Historical / Cultural	Low	- items of historical and cultural value (cemeteries, churches, museums, historic sites) - includes data from *(hist_cultural)*
0	No Data	--	No data - Lake Erie, Big and Little Otter Cks., outside study area or 529m erosion setback

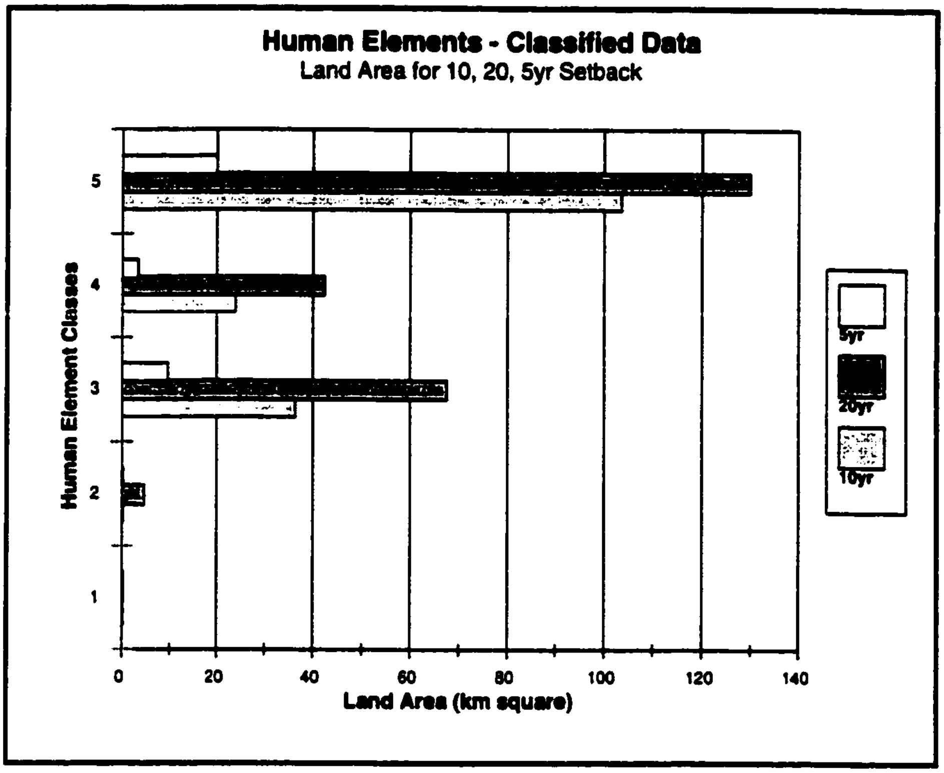


Figure 6.15: Human Elements at Risk - classes are graphed by area using statistics from the Idrisi image. Area is calculated by summing the number of grid cells at $100m^2$ (10x10m).

6.3 - Other Data Layers

In addition to the seven main layers used in the analysis, several others were compiled to enhance the final risk maps in MapInfo. These layers were digitized solely from the OBMs and include creeks and agricultural drains, ponds and reservoirs, the Hahn Marsh, Iroquois Provincial Park just west of Port Burwell, a host of trails, and various labels as described in the metadata in Table 6.1. A total of 57 lines were digitized

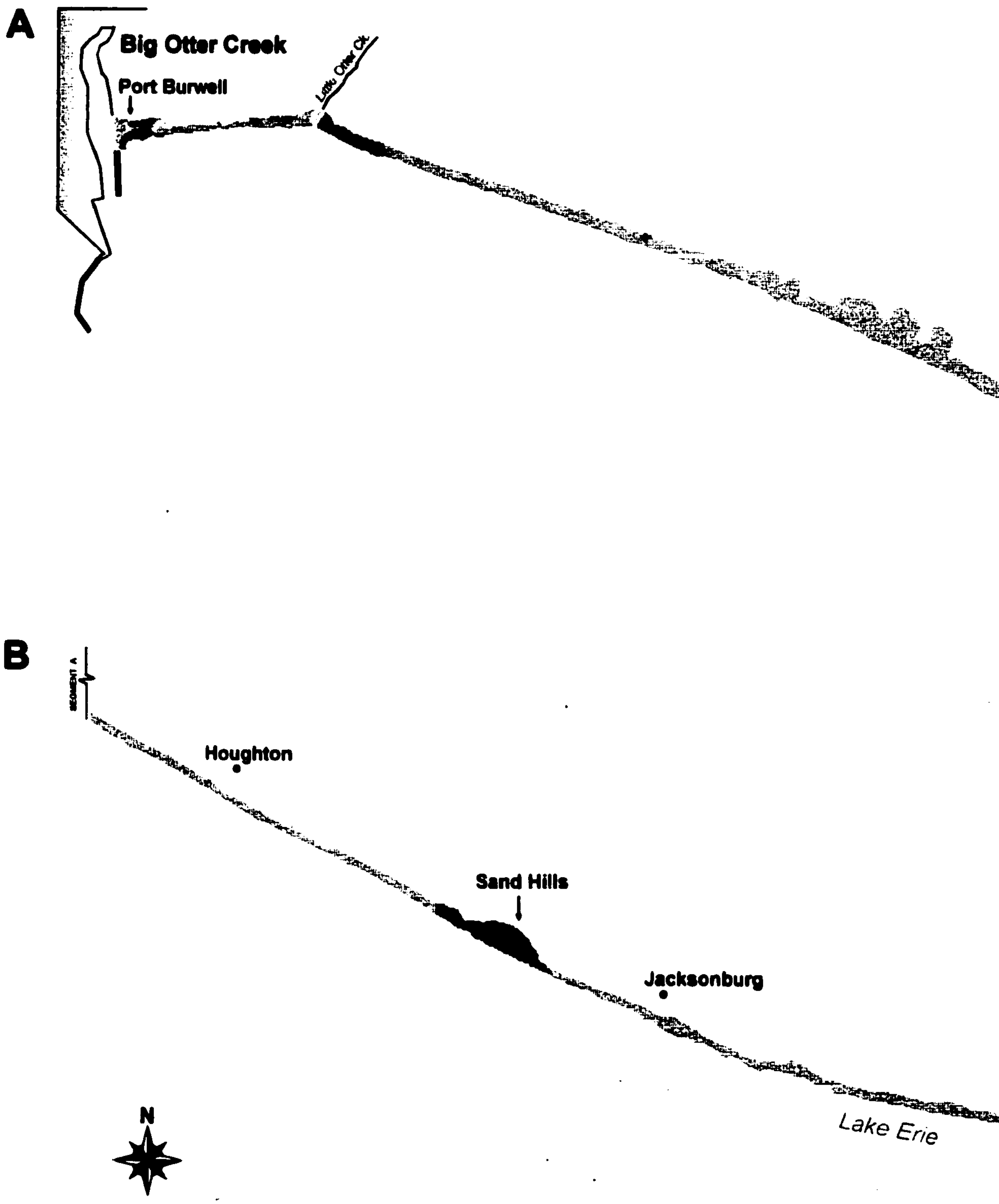
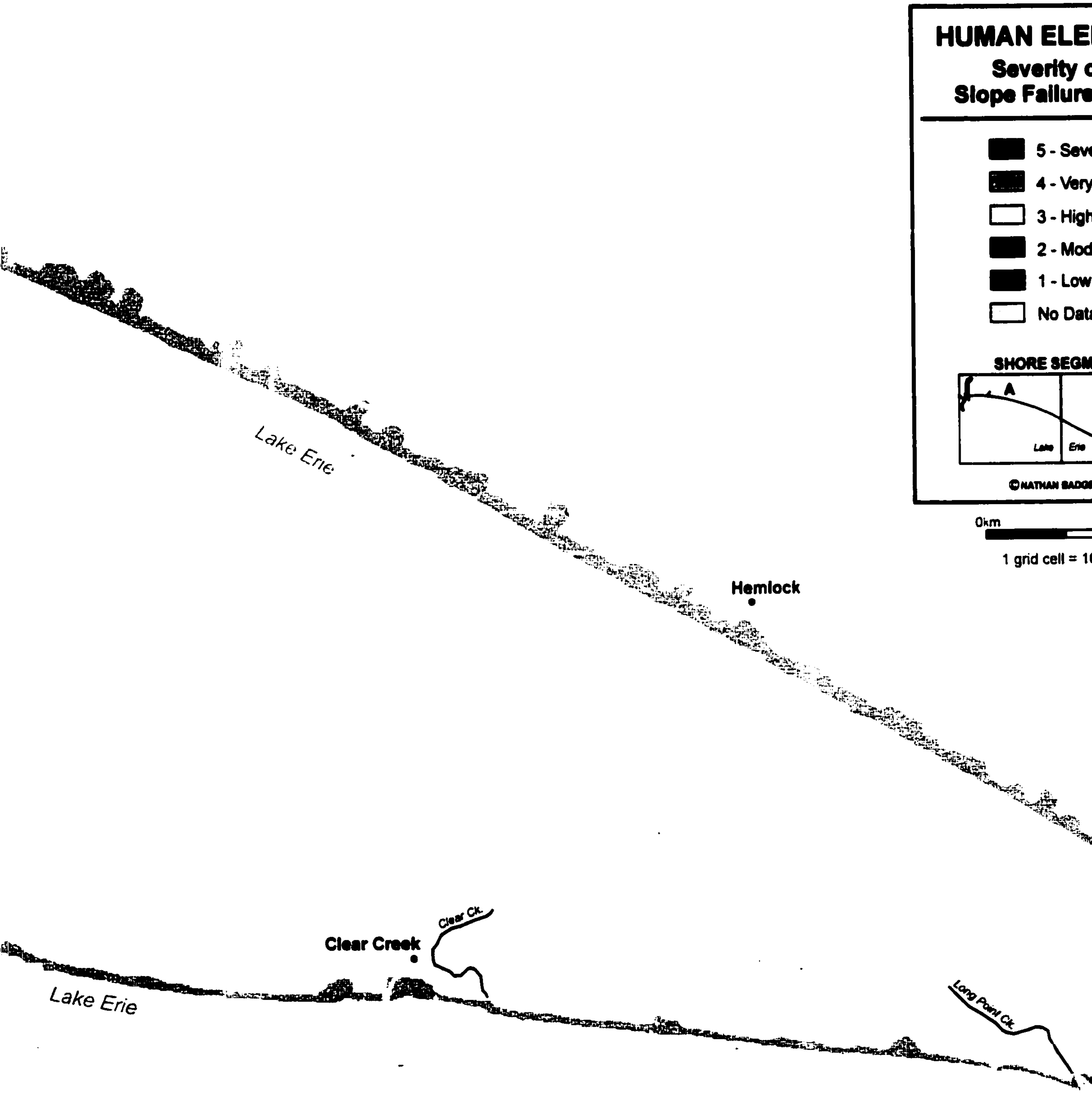
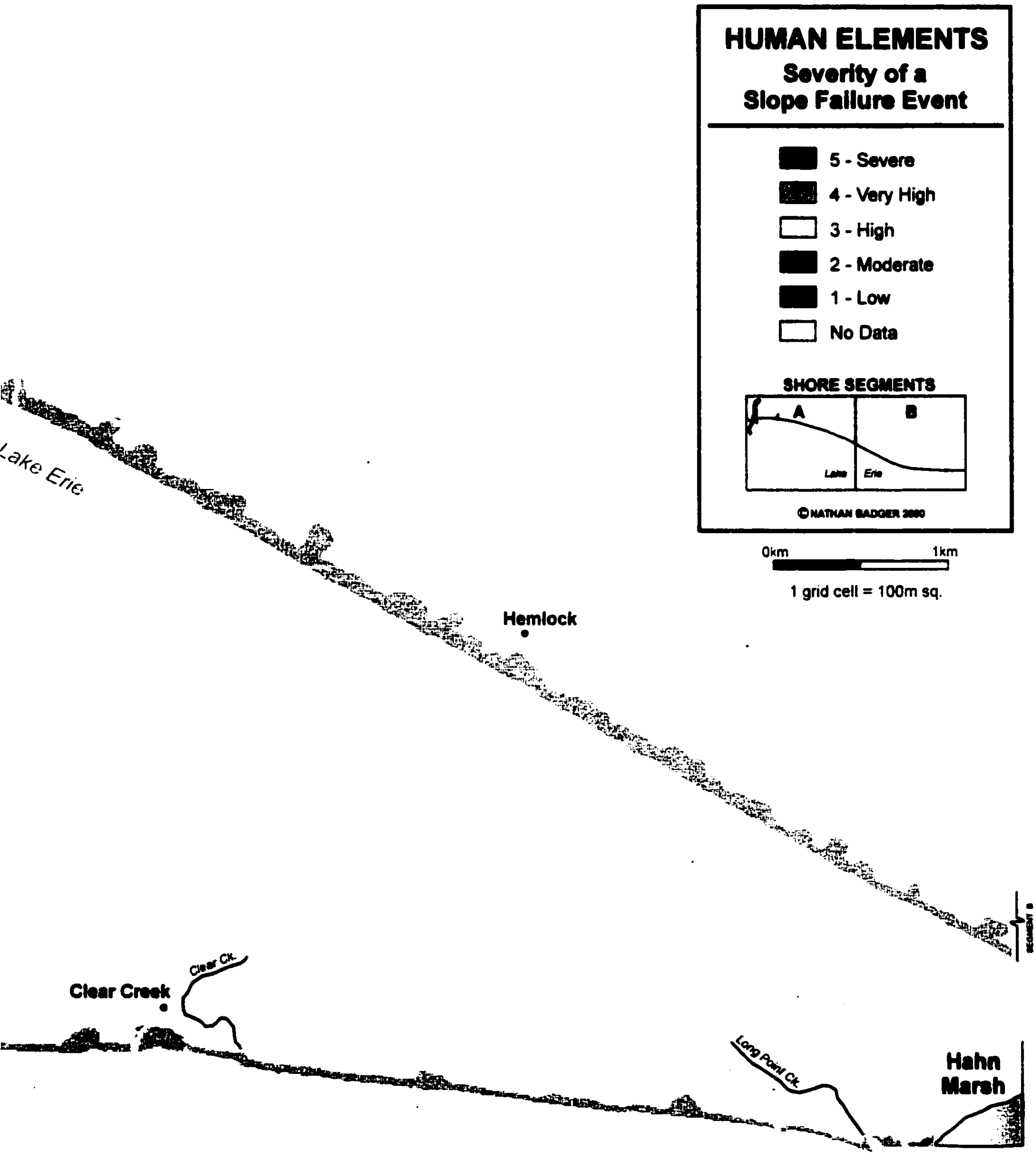


Figure 6.16: Human elements within a 10 year recession setback. In the event of a slope
theoretically, determine the severity of the event, as indicated in the legend. Buffered cells



he event of a slope failure, the value of various human elements would,
end. Buffered cells are included within the image.



the value of various human elements would,
luded within the image.

to depict the location of creeks and agricultural drains along the study reach, including the upper extension of Little Otter Creek, Clear Creek, Long Point Creek, the Hahn Ditch, and several other significant, yet unnamed creeks and agricultural drains. A total of 69 ponds were also digitized as polygons from the OBMs, in addition to a large polygon drawn in the southern area to represent Lake Erie. Those polygons representing ponds, also include irrigation reservoirs. At the far west end of the mapped area, Iroquois Provincial Park was digitized since it attracts large numbers of people to Port Burwell and the general bluff area during summer months. Items located within the Park polygon, such as buildings and roads, were not digitized. At the far east end of the mapped area, a large polygon ($1.34 km^2$) was drawn to represent the Hahn Marsh, which marks the westernmost area of the Long Point Marsh. This marsh is located within a globally significant flyway for migratory birds, and forms a portion of UNESCO's Long Point World Biosphere (Lawrence and Nelson 1992).

Finally, 100 trails were digitized across the mapped area. Though the OBMs provide no information as to the nature of these trails, field work determined that these trails were unpaved and largely marked routes which cut across fields and through vegetation stands. In most cases these trails are generally navigable by car and appeared to be used by farm machinery, All Terrain Vehicles and local residents who wished an access route to forest plots, crop fields, and in many cases, the bluff edge. Though not noted during field work, these paths may also be rights of way for hydro, and other services. The major importance of these trails is their perceived usefulness for emergency crews and vehicles to access the bluff edge, and then beach areas below the bluffs.

Recommendations from the Corner's Inquest after the Sand Hills tragedy suggested that potential emergency access routes be mapped in order to speed the process of reaching the shoreline and bluff areas. During the Sand Hills tragedy, emergency crews had great difficulty reaching the disaster zone. The data layer of trails may provide a useful source of information from which to locate access routes to high risk areas, should a disaster occur. Although the OBMs show several trails leading to the beach area below the bluffs, field work indicated that most of the trails have since been eroded. Trails to the beach at Sand Hills Park are graded out at least once a year due to failures and bluff recession.

6.4 - Data Analysis: Determining Susceptibility

Once the seven data layers had been constructed in MapInfo and imported into Idrisi, the analytical stages of the research could progress. The first step in the analysis was to determine the susceptibility of the shoreline bluffs to failure by combining each of the six susceptibility factors. The following sections describe some of the steps necessary before the final overlay of the susceptibility factors. Once these layers had been combined to determine susceptibility, the resulting data layer could be combined with human elements to determine maps of risk, as described later in the chapter.

6.4.1 - Limiting the Spatial and Temporal Scale of the Analysis

In order to limit the spatial extent of the analysis, susceptibility and risk were only assessed within 20, 10, and 5yr erosion setbacks from the edge of the bluff. The tables and graphs included with the summary of each data layer earlier in the chapter summarize the results of these overlays. Each table lists the frequency and proportion of the number of cells in each data layer, by both the class (1 to 5), and the recession rate setback used (20, 10, and 5yr). Use of the recession setbacks aided the analysis in two ways. Firstly, it limited the spatial area of the analysis to a defined, standardized region, which could be to each factor layer. Secondly, the setbacks incidentally implied that the results of the analysis were pertinent to a defined time frame (eg.20, 10, and 5yr). Within these time frames, the results of the analysis could be readily interpreted from the perspective of township land use plans or other plans subject to 5year reassessment periods, as discussed earlier in this chapter.

The analytical area could be limited to 20, 10, and 5yr erosion setbacks, in two ways. The flowchart in Figure 6.2 describes both ways. The most logical way is to include the recession rate images as 'constraints' within the Multi Criteria Evaluation Module, as will be explained in Section 6.10.2. The second way, is to reclass the recession rate images to boolean images (values of 1 and 0 only), and then overlay them with each of the factors (and later, the human elements), to 'cookie-cut' out the setback areas. The only advantage to this approach is being able to obtain summary stats for each image. The 10yr recession rate image is used as an example in the FlowChart, but the entire procedure for determining susceptibility and risk was actually run two more times with the 20 and 5yr images.

Aronoff (1989) notes the difficulty in managing raster data files, which are typically very large due to the data format. The size of these files contrasts those of vector files, which are typically much smaller. Hansen A. (1984) also comments on the difficulties of raster data format, particularly in large scale, regional slope stability analyses. Since each Idrisi data layer was just over 3Mb in size, and Idrisi utilizes 4 files for the production of each image (as MapInfo does as well), the entire process of data preparation and analysis within Idrisi resulted in close to 200 files and 600Mb of images. Shear size and file numbers created havoc when managing files, and a great deal of time was spent organizing, backing-up files, flowcharting the process, and recording metadata for each image in order to avoid errors, and to keep track of the data.

6.4.2 - Weighted Linear Combination, and Multiple Criteria Evaluation

Carrara et al. (1995) and Hansen A. (1984) outlined several ways of constructing a landslide hazard model in a GIS, as discussed in Chapter Four. The procedures used in this analysis follow those by Reading (1993) and Gornitz et al. (1994) who used an Indirect Approach to susceptibility and risk assessment. The Indirect Approach fully exploits the most basic function of a GIS, in the form of a map overlay (Figure 4.1). This approach involves the classification of each slope instability factor into a few significant qualitative classes which are stored into a single map or data layer. Each data layer can then, optionally, be weighted by its perceived importance in slope instability. By sequentially overlaying all the ranked or weighted layers for a study area, homogenous polygons are singled out whose number, size and nature are strictly dependant on the criteria used in classifying the input factor (Carrara et al. 1995). Since no data pertaining to the previous occurrence of slope failures were available for the study site, an Indirect or quantitative statistical approach could not be used for the analysis. It should be noted, however, that the data used in this research were not entirely qualitative. Factor layers, such as elevation, slope and recession rate, were all originally based on quantitative data, and then subsequently reclassified to fit a qualitative scale of High to Low (1 to 5). The quantitative nature of this original data is believed to reduce the 'subjectiveness' of the data.

The overlay of the susceptibility factors was accomplished using Idrisi's module for Multiple Criteria Evaluation (MCE). Very generally, the MCE module allows several criteria to be overlaid in a weighted or unweighted fashion to produce a final image representing the correlation between each factor (Eastman 1997). This section details the MCE and how it was used in the analysis to determine susceptibility to failure within the study reach.

The primary issue in MCE is concerned with how to combine the information from several criteria to form a single index of evaluation. The basis for a decision is known as a criterion. In an MCE, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. In the case of this research, a decision must be made about what areas are most susceptible to slope failure (Clark Labs 1997).

Criteria may be of two types: factors and constraints. Factors are generally continuous in nature, whereas, constraints are always Boolean in character and serve to exclude certain areas from consideration through the process of 'zeroing out' during overlay. In the case of this research, the six susceptibility factors served as the factors, and the boolean recession rate setback images (20, 10, and 5yr) served as the constraints. It should be noted at this point, however, that these constraints had already been overlaid with each of the factor layers earlier (as described in the previous section) in order to limit the spatial and temporal scope of the analysis.

Factors and constraints can be combined in the MCE module using several methods (Eastman 1997). The most applicable method for the data layers compiled in this research was the Weighted Linear Combination (WLC). Here criteria may include both weighted factors and constraints. WLC starts by multiplying each factor by its factor/tradeoff weight and then adding the results. Constraints, if necessary, are then applied by successive multiplication to 'zero out' those areas to be excluded from the outcome (Clark Labs 1997).

Factor weights are very important in WLC because they determine how individual factors will 'trade-off' relative to each other. The higher the factor weight, the more influence that factor has on the final susceptibility map (Clark Labs 1997b). Factor weights are given for each factor such that all factor weights, for a set of factors, sum to one. They indicate the relative importance of each factor to the objective under consideration. A factor with a high factor weight may compensate for low suitability in other factors that have lower factor weights (Eastman 1997). The equation used to describe this process is included in the Idrisi Manual (Eastman 1997), and can, with modifications for the sake of clarification, be stated as follows:

(6.1)

$$S = \sum w_{i \ldots n} x_{i \ldots n}$$

Where,
S = susceptibility
$\sum$ = sum
w_i = weight of factor i
x_i = criterion score (value) of factor i
$_n$ = number of factors and weights

In cases where Boolean constraints also apply in a WLC, the procedure can be modified by multiplying the suitability calculated from the factors by the product of the constraints (Eastman 1997):

(6.2)

$$S = (\sum w_{i \ldots n} x_{i \ldots n}) (\prod c_{i \ldots n})$$

Where,
$\prod$ = product
c_i = constraint

Because of the different scales upon which criteria are measured, it is necessary that factors be standardized before combination using Equations 6.1 and 6.2, and that they be transformed, if necessary, such that all factors maps are positively correlated with susceptibility (Clark Labs 1997). In the case of this study, each factor map had been standardized to a scale of 5 classes. Where data was essentially boolean, such as vegetation and shore protection, the data was 'stretched' to fit the same 5 tier scale where 'presence' was assigned a value of 1, and 'absence' assigned a value of 5. In the case of each factor layer, data was pre-classified to a 5 tier scale in order to aid in the interpretation of the resulting UCU values. 'Stretching' of the data to values of 1 to 100, or 1 to 255 was believed to ignore the variable contribution of varying classes (eg. low elevation vs. high) to the susceptibility and risk of the bluff failures.

Although a variety of techniques exist for the development of weights, Eastman (1997) noted that one of the most promising is that of pairwise comparisons developed by Saaty (1977, as cf. Eastman 1997). In the procedure for MCE using a WLC, it is necessary that the weights sum to one. In Saaty's technique, weights of this nature can be derived by taking the principal eigenvector of a square reciprocal matrix of pairwise comparisons between the criteria. The comparisons convey the relative importance of the two criteria involved in determining susceptibility for the stated objective (Eastman 1997).

Table 6.10 displays a Pairwise Comparison Matrix (PCM) constructed to calculate weights for the criteria involved in this research. Ratings are provided on a 9 point continuous scale, as depicted at the bottom of the matrix. For example, if one felt that geology/stratigraphy was very strongly more important than slope inclination in determining slope failure susceptibility, one would enter a 7 on this scale. If the inverse were the case (slope inclination was very strongly more important than geology/stratigraphy), one would enter 1/7 (Eastman 1997).

Table 6.10: Pairwise Comparison Matrix (PCM) for assessing the comparative importance of six factors to short-term slope failure susceptibility. Top number in each cell is a value from the Continuous Rating Scale (below). The values are summed at the bottom of each column, and used to calculate the average weights for each column cell, which are listed at the bottom of each cell. These weights are then summed across the rows, and averaged by the number of columns to determine the principle eigenvector. The principle eigenvectors sum to one, and are used as the factor weights in Idrisi's MCE module.

Rating of the Row Factor Relative to the Column Factor

↔ FACTORS ↕	Elevation	Slope/ Inclination	Geology/ Stratigraphy	Recession Rate	Vegetation Cover	Shore Protection	Σ of Weights	Principal Eigenvector
Elevation	1 *0.075*	36528 *0.028*	36528 *0.1042*	36526 *0.0546*	36526 *0.039*	3 *0.4186*	*0.7194*	***0.1199***
Slope/ Inclination	4 *0.3*	1 *0.1122*	36528 *0.1042*	36527 *0.0363*	3 *0.026*	36527 *0.0465*	*0.6252*	***0.1042***
Geology/ Stratigraphy	4 *0.3*	4 *0.4486*	1 *0.4167*	5 *0.5455*	5 *0.3896*	2 *0.2791*	*2.3795*	***0.3966***
Recession Rate	2 *0.15*	3 *0.0373*	36529 *0.0833*	1 *0.1091*	3 *0.2338*	36526 *0.0698*	*0.6833*	***0.1139***
Vegetation Cover	2 *0.15*	36527 *0.0373*	36529 *0.0833*	36527 *0.0363*	1 *0.0779*	36527 *0.0465*	*0.4313*	***0.0719***
Shore Protection	36527 *0.025*	3 *0.3365*	36526 *0.2083*	2 *0.2182*	3 *0.2338*	1 *0.1395*	*1.1613*	***0.1936***
Σ of Ratings	13.333	8.916	2.4	9.166	12.833	7.166		[illegible]

		1/5	1/3	1	3	5		
extremely	very strongly	strongly	moderately	equally	moderately	strongly	very strongly	extremely

less important **more important**

To simplify this weighting procedure, Idrisi has incorporated this technique into a module called WEIGHT, where each of the criteria and weights is typed into a matrix, and the resulting weighting scheme automatically calculated using Saaty's technique. Unfortunately, the module would not work using six factors (for unknown reasons) and the pairwise comparison and weighting technique was calculated manually, as seen in Table 6.10. In developing the weights, a comparison is made of every possible pairing and the rating entered into a pairwise comparison matrix. Since the matrix is symmetrical, only the lower triangular half actually needs to be filled in. The remaining cells are then simply the reciprocals of the lower triangular half. For example, since the rating of vegetation cover relative to recession rate is 1/3, the rating of recession rate relative to vegetation cover will be 3. Note that where empirical evidence exists about the relative efficacy of a pair of factors, this evidence can also be used (Eastman 1997).

Once the matrix has been filled out, the procedure then requires that the principal eigenvector of the PCM be computed to produce a best fit set of weights (Table 6.10). If no computerized procedure is available to do this, a good approximation of this result can be achieved by summing the columns of the matrix to get a column marginal sum (ie. $\sum$ of the ratings). Each entry in the column is then divided by the marginal total to obtain an estimated set of weights. The weights of each cell are then summed across each row (ie. $\sum$ of Weights) and averaged to achieve a result similar to that achieved using the principal eigenvector (Clark Labs 1997).

Since no computerized procedure was readily available for computing the principal eigenvectors (eg. SPSS, SAS), they were calculated manually. Table 6.10 lists the pairwise ratings, weights, and principal eigenvectors that were assessed for the factors in this study. Though it was sometimes difficult to assess which factor may be more important than another, the literature review and field work on the study site aided this process tremendously. The matrix was filled in to reflect the perceived relative importance of each factor in the instability of the bluffs. Generally speaking, geology/stratigraphy were perceived as being the most important factor, followed by shore protection, elevation, recession rate, slope and vegetation cover. In hindsight, some of these factors may have been weighted slightly differently (and compared through a sensitivity analysis), but the purpose of this exercise was largely exploratory and further research would illuminate the results of different schemes. Geology and Stratigraphy, however, are perceived to have the greatest influence on the stability of the bluffs, and the type of failure movements, and this was justly highlighted by the final weight scheme.

6.4.3 - Susceptibility to Failure: Big Otter Creek to Hahn Marsh

Using the weighting scheme described in Table 6.10, Idrisi's MCE module could then be set in action to evaluate and combine the factors and constraints for the Lake Erie study area. Using the WLC logic outlined in Section 6.10.2, it was a fairly simple matter to specify and multiply each factor map (ie. each raster cell within each map) by its weight and then sum the results. Using different methods, Naranjo et al. (1994) noted that the crucial and most difficult part in the analysis turned out to be the classification of the summed weights. However, since the weights sum to one using the WLC method, noted in 6.10.2, the resulting susceptibility maps have a range of values that match that of the standardised factor maps that were used (ie. 5 classes, from values 1 through 5). No further reclassification steps needed to take place. After all of the factors had been incorporated, Idrisi automatically multiplied the resulting susceptibility map by the specified constraints to 'zero out' unsuitable areas (Eastman 1997).

At this point, it should be noted that each of the factors had already been overlaid with a 'recession rate' constraint before entering the MCE, as discussed earlier, and indicated on the flowcharts in Figure 6.2. This step was only completed to standardize and compute summary statistics for each individual data layer as soon as it had been imported into Idrisi. Although it had the effect of constraining the data at an earlier stage, it is most logical to simply automate the 'constraint' process in the MCE module.

Table 6.11 is included as a means of clarifying the MCE procedures. Idrisi's MCE WLC operates to calculate the weighted and constrained susceptibility value for one 'theoretical' grid cell. The listed weights were calculated within Table 6.10.

Finally, as a means of determining the effects of a weighted overlay, the MCE module was run twice to produce two different images of susceptibility. The first assessment of susceptibility applied equal weights to each factor layer, and the second examination applied the weights to each factor as achieved from Table 6.10, and demonstrated in Table 6.11. Figures 6.17 and 6.18 graph the land area (km^2) occupied by the unweighted and weighted slope failure susceptibility classes. The corresponding data tables are included in Appendix A(x) and A(xi). Figures 6.19 and 6.20 map the images which were generated for unweighted and weighted susceptibility in Idrisi, using the MCE assessments for a 10yr recession setback. The unweighted and weighted maps, graphs, or data tables, can be compared and contrasted to provide a simplified 'sensitivity analysis', whereby the effects of weighting, versus no weighting, are able to be assessed. A similar method was applied by Gornitz et al. (1994). Beyond a visual comparison of the two maps, a Cross Tabulation helps to better summarize the differences between the two susceptibility weighting schemes. The process of Cross Tabulation is described in the following section, Section 6.4.4.

Table 6.11: Example evaluation of susceptibility for one grid cell, using a MCE WLC, with the resulting classification of the grid cell.

Factors	Class Rank	Function	Weights	Sub-Total
Elevation	4	x	0.1199	0.4796
Slope Inclination	3	x	0.1042	0.3126
Geology / Stratigraphy	5	x	0.3966	1.983
Recession Rate	3	x	0.1139	0.3417
Vegetation Cover	1	x	0.0719	0.0719
Shore Protection	1	x	0.1936	0.1936
			Total	3.3824
			Constraints: 1 and 0 **10Yr Recession Rate Setback** ***1 = Inside 10yr Setback*** ***0 = Outside 10yrSetback***	1 x 3.38 = 3.38
			MCE Weighted Classification	**Class 3** **Moderate**

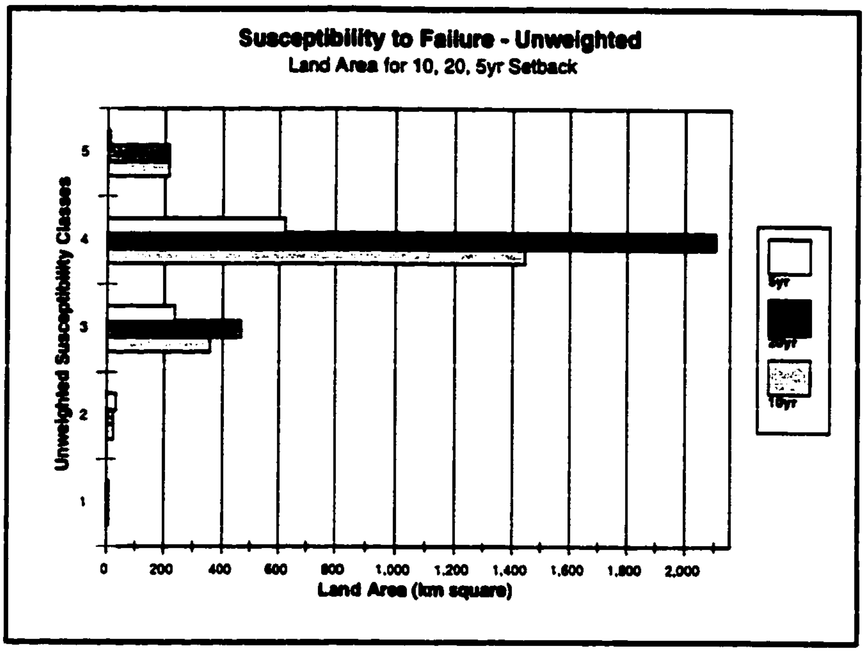


Figure 6.17: Summary graph for unweighted susceptibility classes, by land area.

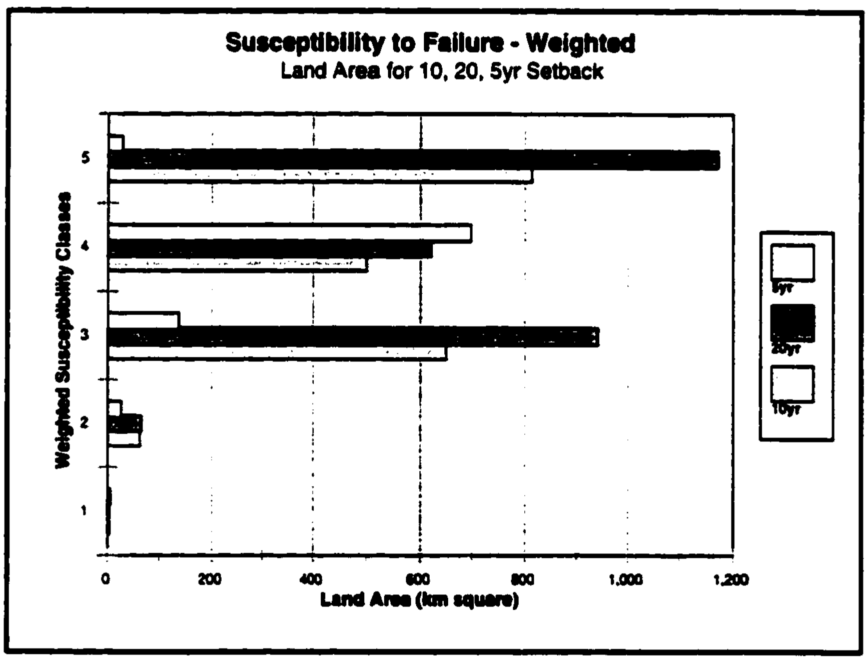


Figure 6.18: Summary graph for weighted susceptibility classes, by land area.

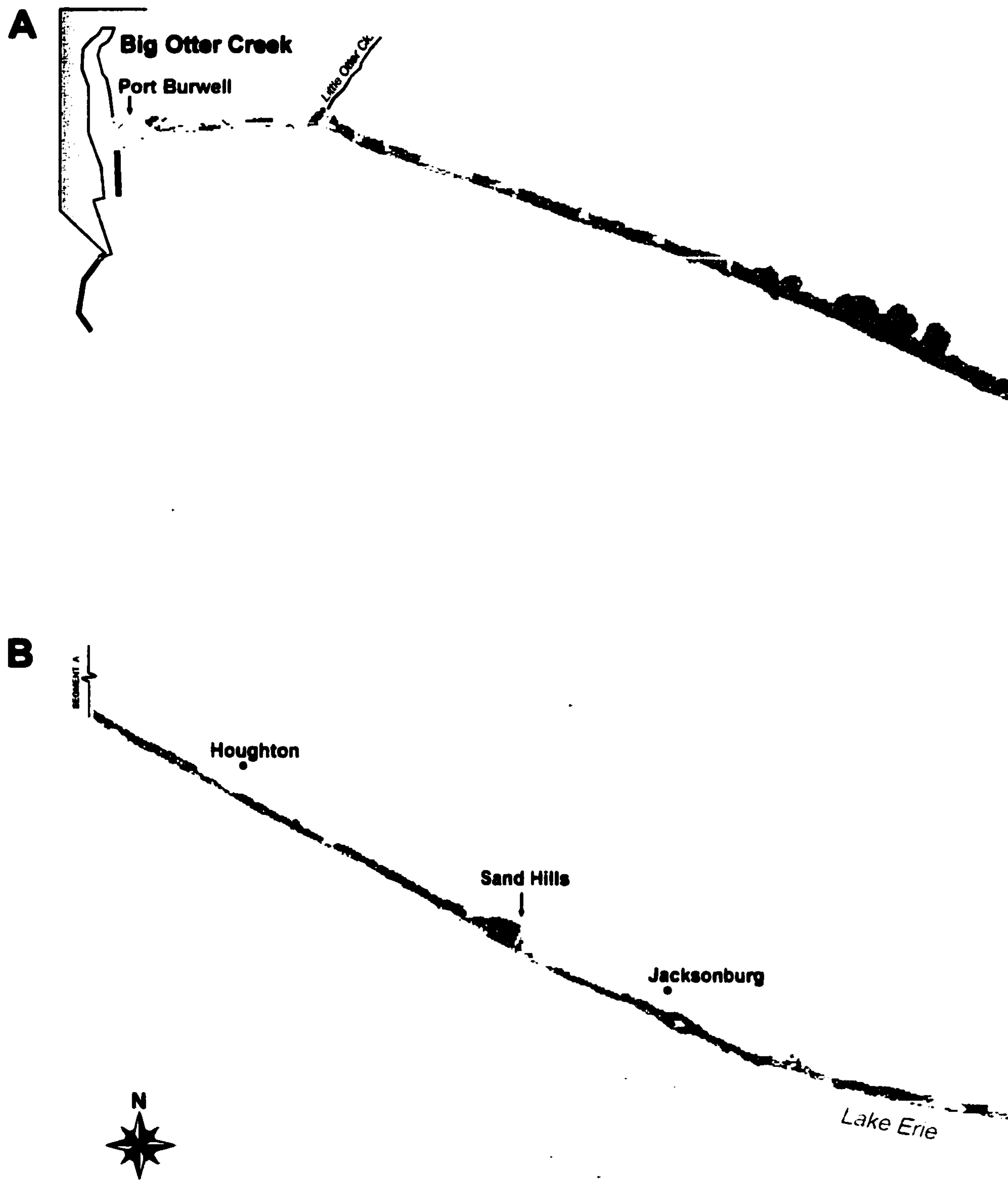
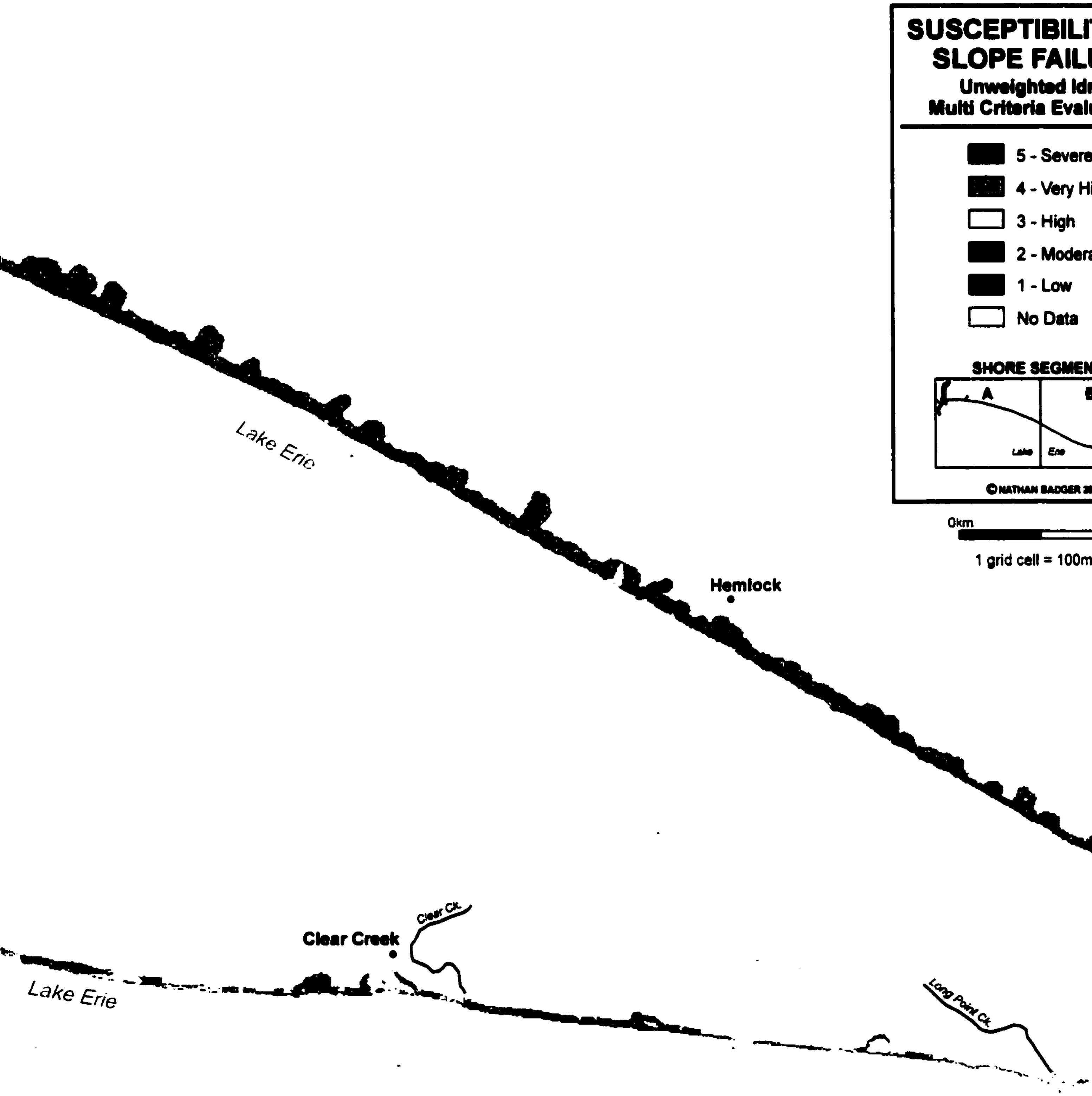
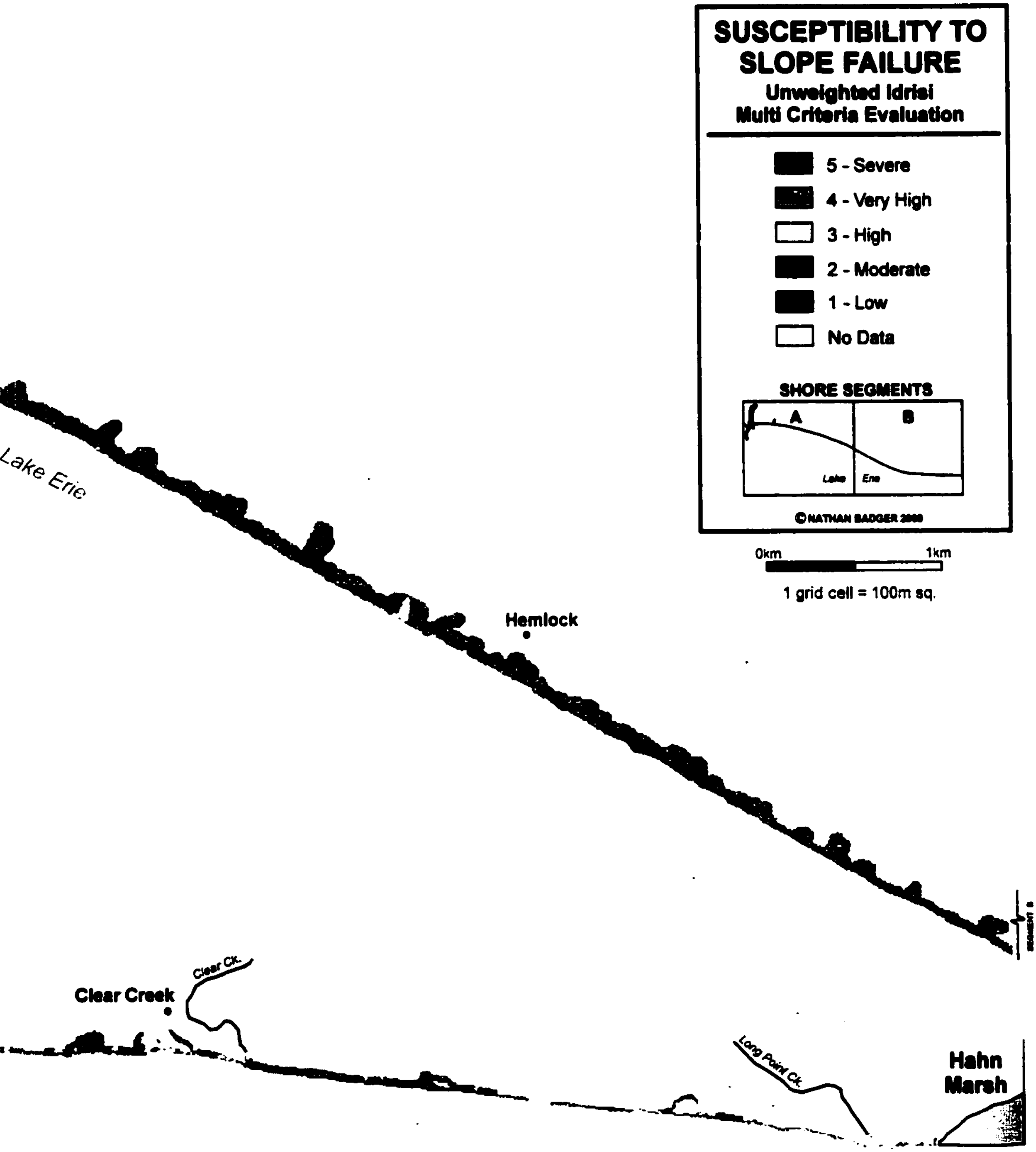


Figure 6.19: Susceptibility to slope failure within a 10 year recession setback. Susceptibilit
module (MCE). Unweighted factors included: elevation, slope inclination, geology/stratigrap



back. Susceptibility was evalutated using Idrisi's Multiple Criteria Evaluation
geology/stratigraphy, recession rate, vegetation cover, and shore protection.



s evalutated using Idrisi's Multiple Criteria Evaluation
ecession rate, vegetation cover, and shore protection.

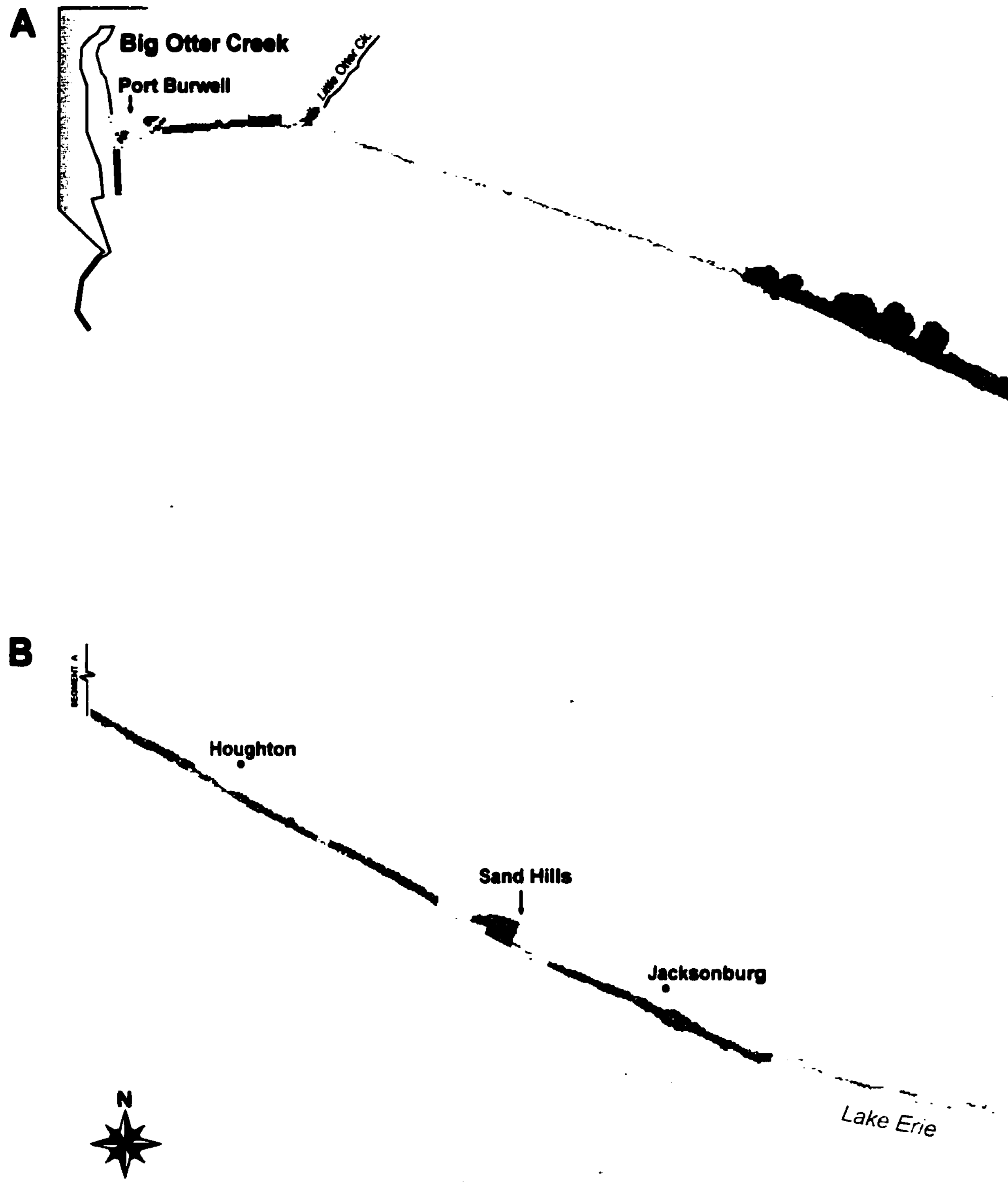
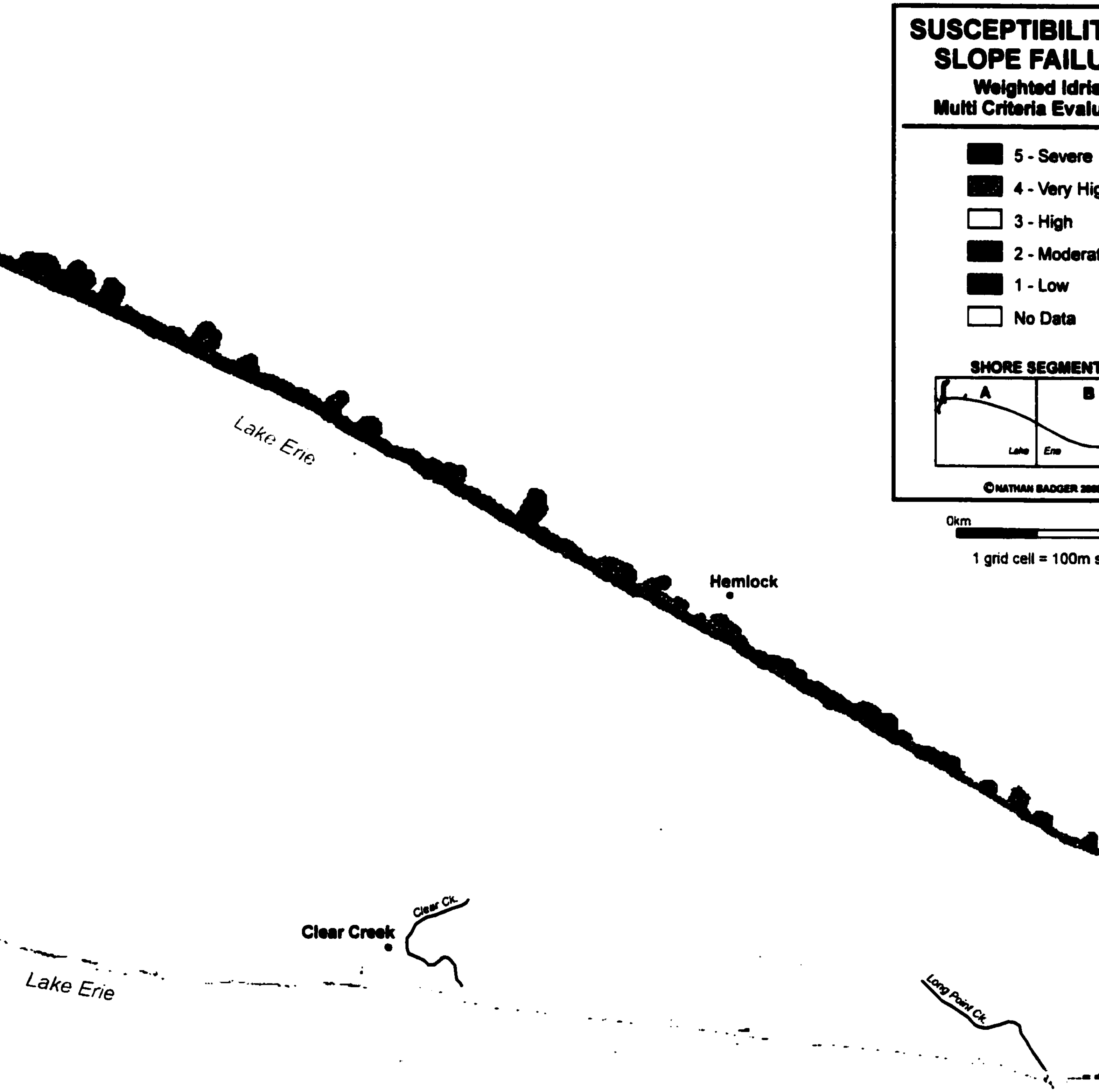
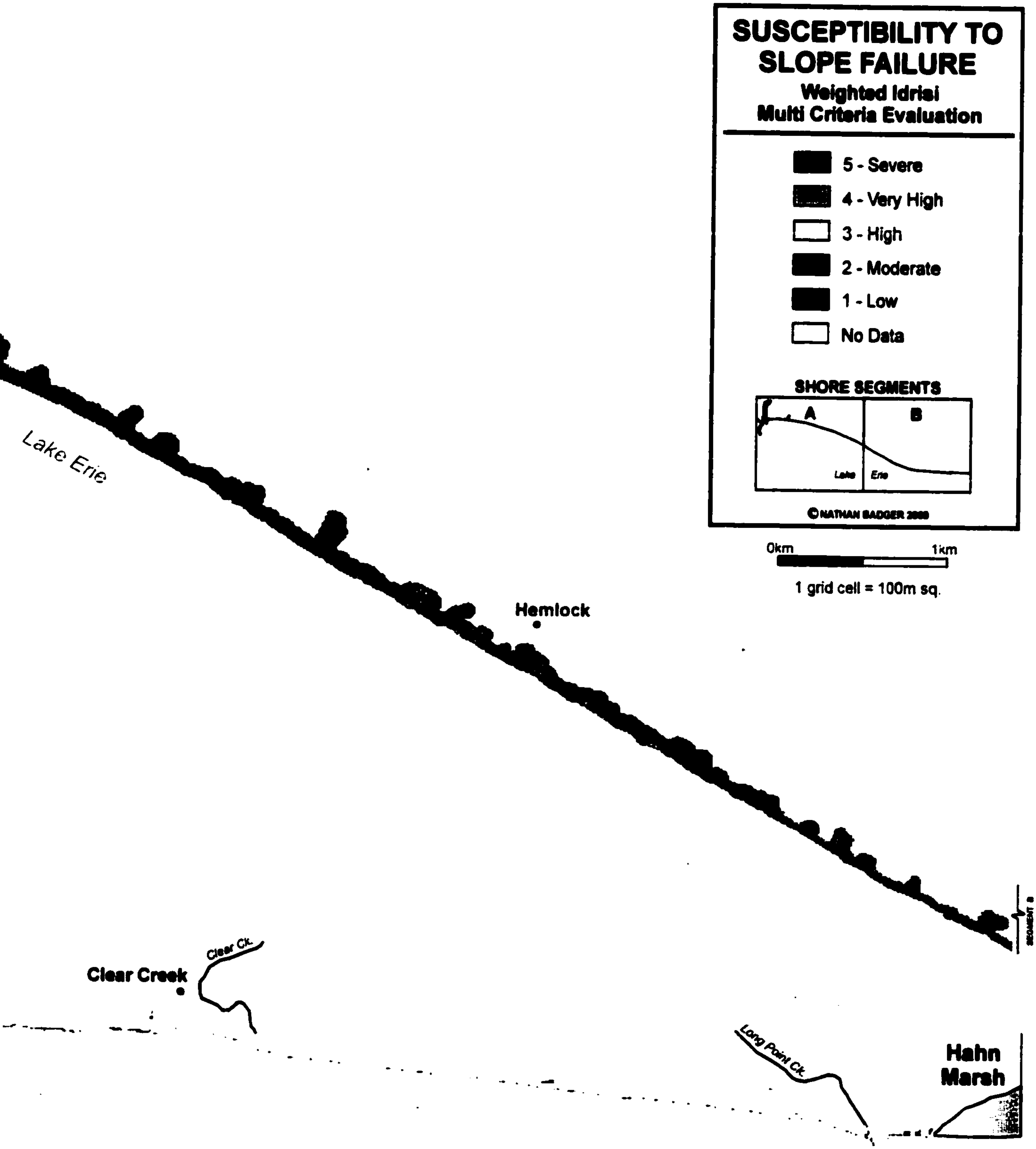


Figure 6.20: Susceptibility to slope failure within a 10 year recession setback. Susceptibilit
and evaluated using Idrisi's Multiple Criteria Evaluation module (MCE).



ack. Susceptibility factors were weighted using a Pairwise Comparison Matrix,



ctors were weighted using a Pairwise Comparison Matrix,

6.4.4 - Cross Tabulation of Unweighted and Weighted Susceptibility

Cross tabulation module in Idrisi provides a useful comparative technique for qualitative data (as opposed to the quantitative data that *REGRESS* acts upon). This method is recommended by Bonham-Carter (1994) who discussed several applications of its use with GIS and the Geosciences. Within Idrisi, the most fundamental output of *CROSSTAB* is a Cross tabulation table which lists the frequency with which each possible combination of the categories on the two images occur (Eastman 1997). In addition to this table, *CROSSTAB* also has the ability to create a cross correlation image. A cross correlation image has new categories to illustrate all existing combinations of the categories on the two input maps. It is thus directly related to the cross tabulation table. In essence, the cross correlation image can be considered as a multiple AND overlay showing all possible combinations of the categories on one image AND those on the other (Eastman 1997). The cross tabulation between the Susceptibility Weighted and Unweighted is described in Table 6.12, while the cross-classification map is shown in Figure 6.21.

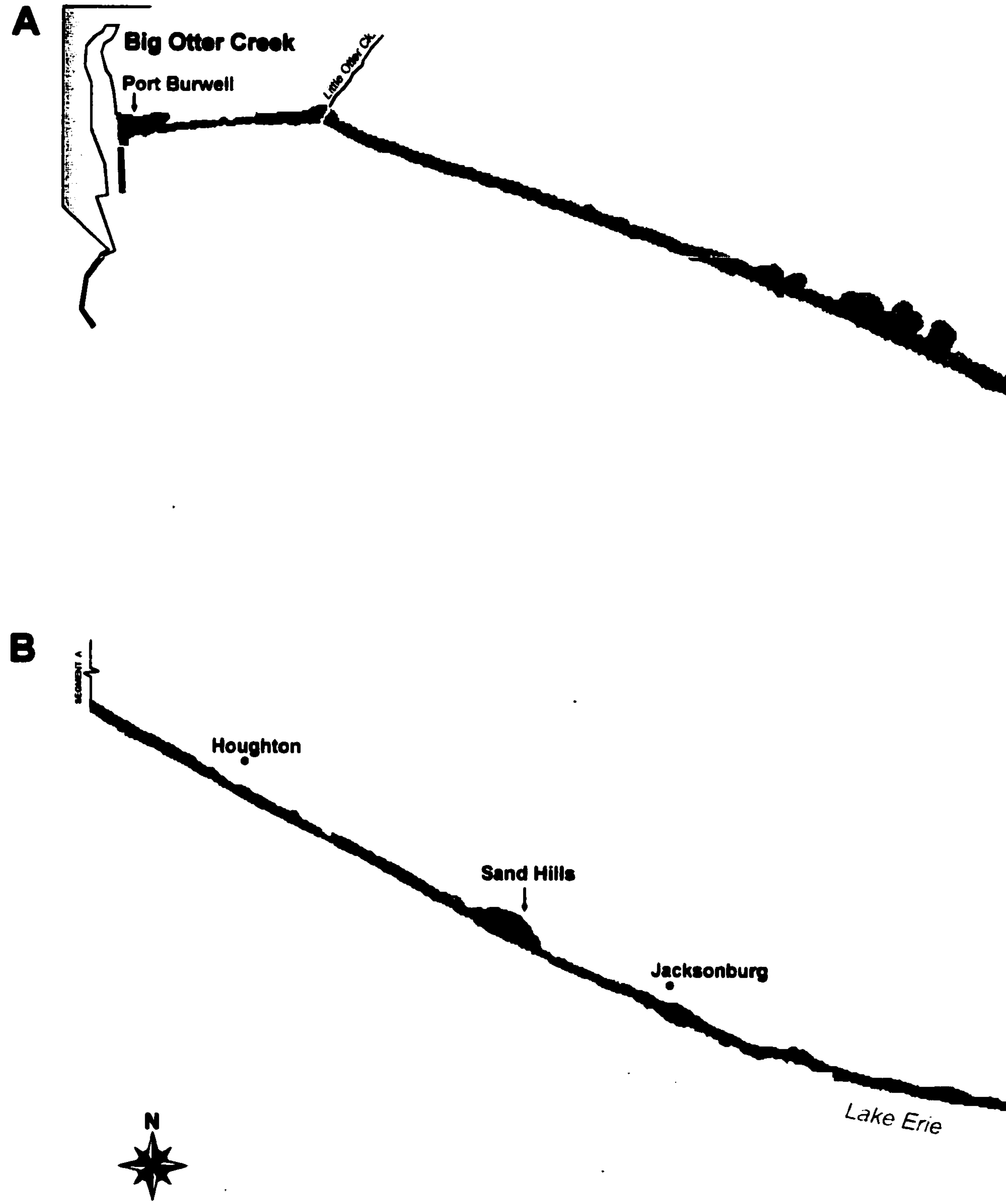
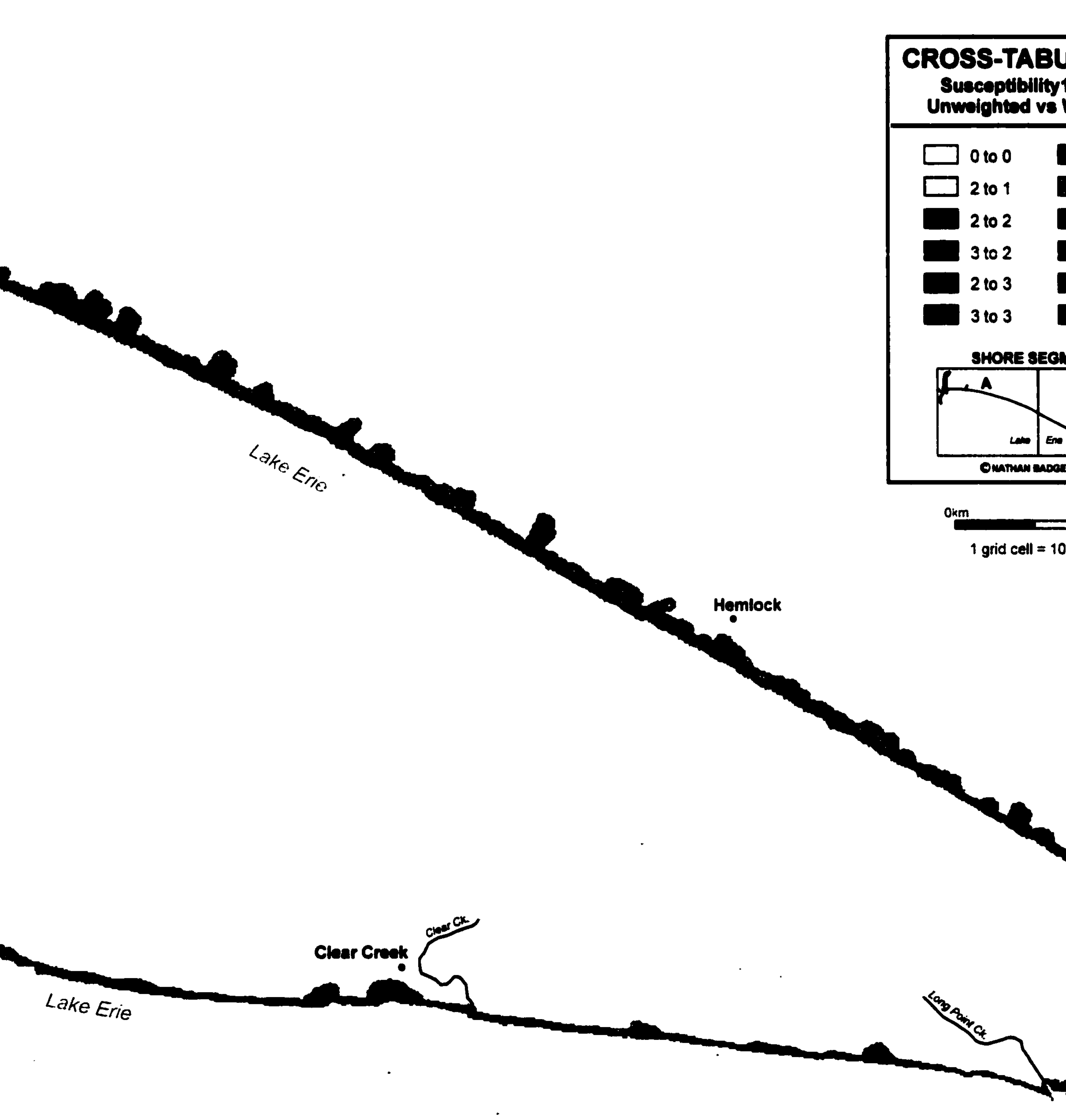
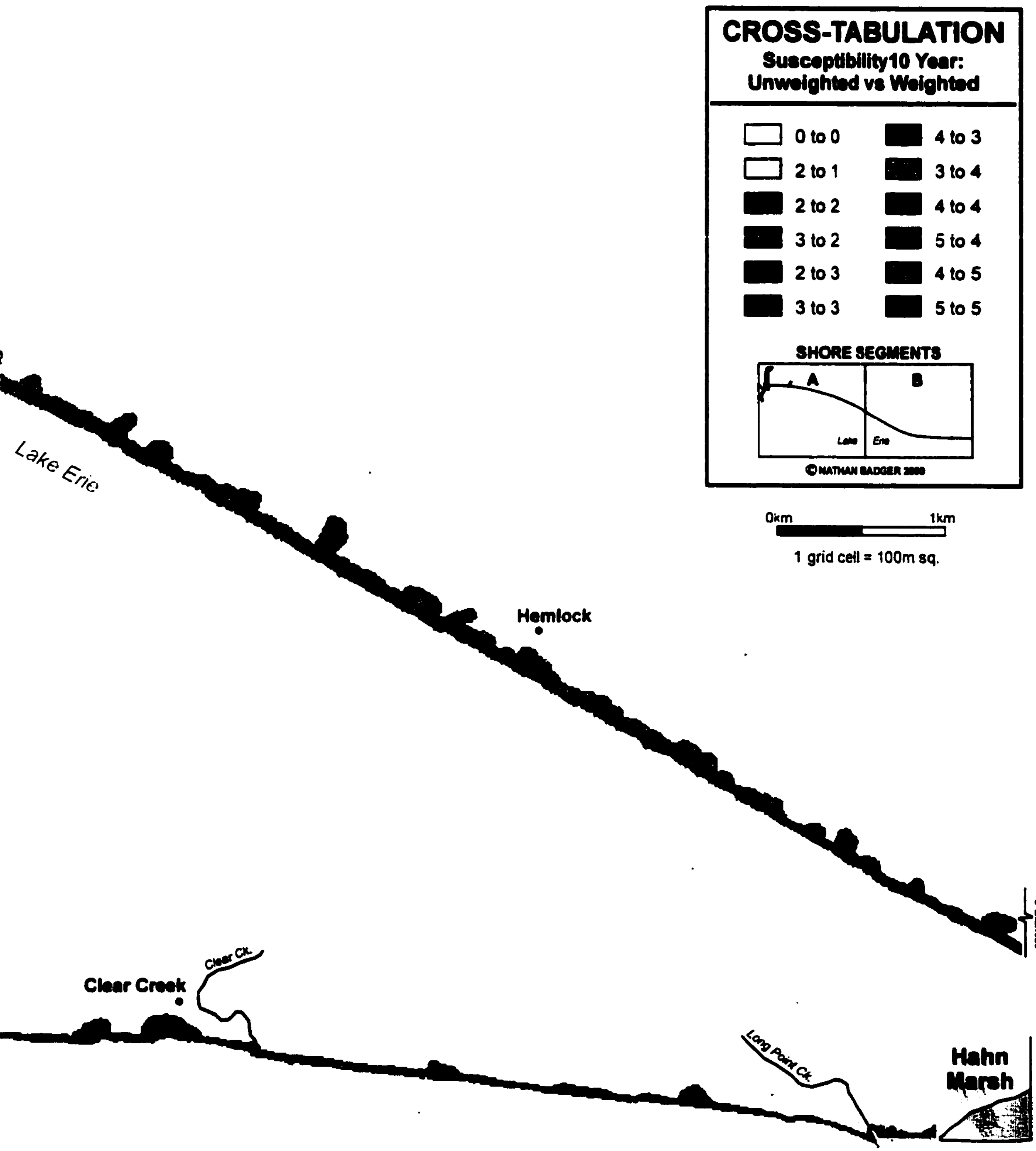


Figure 6.21: Cross-correlation image of unweighted vs weighted susceptibility, for a ten ye
combinations of the input images. Yellow, green, bright blue, and rusty red are pixels wher



ptibility, for a ten year recession setback. The image and legend show all
red are pixels where susceptibility increased after factors were weighted.



cession setback. The image and legend show all
ceptibility increased after factors were weighted.

Table 6.12: Cross-tabulation of unweighted (columns) against weighted susceptibility (rows). The matrix shows number of pixels and overall proportion (italics) within a 10yr recession setback. The setback contains 20,163 cells of total 3,25,000 in the entire image. 10,521 cells were reclassified by weighting.

↔ CLASSES ↕	CLASS 1 Low	CLASS 2 Moderate	CLASS 3 High	CLASS 4 Very High	CLASS 5 Severe	Total
CLASS 1 Low	0 *0*	5 *0.0003*	0 *0*	0 *0*	0 *0*	5 *0.0003*
CLASS 2 Moderate	0 *0*	187 *0.0093*	400 *0.0198*	0 *0*	0 *0*	587 *0.0291*
CLASS 3 High	0 *0*	23 *0.0011*	2859 *0.1418*	3593 *0.1782*	0 *0*	6475 *0.3211*
CLASS 4 Very High	0 *0*	0 *0*	234 *0.0116*	4632 *0.2297*	118 *0.00585*	4984 *0.2472*
CLASS 5 Severe	0 *0*	0 *0*	0 *0*	6148 *0.3049*	1964 *0.0974*	8112 *0.4023*
Total	0 *0*	215 *0.0107*	3493 *0.1732*	14373 *0.7128*	2082 *0.1033*	20163 [illegible]

In addition to the Cross-tabulation and Cross Classification Image, Idrisi also produces a ChiSquare statistic (to judge the likelihood of association), degrees of freedom to test for testing ChiSquare significance, Cramer's V statistic (to measure the degree of association), and in cases where the categories of two images are identical, a Kappa Index of Agreement measure to compare with Cramer's V (Eastman 1997, Clark Labs 1997). Unfortunately, it was not possible to evaluate the correlation between the two images using statistics provided by Idrisi. The reason for this was that much of the image contains pixels with values of '0', which heavily bends the statistics towards this value.

Since Idrisi provides no option to eliminate '0' values in the evaluation or the calculated statistics, the cross tabulation table was used as the main source of comparative information. In his discussion of this problem, Bonham-Carter (1994) suggested, however, that no mention of significance can be assured from the cross tabulation, and that correlations be discusses in terms of interesting or unusual correlations and observations.

6.5 - Determining Risk of Shoreline Slope Failures

With the completion of the susceptibility maps, attention could now be focussed towards completing a comprehensive data layer containing all human elements. This layer was subsequently overlaid with susceptibility to produce the risk maps. Seven data layers had been prepared to represent various human elements at risk to bluff failures within the study area (Figure 6.2). These data layers included recreation areas, residential, other buildings, roads, railway, communications towers, and historical cultural features.

6.5.1 - Human Elements and Buffers

Beyond simply the items contained in these maps, it was felt that some area around each of these items should be regarded as being just as critical when evaluating the severity of a slope failure. For example, in the case of the data layer 'other infrastructure', a slope failure within 5m of a road would pose a severe threat to the stability of the road, in addition to several other key services that are constructed alongside roadways. Field work confirmed that road side service corridors included hydro lines, gas lines, water and sewer lines, and phone lines. As a means of including these items and areas deemed equally important around human elements, a series of buffers was generated within several of the data layers using Idrisi's *BUFFER* module. Figure 6.2 describes some of the important values and choices made while performing the buffers. In the case of each buffer, Idrisi requires that you specify a value above the width the pixel in order to include that pixel in the buffer. Thus buffers of 10m were specified in Idrisi as 11m. It should also be noted that buffers are somewhat limiting in a raster environment. Idrisi does not include diagonal cells and therefore a buffer is only created on the four sides of each cell. In any case, it was decided that some buffer was better than no buffer at all.

In the case of residential buildings (*buildings_houses*), a 20 metre 'radial' buffer was established around each building. This buffer was assumed to accommodate surrounding yardage on the house, cars parked close to the house, play areas for children, and other areas in close proximity to the house where heavy human traffic would exist, or other expensive items may be stored.

A 'corridor' buffer was also included around the *roads* to provide leeway for road stability in the event of a nearby failure, and to include other important infrastructure discovered during field work, such as hydro lines and water mains. Thus, a 10m buffer was generated on either side of the road, making the total width of the road and buffer 30m. Since similar services were also believed to be located around railway lines, a buffer of 10m was also generated around the *railway*. A 10m buffer was also placed around *buildings_other* to accommodate expensive machinery (eg. tractors) often noted parked alongside barns and sheds, in addition to parking lots and smaller sheds not noted on the OBMs, but often observed during field work.

During field work it was noted that the two communication towers in the study area (*comm_towers*) were supported by guy wires that reach out from the towers a distance of just over 30m. Since these wires are integral to the support of the towers, a 30m radial buffer was placed around the location of these towers to protect their stability from the effects of a bluff failure. No buffers were placed around the data layers for *recreation* areas or historical cultural features (*hist_cultural*).

6.5.2 - Combining the Human Elements

In order to overlay human elements with susceptibility, it was advantageous to combine all seven layers into one data layer under a 5 tier classification scheme which would fit that of the susceptibility map. As a first step, rail and road were overlaid in Idrisi to form a single layer called *infrastructure*. Combined, these data layers were believed to represent major forms of transportation within the study area. Other buildings and the communications towers were also overlaid together to form a data layer called *other_infrastructure*. This data layer represented infrastructure believed to be not as critical or of a severe ranking as the roads and railway. The overlay of these four layers into 2 layers reduced the number of human element layers to 5, each representing a different classification of severity.

Each of the human data layers was then overlayed with the boolean recession rate data image (20, 10, and 5yr) to obtain summary statistics within each setback. During this process, it was discovered that several human elements were not located within the erosion setbacks. In the 10 and 5yr setback, rail, other buildings, communication towers, and historical cultural did not appear. In the 20yr setback, rail, communications towers and historical cultural did not show up.

The final task in preparing the human elements was to combine all 5 layers into one single data layer. This was accomplished through a series of overlays in which each layer was consecutively laid upon each other. Where data layers contained no data within the 20, 10, and 5yr recession the data layers were not included in the overlay process, as indicated by a dashed line in the flowchart of Figure 6.2. At several instances, pixels in one human element layer overlapped pixels in other layers, and the pixel was reclassified to represent the layer with the higher severity ranking before the consecutive overlay process continued. For example, where houses overlaid recreation areas (eg. Sand Hills Park), pixels representing the house were reclassified to represent the recreation areas. The ultimate end to this process was the creation of a single human element data layer which could be overlaid with susceptibility to create a risk map.

6.5.3 - Risk of Bluff Failure: Big Otter Ck. to Hahn Marsh

At this stage, both data layers required to evaluate risk had now been constructed. The data layer representing the susceptibility of the bluff area to failure could be overlaid with the human elements to determine where bluff failures could potentially threaten human well-being at various scales of severity.

Several options were available for combining these maps in order to evaluate risk. After testing several options, including variations in Idrisi's *IMAGE CALCULATOR*, it was decided that the MCE module would, once again, prove useful. Human elements and susceptibility were entered into the MCE, with equal weights for each layer (0.5 and 0.5), to produce the outcome data layer, 'risk'. The following example describes the process using theoretical pixel values of 2 and 5:

(6.3)

$$\boldsymbol{R} = \sum w_{i...n} x_{i...n}$$

$\boldsymbol{R}$ = [(0.5)(2)] x [(0.5)(5)]
$\boldsymbol{R}$ = 3.5
$\boldsymbol{R}$ = Class 3 - Moderate Risk

Where,
$\boldsymbol{R}$ = Risk

This process was completed for 20, 10 and 5yr recession setbacks, using both unweighted and weighted susceptibility images. The flowchart in Figure 6.2 describes this process in detail, while Figures 6.22 and 6.23 graph the land area occupied by the weighted and unweighted risk classes within the study area. The corresponding data tables are also important, and listed in Appendix A(xii) and A(xiii). These tables also list the area of land as a percentage of the entire study area. Since the weighted versions of susceptibility were felt to be more representative of the relative contribution of slope instability factors within the study site (particularly geology/stratigraphy), only the weighted Idrisi risk images were printed as maps. Figures 6.24, 6.25 and 6.26 display these weighted risk maps for 20, 10, and 5yr recession setbacks, respectively.

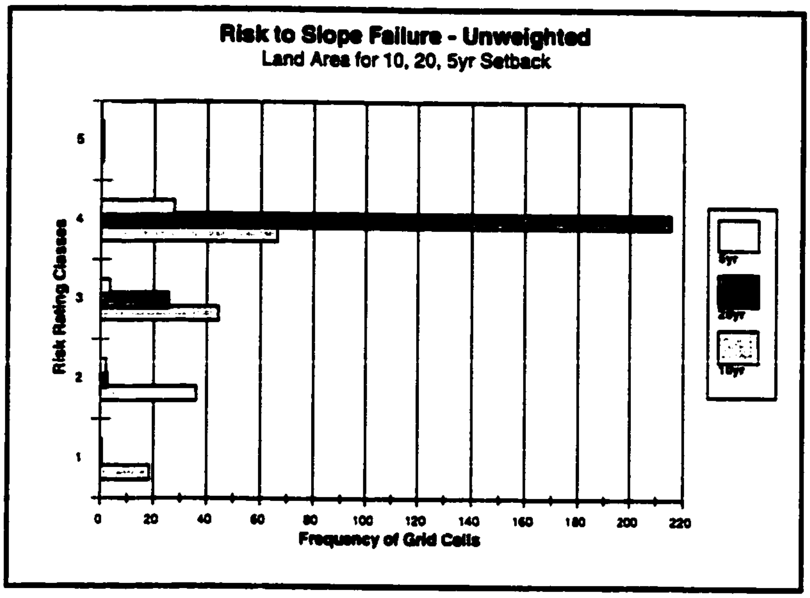


Figure 6.22: Summary graph for unweighted risk classes, by land area.

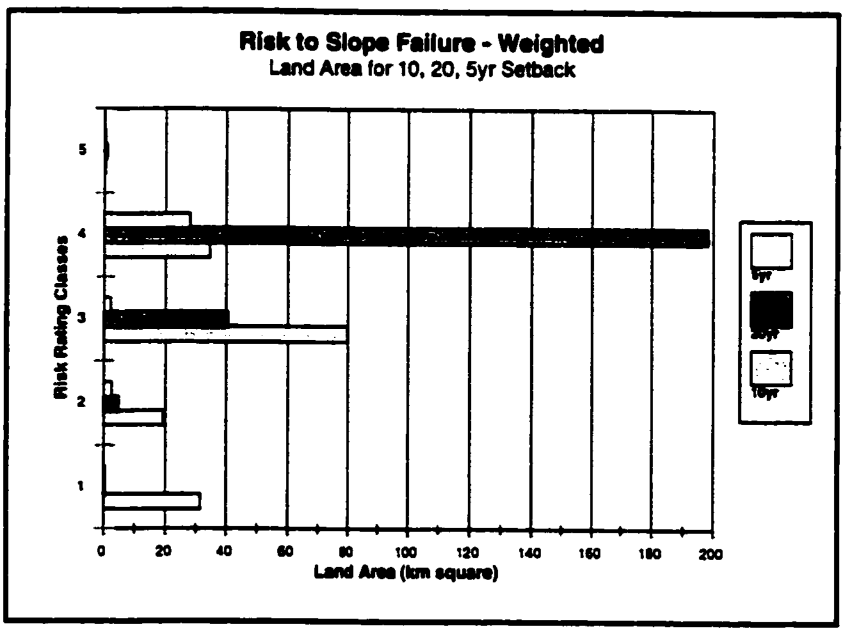


Figure 6.23: Summary graph for weighted risk classes, by land area.

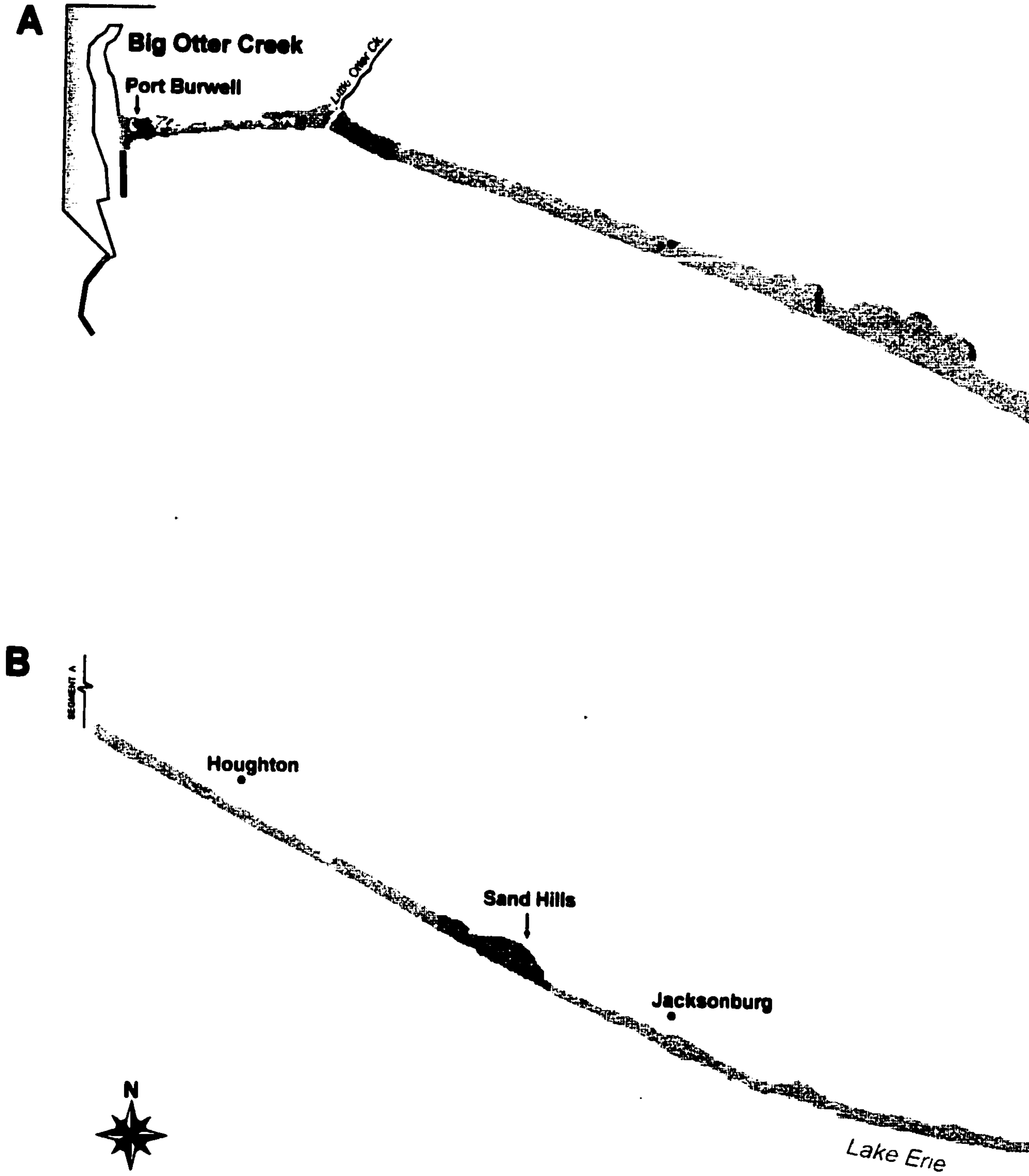
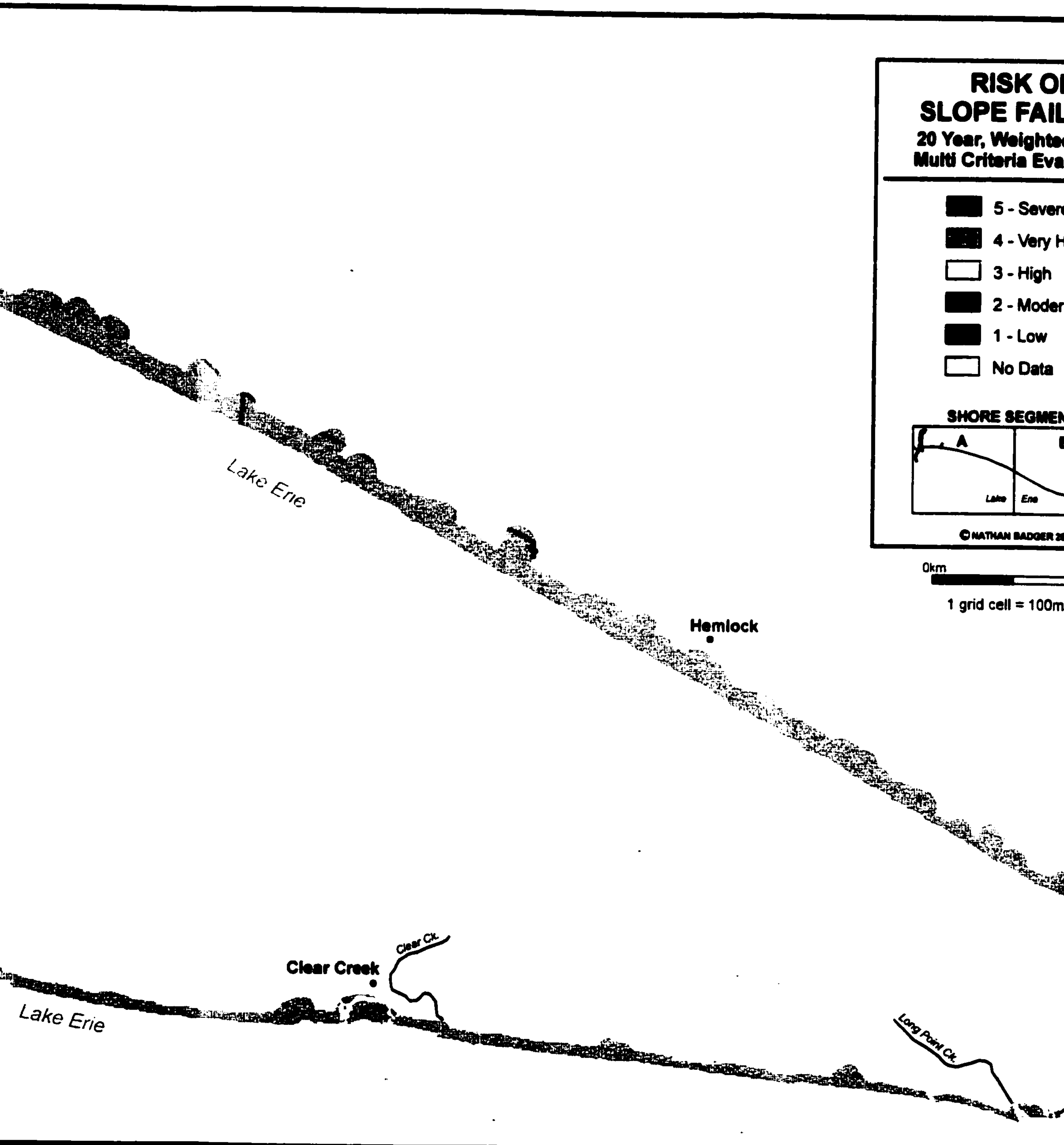
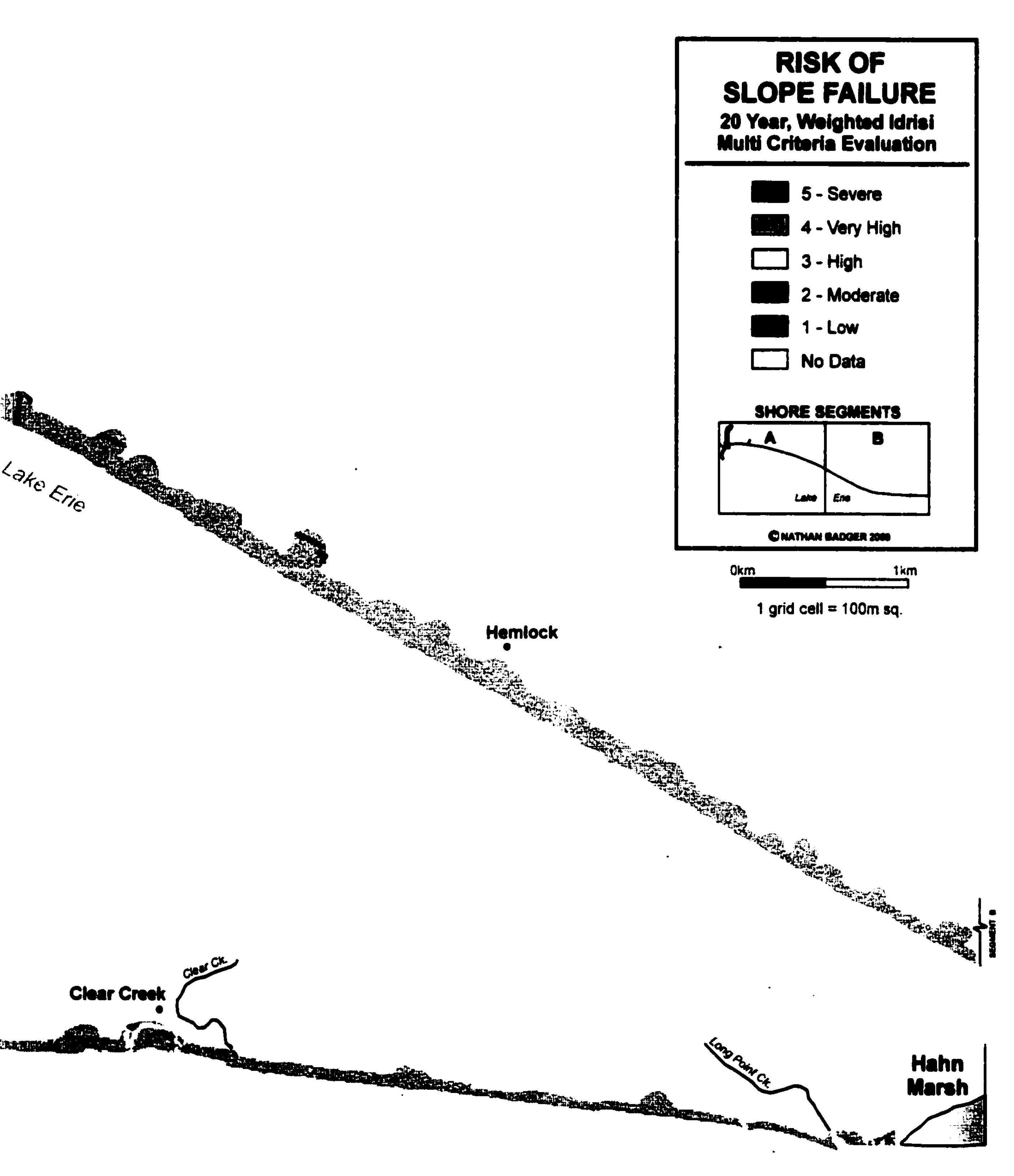


Figure 6.24: Risk to slope failure within a 20 year recession setback. Risk was evaluated us
human elements were overlaid, and the resulting image has been classified by the degree of



k was evaluated using Idrisi's Image Calculator. Slope susceptibility and
d by the degree of risk which exists within the study reach.



drisi's Image Calculator. Slope susceptibility and
which exists within the study reach.

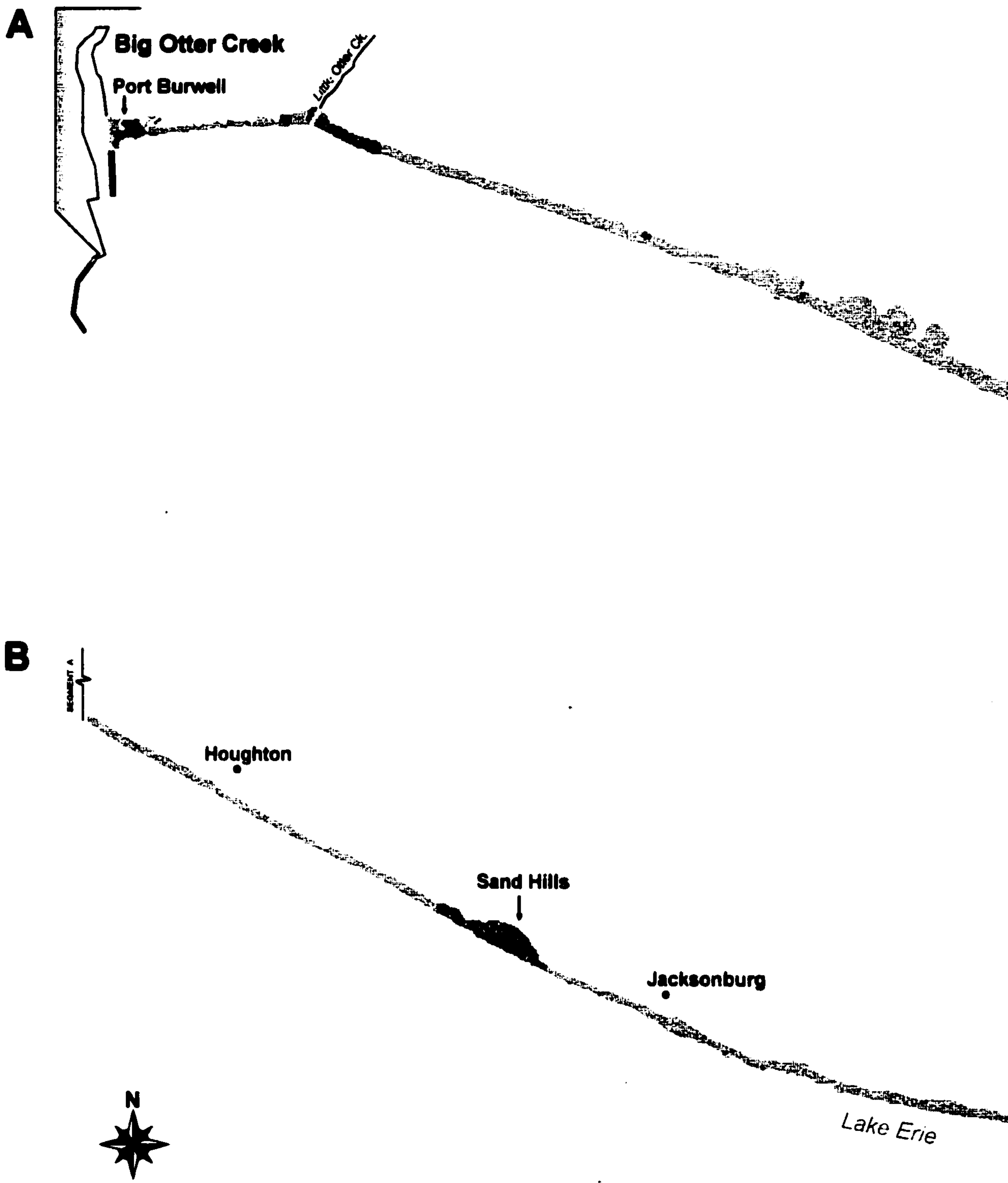
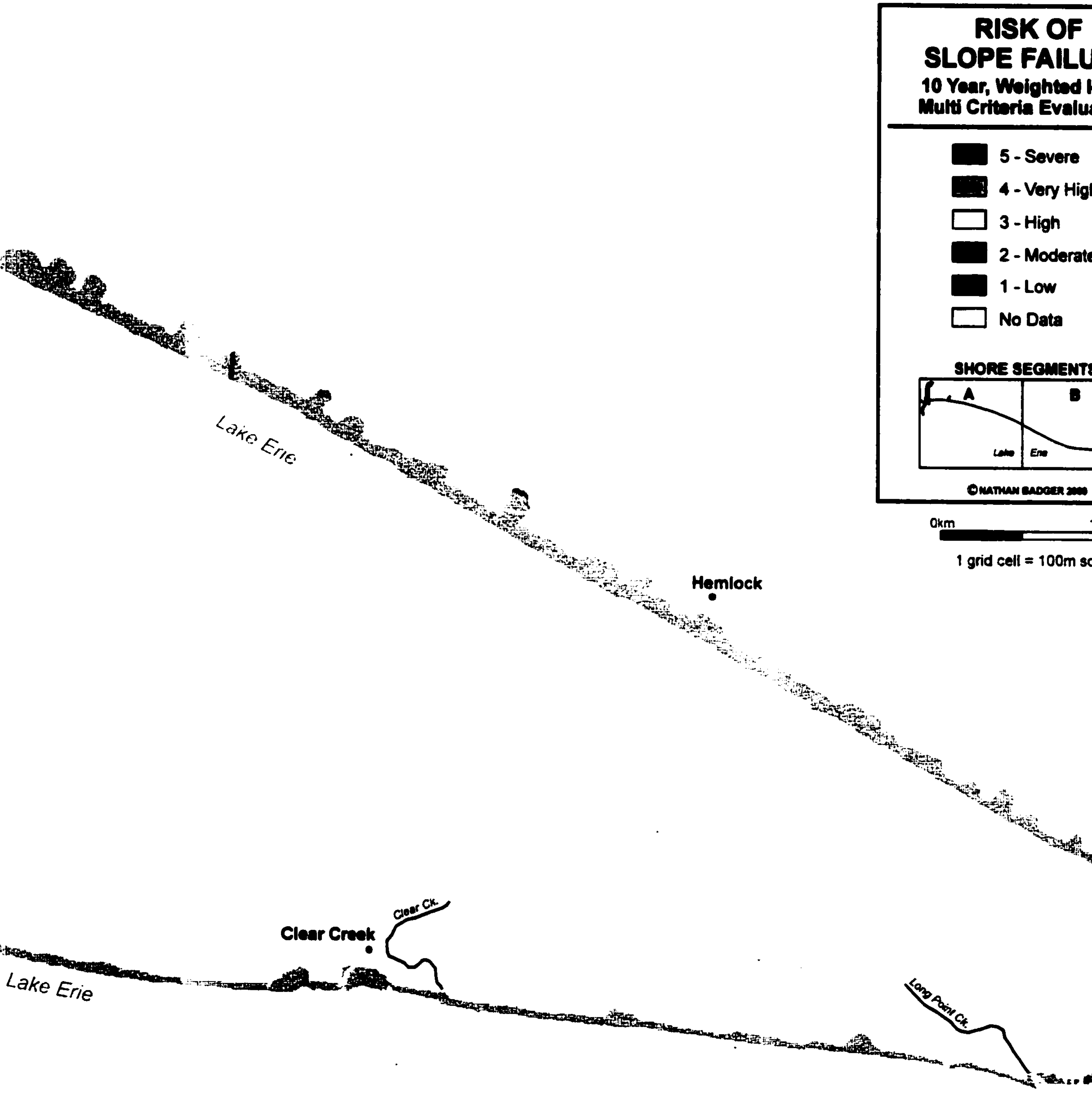
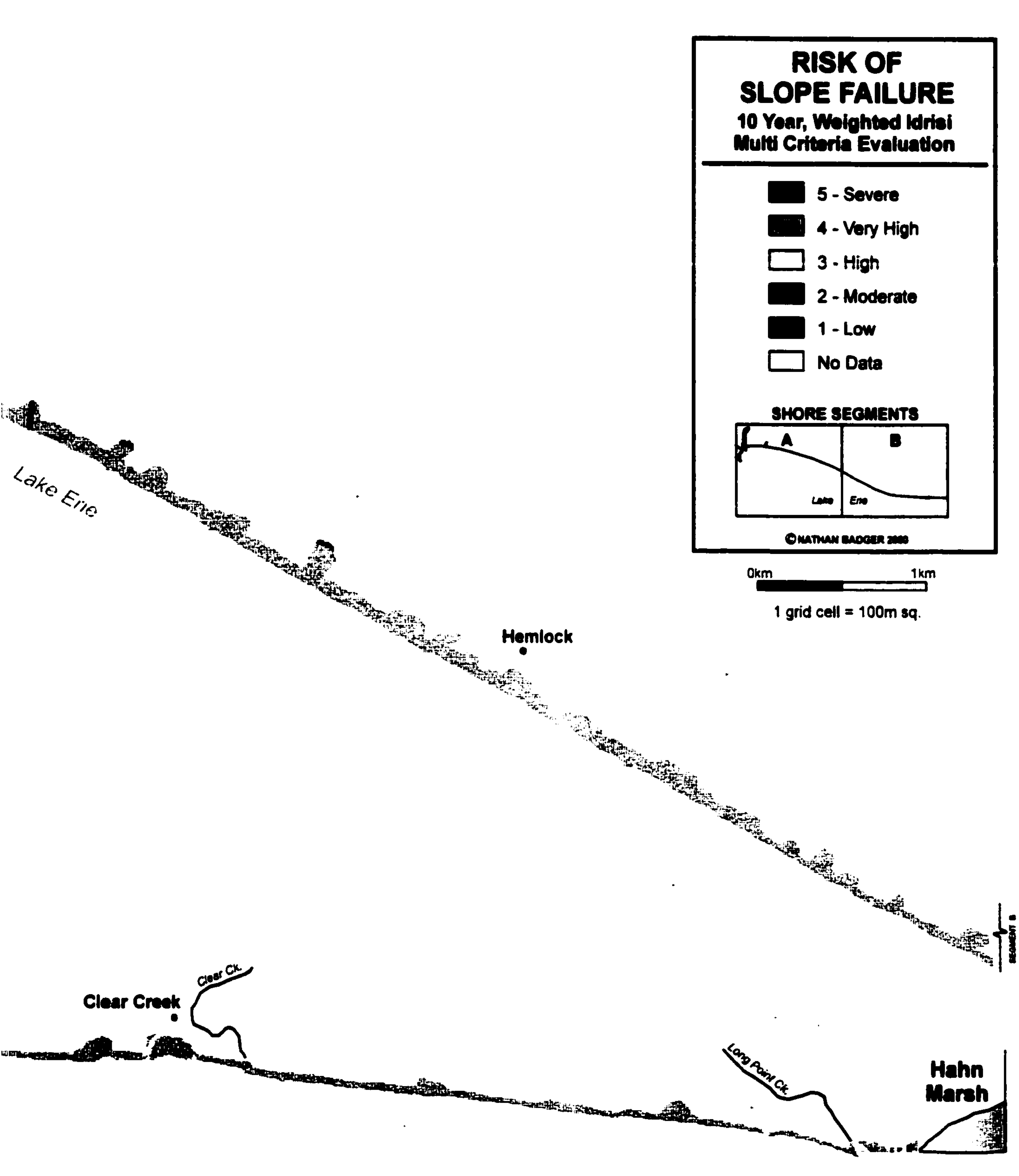


Figure 6.25: Risk to slope failure within a 10 year recession setback. Risk was evaluated
human elements were overlaid, and the resulting image has been classified by the degree



was evaluated using Idrisi's Image Calculator. Slope susceptibility and by the degree of risk which exists within the study reach.



Idrisi's Image Calculator. Slope susceptibility and
which exists within the study reach.

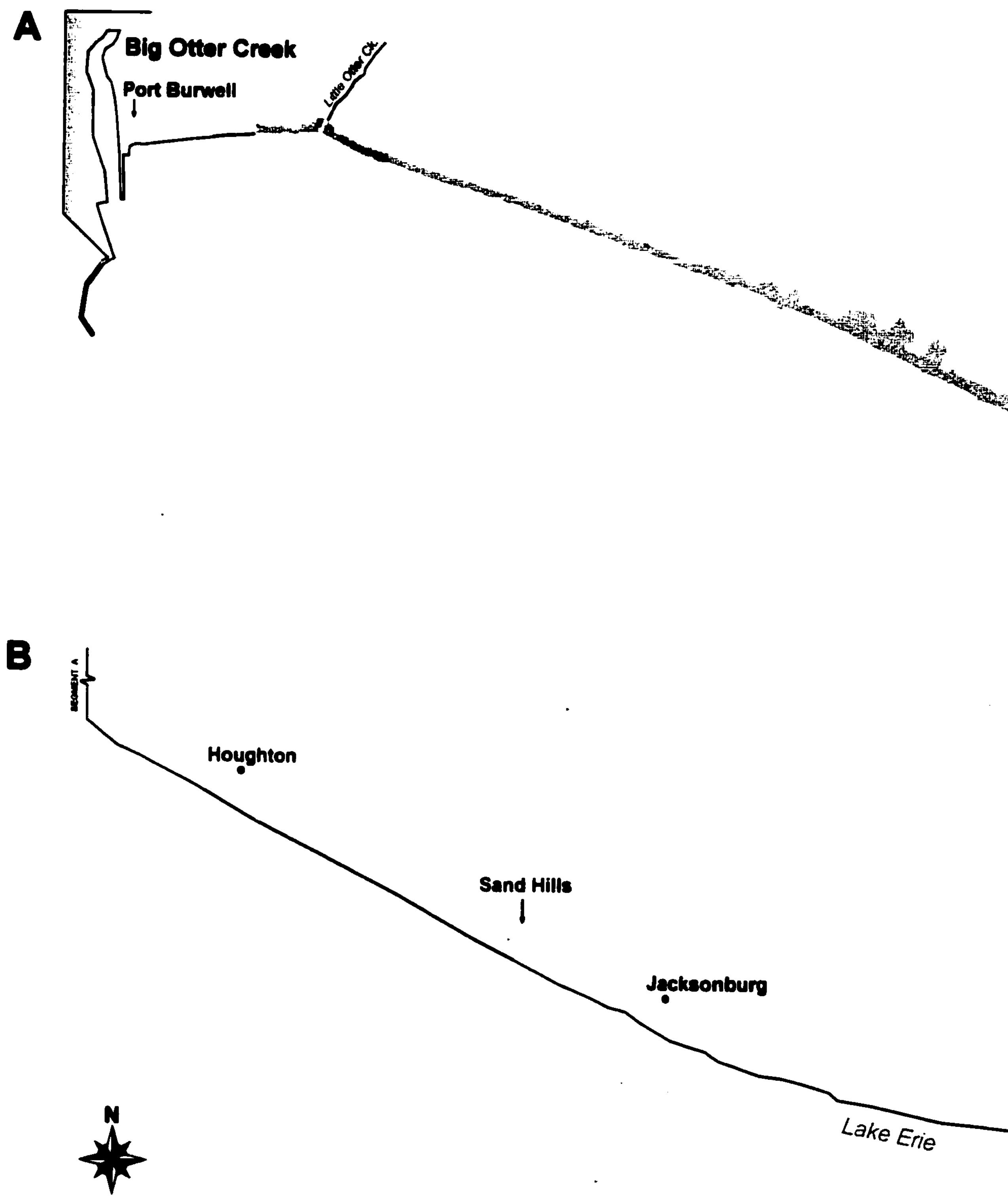
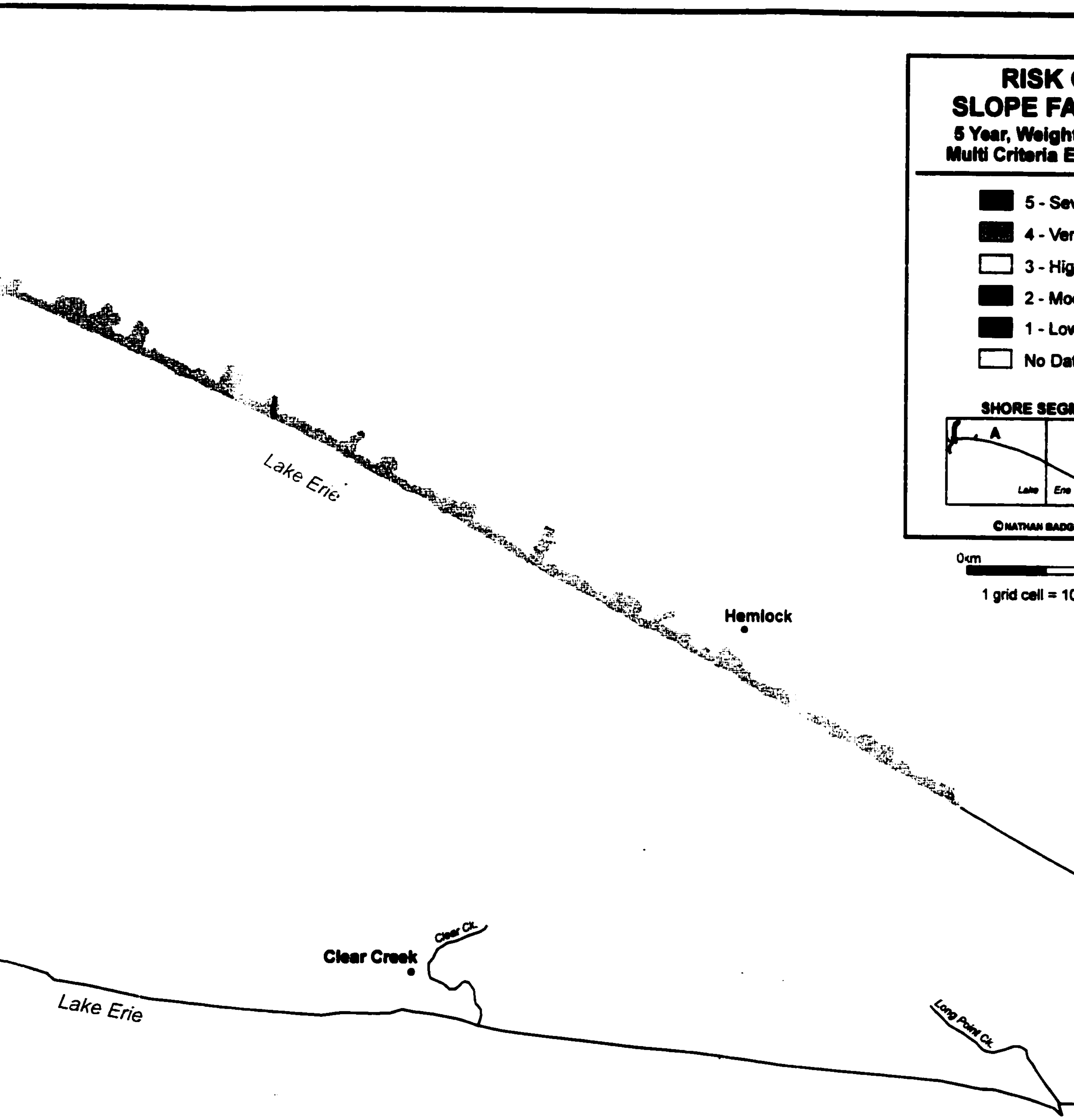
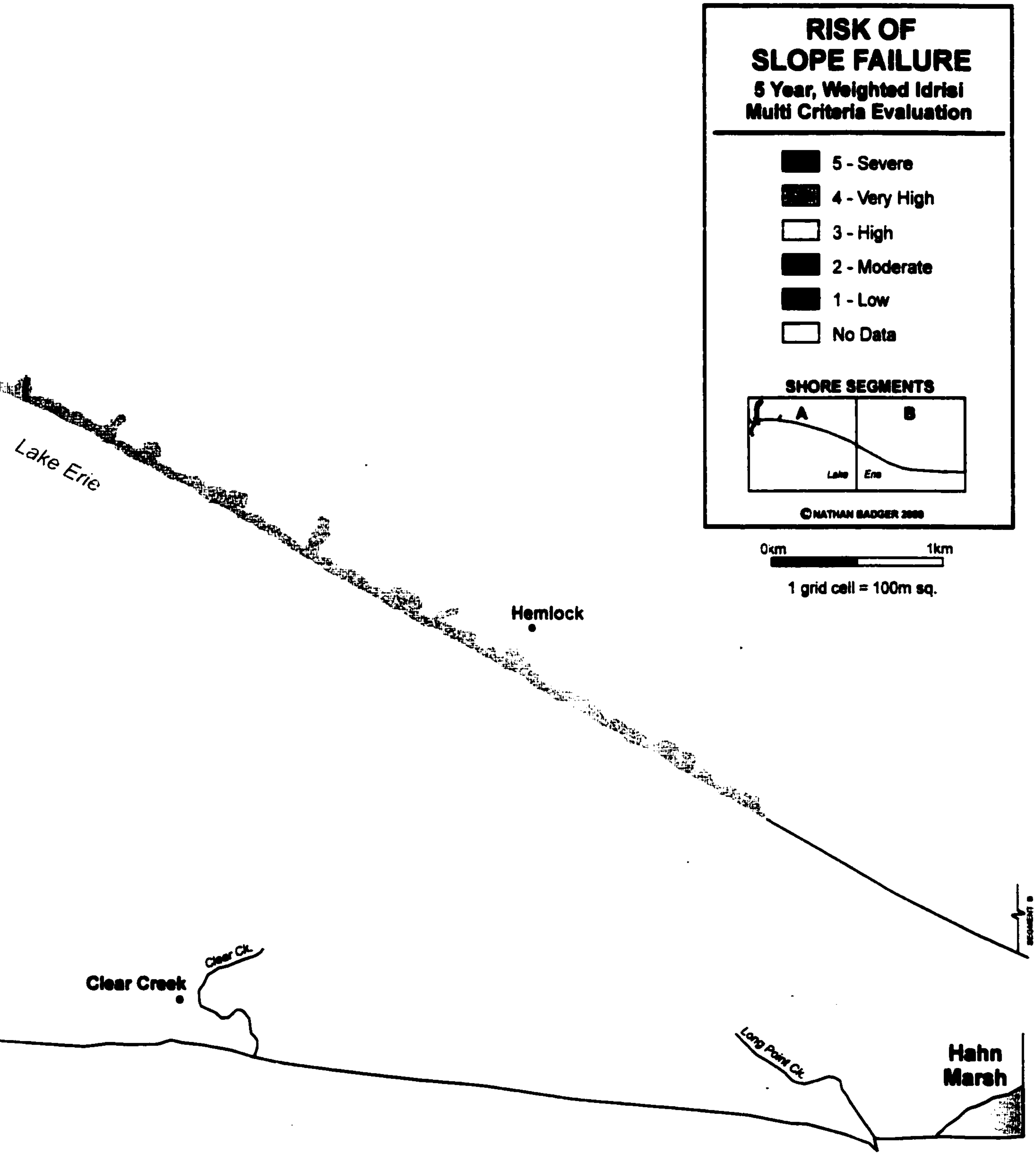


Figure 6.26: Risk to slope failure within a 5 year recession setback. Only the highest erodi
evaluated using Idrisi's Multiple Criteria Evaluation module (MCE). Evaluated data included



Only the highest eroding sub-reach of the study shore is displayed. Risk was
aluated data included six weighted slope failure factors, and human elements.



ub-reach of the study shore is displayed. Risk was
weighted slope failure factors, and human elements.

As a means of examining the Idrisi evaluation more clearly, and at a larger scale, the Idrisi images were also exported back to MapInfo and overlaid with various geographic locators. These maps represent the finished products of this analysis, and take the form of a small 'Risk Atlas' that may be useful to regional planners, the Long Point Region Conservation Authority, or even the general public.

Eleven maps were produced in full colour at a scale of 1:10,000 from MapInfo and are included, with a legend, as Appendix C. Each map shows risk of bluff failure for a 10yr recession setback along the bluffs from Big Otter Creek, near Port Burwell, to the Hahn Marsh, just west of Long Point. Since much of the area is not considered to be at risk, the data layer for susceptibility was also included in the map as a pastel equivalent of the more saturated hues used to indicated risk. Recreational areas, residences, other buildings, roads and human cultural features are all displayed on the map for reference. Physical features such as Lake Erie, vegetation cover (where not covered by the risk or susceptibility layer), creeks, ponds and dugouts, marsh and contour lines are also displayed. Finally, the data layer for trails was overlaid onto these maps. This data layer is believed to a useful aid in guiding emergency crews to access points along the bluff, should an emergency situation arise.

The 'Risk Atlas' completed the analytical aspect of the GIS research. The final chapter of this paper discusses the results of the analysis, as displayed through these maps, in addition to benefits and limitations of the study, further research, recommendations, and finally, conclusions.

CHAPTER SEVEN

Discussion, Recommendations and Conclusions

"Preventative measures can be painful, though, and cartographic warnings often go unheeded until an unprecedented, yet foreseeable catastrophe demonstrates the wisdom of listening." M. Monmonier (1997)

7.0 - Research Discussion, Recommendations and Conclusions

The research contained within this thesis can be divided, roughly, into two major sections. Chapters One through Four discussed the nature of coastal slope failures, their hazards and risks, the global expanse of these events, particularly within the Great Lakes and Lake Erie basin, and finally the application of GIS and hazard zone mapping in slope stability assessments, with applications to coastal environments. The second half of the thesis, including Chapters Four through Six, focussed on a reach of bluffs along Lake Erie's north central shore between Port Burwell and the Hahn Marsh, Ontario. Data were collected, prepared and analysed in a GIS such that the susceptibility to failure was determined within this reach, in addition to the risk of these events to a selection of human elements. The maps in Appendix C summarize the results of this analysis in the form of a 'Risk Atlas'.

A great deal of time could be spent analysing and interpreting the results of the GIS research and other data collected through this study. This information, would however, involve the efforts of a separate thesis, and instead, the purpose of this chapter is to simply summarize and conclude the study through a discussion of key observations and results, the implications of the study, and finally, recommendations for future research.

7.1 - Discussion, Interpretation and Implications of Results

This research has generated a great deal of information, both through literature review, field work, interviews and other communications, and most notably, the practical application of GIS analysis of bluff failure susceptibility and risk. In order to best summarize this information, the following sections discuss and interpret the results in terms of the literature review, the preparation of data, the use of GIS for research along Lake Erie, the actual analysis of this data, including such topics as the weighting and cross tabulation of susceptibility factors, outcome of the susceptibility analysis, and the final risk analysis.

7.1.1 - Literature Review

The literature reviewed for this research was necessarily expansive, and multidiscplinary. A comprehensive, and effective analysis of the bluff risks required an examination of slope failure dynamics, factors affecting slope stability, particularly at the coast, the nature of hazard, risk and vulnerability, the nature of coastal bluffs at a global and local level, planning and shoreline management along the Great Lakes, methods of applications of GIS in slope stability, and analysis of the human and physical processes and contributions to bluff instability along the north-central shoreline of Lake Erie. Combined, these reviews evidenced that coastal slope failures are a serious, yet relatively unstudied, global hazard and risk. The literature also provided a rich understanding of various subjects so that a GIS assessment of the bluffs could be carried out with a relatively high degree of competency. These findings indicate that an exploratory analysis of bluff failures along a portion of the Great Lakes, is both important, and highly justified. The information contained within the thesis provides an excellent foundation for further research along the study area, and the Great Lakes. This information is especially important when GIS applications are capable of being abused, misused and performed in an undirected and unguided environment, so that information is not useful, or worse yet, misleading.

Several important points were gleaned from the literature review and should be summarized here in the conclusions. Firstly, slope failures are complex, especially at the coast where subaqueous, aeolian, terrestrial and anthropogenic factors all play a contributory role in bluff instability. The mix of physical and human factors is particularly important to note, since both sources also help to define the hazards, severity, vulnerabilities, and risks associated with failure events.

The combination of coastal occupation and coastal slope failures has created a hazard with a global geography, a wide range of risks, and numerous attempts and methods to mitigate the problem. A large number of reports discuss bluff research, lists of damages, and attempts to mitigate the problem along international coastlines and the Great Lakes. Unfortunately, many of these reports focus on issues of flooding and erosion, or the physical aspects of the bluffs, rather than the risks and/or 'indirect' methods of mitigating the problem.

Various methods and tools are currently used to assess slope stability, and to mitigate risk, most of which are applied to inland slope failures, but are highly compatible and beneficial in a coastal environment. One particularly useful method is approach discussed in the literature is GIS and hazard zone mapping. By combining influential factors in bluff failures, with the location of various human elements, an assessment of bluff failure susceptibility and risk can be achieved. Despite the ubiquitous and beneficiary nature of GIS, literature does not elaborate on any applications of these techniques to coastal bluffs. This is clearly evident along the Great Lakes, where the focus has, instead, been flooding and erosion, geotechnical assessments, and shoreline inventories. For these reasons, an exploratory, GIS analysis was developed and implemented to evaluate bluff failure susceptibility and risk along a portion of the Great Lakes.

7.1.2 - Data and GIS Development

Despite the complexity of coastal bluff failures, extensive literature review and field work enabled the identification of several major factors contributing to the failure of the bluffs between Port Burwell and the Hahn Marsh on Lake Erie, Ontario. Data were collected for these factors, entered into a GIS, and eventually represented and analysed as a series of large-scale maps.

During the process of data collection, entry and management, several important issues came to light. Though not new information, data is often difficult to obtain, and is often in disparate analog and digital forms, such as point, line, or area data, hard copy maps, digital images, and tabulated records. The collection, preparation, and conversion of these data to a digital format involved substantial amounts of time, as also discovered by Gornitz et al. (1994), Small (1992), and Soeters and Van Westen (1996). Often it is difficult to evaluate how these data can be incorporated and assessed in a GIS, particularly when the bluffs are three dimensional in form and dynamics. The management and manipulation of data, therefore, took a great deal of thought and consultation.

Despite the capabilities of the GIS, certain stages were tedious due to the size of data files (particularly in Idrisi), and the lack of a readily available, user-friendly GIS software package which could perform all the analysis without interplay between several packages (eg. MapInfo to ArcView, to ArcInfo, to Idrisi). In order to increase efficiency, it must also be stressed that research of this nature requires hardware and a system capable of storing or backing up large amounts of data, and processing data analysis through a high speed CPU. Due to the size and scale of the mapping involved, and the interplay between various software packages, often simultaneously, a large display monitor, printer and digitizer is also required for the reliable, efficient and effective input, presentation, and output of information. Combination of the GIS software, hardware, and text and graphic editors on one single workstation greatly improves the efficiency of such a project.

Despite some of the limitations, this study determined that a GIS offers several distinct advantages for a multi disciplinary, multivariate study, including the relatively efficient storage of data, ease of correction, updating, and customizing, in addition to powerful analysis. On the overall, a GIS is a highly effective tool for coastal slope hazard and risk assessment, and is far more efficient and robust than conventional methods.

7.1.3 - Susceptibility, Weighting and Cross Tabulation

Two major stages of investigation were implemented to assess the stability of the Lake Erie bluffs. The first investigation focussed on the susceptibility of the bluffs to failure. This included the classification and weighting of instability factors, MCE overlay analysis to determine susceptibility, and a cross-tabulated and cross-classified comparison between the weighted and unweighted schemes. It should be noted that this research was, first and foremost, oriented towards generating an exploratory set of methods, and only some introductory analysis. Due to the time required in researching the topic, as well as collecting and managing data, serious analysis and application of the results are best examined through a separate, yet equally important, and intriguing study.

Section 5.2 provides an excellent prelude to each of the susceptibility factor maps contained within Chapter Six. Graphs were also included with each map to help summarize the classified data. In the case of *elevation*, much of the study area contains bluffs which are classified as high (Class 5 - Red) and, therefore, a great majority of the shore reach contributes severe elevation to slope instability. Elevation tails off to high, medium and low near Big Otter Creek, and east from Clear Creek. It is important to note the lack of beach area in front of a great majority of the bluffs. Should a failure occur, there is little place to move from its runout. The map and graph for *slope inclination* indicates that a large portion of the study area has a moderate or low contribution to susceptibility. However, much of this area includes the bluff tops, which are naturally flat, and instead, the graph describes the majority of the bluff faces and beach area as severe, followed by very high, and finally high. Steep bluff faces are most noticeable in areas where the there is cohesive material (eg. clays and clay rhythmites), such as the eastern portions, whereas, the central portion has a mix of slopes due to gully formation and rotational slides in material where sand and sand rhythmites overlay clays and clay rhythmites. *Geology and stratigraphy* is much less complex than elevation and slope, and the classification scheme, map, and graph indicate that the much of the study area exhibits a severe contribution to susceptibility. This is partially due to the extra area created by the gully undulations on the map, but is still indicative of the unstable material which exists within much of the eastern portion of the reach. In terms of *recession rates*, the majority of the reach, once again, exhibits severe characteristics. This is not surprising when this portion of the Erie shore exhibits some of the highest recession rates in the world. Very little of the shoreline has a low, moderate or even high recession rate. Maps and graphs depicting *vegetation cover* indicate that much of the bluff faces and bluff tops are unvegetated (over 2,200km^2), and are therefore classed as severe contribution to susceptibility. Much of the land above the bluffs has been cleared for agricultural practices, but the un-cleared portion of the Galt Moraine between Jacksonburg and Clear Creek, is evidently more vegetated. Finally, *shoreline protection* exhibits many of the characteristics of vegetation cover, where much of the shore reach is classed as severe, due to limited installation of shore protection, apart from Port Burwell, Sand Hills Park, and the cottages beside Hahn Marsh. In hindsight, the area just east of Long Point Creek may have been included, since it is partly protected by a sunken barge.

The classification schemes used to group the data within each factor layer played an important part in the evaluation of susceptibility. A five class scheme was used to represent the geohomogenous and UCUs within each factor. Five classes were also used by Gornitz et al. (1994), which is believed to be an improvement from the three class scheme (low, medium, high) used by Small (1992). A five class scheme ensures that data is not over-generalized, but, not so confusing or complex that analysis of the results requires specialized personnel and hardware beyond that available within the offices of the local CAs.

Though attempts were made to quantify the factor data as much as possible, some of the classification schemes are inevitably qualitative, or based on subjective decisions. This does not undermine the analysis, but undoubtedly the results of the analysis could be improved through further research and 'educated' adjustments. For example, classifications for elevation and slope could, perhaps, be adjusted to more closely reflect the characteristics of the bluffs which lead to bluff failures, and affect the scale and severity of the failure. In addition, classifications for some factors could be expanded, particularly in the case of the boolean schemes for vegetation cover and shore protection. For example, vegetation could be subdivided to include varius forms of vegetation, or even land use, which exhibit different influences on slope stability (eg. forest, bush, crops, grass, no vegetation). Despite the apparent benefits, the work required for such a classification was beyond the resources available for this research.

Having digitized and classified the factor maps, each were weighted by their relative contribution to slope instability and failure. Geology/stratigraphy was weighted relatively higher than all the other factors, due to its strong influence on shear strength, and seepage and ground water movement based on evidence through field work and literature. The strong weighting of this factor was also believed to compensate, in part, for seepage or ground water which was not available for the analysis. The differential role of geology/stratigraphy amongst other factors illustrates the importance of enhancing the data analysis through weighting schemes. Factors believed responsible for increased contributions to bluff instability, such as geology and stratigraphy, can be better represented in the final assessment of susceptibility. Though geology/stratigraphy, in hindsight, may have been overweighted, the weighting scheme used in this research is believed to have enhanced the analysis through the assessment of the relative contribution of each factor to the susceptibility of bluff failure.

Despite the usefulness of weighting, there are several limitations to this approach. One of the major problems is in determining the exact weighting to be assigned to each factor map. Insufficient field knowledge of the important factors often prevents the proper establishment of the factor weights, and leads to unacceptable generalizations (Soeters and Van Westen 1996). Weighting should only be used when the variable effect of certain factors is known. Literature review and field explorations helped to reduce the subjectivity of the weighting within this research, so that a relatively accurate assessment of factor contributions could be achieved. Though Gornitz et al. (1994) applied and assessed the usefulness of at least eight different weighting schemes and techniques for their research, the unweighted, and weighted methods used in this study provide a very useful introductory scheme for the purpose of this analysis. Future research should, however, examine and develop the weighting methods and schemes more thoroughly, particularly if extra factor layers are introduced to the analysis. Future research should also examine correlation between factor layers, so that weighting schemes and choices of factors can be further evaluated and adjusted.

The final susceptibility maps are included in Chapter Five as Figures 6.19 and 6.20. Using both the maps, graphs (Figures 6.17 and 6.18), and tables (Appendix A(ix) and A(xi)) the following observations can be made about the susceptibility of the study area bluffs to failure, using the weighted evaluation. For the most part, susceptibility is classed as severe throughout the study area (1,800km^2). This is due mainly to the Class 5 rating of geology/stratigraphy which extends through much of the western portion of the study area. Much of the central portion of the reach is classed as Very High susceptibility, while eastern and far western is mainly High susceptibility. Very High susceptibility is also evident in and amongst the gullies, presumably due to lower slope inclinations and elevations. It also appears midway between the landward extent of the setback and the shoreline in High susceptibility areas, perhaps as a result of increased slope angle near the top face of the bluffs. The effects of shore protection are evident within Sand Hills Park, Port Burwell, and the cottages near the Hahn Marsh. Several regions of only Moderate susceptibility also exist within the study area, including the bluffs near Port Burwell which are vegetated, sheltered by the shore protection (including the jetty), and composed of relatively cohesive materials. This section of shore also exhibits the only area along the study reach with Low susceptibility to failure,. This is not surprising when some of these bluffs are well-vegetated and appear to be relatively stable. Moderate susceptibility is also sprinkled through the eastern portion of the study area, particularly at the base of the bluffs where elevation is low and the bluffs are more cohesive. Overall, it would appear that a wide range of factors, influenced the outcome of the susceptibility rating, including geology and stratigraphy which were purposely weighted relatively higher.

Cross tabulation (Table 6.10) and cross classification (Figure 6.21) were useful tools with which to evaluate the effects of weighting each factor layer. Several observations can be made from these procedures. Firstly, the two major changes in classification appear to be Class 4, where 3,593 unweighted pixels were reclassified, once weighted, to Class 3, and 6,148 were reclassified through weighting to Class 5. These changes account for almost half the pixel reclassifications, of which there were 10,520 total changes from a total of 20,163 pixels within the 10yr setback. Beyond these reclassifications, changes only ranged from 5 to 400 pixels, and are therefore, less significant.

It is interesting to note that the weighting of factor layers generated reclassifications of no more than one class higher or lower. The majority of the changes, that is, 32%, were reclassifications to higher classes, particularly from Class 4 to 5 (30%). It would appear from the cross classification map that pixels were reclassified to a higher class in the area of high risk geology/stratigraphy. This is not surprising when the new weighting scheme favoured the relatively greater contribution of geology/stratigraphy to slope instability and failure. Pixels are reclassified to a lower class in areas of low and moderate geology/susceptibility, as evidenced west of Little Otter Creek.

In summary, it could be said that the weighting scheme has altered the outcome of the susceptibility maps. Though changes are large in volume or numbers, they are not drastic, in the sense that pixels were reclassified to extremely different classes. For these reasons, the weighting scheme is believed to have positively reclassified the susceptibility image, by adjusting the assessment to reflect the relatively different contributions of each factor in bluff stability. Future applications should, however, focus on evaluating several weighting schemes, and reevaluating the weights of each individual factor, particularly if new ones are added to the analysis. In addition, some effort should be made to evaluate the similarity and dissimilarity of the images in a statistical software package, through evaluations such as ChiSquare, and Kappa Indexes of Agreement. This process is long and tedious, and unfortunately not able to be completed in Idrisi due to it's automated inclusion of Class 0 values.

7.1.4 - Risk Analysis and Risk Atlas

Stage two of the analysis formed the focus of the GIS research, and the basis of the Risk Atlas (Maps A to K) included in Appendix C. Figures 6.24, 6.25, and 6.26 also display the same results of the risk evaluation, albeit without the extra MapInfo data layers, and for recession setbacks of 20, 10 and 5 years. The results of the evaluation are also graphed in Figures 6.22 and 6.23, and the related data tables included in Appendix A (xii), and A (xiii). Since the weighted evaluation of risk is believed to be more representative of the factors responsible for susceptibility, the weighted risk evaluations are the focus of this discussion.

The final risk evaluation, like the factor maps, uses a five class evaluation scheme that is illustrated through a hot to cold colour scheme. Due to the spatial variation of susceptibility and risk on the maps, this colour scheme was found to work best in terms of readability, comparability between classes, and overall ease of interpreting the results. Dent (1996) noted that schemes with more than five classes are difficult for the map reader to readily decipher, and that gradations from hot to cold are fairly well understood, even by the uninformed map reader.

An evaluation of risk necessarily required that human elements be included in the analysis. Many of the GIS slope analyses described in the literature avoided this final step, noted its difficulty, or failed to describe the process in any useful detail. Likewise, the technique used to include human elements in this analysis took some time to develop and test to ensure that the final risk analysis would provide useful information to shoreline managers and even the public. After several possible schemes were drafted, a simple, yet effective method was developed, whereby human elements within the study area were mapped and classified by their relative human worth or value. These elements were overlaid with the data layer describing susceptibility to failure, and the coincidence of pixels and their values between the two data layers was finally assessed through the MCE. This Idrisi module overlaid and reclassified the resulting pixels to UCUs which described the overall risk to slope failure within the study area. This approach improves upon that of Gornitz et al. (1994) who simply divided the results of the final overlay into quartile classes. The technique also improves on those of Small (1992) who simply multiplied the maps against each other to create a large number of classes which were difficult to interpret or apply meaning.

The Risk Atlas, in addition to the risk maps, and graphs in Chapter Six, indicate that risk exists in several 'pockets' along the shoreline, which naturally reflect the presence of human elements near the bluffs. Within the 10yr recession setback, these areas of risk include the area around Port Burwell and Little Otter Creek, several instances between Little Otter Creek and Hemlock, Sand Hills Park, Clear Creek, and the area of Long Point Creek near the Hahn Marsh. By means of comparison, the 5yr assessment restricts risk to Port Burwell and Little Otter Creek, as well as small bits between Port Burwell and Hemlock, while the 20yr expands on both the 5 and 10yr assessments to include a greater number of risk areas between Port Burwell and Hemlock.

The maps indicate that risk exists around three major items, including roads/associated infrastructure, residences, and recreation areas. Human/cultural items do not fall within any of the recession setbacks, and only several 'other infrastructure' cells (eg. barns, large buildings) fall within the 20yr setback. In the case of all three setbacks, there is a range of risks, with the exception of Class 5 - Severe. This class only appears in the 20yr setback and is attributed to a residence located near the head of a gully, just west of Hemlock. Class 1 - Low, is also excluded from the 10 and 5yr setbacks.

Within the area of Port Burwell and Little Otter Creek, risk is attributed to several factors. The recreation areas of Port Burwell beach, and Erie View Trailer Park are located within areas classed as high susceptibility to failure, and are therefore classed as Very High risk. Clusters of residences at the top of the bluff near the beach, and just west of Little Otter Creek, are also located in areas of high susceptibility and classified as Very High risk. Several additional clusters of residences are also located along the top of the bluff, in Moderately susceptible areas, and are classified as High risk.

Apart from these items, several roads leading to the beach areas near Port Burwell are classified as Moderate risk within Moderately susceptible areas. Ground truthing was implemented in the Fall of 1999 to examine each of the risk areas, and to briefly evaluate the ability of the analysis to predict risk. The residences overlooking the beach area were all found to be located at the very edge of the bluff, and efforts have been made to stabilize the slopes through concrete blocks and terraces. Stairs and decks along the back of these houses/shops have, in some instances, already fallen down the bluff face. Cottages located next to Little Otter Creek appeared to be in better condition due to the stabilization of the shoreline below. Over the past several years, however, close to thirty extra cottages have been built in this area, and are not shown on the OBMs. The roads classified as Moderate risk were in both cases, not major roads, and rather, gravel access routes to the bluff base. The road within Port Burwell, however, had been blocked off to prevent further use due to damage at its base. In terms of the recreational areas, Port Burwell beach is located directly below high, steep bluffs, and the Trailer Park, with up to 30 mobile homes, is located over high bluffs with very little beach area, and bluffs which exhibit frequent topples.

Between Little Otter Creek and Hemlock, much of the risk can be attributed to roads and the infrastructure located within their buffers. Many of the roads classified as risky, are located close to the sides, or heads of gullies. Though several sections of road include the well-traveled Road 42, several other sections included roads that were gravel access routes to removed houses or agricultural fields. It should be noted that the two new gullies just west of Stafford Road (noted in Chapter Five as recent occurrences) would cause the road and house at the head of the gullies to be classified as Severe risk if they were digitized. Field work confirmed that the house and road are currently both at serious risk to damage, and/or destruction. In addition to the roads, two residences were determined to be located within Very High risk areas. During field work, the residence east of Csinos Road was identified as a small barn which had already fallen over the bluffs, while the other residence was within close proximity to the head of a gully which already threatens the stability of nearby Road 42.

Moving from west to east, the next area of risk is Sand Hills Park, which is appropriately ranked as Very High risk due to the many people who recreate on the bluffs or at the beach below. The information, if made available to the Park before 1994, may have eliminated the deaths of four young boys. The information in the Risk Atlas indicates that the Park bluffs will continue to exhibit a very high degree of risk to human life unless some form of risk mitigation is employed.

Clear Creek also includes areas ranked as either High or Very High Risk. These items include the road which runs through the hamlet, and several residences. During field work, the risk associated with these residences and roads was confirmed. Much of the road leading to the lake has eroded back and even damaged nearby sewer drains. The residence closest to the lake was put up for sale shortly after this research was begun in 1997, and land in front of the house shows obvious signs of erosion and continued recession. Though this area is at risk to coastal slope failures, it should be noted that this hamlet is also at risk to tornadoes. While conducting field work near Clear Creek during the summer of 1999, a Class 1 tornado was seen to twist its way across Lake Erie and up through the hamlet, resulting in over $50,000 dollars damage.

Finally, areas of risk are evident just west of the Hahn Marsh, near Long Point Creek. Here, gravel or dirt access roads to the bluff edge are classified as High risk. while an access road and cottages near Hahn Marsh are ranked as Moderate, High, and Very High risk. On-going erosion was evident here during field work, and residents indicated that previous access roads and cottages had already been destroyed or relocated.

Despite the fact that shore protection has now been employed below the bluffs, the cottages appear to be located on highly unstable terrain.

In summary, field work and ground truthing indicated that the GIS and maps provide an excellent tool and reference with which to estimate and evaluate risk of slope failure along the study shoreline. In several cases, the risks had already manifested themselves through property damage, and loss of lives. Where risk was not readily apparent during regular field work in the study area (eg. Port Burwell), the risk maps and further ground truthing helped to illuminate failure factors and hazard zones which, after further investigation, could very well present a threat to human well-being. Ground truthing is an essential part of the risk analysis and its importance should not be minimized. By visiting the study area, and comparing the results of the analysis to the 'real world' the risk maps can be verified or even re-evaluated. Although time was not available during this research to systematically verify all occurrences of risk on the Risk Maps, future research should focus more time and effort on this procedure.

Despite the advantages of the application, there are several limitations that should be noted. Firstly, estimations of risk could be evaluated more accurately through the reclassification of gravel and access roads to a lower class ranking, and the removal of small barns and buildings from classification as 'residential'. Since both forms of information are obscured on the OBMs, and would involve large amounts of field work to reevaluate, it is suggested that these items be left in their present class, and simply verified through ground truthing after risk maps are generated. Analysis is also somewhat dated and could be strengthened through the identification and digitization of recent human development in the study area, such as the residences in Port Burwell. This could be achieved through relatively simple ground work, or consultation with the Townships. Ground work is of a major necessity with any GIS work, including this research, and should not be under emphasized, especially when OBMs are dated and necessarily generalized in some cases. Although the OBMs are an excellent source of data, several different items are necessarily generalized into certain classes (eg. roads and buildings), and if not checked before or after the generation of risk maps, can alter the interpretation of the risk maps.

An important consideration with the maps and analysis, is that the classification of human elements is culturally defined, and largely biased towards Western values, and the values of the map author. For example, items of cultural or historical significance, such as cemeteries, may be evaluated differently from person to person, country to country, shoreline to shoreline, conceivably at both local and international scales. The classification of human elements, and subsequent evaluation of risk, reflects a simplified view of values that may not be shared by all. For these reasons, the methods of classification and evaluation may need to be changed, should this study be applied elsewhere.

A further consideration with regards to the Risk Atlas, is that the evaluation of risk assumes a worst-case scenario. The classification scheme used on the risk maps, and all maps in this research, are somewhat slanted towards 'severe', which also reflects the classification schemes used as the basis for these schemes. In addition, the maps assume that the presence of human elements, such as human lives, is constant throughout the year. This is obviously not the case, and instead, recreation areas are largely unused in winter, and some residences are left empty outside of the summer months. For these reasons, the evaluation of risk used in this research applies more directly to the months of June, July, August and September, when human presence and activity are highest along the shoreline. This approach was felt to be best for the purposes of this study, but it is conceivable that future evaluations could, and may wish, to evaluate risk using scenarios that are not slanted towards 'worst case', or exclusive of temporal variations.

Finally, it should be expressly stated that the risk maps are not generated for the average shoreline resident. Instead, information contained within the maps is geared towards the planner and those with at least partial knowledge of the processes and management of the bluffs. This 'first approach' to hazard mapping is recommend by Gilbert and White (1978), Monmonier (1997), and McGowan et al. (1988) They are not for the general public, nor are they to be interpreted literally as having direct and predictive qualities. Such interpretation would inevitably incur legal implications, which are a concern in many recent GIS studies (Epstein et al. 1998). Instead, the maps are best suited as a reference to planners or managers, and as a guide for decisions on where to concentrate more intense research into bluff stability or risk mitigation. Information contained with this research should be distilled to a form that is stimulating, informative, motivational, and useful to the public in order to encourage and mitigate risk by shoreline users and manager.

Apart from several considerations and limitations within the evaluation, the benefits of GIS for the analysis are not to be underestimated. The use of GIS was of prime importance in the ability to evaluate and display risk in a useful and competent manner. GIS was felt to be an efficient, effective, and extremely useful tool in assessing bluff stability and risk along the shoreline, and through hazard zonation maps. Its flexibility, ease of use, and effective modes of presentation are highly useful for providing information to shoreline managers, and ultimately, to the public. The ability to perform most of the analysis on relatively inexpensive PCs, and with readily available, relatively inexpensive software also means that this analysis could be easily incorporated into the tools of local Conservation Authorities or other governing bodies, such as the OMNR. Familiarity and use of GIS is increasing within CAs, and combined with a likely increase in the power of Windows based GIS software, such as ArcView, could be incorporated into land use, hazard, and emergency planning.

In addition to the benefits of the hard copy risk maps, which GIS are readily able to produce, the graphical user interfaces are also very useful, particularly within an office environment. Changes can be made directly on screen, and various hypothetical, trial and error scenarios can be tested within small time frames. GIS is particularly amenable to answering 'What If ?' questions. This is especially helpful when slope stability and risk analysis requires the input and adjustment of a large number of factors, weights, variables and methods of data presentation. These operations are typically quite complex, certainly prone to greater error and inaccuracies through conventional analog methods. Instead, GIS is highly capable of storing, organizing, and performing quick analysis on large amounts of data. It is also capable of generating data, such as DEMs, from which data, otherwise difficult to obtain, can be obtained.

Despite some of the weaknesses, GIS also provides several advantages to coastal bluff analysis. Hazard zonation based on less data and completed in a short amount of time can still be of considerable use to planning authorities and engineers in arriving at regional policies for development and public access, in addition to useful dissemination of information to the public (Grainger and Kalaugher 1988).

7.1.5 - Implications of the Research, and Other Notes

The Risk Atlas, and observations from these maps, can be used to formulate several methods of dealing with the problem of bluff failure along the study site, and even the Great Lakes. Although a large amount could be written to develop these methods. and discuss comprehensive, alternative approaches, on the application of these methods and dissemination of information to the public, it is sufficient for this paper to simply summarize and suggest several options. This is not to say that these items are not important, and instead, this research fully supports such efforts, and wishes to guide and stimulate further research, as well as illustrate the potentially, practical nature of GIS and the results of analysis.

For a comprehensive review of management alternatives, as relevant to coastal slope failures, the reader is referred to reports listed in Chapter 3, Section 3.1, in addition to reports by Bird and Rosengren (1987), Bird (1994), Marsh (1983), and Kockelman (1986), who discussed a total of twenty seven ways that coastal and inland slope failures can be reduced. Risk and susceptibility maps are useful tools for use with almost all of his suggestions, particularly in terms of identifying where efforts should be focussed, and in determining what techniques should be applied. Many of methods recommended by these authors include hazard zonation maps, and allusions to the benefits of computers, and GIS. Coastal slope, hazard, and risk management are discussed in useful reports by Monmonier (1997), McGowan et al. (1988), and White (1978).

Throughout the GIS research of this study, a solid attempt has been made to use software, hardware and tools readily accessible to CAs and shoreline managers. Efforts have also been made to coordinate the methods and data of this research with those recommended by the GPSS (TL and AS 1998) and the TGGLSLS (OMNR 1994). By following these guidelines, the methods and direction of this research are readily incorporated into future plans of local governing bodies and CAs in the study area, and around the Great Lakes. The amount of work and time in this project is also reduced by using a team of researchers with more ready access to digital and analog data.

With this in mind, it makes sense that some of the recommendations from this study also help to further the stated goals of local governing bodies, such as the LPRCA. Contained within the LPRSMP (PA, TA, and PWA 1989), the LPRCA lists several key goals for shoreline management within their jurisdiction, including: **i)** prevention, **ii)** emergency response, **iii)** environment, **iv)** monitoring, **v)** protection, and **vi)** public information. Each of these goals also echo the objectives of the IDNDR, as stated in Chapter Two. The following discussion applies these goals to the application of this research, and the use of a GIS, in the management of shoreline bluffs within the study area, and Long Point Region. Since the LPRCA has oriented its goals towards dealing with issues of flooding and inundation, they would do well to update the LPRSMP to reflect and address bluff hazards and risks.

7.1.5.1 - Monitoring

As evidenced throughout this research, GIS is a useful tool for *monitoring* bluff erosion, gully formation and other factors which contribute to bluff failures and shore erosion. This is accomplished through the storage of information, as well as the generation of new data through the comparison of data sets. For example, recession rates can be monitored and measured by comparing temporal locations of bluff edges on an annual basis. By preparing data in a GIS, these bluff failure factors can be evaluated, and updated for planning and other purposes on a regular basis.

7.1.5.2 - Public Information

Perhaps one of the most important discoveries in this research, is that human action plays a major role in whether a slope failure manifests itself as a hazard or risk. Humans not only contribute to the hazard, but also take part in actions which increase their vulnerability. Unfortunately, residents, tourists, or others shoreline visitors often increase their vulnerability without even being cognisant of the reasons why. Since many people along the shoreline do not appear to be particularly aware of the magnitude or potential threat of coastal slope failures, it is suggested that lack of information and education plays a major role in determining risk. This problem should be addressed through *public information and education*, as provided by those 'in the know'. The

LPRCA, and other governing shoreline bodies, therefore have some responsibility to take a proactive role in this educating process, and ultimately, in reducing risk.

Literature and field work within the study area, made it clear that those who live near the shoreline, or those who visit the shoreline do not fully understand the factors, location, dynamics, vulnerabilities, or even the severity or magnitude of the slope failure hazards and risks. Several residents were informally interviewed east of Port Burwell, and in both cases they suggested methods to mitigate the bluff hazards which clearly indicated that they misunderstood bluff dynamics. One resident within the study reach suggested that the bluffs all along Lake Erie be graded to an angle where the hazard was eliminated (Miller 1998). Such a plan ignores the unfathomable cost, time and magnitude of such a project, in addition to the fact that bluff grading often exacerbates the problem (Kuhn and Shepard 1983), and that the bluffs will continue to erode regardless of slope. Sooner or later, wave energy and other subaqueous process would return the bluffs to their former angle and level of hazard.

A second resident had spent hundreds of dollars to spread Sakcrete (powder concrete) across small sections of the bluff face which exhibited seepage 'in an effort to stabilize the bluffs' (Allenson 1998). The concrete was of limited strength to hold back mass movements, and only trapped water behind the bluff face, increasing pore water pressure, and ultimately reducing shear strength. Upon a return visit to the property several months later, a 10 by 30m section of bluff, previously behind the concrete, had fallen to the lake through a large rotational slide. Similar misunderstandings are evidenced around the globe, such as in Australia, and the United Kingdom by Bird (1994).

There are numerous ways of educating, or providing information to the public about bluff hazards and risks. These could include, among other possibilities, education programs in the schools, pamphlets, programs and information stands at travel, visitor, or information booths in the region (eg. Port Burwell heritage sites, Backus Woods Heritage and Education Centre near Port Rowan), information at the LPRCA World Wide Web Site (or other sites), pamphlets or brochures available in major villages along the lake shore, and in public or private recreation areas, in addition to signs warning of the dangers of the bluffs. Information generated through the GIS research is useful in identifying where these efforts might be focussed, and what information needs to be made public. Based on the risky areas identified through the Risk Atlas, Port Burwell, Erie View Trailer Park, and Sand Hills Park are ideal locations for the posting or provision of information within the study site. Township engineers, planners, residents, and cottage owners are also ideal candidates to receive information.

Education through school systems is a particularly useful method of dispersing information to large numbers of people, and to individuals who are particularly vulnerable to slope failures during summer vacations, and family trips. During an interview with a curriculum coordinate at the Grand-Erie Board of Education (including Brant, Haldimand and Norfolk Counties), J. Rubas (1997) indicated that similar projects had been implemented in Brantford, as a result of recommendations after the death of the four young boys from nearby Paris. Plans called for inclusion of several classes on

Coastal Hazards within the upcoming Science curriculum for public schools, in addition to a continued publication of 'Shoreline Safety' brochures made available to teachers prior to summer holidays. In addition to these options, Cross (1988) discussed the benefits of examining hazard maps within the classroom. His discussion included mention of the hazards along coastal cliffs and bluffs.

Pamphlets or information brochures are also a useful method of informing the public of bluff hazards, particularly those within an older age bracket. Several public pamphlets have recently been published (eg. GLBC 1977) which encourage residents to be proactive in reducing bluff hazards and risks along the Great Lakes shoreline. This approach is readily evidenced in <u>Buyer's Guide to Shoreline Property</u> (EC and ACAO 1995). This pamphlet discourages people from buying bluff property, but alternatively, encourages those who are already located on bluffs, or wish to locate near bluffs, to look closely for tell-tale signs that the bluff is unstable, or eroding quickly. Distribution of these pamphlets to current and potential shoreline residents is an excellent method of informing the public. These pamphlets also encourage shoreline residents to consult CAs and Ontario Ministries for guidance and assistance in dealing with the bluff hazards.

Warning signs are a further useful method of educating and informing the public, and GIS can help identify where these signs should be located. Since the tragedy in 1994, Sand Hills Park has erected several signs within the confines of the park, and at the base of the bluffs, warning of the dangers of the bluffs. Unfortunately, the message within the signs is often long, of small lettering, and as a result, possibly unobserved by those who use the park. Signs might also include the fact that high rain events only exacerbate the instability of the bluffs, and shoreline visitors should completely avoid the bluffs subsequent to these events. In a fascinating report by Williams and Williams (1988), the pros and cons of sign warnings are discussed for coastal bluff hazards within Glamorgan Heritage Coast in Wales, UK. Extensive research indicated that the most effective signs are simple, of a bright colour with a border, utilize large letters that directly indicate the loss of life, and are used in combination with a simple diagram showing the combination of human presence and slope failure. The advantages and disadvantages of signs are also discussed by Bird (1994).

7.1.5.3 - Protection

In their report, Williams and Williams (1988) questioned who's responsibility coastal slope risk mitigation is ... 'the individual, or other governing bodies'? In the end, they concluded that the public cannot be trusted to use good sense with matters concerning their own safety. The research and results of this study should therefore be utilized directly by shore managers, such as the LPRCA to provide *protection* and planning with which to reduce risk.

One important way in which the LPRCA, or the local townships can provide protection is through land use zoning, as part of the Official Township Plans. These plans are particularly effective as they are backed by law, and reviewed and updated on a regular basis (OMMAH 2000). Risk and Susceptibility maps should, in future studies, be compared to the Official Plans to determine how Official Plans and land use zones could be improved through the GIS susceptibility and risk zonations generated in this research.

The results of the study could also be utilized as a short-term planning tool aimed at protecting the public and shoreline residents through temporary land zonations, running of risk scenarios for shoreline residents concerned about bluff recession, decision support for the location of seasonal dwellings (eg. mobile homes), construction of additions or extensions to existing homes or buildings, or simply to monitor and record changes in the bluffs. Monitoring and storage of information is very useful as a resource for updating and adjusting Official Plans when they are reviewed every five years. Short-term bluff information is also useful in providing information to engineering crews faced with relocation of roads or other infrastructure due to the rapid formation of gullies. Quite clearly, short term planning tools are of key importance within the highly dynamic environment of the coast, and GIS assessments can provide effective, efficient and quick analysis with which to support planning and public protection.

7.1.5.4 - Emergency Response

Finally, the LPRSMP (PA, TA, and PWA 1989) suggests that its management plan should provide some assistance in the realm of *emergency response*. Unfortunately, the plan does not discuss this goal at any great length, but it is recommended that the GIS research and other information collected in this study be used by either the LPRCA, or local emergency crews to aid in emergency responses to disasters or other bluff related events which threaten human well-being within the area of the bluffs. In the case of the Sand Hills Park tragedy, emergency crews travelled long distances from Simcoe, and rescue efforts were hampered by lack of familiarity with the bluff area, lack of familiarity with the bluff dynamics, and unknown access routes to the bluff base. Local residents also indicated that emergency crews had a difficult time accessing and attending to a para-sailor who had crashed into the face of the Sand Hills Park bluffs during the summer of 1999.

Information contained within this thesis, or generated through a summary of its contents could be provided to emergency crews responsible for the study area, to familiarize them with the bluff hazards and dynamics. Data digitized for the bluff area also included trails and access routes to the bluff edge, which may be fed into emergency crew GPS systems, or used a general reference with which to formulate timely, and effective responses to bluff emergencies.

7.1.6 - Error and Inaccuracies, Research Limitations

The preceding discussion has highlighted the benefits of using a GIS in slope stability analysis, potential implications of the research, and in some cases, cautions, considerations and limitations of the methods, analysis and results. With any GIS research, there are inherent errors and inaccuracies which make their way to the final product. Though it is often difficult to completely quantify these errors, it is important to identify sources so that the final product may be interpreted with these cautions, and future efforts be made to eliminate or reduce their effects.

Errors and inaccuracies were encountered throughout this study within the original sources, during input and output, and through data generalizations. For the purpose of this study, it was difficult to quantify the combined effects of these errors, but this should be attempted in future applications. Errors from *original sources* included errors of omission within the OBMs (eg. missing houses, outdated information), and errors of commission by those who digitized the original OBMs from air photos. Inevitably, these errors are transferred to this project. Errors may also be contained within the recession rate data set by Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989). Errors and inaccuracies were also noted through the digitization of the OBMs within MapInfo, including the offset of linework by 1 to 10m. Aside from known or detected errors, there may also have been undetected errors through omission or commission during the digitization, or the replication of Fleming's data set into the Quattro Pro database.

Several attempts were made to identify and reduce errors thorough the systematic comparison and verification between original data and digitized or tabulated datasets. Digitized maps were also compared to digital OBMs provided by the OMNR. Although not attempted, Aronoff (1989) suggested checking replicated maps against originals using a light table. In future applications, this method may be a useful method of detecting errors and inaccuracies. Field work was also used to verify physical, and human/cultural items on the OBM and NTS maps. Several differences were noted due to the date of the OBM culture checks, but not included on the digitized maps due to the time and work necessary to make these changes. The discussion of the risk maps has attempted to account for risk associated with these developments, but in future, these changes should be directly included in the human element maps.

Generalizations are another source of error, and are inherent with any mapping application. The original OBMs are themselves, generalizations of the study area, as noted in the case of the roads and buildings. Replication of the OBMs also requires generalizations, as evidenced in the digitizing of vegetation stands where straight lines must be interpolated from undulating lines in order to recreate the stands. With each factor map, the data were generalized into five classes, and then generalized further through the conversion of vector data to raster format. Although the small grid resolution is believed to reduce as much of this generalization as possible, assessments can only be applied, at best, to $10m^2$ grid cells, rather than specific points.

Generalizations were also generated during the weighting of factor layers, and during the MCE WLC evaluation, where algorithms and rounding of values are used to fit data to the final five tier classification. Above all, the choice of factors believed to contribute to bluff failure susceptibility greatly generalize the causal relationships and dynamics of bluff failures. A completely accurate model of the bluff susceptibility is, however, almost impossible, and the analysis used here is believed to represent, as best as possible, the bluffs along the study area shore. Further research into the nature of the Erie bluffs, and the inclusion of new data would only enrich the results, and could conceivably, reduce generalizations.

Finally, errors and inaccuracies occur through the output of the results. The maps contained within the Risk Atlas are only capable of holding a certain amount of information, and at a certain scale (1:10,000). A balance must be struck between displaying the maximum amount of information possible, and ease of interpretation. Graphical User Interfaces are far more effective at displaying large quantities of information and are recommended for this type of research.

Despite the errors and inaccuracies encountered throughout this research, it is felt that sufficient attempts were made to reduce these as much as possible, and that the final product reflects a carefully constructed, representative piece of work where calculations are made using quantitative to semi-quantitative assessments, information is not over-generalized, or fraught with so many errors that it is rendered useless. Although some generalizations are inherent and unavoidable for the purpose of this research, generalizations are of certain benefit in regional studies, and can be used to guide more detailed, precise, accurate, and reliable studies, and reduce the number of expensive, site specific, geotechnical studies.

7.2 - Recommendations for Further Research

Throughout the course of this research a wide variety of ideas for future research were generated. This is particularly when the nature of this study is largely exploratory. Many suggestions have already been noted, where appropriate, in the previous discussion, while those listed within this discussion are additional possibilities. These ideas can be broadly categorized as ideas for future data, and secondly, avenues of research which could be used to enrich the general methods and results of this study, or to simply investigate other aspects of bluff stability and dynamics.

7.2.1 - Data Sources

This study has highlighted the complexity of slope failures, especially the nature and interaction between factors which contribute to slope failures. Only several variables were able to be collected and included in the analysis, and though they are key factors, several additional factors and sources of data would greatly enrich the analysis. As noted previously, one of the advantages of GIS is the ease with which new information can be added to a database, reweighted, and included in revised or exploratory modeling.

An important indicator of slope stability, is the presence of previous landslide activity (Varnes 1984). This information has been used to assess the stability of many inland slopes (eg. Carrara et al. 1995, Joshi and Gupta 1990) and would be very advantageous for the analysis of slope failure susceptibility within the Lake Erie study reach. The primary advantage of this information is its use in performing higher level, statistical analyses of slope stability by calculating the relationship between the coincidence of former slope failures and certain slope instability factors (eg. elevation, vegetation). These relationships are used to predict the susceptibility or probability of slopes to failure, outside of a training unit. The process is often accomplished through probability analysis, regression analysis, and principal component analysis (Hansen A. 1984).

Aerial photographs of the study site are a cost-effective means of locating former coastal slope failures, as noted through research by Grainger and Kalaugher (1988). Although time was not available to obtain or digitize former failures from the photos, aerial photos are available for the site from the LPRCA, UW and WLU map libraries, National Air Photo Library in Ottawa including, in whole or in part, the years 1946, 1959, 1963, 1965, 1966, 1970, 1972, 1973, 1976, 1978, 1980, 1988, 1985, and 1990. Over the past decade, several video tapes (1990, 1994, 1995 and 1996) have also been taken from a plane along the study reach by LPRCA, and may be useful in locating former failures. In addition to statistical analysis, aerial photos would also be useful for verifying the results of the susceptibility maps produced in this research, determining temporal variations in the size or occurrence of failures, the spatial location of landslides, or their type of movement (eg. flows, falls, slides).

Groundwater and seepage has also been cited throughout the paper as a critical factor in the stability of slopes, and this was confirmed through field work and literature. Both play a major role in the stability and instability of the Great Lakes bluffs. Though it was originally hoped this information could be included in the analysis, information is difficult to obtain, or often recorded through hazardous (eg. walking along the bluff base), or expensive geotechnical studies (eg. well-drillings, bore logs). Hickinbotham (1977), and the OMOE (1972) both mapped ground water probability for Haldimand-Norfolk and Elgin County, but these were of a small scale, and outdated. Additionally, time was not available to evaluate how to use this information in a meaningful way. Despite limitations in obtaining seepage and ground water information, it would greatly enrich the analysis. Possible solutions to data problems may include investigations into ground water characteristics at site-specific locations, rather than at a regional scale (perhaps guided by the susceptibility maps), or through the mapping of bluff face seepage from a boat or plane travelling close to the shore. Video tapes from the LPRCA may also record this information.

Slope aspect data could also be useful in assessing bluff stability within the study site. One of these factors is slope aspect, which was inadvertently generated while processing elevation and slope from the TIN DEMs in ArcInfo. A data layer of polygons was generated through the *TINARC* command, in like manner as slope inclination, but was not included due to uncertainty surrounding the role of aspect in slope stability, and the lack of a suitable classification scheme. Literature noted that slope aspect is believed to control freezing and thawing in the slopes during winter months, and drying or dessication of the bluffs during summer, as controlled by available sunlight (Quigley and Gelinas 1976). Aspect also determines the amount of wave energy which reaches the bluff toe, as generated through prevailing winds. With further research, it is believed that this data could be classified and perhaps used as a further factor in the analysis.

Though GIS have not often been used to incorporate temporal factors into slope stability analysis, triggering factors are believed to play an important part in the stability of the study site bluffs. Data pertaining to rainfall, which increases ground water and reduces shear strength, would be particularly useful, in addition to the probability of short-term climatic events which raise water levels. Storms, seiche and high winds all contribute to rainfall and the erosion of bluff toes and the probability or characteristics of these events could be included into the analysis. As alluded to several times throughout this paper, GIS is somewhat limited in terms of its ability to assess temporal variations in dynamic systems such as coastal bluffs. Short term events such as rapid failures, human variations in location, storms, and ground water movement all vary temporally and are difficult to assess without recreating a new 'snap shot' in time. Further research should focus on accommodating these temporal variations.

Aside from the physical factors which influence the susceptibility of slopes to failure, many human factors are also important. Due to limited data included on the OBMs and NTS, this information was difficult to obtain, but would greatly enrich the analysis at a later date. Chapter Two noted that septic tanks, rainfall drains, culverts, agricultural irrigation, tile drains, agricultural practices (eg. furrows directed to bluff edge, drainage schemes), and vegetation removal, all contribute to slope instability. The spatial distribution of these factors, in addition to a better understanding of their effects on the bluffs, could be used to evaluate human contributions to slope stability. Human testimonies of previous tragedies and bluff failures would also be useful for background information and assessing factors which contribute to risk, or increase vulnerability.

Apart from extra data that could be useful in further stages of this research, several potentially important sources of research assistance or bluff information were also identified. These include information compiled during the Port Burwell Litigation, research at UWO, and investigations conducted at CCIW.

Kamphuis (25 Nov. 1998) noted that a wealth of information was collected during the Port Burwell Litigation, and filed away at the Ontario Regional Office of Public Works, Shepard and Yonge Street, Toronto. The nature of this data or information is unknown, but based on summary reports by Philpott (1983, 1986), could be very useful. Fleming's recession rate data (Fleming 1983, as cf. PA, TA, and PWA 1989) may also be available here, and could help to improve the application of recession rate data and sub-reaches within the analysis.

The literature review also indicated that a great deal of work was completed on geotechnical aspects of the bluffs by R. Quigley at the Faculty of Engineering Science, UWO. Much of this work is described in joint publications between Quigley and P. Gelinas from the Department of Geology at University of Ottawa (eg. Quigley and Gelinas 1976, Quigley et al. 1978, Gelinas and Quigley 1973), but it is recommended that time be spent contacting these individuals, or their respective University departments. Some of Quigley's publications were also completed with A. Zeman, and N. Rukavina at the Hydraulics Research Division, CCIW, in Burlington (eg. Quigley and Zeman 1978, 1980, Rukavina and Zeman 1987, Zeman 1978). Literature and discussions with individuals at CCIW (Holland-Hibbert 1997) indicated that useful data and reports on the Great Lakes bluffs are available through these individuals, and would be useful in future research, particularly with regards to subaqueous processes acting at the base of the bluffs and in the nearshore region.

7.2.2 - Additional and Related Research

During the process of this research, several recommendations for future research were identified. These suggestions include studies which would improve data or methods contained in this research, and research which would be interesting to pursue as part of largely unrelated bluff studies.

The literature review for this paper clearly indicates that more research needs to be either conducted or reported on coastal bluffs, particularly in terms of their hazards and risks. This is true for both international and Great Lakes shorelines. Much of the literature focusses on sensationalised, media-amenable events such as coastal storms, flooding, and inundation, when a great deal of damage, loss of life, and risk is incurred by coastal slope failures. A comprehensive summary needs to be generated to highlight the hazards and risks of both cohesive and non-cohesive bluffs to encourage further research, and to highlight its global geography, as encouraged by the IDNDR. Follow-up literature could also include useful methods of mitigating risks and hazards, including case studies, such as the one discussed in this paper, which highlighted the application and benefits of GIS and hazard zone mapping.

Literature also indicates that bluff hazard and risk research needs to be applied to the erodible portion of the Great Lakes. A summary report on the hazards, risks, and mitigation of bluff failures along the Great Lakes would help to stimulate additional research, and highlight the seriousness of the issue. Eventually, these efforts are likely to trickle down to the public, and shoreline residents. To date, a great deal of physical information has already been collected and it is time to summarize and apply this information to the mitigation of risk through the guidance of available resources such as the GPSS and the TGGLSLS. Rather than completely focussing research on lake levels flooding, and subaqueous studies, research and mitigation needs to be focussed towards the 'land side' of the erosion issue, such as slope failures, effective land use planning, education of the public, and reduction of risk. Since the causes, nature, and issues associated with bluff failures, hazards and risks tend to differ from lakeshore to lakeshore, and reach to reach, it is most logical that localized studies and research, such as the one presented in this paper, be reproduced by CAs.

One important observation while working with shoreline recession rates is the generalization involved in calculating recession rates, particularly for shorelines outside of the study site. AARRs are often calculated using short-term data, which does not represent variations in the bluff stability as affected by lake water levels and other short term events. AARRs also tend to imply that recession of the bluffs is linear, when this is hardly the case, and instead, recession rates are impacted by episodic variations brought about through large storm events, mass failures, or even dramatic changes in shoreline geology and stratigraphy as bluffs recede inland. Difficulties with recession rates were evidenced within Fleming's work (Fleming 1983, as cf. PA, TA, PWA 1989) where bluffs were recorded as accreting. Despite the value of research reported by Boyd (1981), the methods used in this study did not account for short-term variations in bluff recession. Thus, future research needs to focus on methods used to calculate recession rates, in order to improve estimates of AARR. This information, or data was not available for this research, but would greatly aid in the assessment of bluff hazards and risks at a local and international scale, and could potentially be developed through specialized algorithms or other methods of prediction.

During field work, it was noted that certain plant species could be associated with recent slope failures. This was confirmed through discussions with a UWO botanist (Allenson 1998), who runs a 'rare plant' nursery along the shoreline just east of Port Burwell. During the research, it was hypothesized that remote sensing could be used to identify recent coastal failures through spectral signatures unique to plant species which grow within recent slides (eg. Coltsfoot, ***Tusilago farfara L.***). The usefulness of such a project is believed to extend outside the Great Lakes, since May (1977) has also noted the presence of Coltsfoot within failures along the English coast.

Finally, it is felt that the methods used in this study would be very useful in aiding and stimulating other coastal slope analyses along the Great Lakes, but also along international coastlines. The results and methods of this study are also amenable to inland slope failures, despite the fact that they exhibit slightly different characteristics and processes. Chapters Three and Four evidenced several attempts to map and classify coastal hazards and risks, but without the use of GIS. This study presents a simple, flexible, effective, and efficient method of generating information that is useful for planners and, ultimately, the public along global coastlines. It is hoped that such methods could be used to reduce risks, such as damage to property, and particularly, the loss of human life.

7.3 - Summary Conclusions

As human activity increases near the shoreline, bluff failures along the north shore of Lake Erie are increasingly hazardous and, over the past two decades alone, are responsible for millions of dollars of damage to shoreline property, as well as the deaths and near deaths of a number of individuals. It is important that efforts be made to mitigate these hazards and risks.

As a first step towards mitigating risks associated with coastal bluff failures, this paper has examined the nature, dynamics, hazards, and risks of coastal slope failures, in addition to the geographic extent of the issue. An extensive review of literature has also noted the benefits of using GIS as a tool in the assessment of slope stability. Despite the fact that GIS is not reported to have been used in the examination of coastal bluffs, the methods and techniques for assessing inland slopes, are equally amenable to coastal slopes, hazards and risks.

Thus, this study focusses on the development and exploratory application of a GIS to the analysis of bluffs along a reach of Lake Erie's north central shore, between Port Burwell and Hahn Marsh, Long Point. Issues associated with data collection, preparation and management, in addition to analytical techniques and results are all discussed within this paper to illustrate the practical benefits of such research.

The results of the study are summarized through an Atlas of Coastal Bluff Risk. It is hoped that this information will be useful for informing local governing bodies of the dangers of the bluffs and the estimated risk at different locations along the shoreline. This information is believed to be extremely valuable to Conservation Authorities and other shoreline managers within the region. Ultimately, information from this study will be useful in educating the public, in order to reduce risk in the form of property damage and loss of human life.

This study has also been completed with the expectation that the methods and data contained in the research will be refined and improved upon. Methods were developed in such a fashion that they could easily be applied to analyses along other reaches of the Great Lakes, or international coastlines, where bluff failures present a serious threat to human well-being. The results and conclusions in this final chapter further suggested that the contribution of GIS should be seen in terms of the whole sequence of coastal bluff disaster reduction, from identifying areas at risk and monitoring and assessing slope stability and failure factors, through to warnings of their onset and measures (both short and long term) to minimize loss of life, injury and damage to property, as the International Decade for Disaster Reduction draws to a close.

> *"Even more, we hope that the general public will realize that sea cliffs are inherently unstable before investing life savings in homes on the cliffs. In the end, of course, the sea cliffs belong to the ocean, and the ocean eventually will reclaim its property."* Emery and Kuhn 1982, 652.

Appendices

APPENDIX A

Appendix A: Summary Data Tables for Unclassified, and/or Classified Idrisi Images of Elevation, Slope Inclination, Geology/Stratigraphy, Recession Rates, Vegetation Cover, Shore Protection, Human Elements, and Susceptibility and Risk to Bluff Failure.

I) Elevation - Unclassified Data: Summary of land area occupied by each elevation range within the raw data Idrisi image for a 10yr recession setback. Final classification scheme also indicated.

Final Class	Elevation Range (masl)	Bluff Elevation (m)	10yr Recession Setback Area (km2)	Proportion
0	0	No Data	322983.7	99.38%
0	-9999.0	No Data	33.7	0.01%
1	173.5	0.0	169.6	0.05%
1	173.5 - 174.9	0.01 - 1.49	43.4	0.01%
2	175 - 179.9	1.5 - 6.49	223.3	0.07%
3	180 - 184.9	6.5 - 11.49	232.5	0.07%
4	185 - 189.9	11.5 - 16.49	262.5	0.08%
5	190 - 194.9	16.5 - 21.49	257.7	0.08%
5	195 - 199.9	21.5 - 26.49	331.9	0.10%
5	200 - 204.9	26.5 - 31.49	360.8	0.11%
5	205 - 29.9	31.5 - 36.49	68.4	0.02%
5	210 - 214.9	36.5 - 41.49	10.1	0.00%
5	215 - 219.9	41.5 - 46.49	6.3	0.00%
5	220 - 224.9	46.5 - 51.49	5.8	0.00%
5	225 - 229.9	51.5 - 56.49	10.3	0.00%
Totals			1982.6	0.59%

Notes:
- Elevation range of '0' indicates pixels outside 10yr recession setback
- Elevation range of '-9999' indicates pixels (Lake Erie specifically) which were assigned a 'no elevation' value in the ArcInfo grid, but are part of the Idrisi 10yr recession setback generated from MapInfo recession polygons.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

II) Elevation - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Elevation Range (masl)	Bluff Elevation (m)	10yr Recession Setback Area (km2)	Proportion	20yr Recession Setback Area (km2)	Proportion	5yr Recession Setback Area (km2)	Proportion
0	0.00	0.0 or No Data	323017.4	99.39%	322245.8	99.15%	324133.4	99.73%
1	173.5	0.01 - 1.5	213.0	0.07%	219	0.07%	87.6	0.03%
2	175.1 - 180.0	1.51 - 6.5	223.3	0.07%	234.6	0.07%	104.6	0.07%
3	180.1 - 185.0	6.51 - 11.5	232.5	0.07%	264.1	0.08%	98.3	0.03%
4	185.1 - 190	11.5 - 16.49	262.5	0.08%	333.5	0.10%	108.4	0.03%
5	190.1 - 230	16.51 - 56.5	1051.3	0.32%	1703	0.52%	467.7	0.14%
Totals			1982.6	0.61%	2754.2	0.84%	866.6	0.30%

Notes:
- Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

iii) Slope - Unclassified Data: Summary of land area occupied by each slope range within the raw data Idrisi image for a 10yr recession setback. Final classification scheme also indicated.

Final Class	Slope Inclination (degrees)	10yr Area (km2)	Proportion	Final Class	Slope Inclination (degrees)	10yr Area (km2)	Proportion
0	-9999.00	30	0.0009%				
0	0.00	3248013.7	99.9389%				
1 & 2	0.01 - 0.99	522.9	0.0161%	5	45.00 - 45.99	6.2	0.0002%
2	1.00 - 1.99	104.5	0.0032%	5	46.00 - 46.99	4.2	0.0001%
2	2.00 - 2.99	74.3	0.0023%	5	47.00 - 47.99	4.7	0.0001%
2	3.00 - 3.99	53.4	0.0016%	5	48.00 - 48.99	2.5	0.0001%
2	4.00 - 4.99	39.7	0.0012%	5	49.00 - 49.99	4.2	0.0001%
2	5.00 - 5.99	29.4	0.0009%	5	50.00 - 50.99	1.9	0.0001%
2	6.00 - 6.99	24.7	0.0008%	5	51.00 - 51.99	1.1	0.0000%
2	7.00 - 7.99	23.7	0.0007%	5	52.00 - 52.99	0.3	0.0000%
2	8.00 - 8.99	21.8	0.0007%	5	53.00 - 53.99	0.6	0.0000%
2	9.00 - 9.99	23.1	0.0007%	5	54.00 - 54.99	0.7	0.0000%
2	10.00 - 10.99	21.3	0.0007%	5	55.00 - 55.99	0.3	0.0000%
2	11.00 - 11.99	23.6	0.0007%	5	56.00 - 56.99	0.0	0.0000%
2	12.00 - 12.99	26	0.0008%	5	57.00 - 57.99	0.3	0.0000%
2	13.00 - 13.99	18.2	0.0006%	5	58.00 - 58.99	0.3	0.0000%
2	14.00 - 14.99	12.4	0.0004%	5	59.00 - 59.99	1.8	0.0001%
2	15.00 - 15.99	14.3	0.0004%	5	60.00 - 60.99	0.0	0.0000%
2	16.00 - 16.99	9.2	0.0003%	5	61.00 - 61.99	0.4	0.0000%
2	17.00 - 17.99	16.2	0.0005%	5	62.00 - 62.99	0.2	0.0000%
3	18.00 - 18.99	23.1	0.0007%	5	63.00 - 63.99	0.4	0.0000%
3	19.00 - 19.99	18.7	0.0006%	5	64.00 - 64.99	0.0	0.0000%
3	20.00 - 20.99	20	0.0006%	5	65.00 - 65.99	0.2	0.0000%
3	21.00 - 21.99	28.3	0.0009%	5	66.00 - 66.99	0.0	0.0000%
3	22.00 - 22.99	31.5	0.0010%	5	67.00 - 67.99	0.3	0.0000%
3	23.00 - 23.99	26.8	0.0008%	5	68.00 - 68.99	0.0	0.0000%
3	24.00 - 24.99	34.5	0.0011%	5	69.00 - 69.99	1.0	0.0000%
3	25.00 - 25.99	35	0.0011%	5	70.00 - 70.99	3.3	0.0001%
4	26.00 - 26.99	34.5	0.0011%	5	71.00 - 71.99	0.0	0.0000%
4	27.00 - 27.99	35.9	0.0011%	5	72.00 - 72.99	0.0	0.0000%
4	28.00 - 28.99	39.5	0.0012%	5	73.00 - 73.99	0.4	0.0000%
4	29.00 - 29.99	30.7	0.0009%	5	74.00 - 74.99	1.0	0.0000%
4	30.00 - 30.99	34.3	0.0011%	5	75.00 - 75.99	1.4	0.0000%
4	31.00 - 31.99	30.9	0.0010%	5	76.00 - 76.99	2.0	0.0001%
4	32.00 - 32.99	33.9	0.0010%	5	77.00 - 77.99	3.1	0.0001%
4	33.00 - 33.99	41.5	0.0013%	5	78.00 - 78.99	3.3	0.0001%
5	34.00 - 34.99	31.2	0.0010%	5	79.00 - 79.99	2.9	0.0001%
5	35.00 - 35.99	23.7	0.0007%	5	80.00 - 80.99	8.0	0.0002%
5	36.00 - 36.99	24.6	0.0008%	5	81.00 - 81.99	6.1	0.0002%
5	37.00 - 37.99	22.8	0.0007%	5	82.00 - 82.99	13.6	0.0004%
5	38.00 - 38.99	19.7	0.0006%	5	83.00 - 83.99	26.1	0.0008%
5	39.00 - 39.99	14.2	0.0004%	5	84.00 - 84.99	24.7	0.0008%
5	40.00 - 40.99	14.9	0.0005%	5	85.00 - 85.99	35.2	0.0011%
5	41.00 - 41.99	11.5	0.0004%	5	86.00 - 86.99	33.9	0.0010%
5	42.00 - 42.99	10.2	0.0003%	5	87.00 - 87.99	28.5	0.0009%
5	43.00 -43.99	17.1	0.0005%	5	88.00 - 88.99	5.6	0.0002%
5	44.00 - 44.99	7.8	0.0002%	5	89.00 - 89.99	0.1	0.0000%
				Totals		1986.3	0.00764

Notes: - Slope inclination of '-9999' indicates pixels (Lake Erie specifically) which were assigned a 'no slope' value in the ArcInfo grid, but are part of the Idrisi 10yr recession setback generated from MapInfo recession polygons.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

iv) Slope - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Slope Inclination (degrees)	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	323013.7	99.39%	322242.1	99.15%	324133.5	99.73%
1	0	312.7	0.10%	470.3	0.14%	137.3	0.04%
2	0.1 - 17.9	746.3	0.23%	1350.3	0.42%	237.4	0.07%
3	18 - 25.9	217.6	0.07%	223.2	0.07%	145.6	0.04%
4	26 - 33.9	281.6	0.09%	283.7	0.09%	191.2	0.06%
5	>34	428.1	0.13%	430.4	0.13%	155	0.05%
Totals		1986.3	0.62%	2757.9	0.85%	866.5	0.26%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

v) Geology/Stratigraphy - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Geology/Stratigraphy	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	322983.7	99.38%	322212	99.14%	324120.6	99.73%
1	Clay Rhythmites, or Clay Rhythmites over Diamicton	279.3	0.09%	386.6	0.12%	8.4	0.00%
2	Sand over Silt, Clay Rhythmites or Sand over Diamicton	414.2	0.13%	597.8	0.18%	143.7	0.04%
3	Sand over Sand Rhythmites	149.1	0.05%	208.3	0.06%	0	0.00%
4	Mixed - Till, Diamicton, Sand, Sand Rhythmites	129.2	0.04%	154.5	0.05%	0	0.00%
5	Sand, Sand Rhythmites over Silt, Clay Rhythmites	1044.5	0.32%	1440.8	0.44%	727.3	0.22%
Totals		2016.3	0.63%	2788	0.85%	879.4	0.26%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

vi) Recession Rate - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Recession Rate (m/yr)	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	0 or No data	322983.7	99.38%	322212	99.14%	324120.6	99.73%
1	> 2.0	4.9	0.00%	5.2	0.00%	0	0.00%
2	1.21 - 2.0	0	0.00%	0	0.00%	0	0.00%
3	0.71 - 1.2	107.6	0.03%	123.5	0.04%	0	0.00%
4	0.31 - 0.7	399.7	0.12%	526.6	0.16%	0	0.00%
5	< 0.31	1504.1	0.46%	2132.7	0.66%	879.4	0.27%
Totals		2016.3	0.61%	2788	0.86%	879.4	0.27%

Notes:
- Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Recession Rates were calculated by averaging annual average recession rates within homogenous recession rate reaches, using data collected by Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989).
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

vii) Vegetation Cover - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Human Elements at Risk to Failure	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	324836.9	99.95%	324757.2	99.93%	324968.5	99.99%
1	Vegetation Cover Present	386	0.12%	503.7	0.15%	139.9	0.04%
2	-	0	0.00%	0	0.00%	0	0.00%
3	-	0	0.01%	0	0.00%	0	0.00%
4	-	0	0.01%	0	0.00%	0	0.00%
5	Vegetation Cover Absent	1630.3	0.50%	2284.3	0.70%	739.5	0.23%
Totals		2016.3	0.64%	2788	0.85%	879.4	0.27%

Notes:
- Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

viii) Shore Protection - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Human Elements at Risk to Failure	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	324836.9	99.95%	324757.2	99.93%	324968.5	99.98%
1	Shore Protection Present	91.4	0.03%	124.9	0.04%	19.3	0.01%
2	-	0	0.00%	0	0.00%	0	0.00%
3	-	0	0.00%	0	0.00%	0	0.00%
4	-	0	0.00%	0	0.00%	0	0.00%
5	Shore Protection Absent	1924.9	0.59%	2663.1	0.82%	860.1	0.26%
Totals		2016.3	0.62%	2788	0.86%	879.4	0.27%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

ix) Human Elements - Classified Data: Summary of land area occupied by each class within the initial Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Human Elements at Risk to Failure	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	324836.9	99.95%	324757.2	99.93%	3249685	99.99%
1	Historical Cultural	0	0.00%	0	0.00%	0	0.00%
2	Other Infrastructure	0	0.00%	4.1	0.00%	0	0.00%
3	Infrastructure	36	0.01%	67.1	0.02%	9	0.00%
4	Residential	23.7	0.01%	42.1	0.01%	3	0.00%
5	Recreation Areas	103.4	0.03%	129.5	0.04%	19.5	0.01%
Totals		163.1	0.05%	242.8	0.07%	31.5	0.01%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

x) Susceptibility to Slope Failure - Unweighted: Summary of land area occupied by each class of susceptibility within the Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Susceptibility Rating	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	322983.7	99.38%	322212	99.14%	324120.6	99.73%
1	Low	0	0.00%	0	0.00%	0	0.00%
2	Moderate	21.5	0.01%	21.9	0.01%	29.6	0.01%
3	High	349.3	0.11%	459	0.14%	232.1	0.07%
4	Very High	1437.3	0.44%	2097.3	0.65%	617.7	0.19%
5	Severe	208.2	0.06%	209.8	0.06%	0	0.00%
Total		2016.3	0.62%	2788	0.86%	879.4	0.27%

Notes:
- Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

xi) Susceptibility to Slope Failure - Weighted: Summary of land area occupied by each class of susceptibility within the Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Susceptibility Rating	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	322983.7	99.38%	322212	99.14%	324120.6	99.73%
1	Low	0.5	0.00%	0.5	0.00%	2.2	0.00%
2	Moderate	58.7	0.02%	63.1	0.02%	22.6	0.01%
3	High	647.5	0.20%	937.6	0.29%	133.8	0.04%
4	Very High	498.4	0.15%	617.3	0.19%	694.9	0.21%
5	Severe	811.2	0.25%	1169.5	0.36%	25.9	0.01%
Total		2016.3	0.62%	2788	0.86%	879.4	0.27%

Notes:
- Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

xii) Risk to Slope Failure - Unweighted: Summary of land area occupied by each risk class within the Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Risk Rating	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	324836.9	99.95%	324757.2	99.93%	324968.5	99.99%
1	Low	18.1	0.01%	0	0.00%	0	0.00%
2	Moderate	35.2	0.01%	2.3	0.00%	1.6	0.00%
3	High	43.8	0.01%	24.9	0.01%	3	0.00%
4	Very High	65.8	0.02%	215.1	0.07%	26.9	0.01%
5	Severe	0.20	0.00%	0.50	0.00%	0	0.00%
Totals		163.1	0.05%	242.8	0.08%	31.5	0.01%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

xiii) Risk to Slope Failure - Weighted: Summary of land area occupied by each risk class within the Idrisi image for 20, 10, and 5yr recession setbacks.

Class	Risk Rating	10yr Recession Setback Area (km2)	10yr Recession Setback Proportion	20yr Recession Setback Area (km2)	20yr Recession Setback Proportion	5yr Recession Setback Area (km2)	5yr Recession Setback Proportion
0	No Data	324836.9	99.95%	324757.2	99.93%	324968.5	99.99%
1	Low	31	0.01%	0	0.00%	0	0.00%
2	Moderate	18.8	0.01%	4.4	0.00%	2.2	0.00%
3	High	79.4	0.02%	40	0.01%	1.7	0.00%
4	Very High	33.9	0.01%	198	0.06%	27.6	0.01%
5	Severe	0	0.00%	0.40	0.00%	0	0.00%
Totals		163.1	0.05%	242.8	0.07%	31.5	0.01%

Notes: - Data for the 5yr setback only summarizes the recession sub-reach with the highest annual average recession rate.
- Totals exclude Class '0' values. Total number of pixels in the entire image is 3,250,000.

APPENDIX B

Appendix B: Annual Average Recession Rates, Big Otter Ck. to Hahn Marsh 1937-1975, as determined by Fleming (Fleming 1983, as cf. PA, TA, and PWA 1989). Sub-reaches and final classification scheme is also indicated.

REACH	FINAL CLASS	AARR * (m/yr)	NO. OF SAMPLES	AVERAGE RR** (per sub-reach)	BASE CHAINAGE (m)		LOT LINE	TOWNSHIP / GEOGRAPHIC LOCATORS	NOTES ON SAMPLE SITES AND CALCULATIONS
								Big Otter Ck	
1	3-High	---	2	1.10	98.191	98.18	11/12	Bayham	No Data
		1.08			98.295				
		1.11			98.399				
2	1-Low	-1.18	1	0.30	98.503				Aver.RR* re-assessed as 0.30
3	4-Very High	[redacted]	2	1.36	98.607	98.6	12/13		
					98.711				
4	5-Severe		100	3.93	98.815				
					98.919	98.96	13/14		
					99.023			Little Otter Ck	
					99.128				
					99.232				
					99.336	99.32	14/15		
					99.44				
					99.544				
					99.643				
					99.743				
					99.842	99.82	15/16		
					99.942				
					100.041				
					100.14				
					111.24	100.3	16/17		
					100.339				
					100.439				
					100.538				
					100.637	100.7	17/18		
					100.737				
					100.836				
					100.936				
					101.035				
					101.134	101.1	18/19		
					101.234				
					101.333				
					101.433				
					101.532	101.5	19/20		
					101.63				
					101.728				
					101.826				
					101.923	101.9	20/21		
					102.021				
					102.119				
					102.217				
					102.315	102.4	21/22		
					102.413				
					102.51				
					102.608				
					102.706				
					102.804	102.8	22/23		
					102.902				
					103				
					103.097				
					103.195				
					103.293	103.3	23/24		
					103.391				
					103.489				
					103.587				
					103.685	103.7	24/25		
					103.782				

		[redacted]			103.88				
					103.978				
					104.076				
					104.174	104.2	25/26		
					104.271				
					104.369				
					104.467				
					104.565	104.6	26/27		
					104.663				
					104.76				
					104.858				
					104.956				
					105.054	105.5	27/28		
					105.151				
					105.249				
					105.347				
					105.445				
					105.541	105.5	28/1	Bayham/Norfolk	
					105.637				
					105.733				
					105.83				
					105.926				
					106.022				
					106.118				
					106.214	106.2	1/2		
					106.31				
					106.406				
					106.503				
					106.599				
					106.695				
					106.791				
					106.887	106.9	2/3		
					106.983				
					107.79				
					107.176				
					107.272				
					107.368				
					107.465				
					107.562	107.5	3/4		
					107.659				
					107.755				
					107.852				
					107.949				
					108.046				
					108.143				
					108.24	108.2	4/5		
					108.336				
					108.433				
					108.53				
5	4-Very High		4	1.91	108.627				
					108.724				
					108.821				
					108.918	108.9	5/6		
6	5-Severe		2	2.10	109.014				
					109.111				
7	4-Very High		5	1.80	109.208				
					109.305				
					109.402				
					109.499				
					109.595	109.6	6/7		
8	5-Severe		2	2.12	109.692				
					109.789				
9	4-Very High		1	1.79	109.886				
10	5-Severe		8	2.26	109.982				
					110.079				
					110.176				
					110.273	110.2	7/8		
					110.37				
					110.466				
					110.563				
					110.66			Houghton	
11	4-Very High		8	1.68	110.757				
					110.854	110.9	8/9		
					110.95				
					111.047				

		[redacted]			111.144				
					111.241				
					111.336				
					111.43				
12	1-Low	-0.55	1	0.30	111.525				Aver.RR* re-assessed as 0.30
13	5-Severe	[redacted]	8	2.68	111.62	111.5	9/10		
					111.714				
					111.809				
					111.903				
					111.998				
					111.093				
					112.187				
					112.282	112.2	10/11		
14	4-Very High		2	1.53	112.377				
					112.471				
15	3-High	1.05	7	0.88	112.566			Sand Hills	
		0.84			112.661				
		0.71			112.755				
		0.82			112.85				
		0.87			112.944	112.9	11/12		
		0.89			113.039				
		1			113.134				
16	4-Very High	[redacted]	10	1.59	113.24				
					113.347				
					113.453				
					113.56	113.5	12/13		
					113.666			Jacksonburg	
					113.772				
					113.879				
					113.985				
					114.092				
					114.198	114.2	13/14		
17	5-Severe		2	2.21	114.304				
					114.411				
18	4-Very High		15	1.70	114.517				
					114.624				
					114.73				
					114.836	114.8	14/15		
					114.943				
					115.049				
					115.156				
					115.262				
					115.357	115.4	15/16		
					115.452				
					115.547				
					115.641				
					115.736				
					115.831				
					115.926				
19	5-Severe		1	2.03	116.021	116	16/17		
20	4-Very High		1	1.87	116.116				
21	5-Severe		27	2.77	116.21				
					116.305				
					116.4				
					116.495				
					116.59				
					116.685	116.7	17/18		
					116.78				
					116.874				
					116.969				
					117.064				
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					117.259			Clear Ck	
					117.36	117.3	18/19		
					117.46				
					117.561				
					117.661				
					117.761				
					117.862	117.9	19/20		
					117.962				
					118.062				
					118.163				
					118.263				
					118.364				
					118.464				
					118.564	118.5	20/21		

					118.665				
					118.966				
					119.066				
					119.167	119.1	21/22		
					119.267				
					119.366				
					119.466				
					119.565				
					119.665				
					119.764	119.8	22/23		
23	5-Severe		2	2.06	119.864				
					119.963				
24	4-Very High		1	1.87	120.063				
25	5-Severe		2	2.08	120.162				
					120.262				
26	4-Very High		3	1.77	120.362	120.3	23/A	Houghton/S.Walsingham	
					120.461				
					120.561				
					120.66				No Data
					120.76				No Data
27	3-High		0	1.20	120.859				No Data - Interpolated Aver.
					120.959				No Data
					121.058				No Data
28	4-Very High		0	2.00	***				No Data - Interpolated Aver.
								Hahn Marsh	

NOTES: - * Annual Average Recession Rate (AARR) in meters per year
- ** Recession Rate (RR) in meters per year. Calculated by averaging all AARRs within each recession sub-reach.
- *** No data collected. Sample site not included in calculation of sub-reach average recession rate (RR).

APPENDIX C

RISK AND SUSCEPTIBILITY OF BLUFF FAILURE:
10 Year Assessment

Port Burwell to Hahn Marsh,
North Central Lake Erie, Ontario, Canada

LEGEND

Risk

- Severe - Class 5
- Very High - Class 4
- High - Class 3
- Moderate - Class 2
- Low - Class 1

Susceptibility

- Severe - Class 5
- Very High - Class 4
- High - Class 3
- Moderate - Class 2
- Low - Class 1

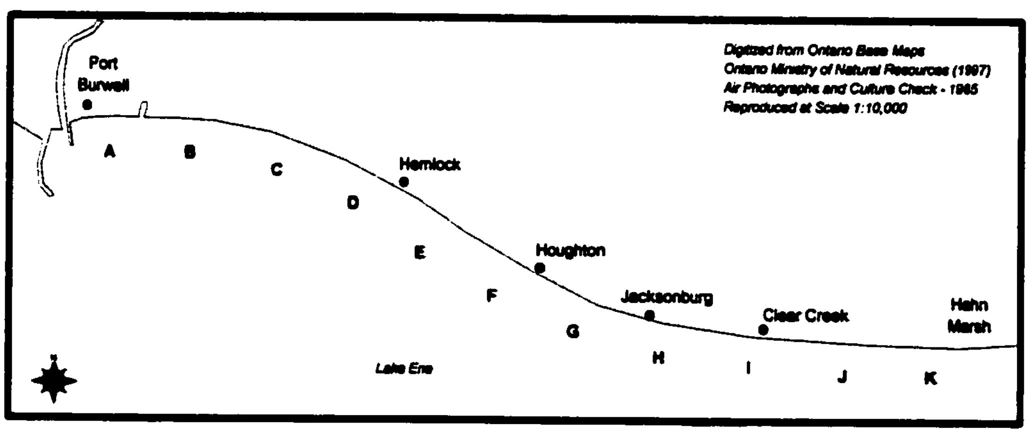
Human Elements at Risk

- Residential (permanent/seasonal)
- Other buildings
- Historical and cultural features
- Church
- Communications tower
- Cemetary
- Recreation area (public/private park, beach)
- Road (paved, or loose surface, driveways)

Other

- Water bodies (Lake Erie, ponds, dugouts, creeks)
- Vegetation cover (forest stands, large hedgerows)
- Marsh (Hahn Marsh)
- Elevation contours
- Trail (loose surface, rough but accessible by large vehicles)

LOCATION OF INDIVIDUAL MAP SHEETS



Wilfrid Laurier University, Waterloo, Ontario

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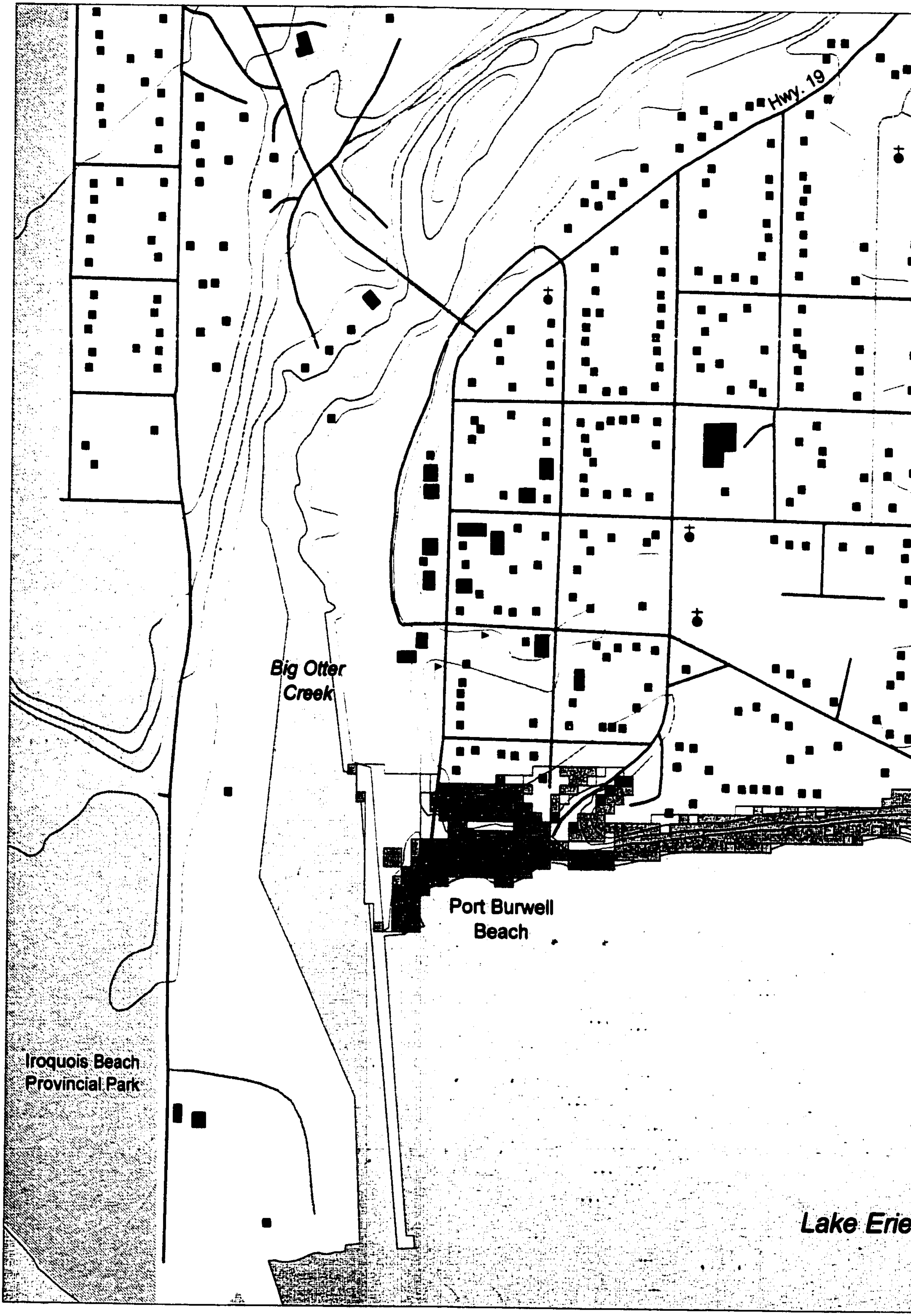
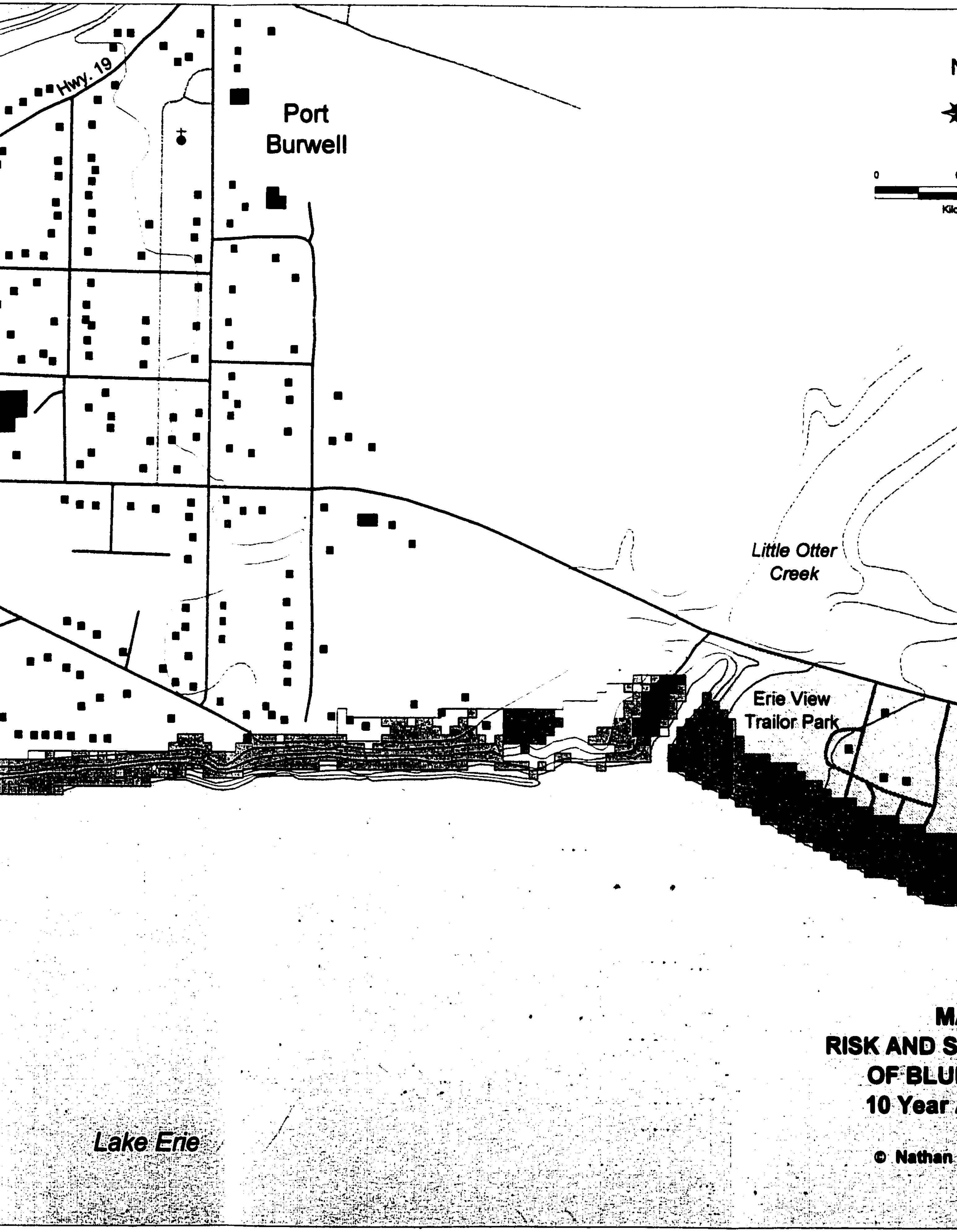

Hwy. 19
Big Otter Creek
Port Burwell Beach
Iroquois Beach Provincial Park
Lake Erie



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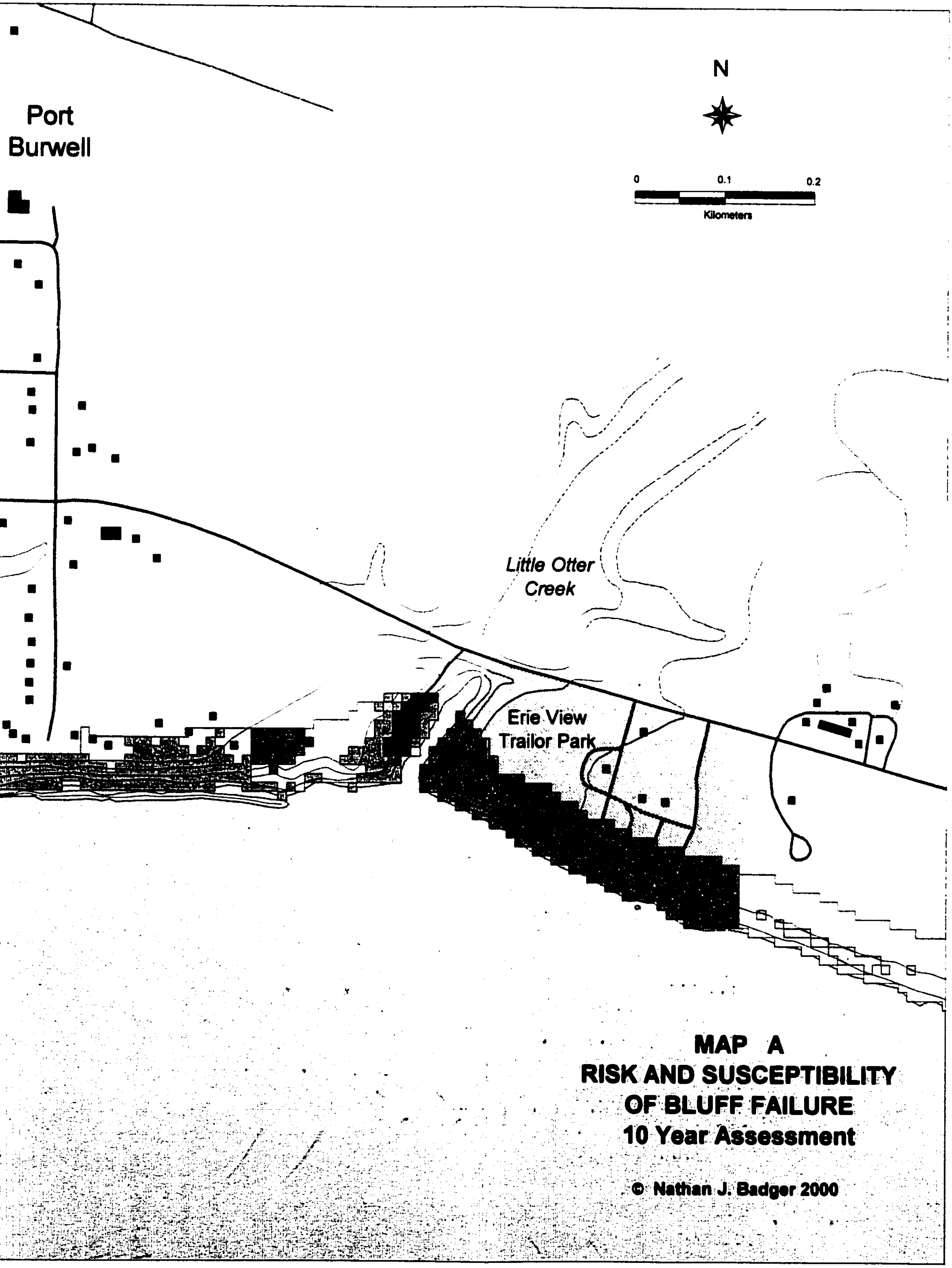

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MAP A
RISK AND SUSCEPTIBILITY
OF BLUFF FAILURE
10 Year Assessment
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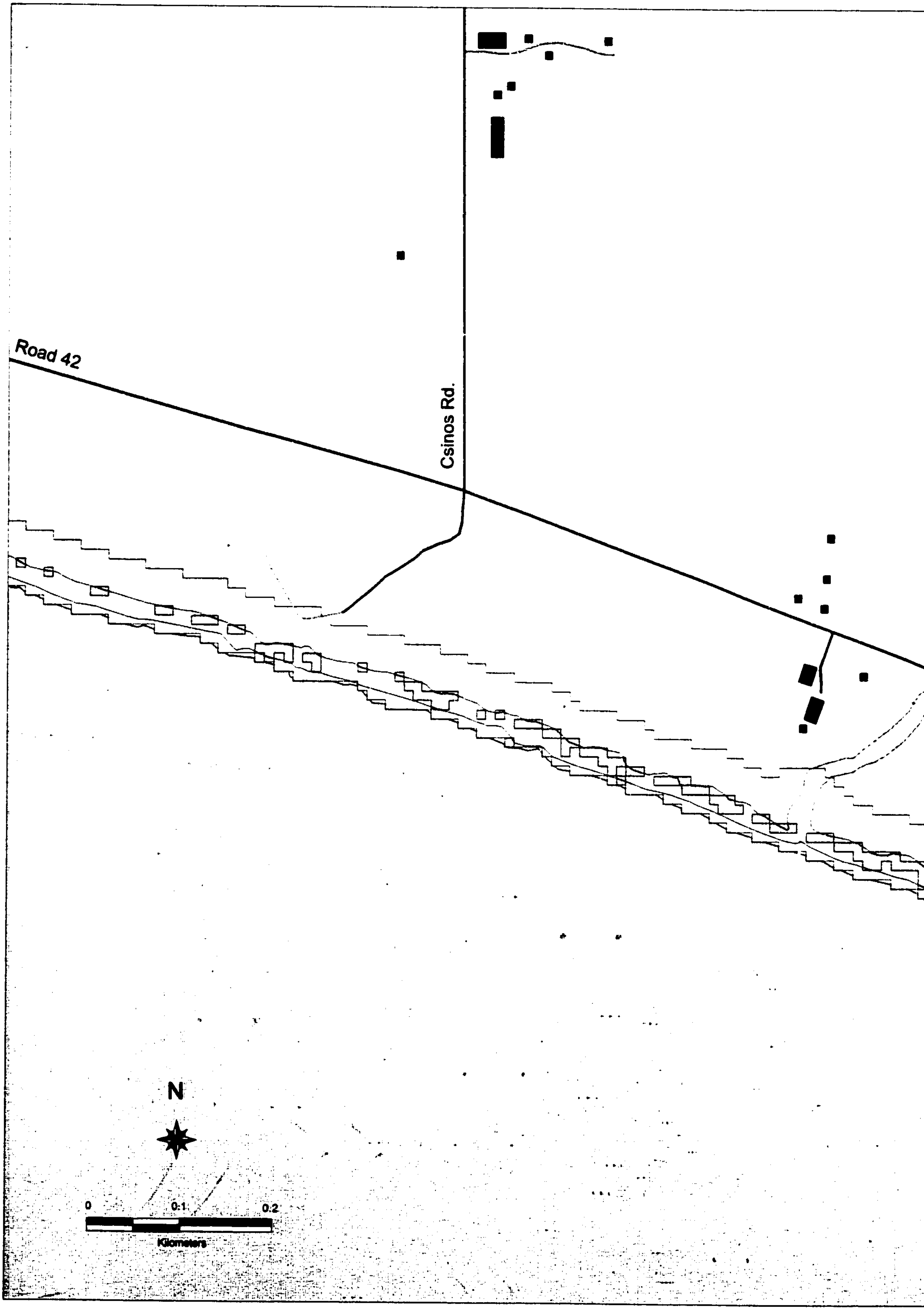

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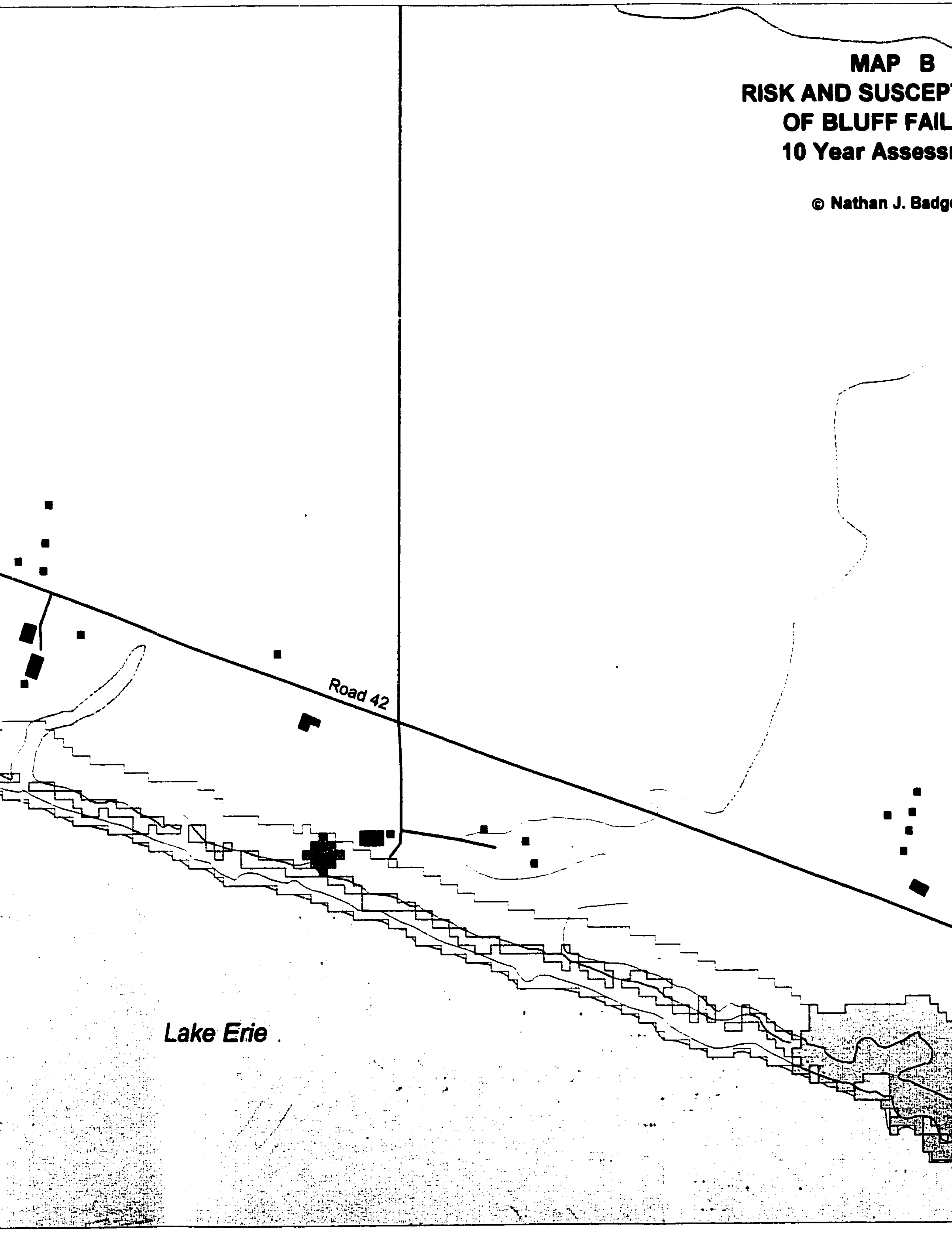

MAP B
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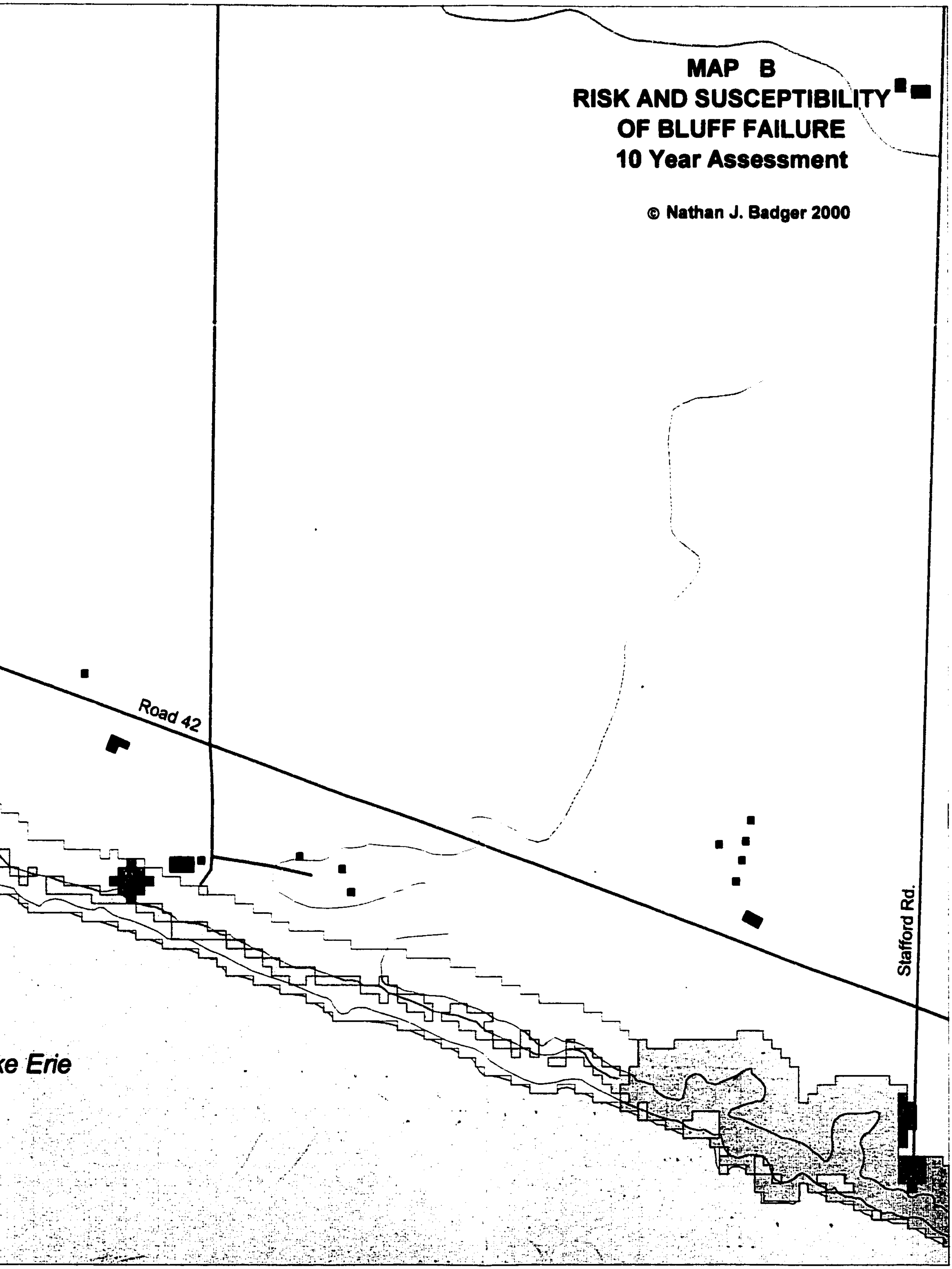
MAP B
RISK AND SUSCEPTIBILITY
OF BLUFF FAILURE
10 Year Assessment
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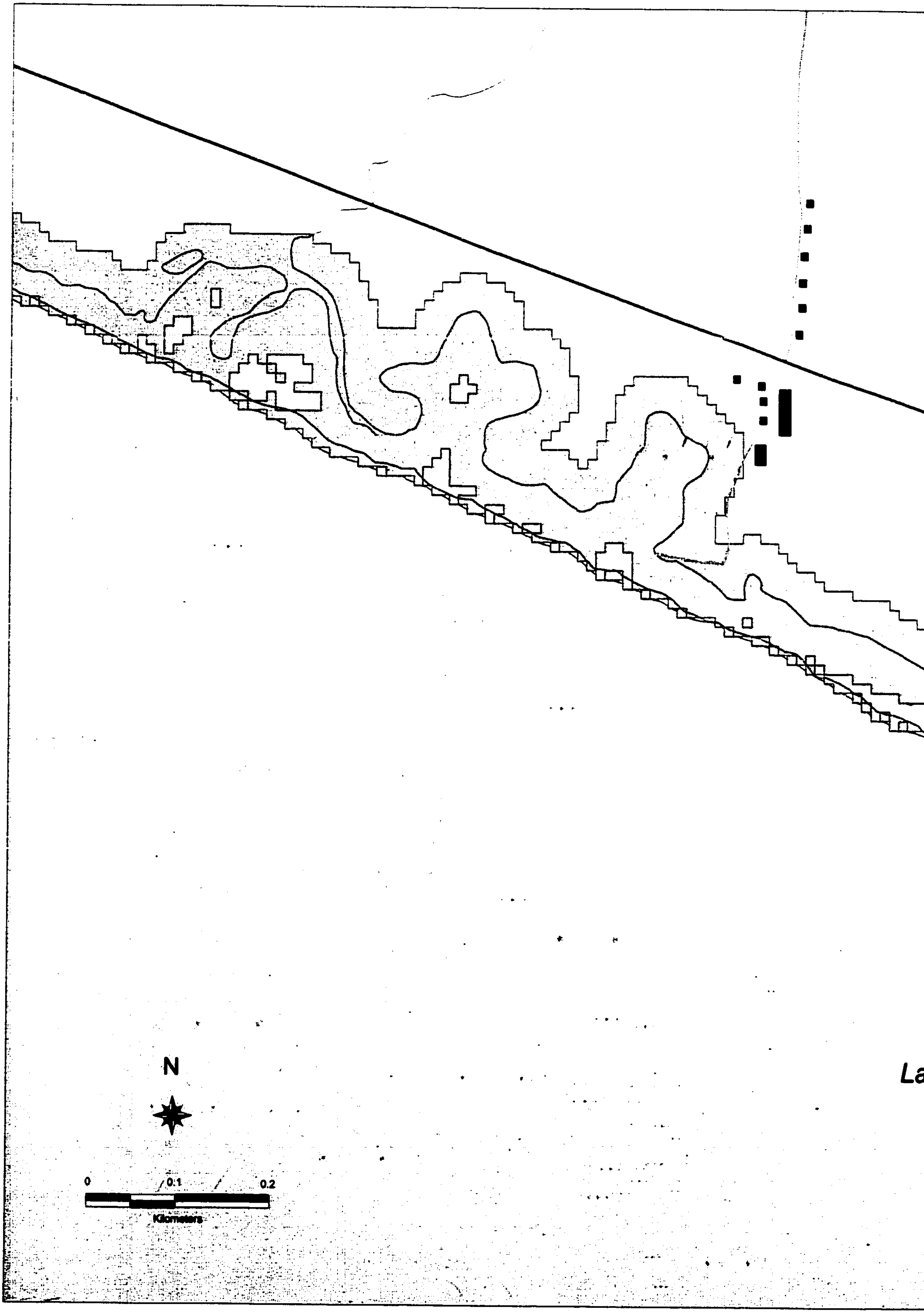
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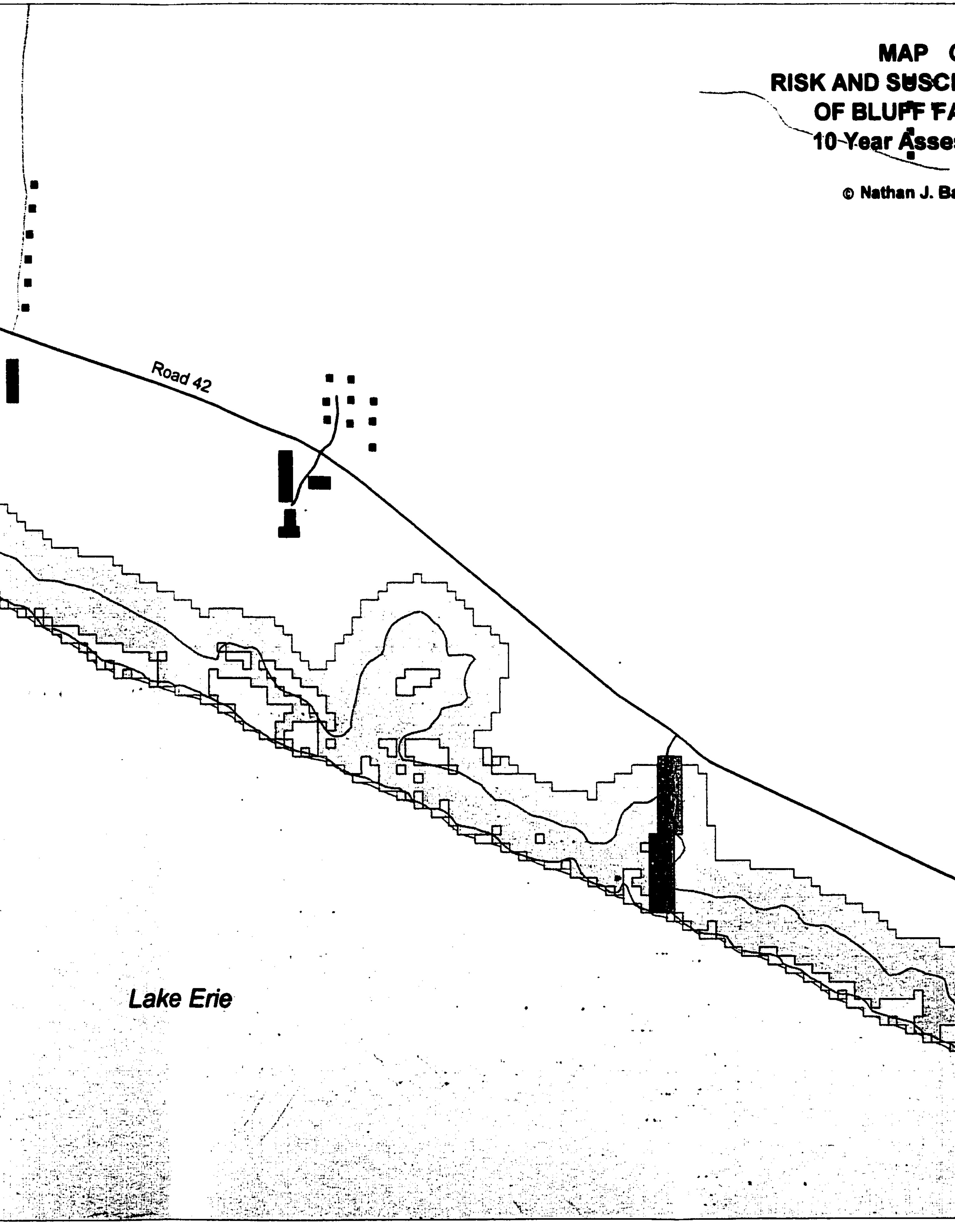

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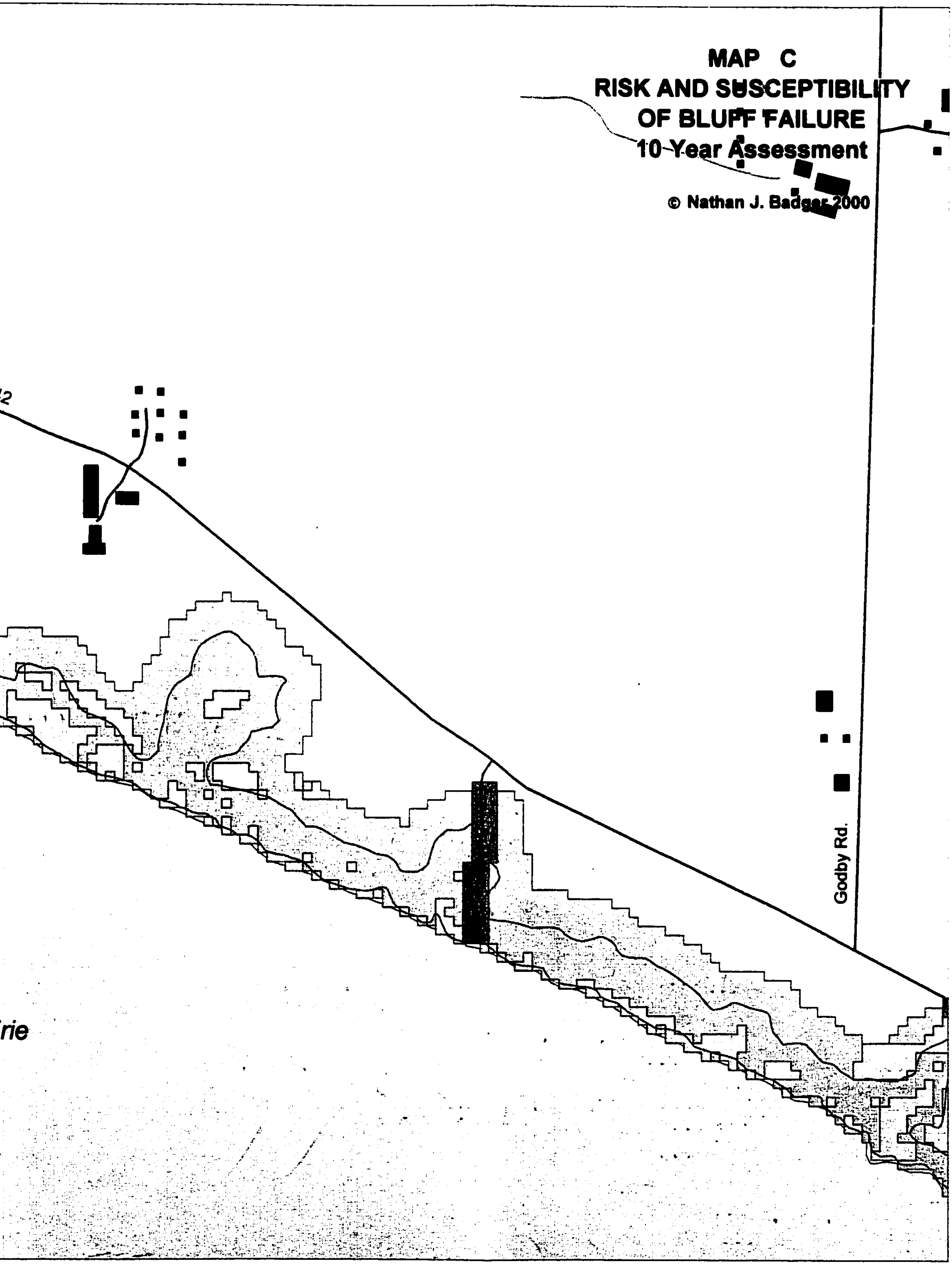
MAP C
RISK AND SUSCEPTIBILITY
OF BLUFF FAILURE
10-Year Assessment
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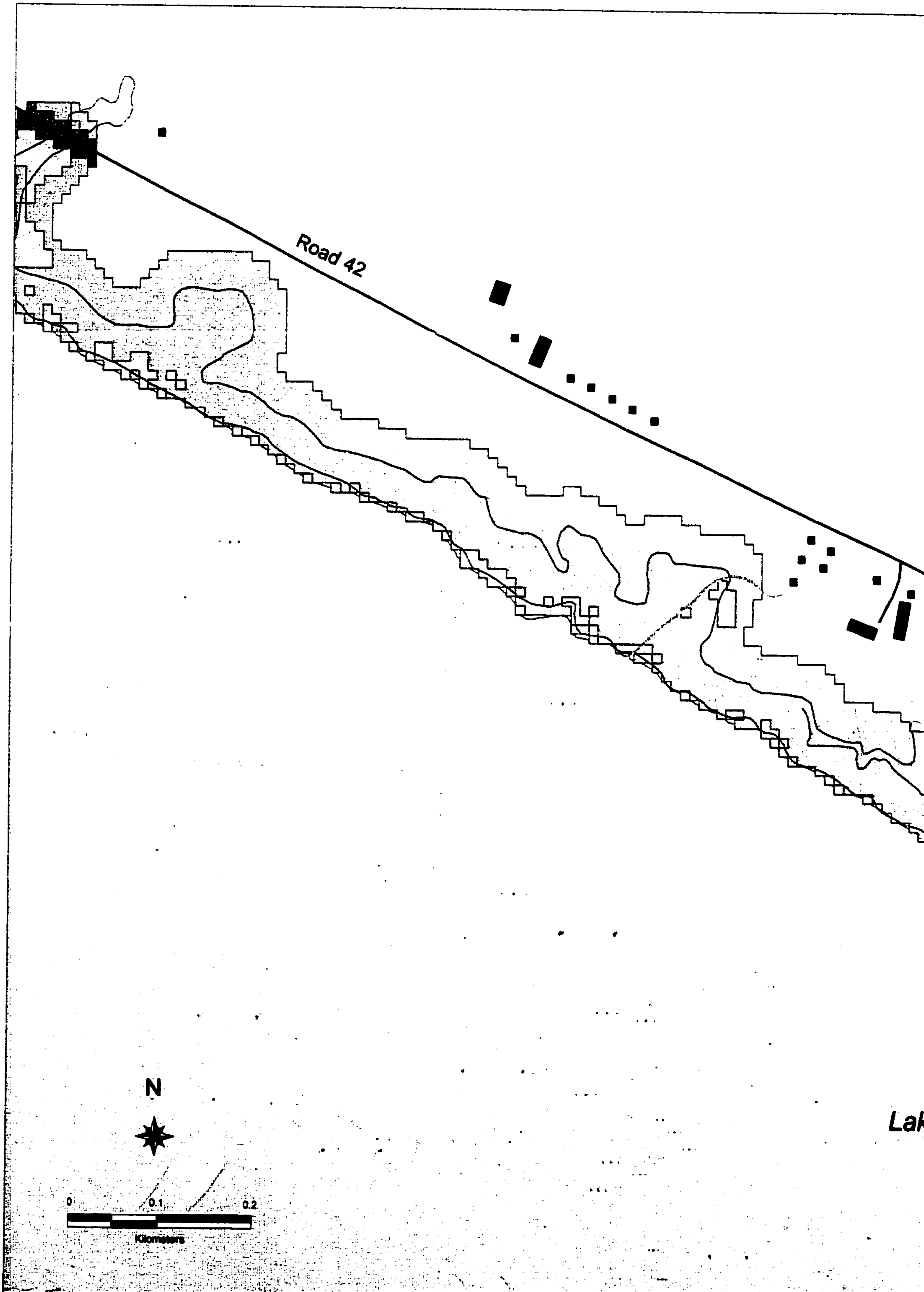
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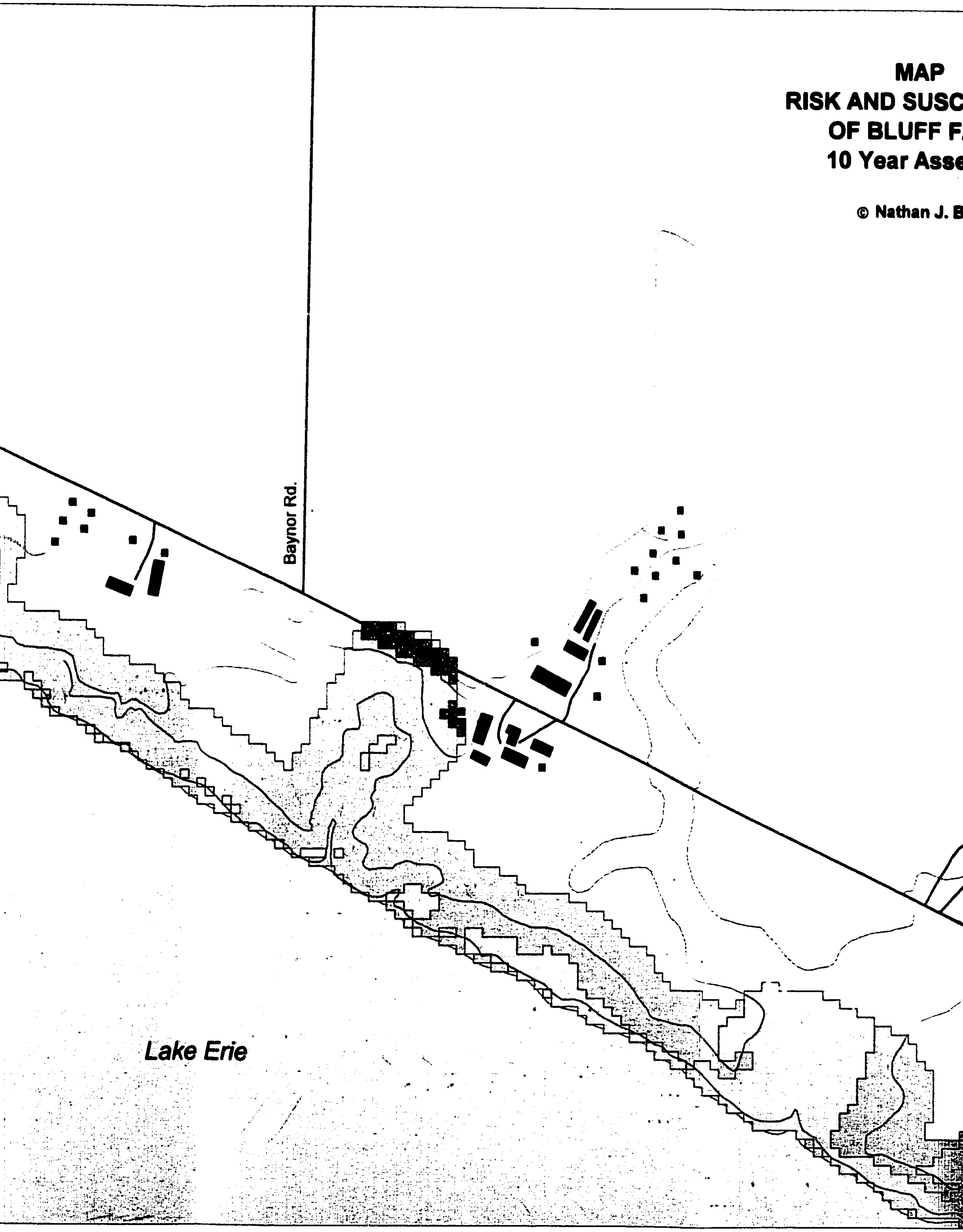

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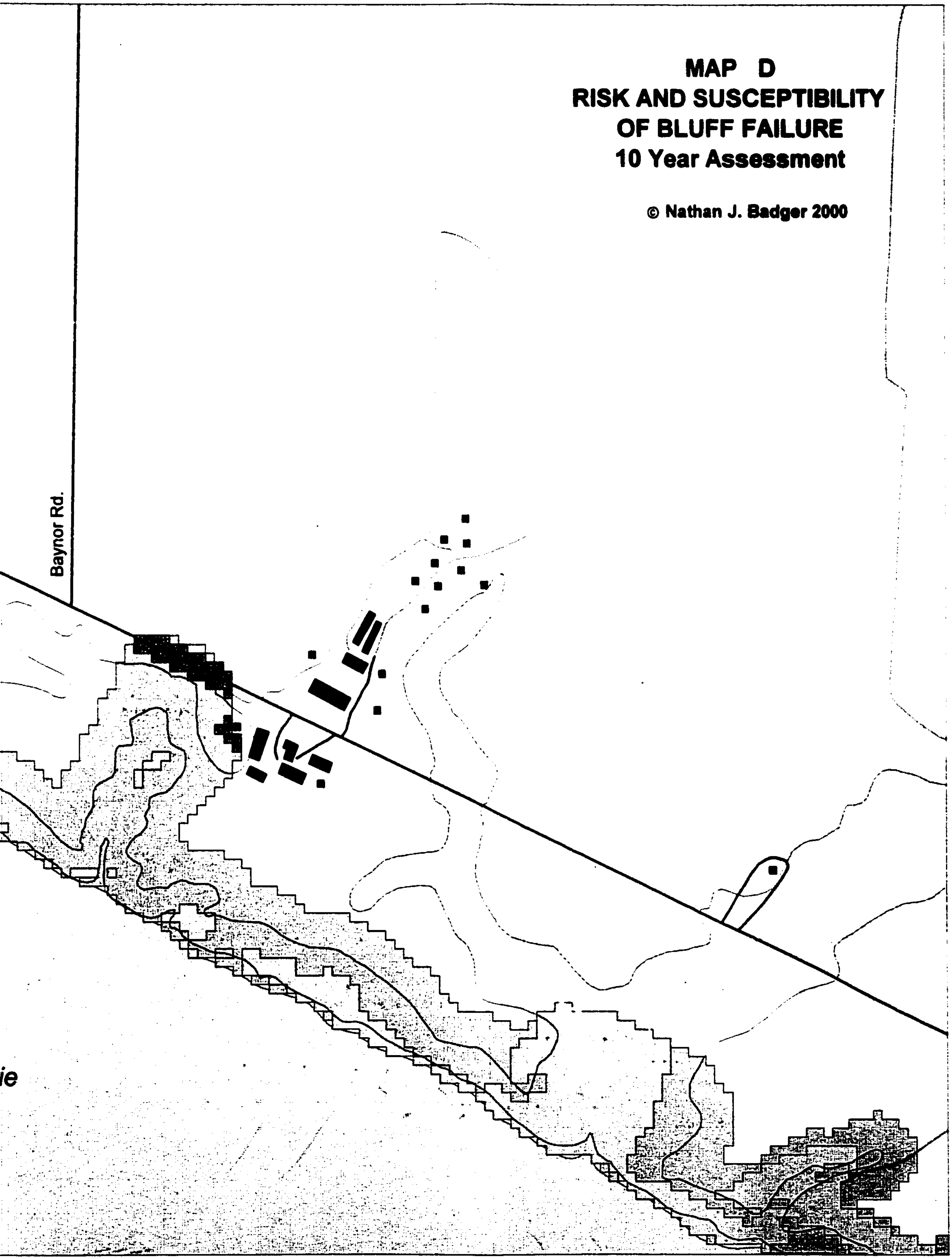
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OF BLUFF FAILURE
10 Year Assessment
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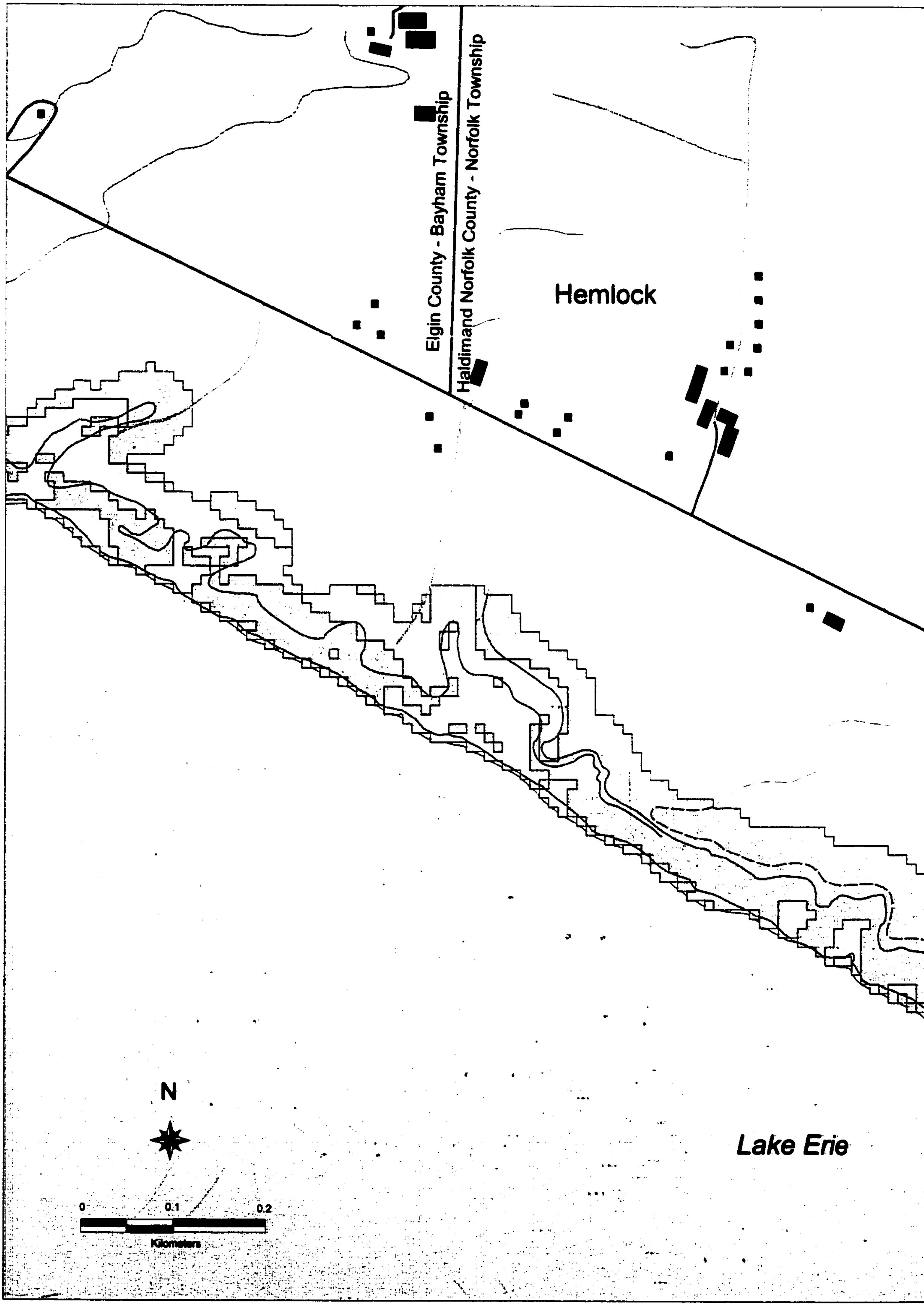
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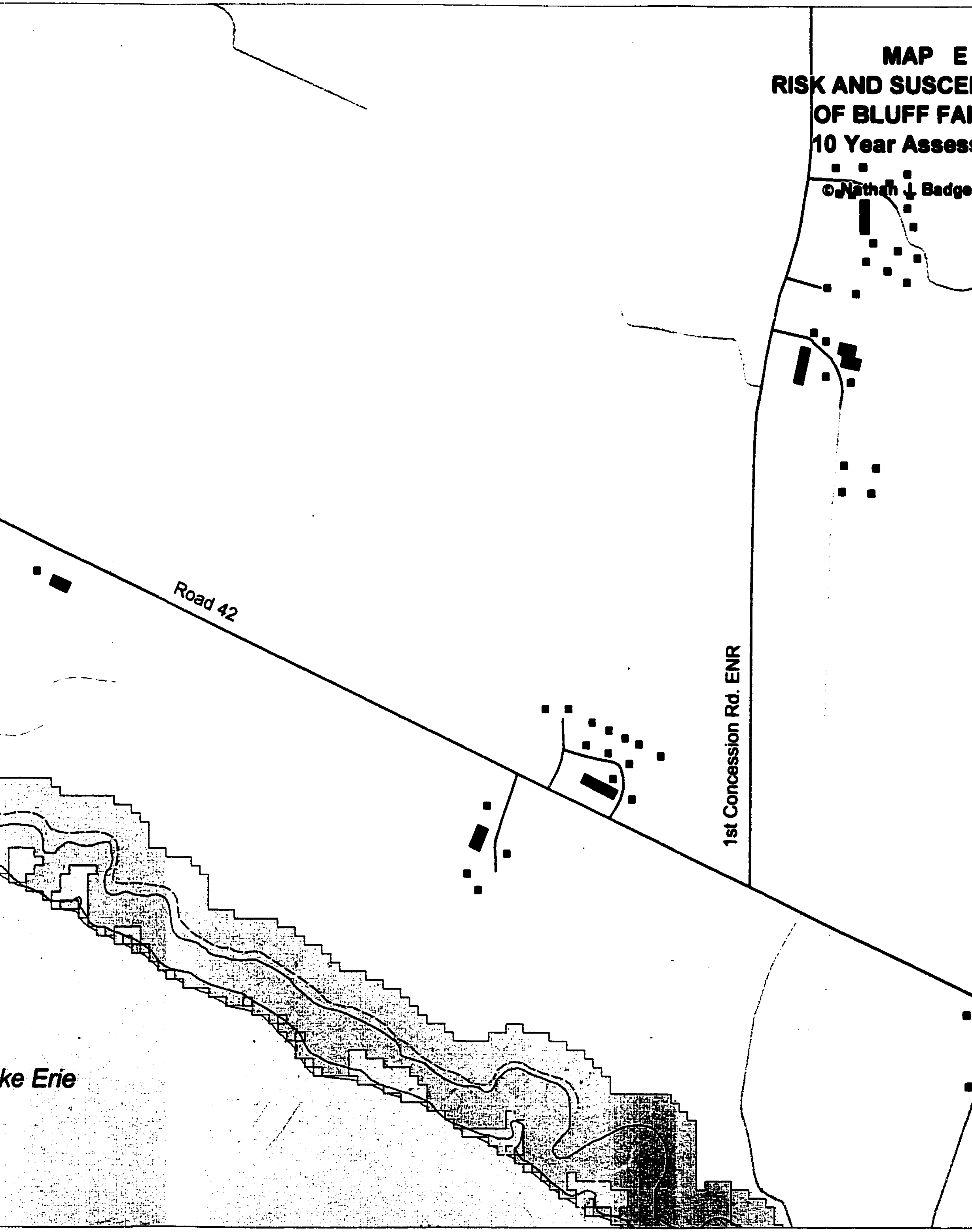
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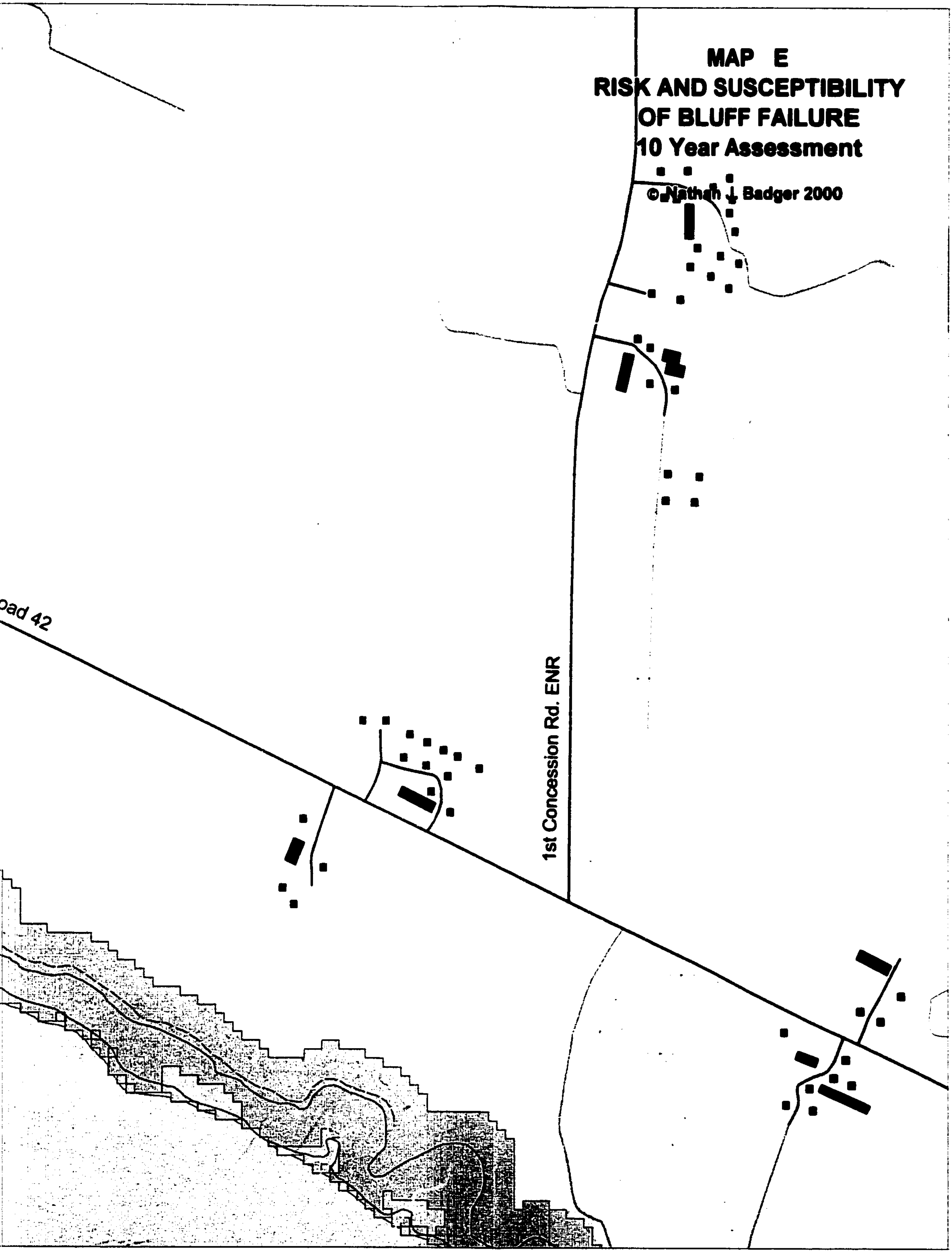
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10 Year Assessment
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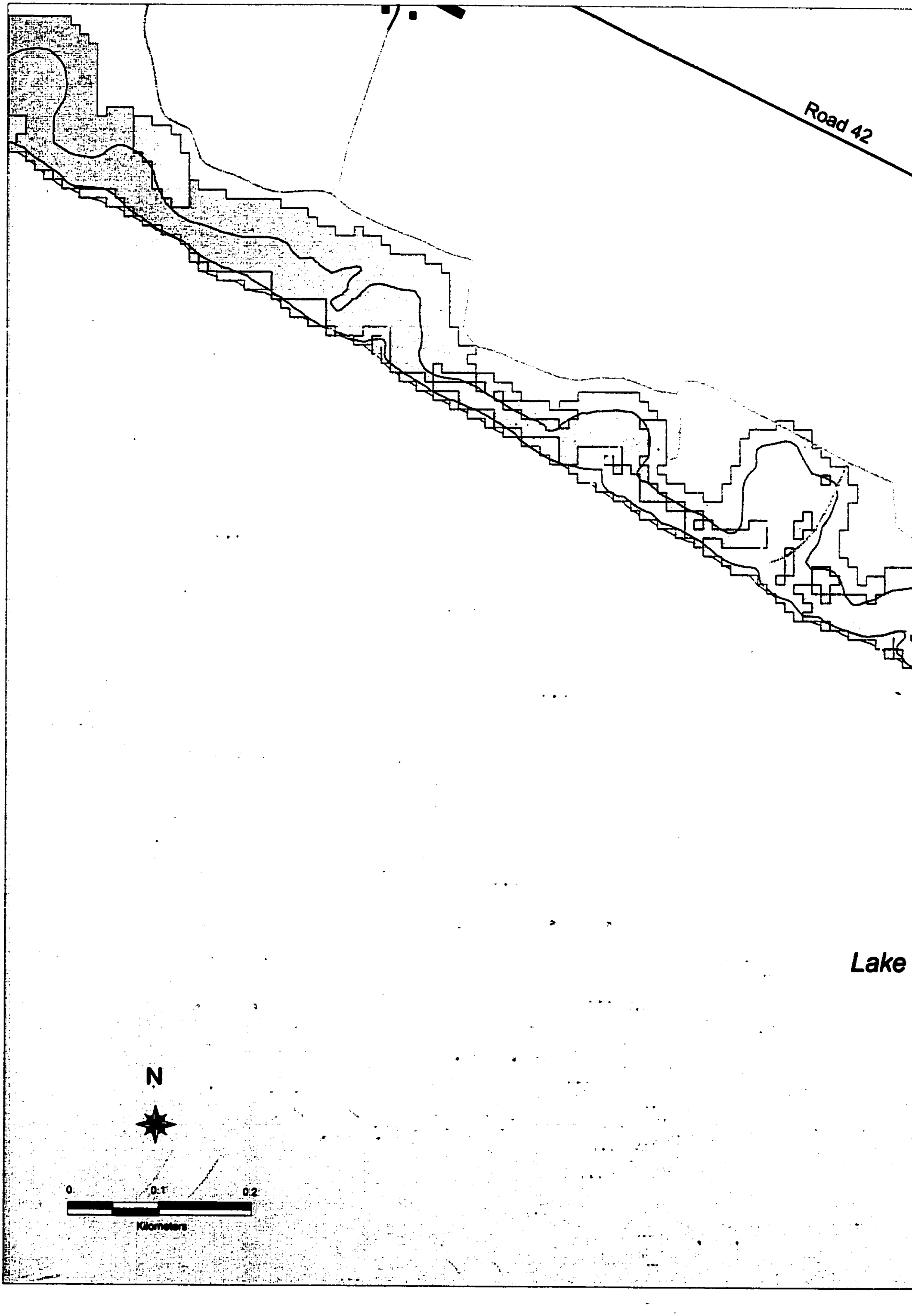

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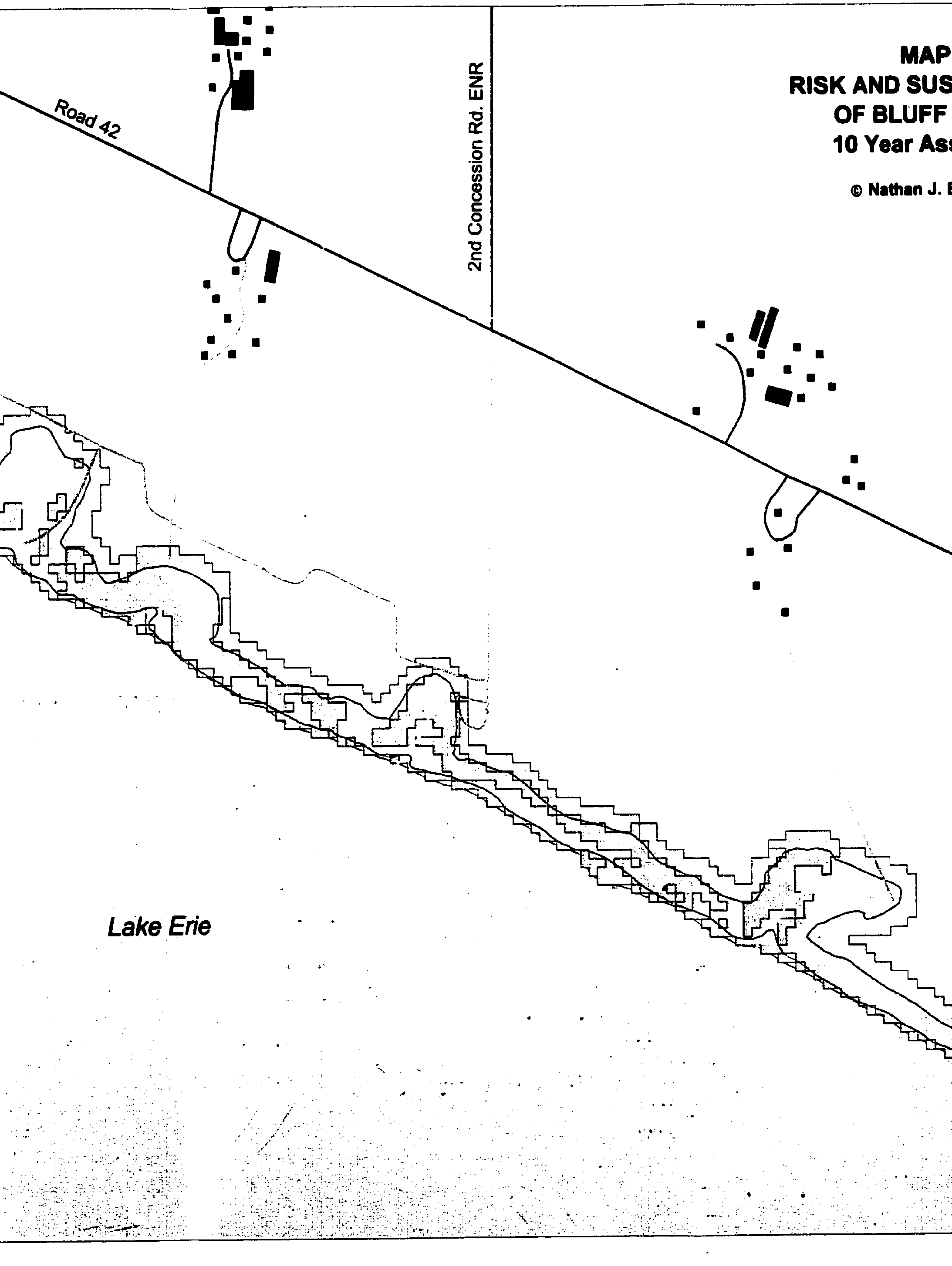
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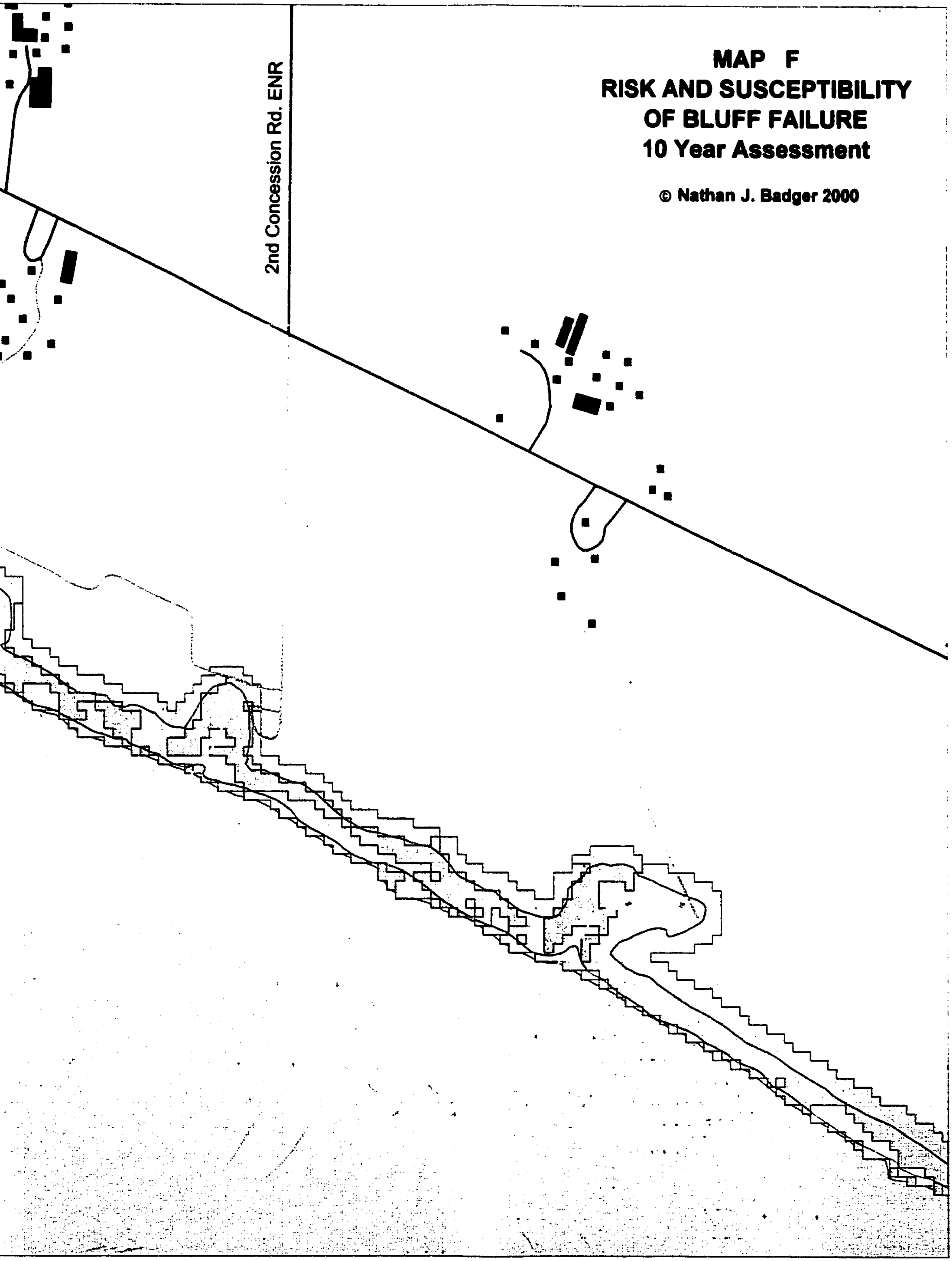

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10 Year Assessment
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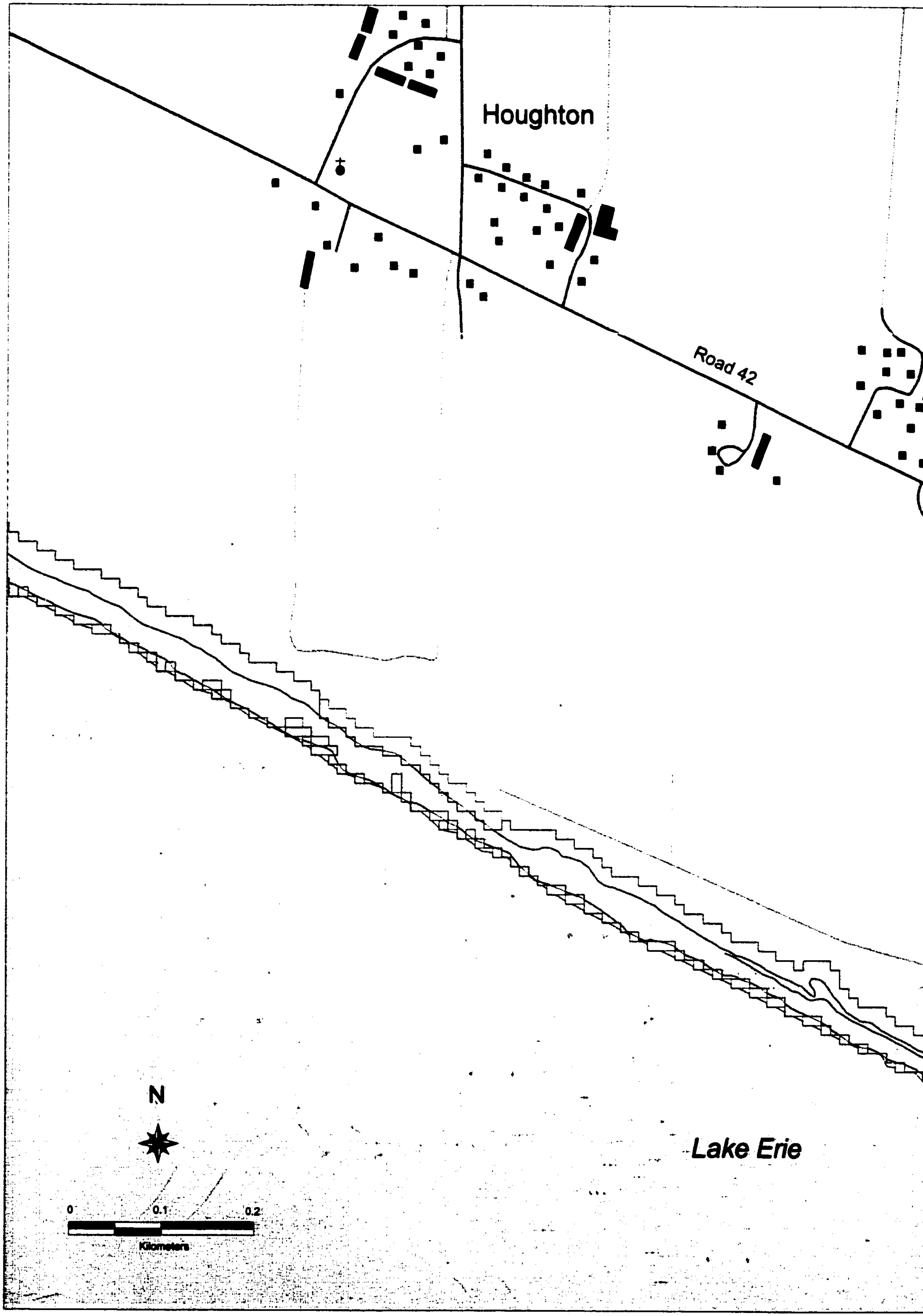
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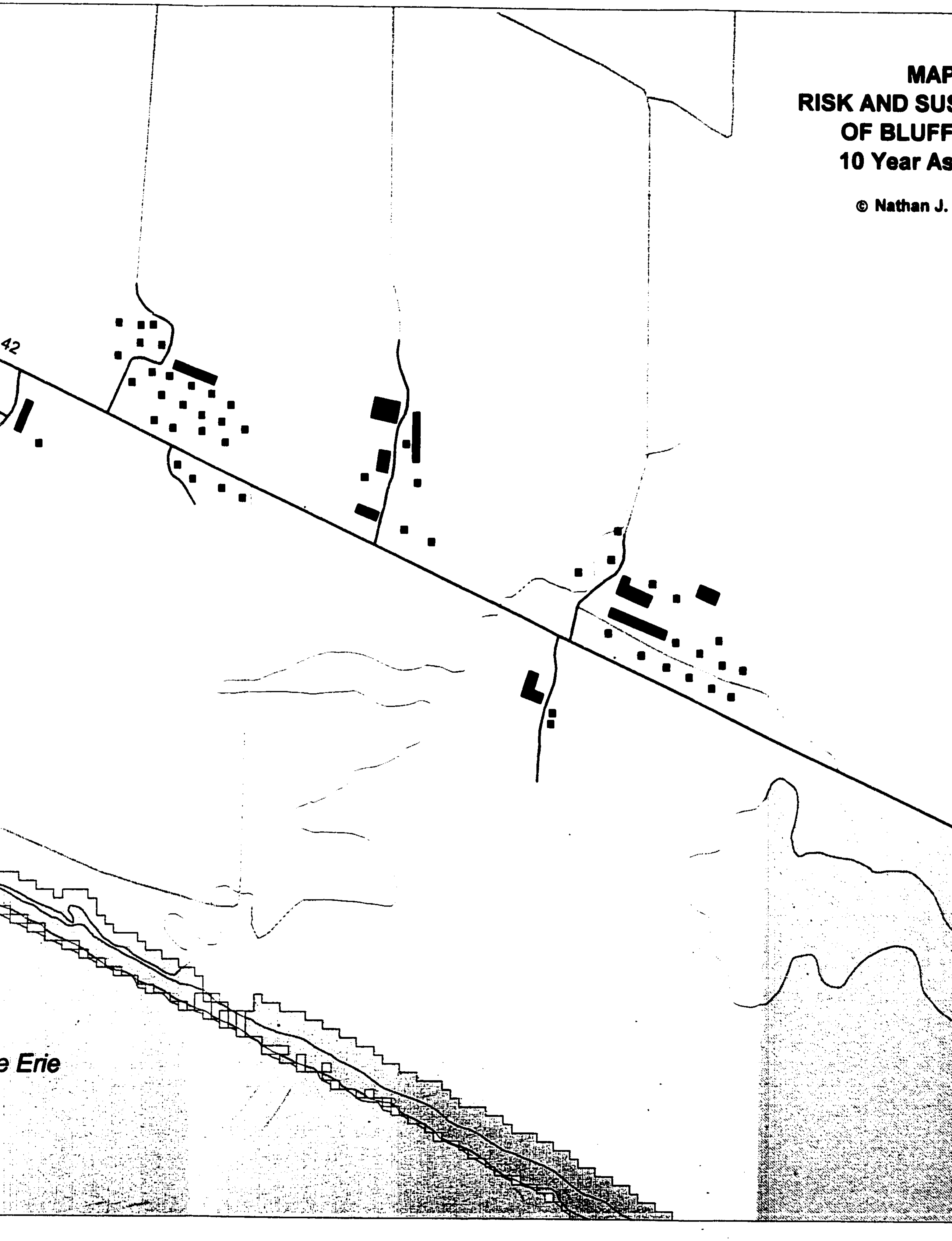

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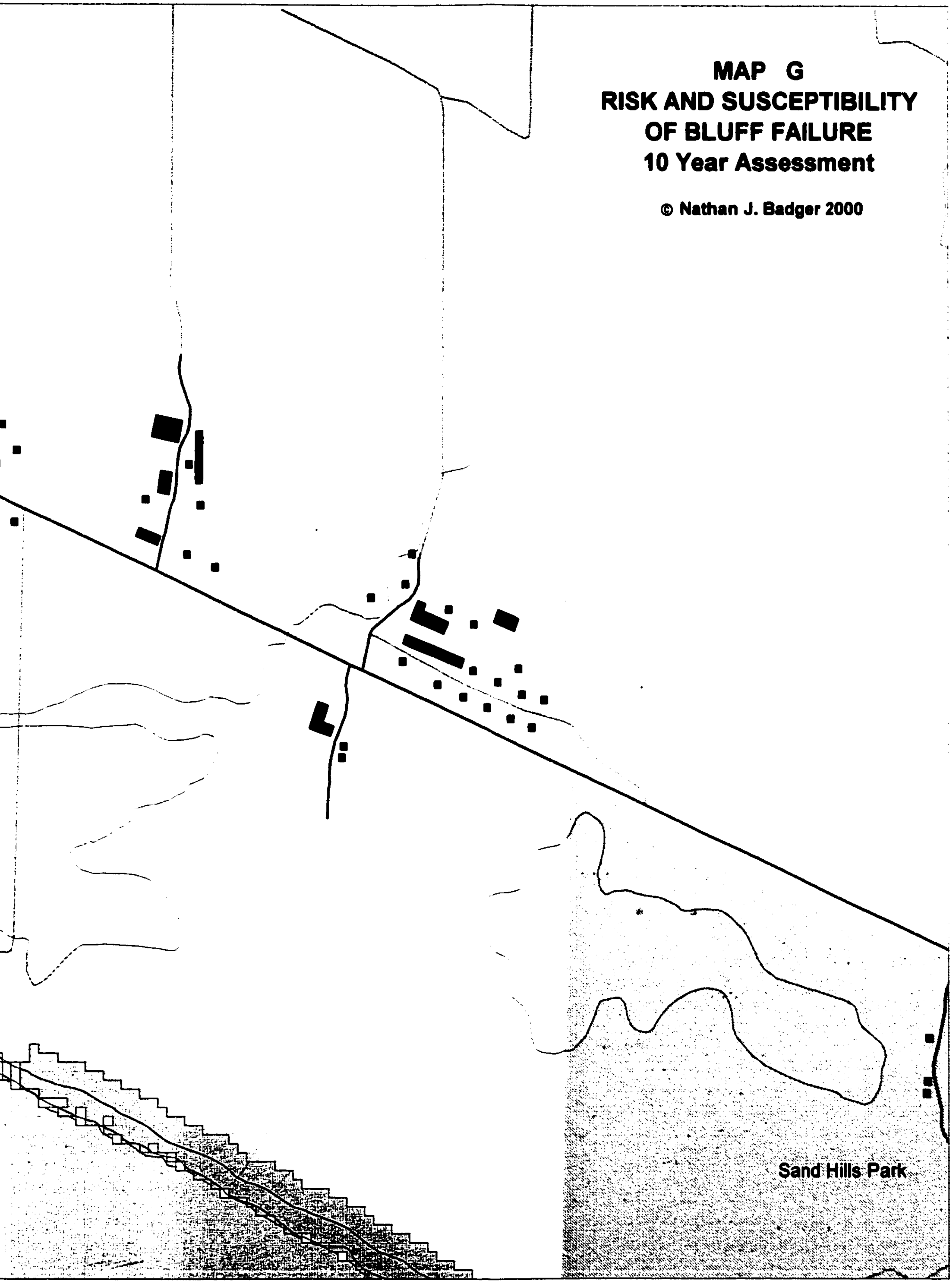
MAP G
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10 Year Assessment
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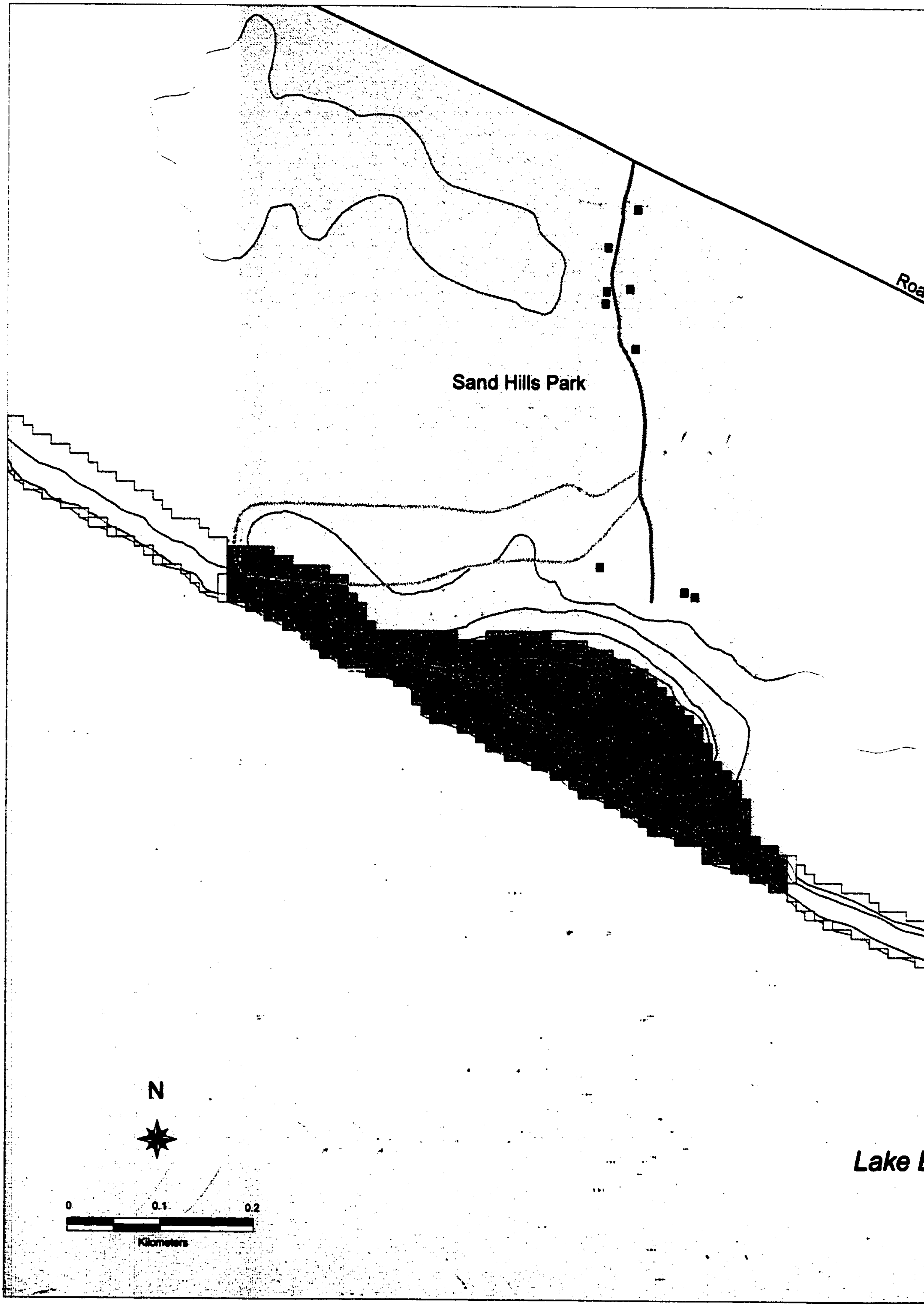
Sand Hills Park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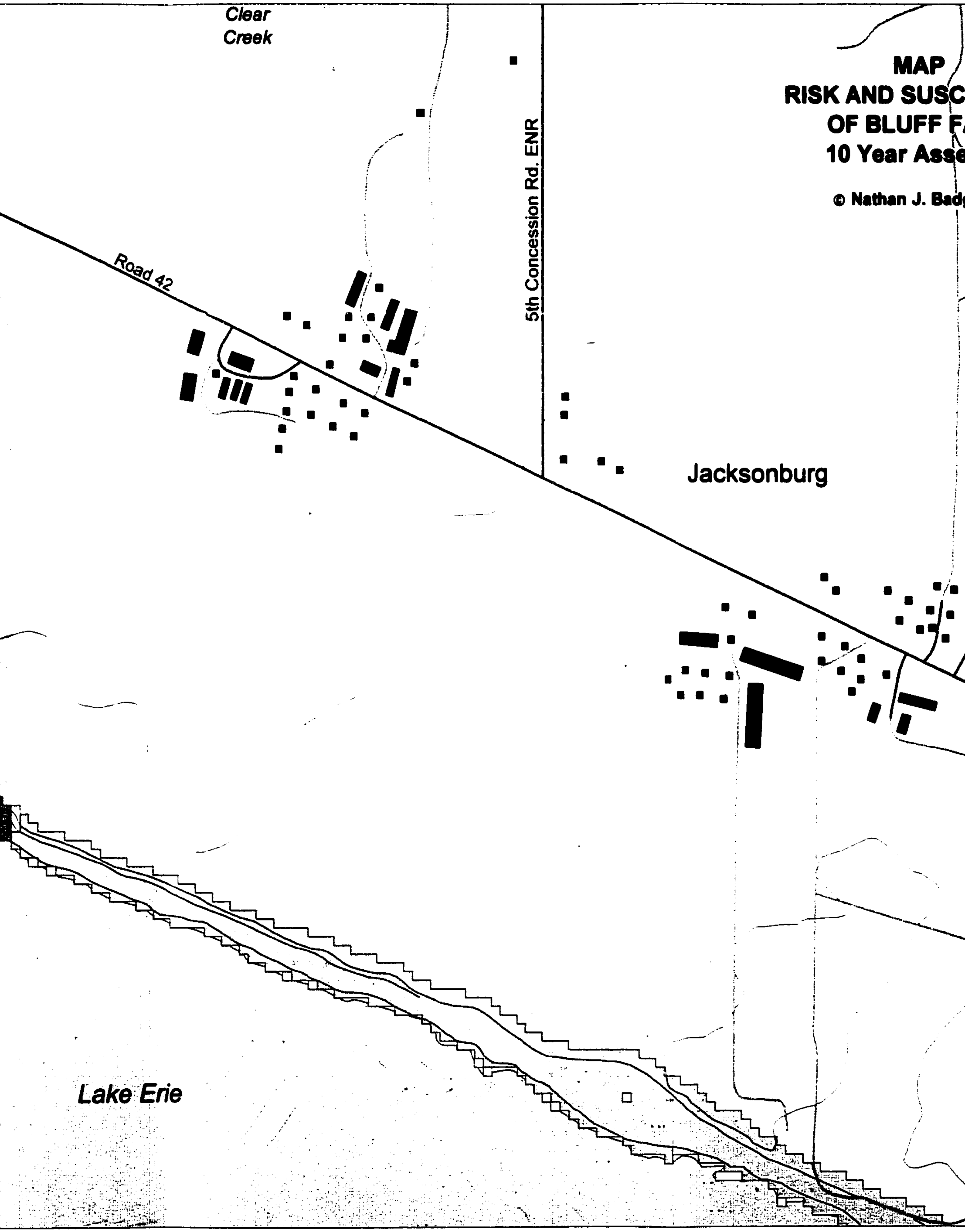

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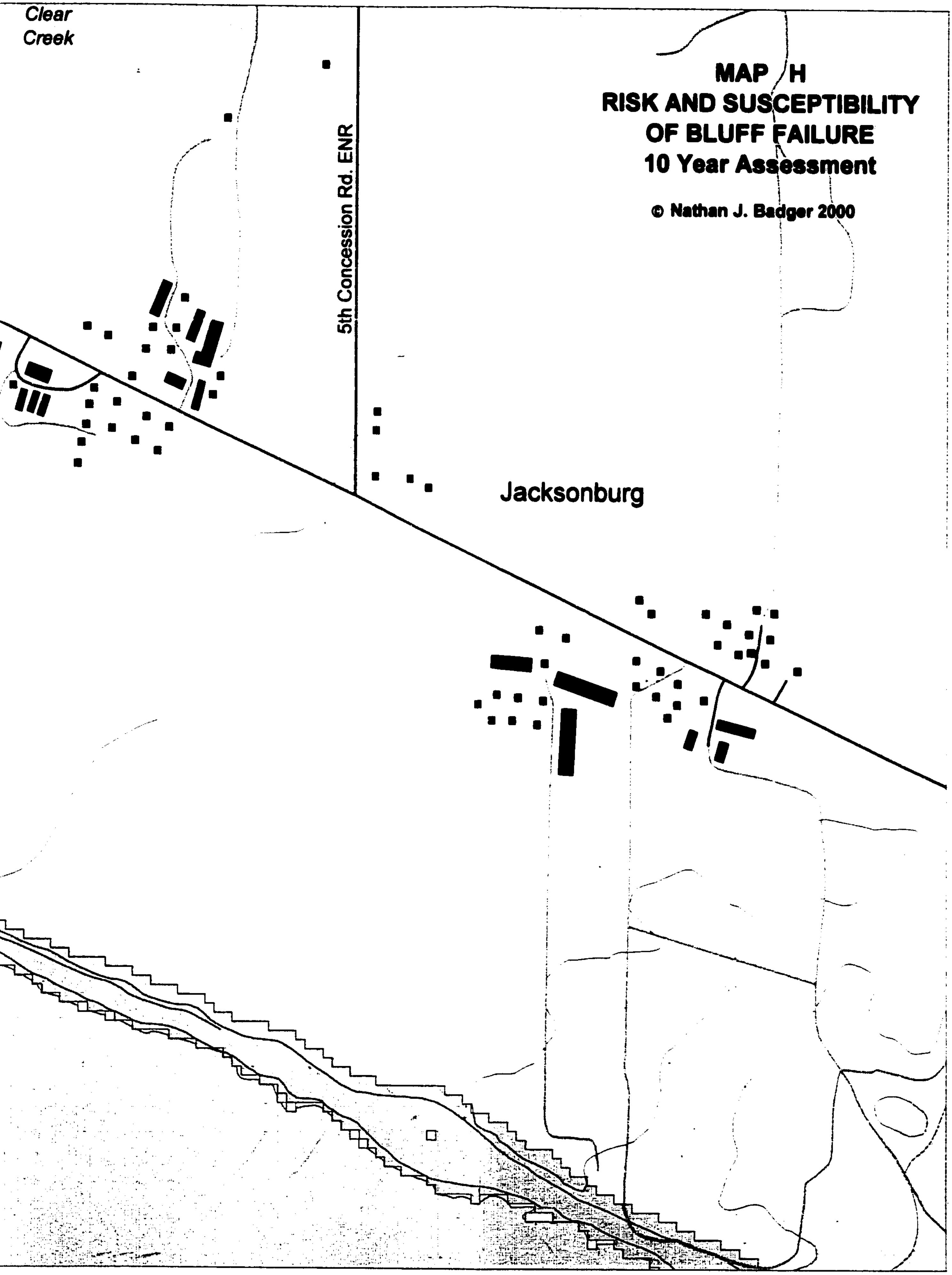

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10 Year Assessment
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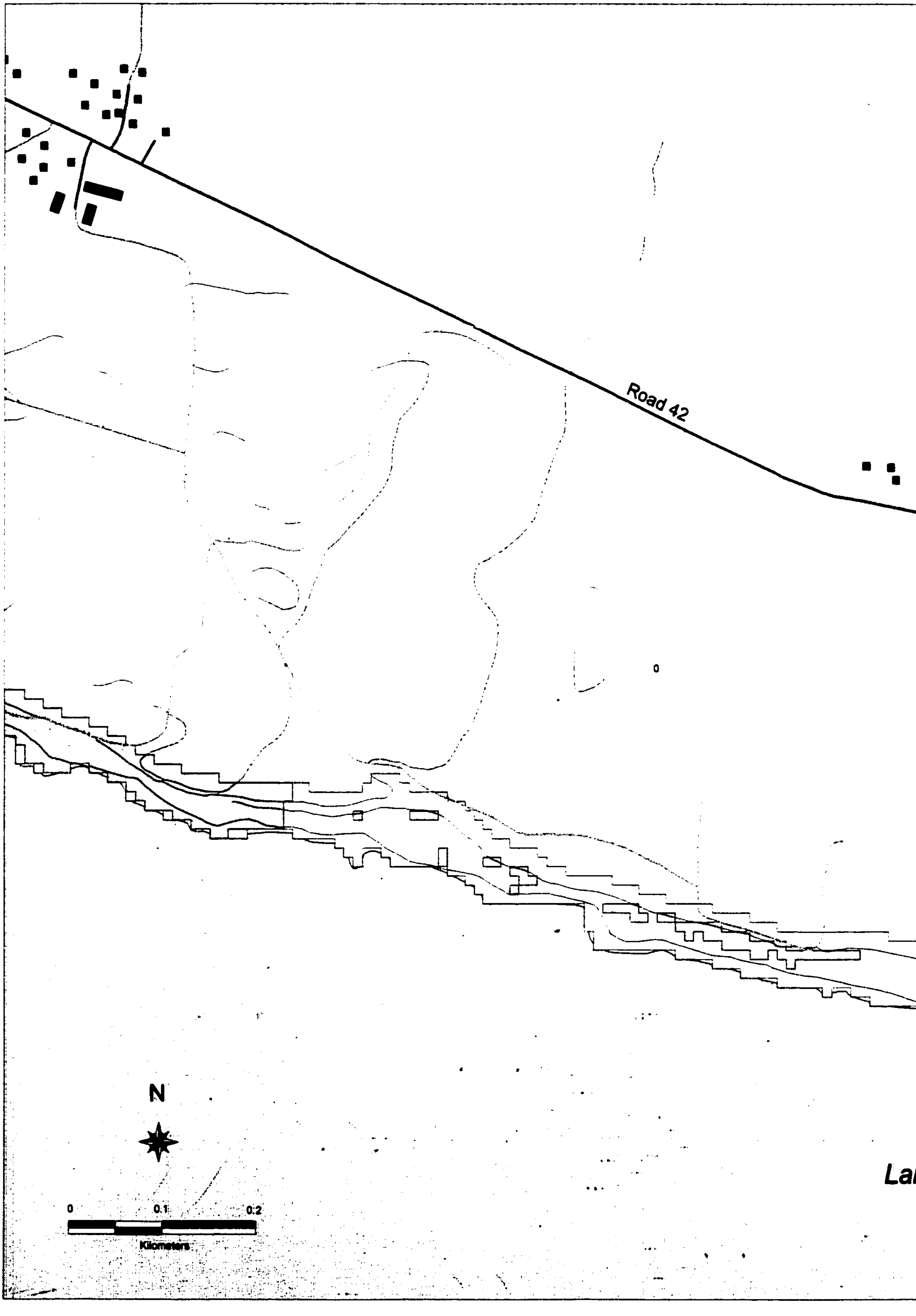

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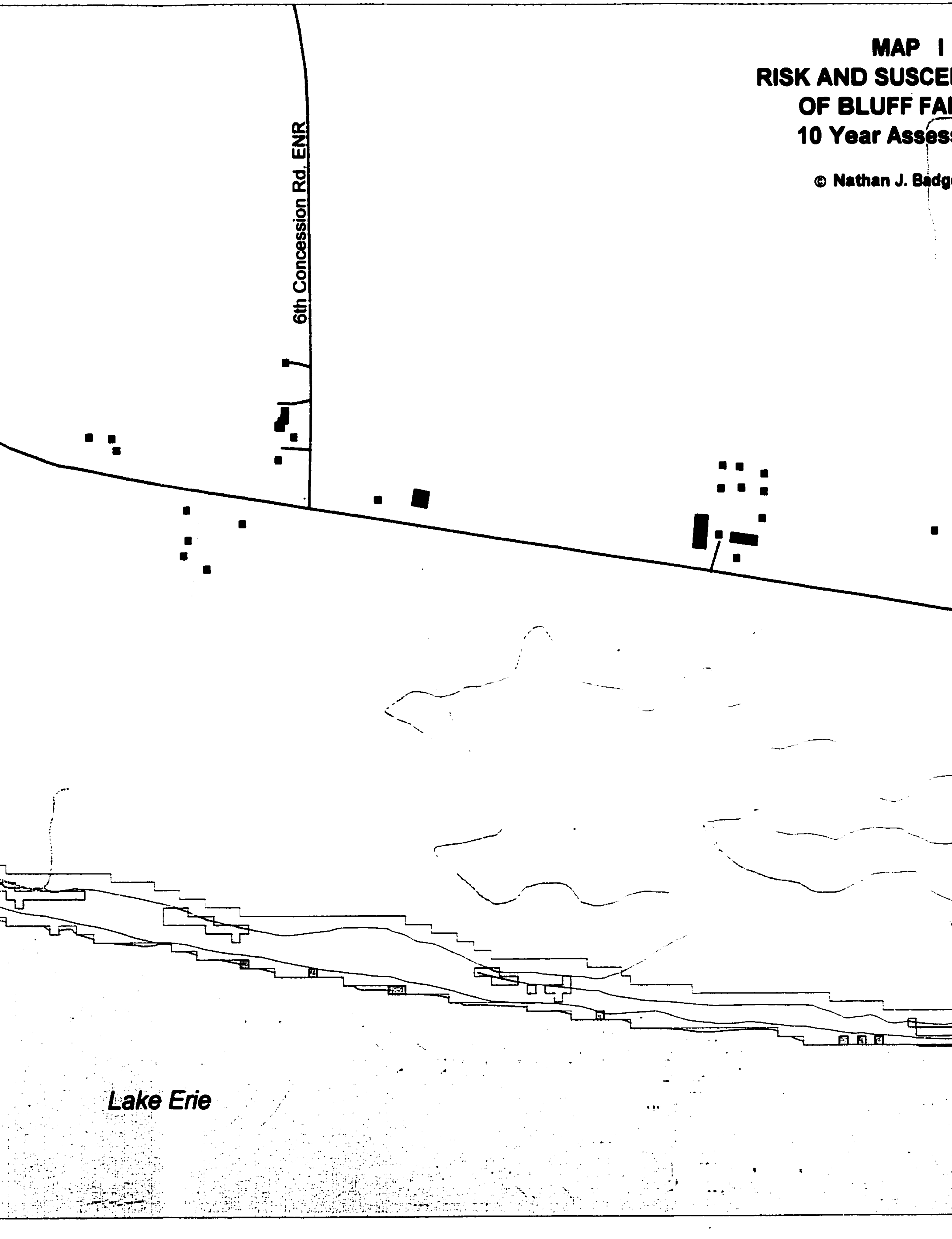
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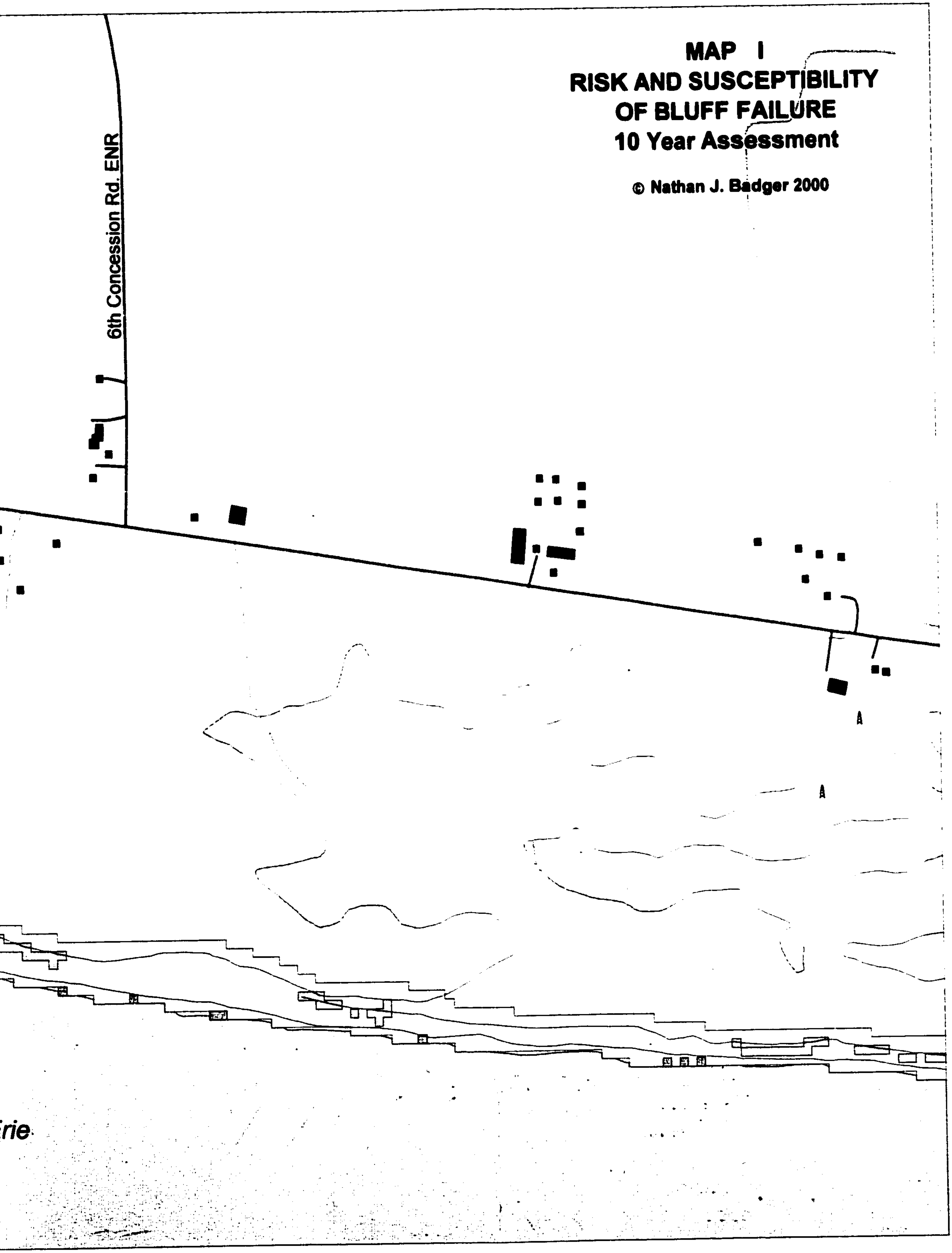
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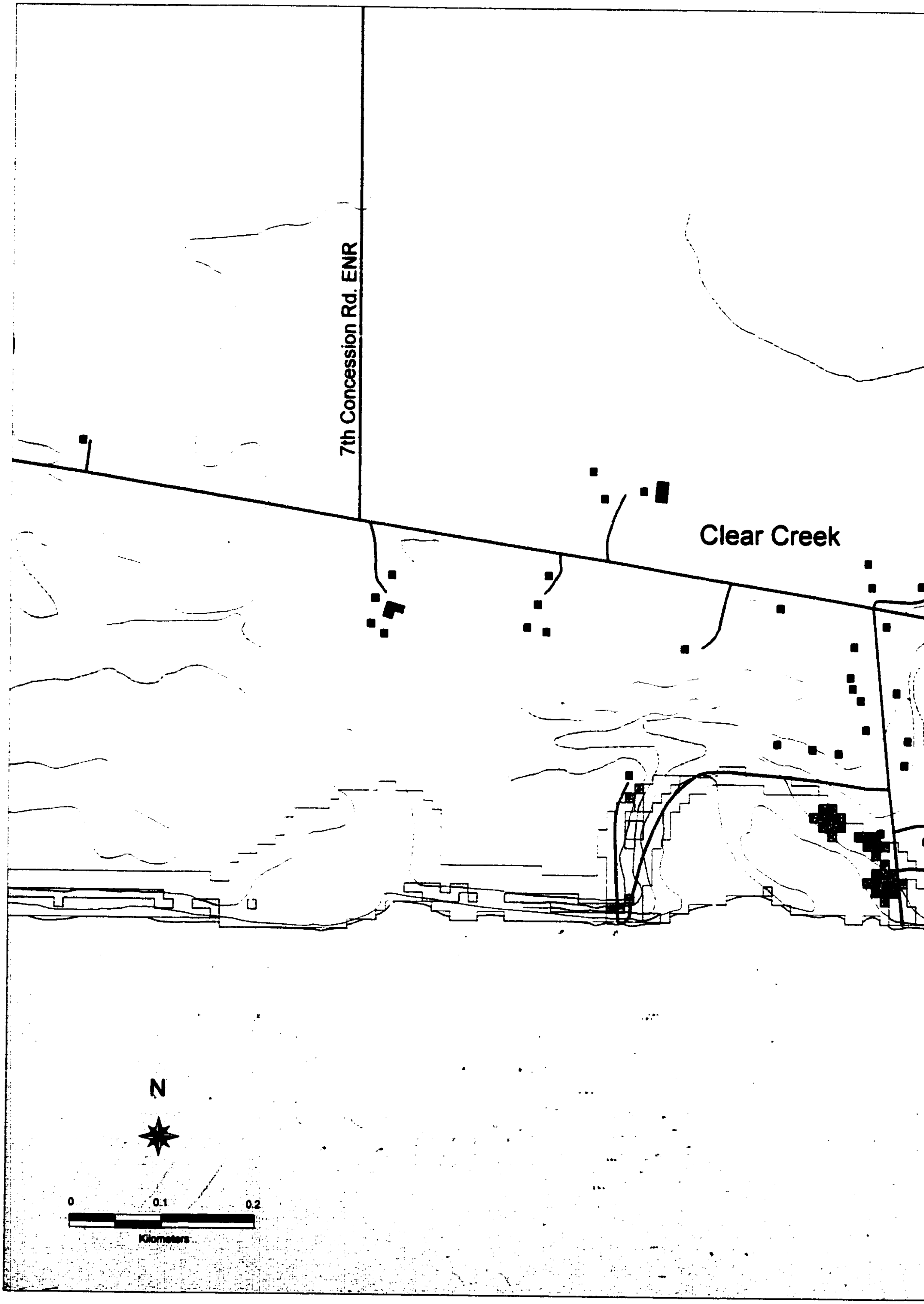
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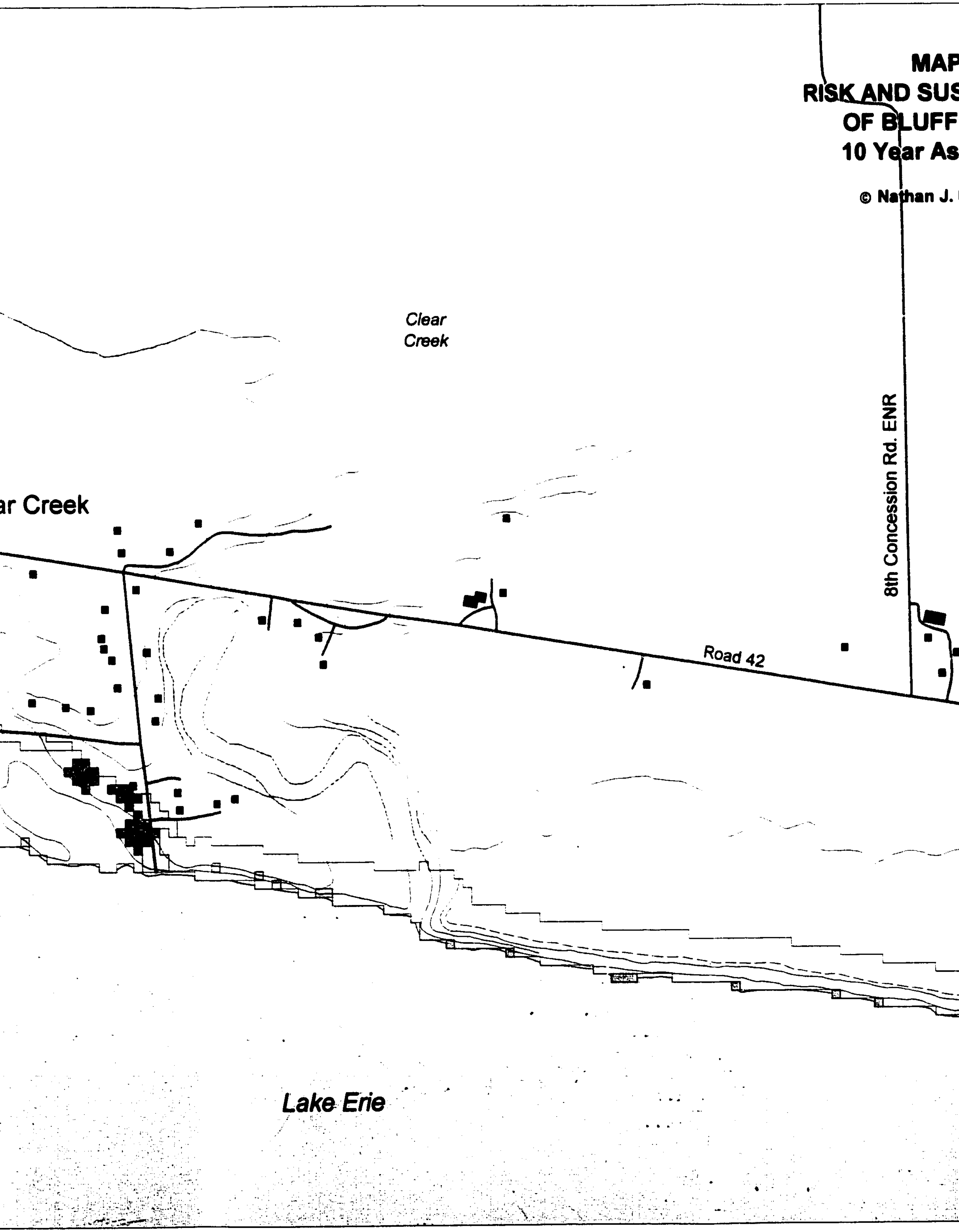

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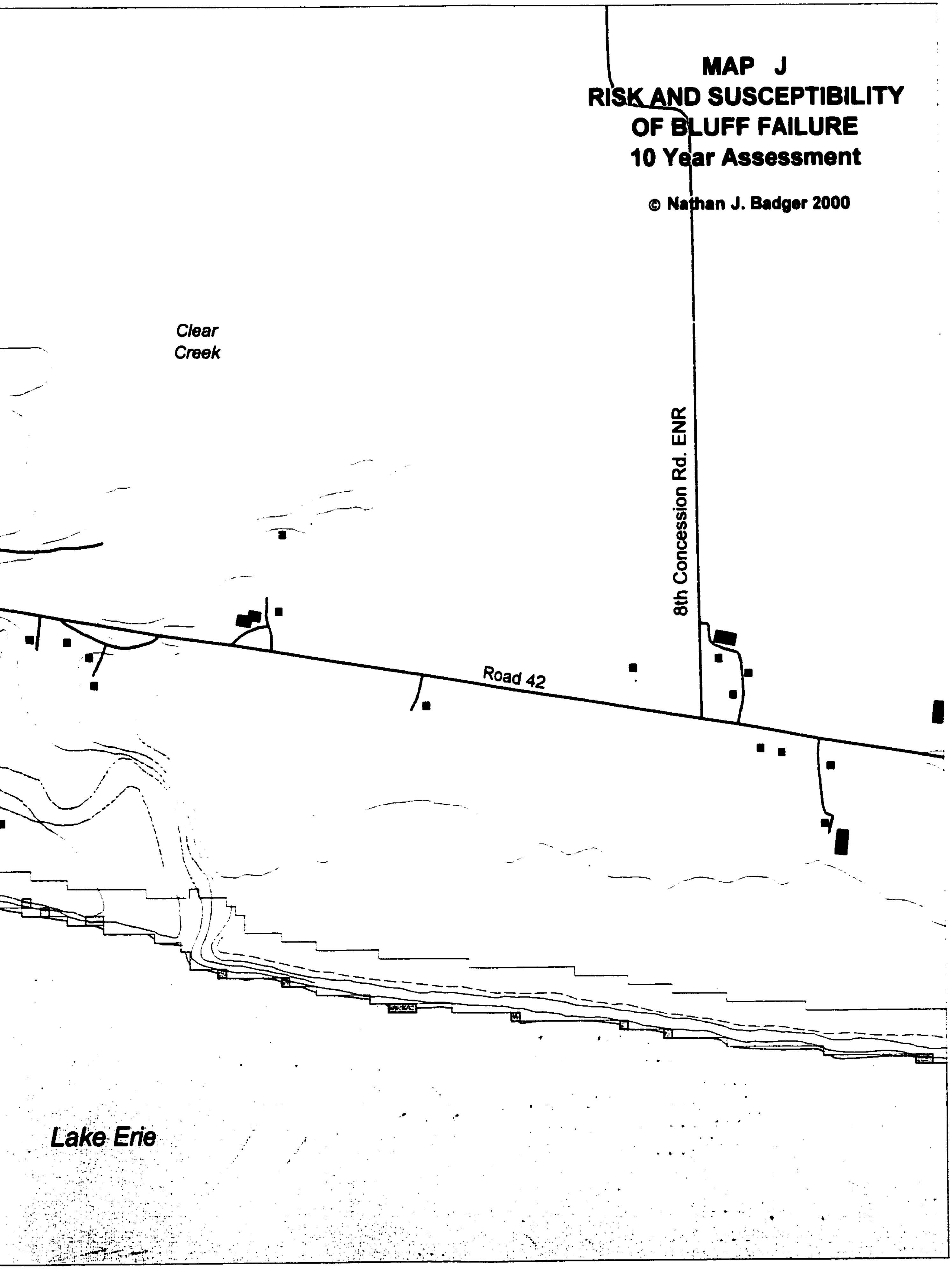
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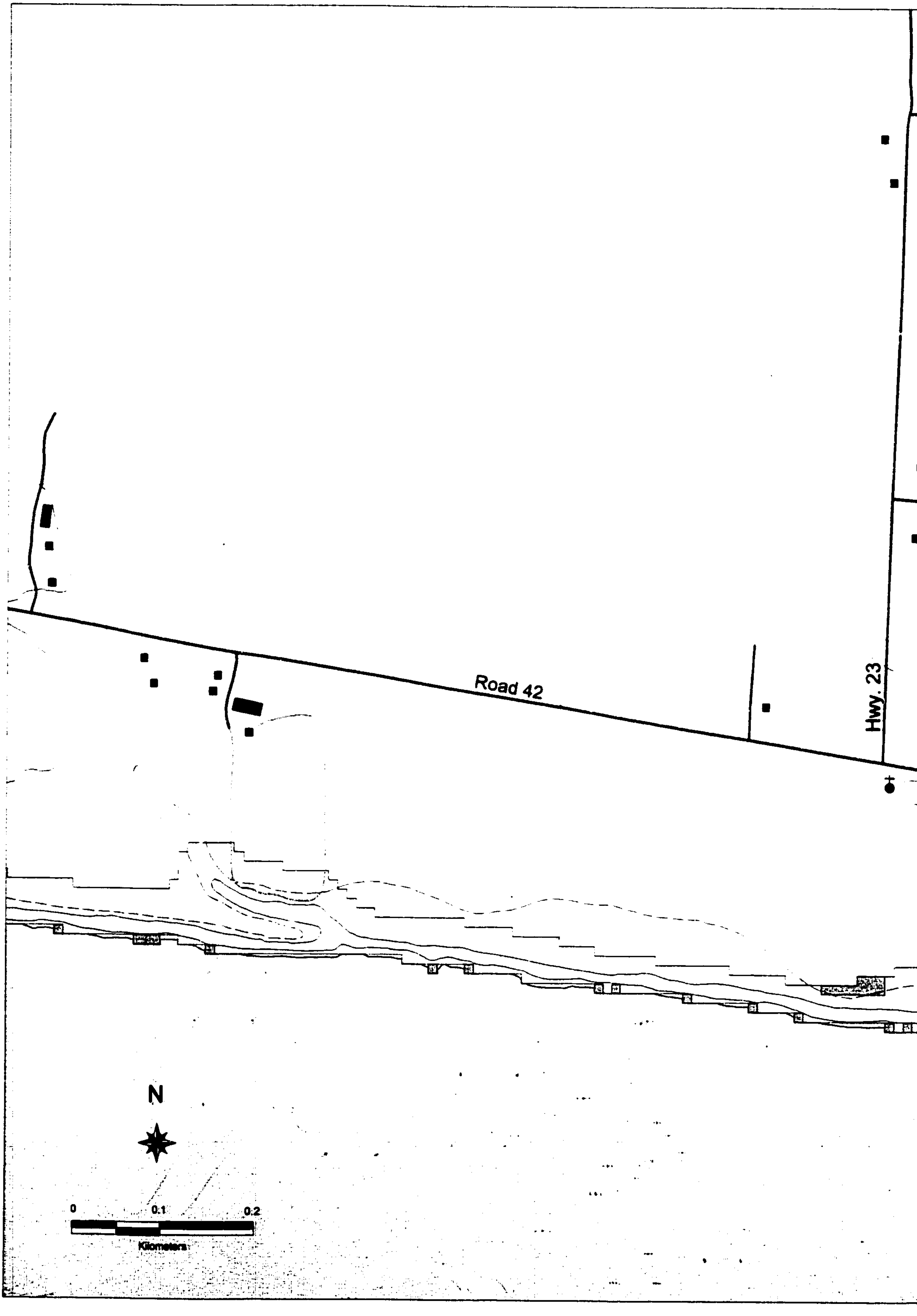

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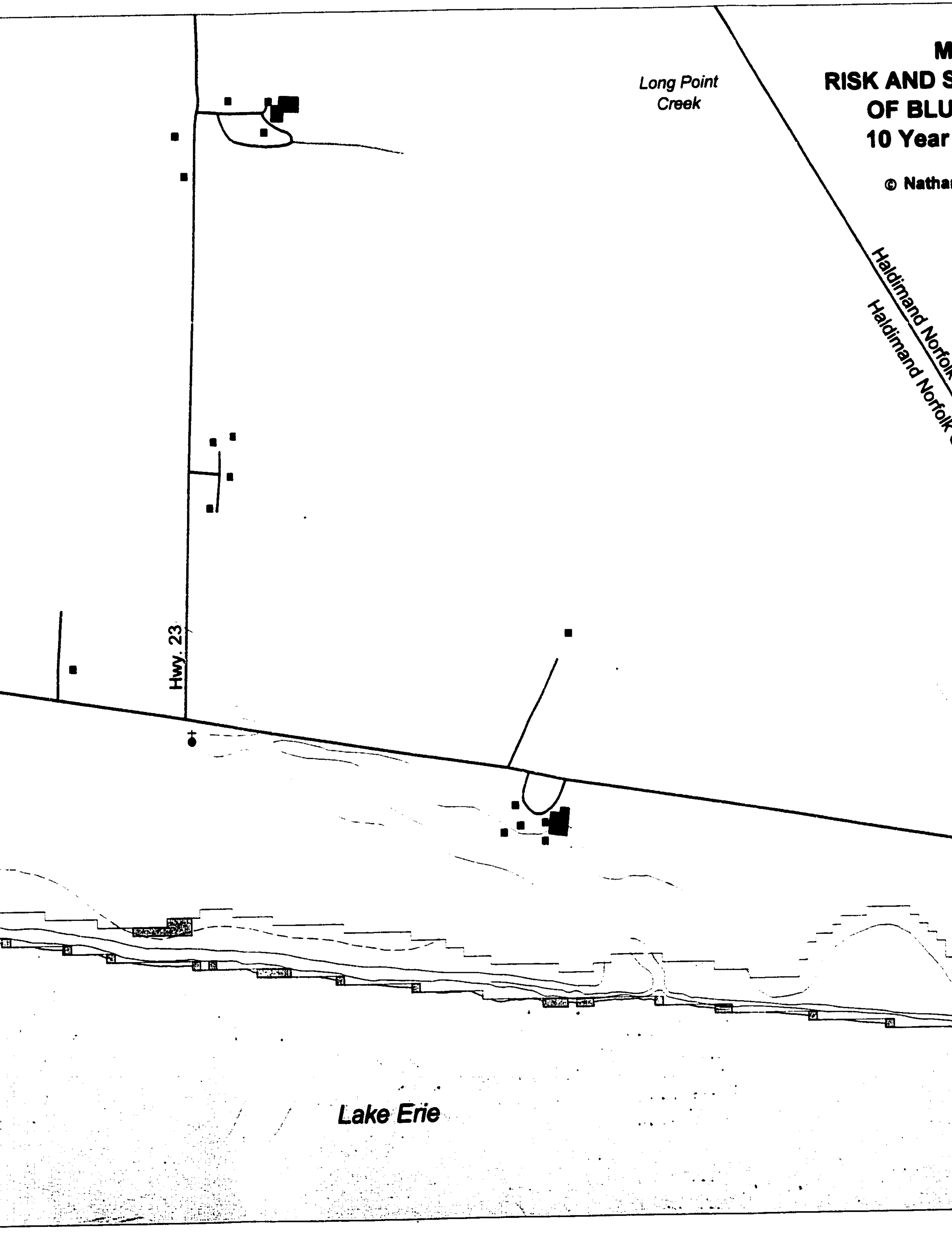

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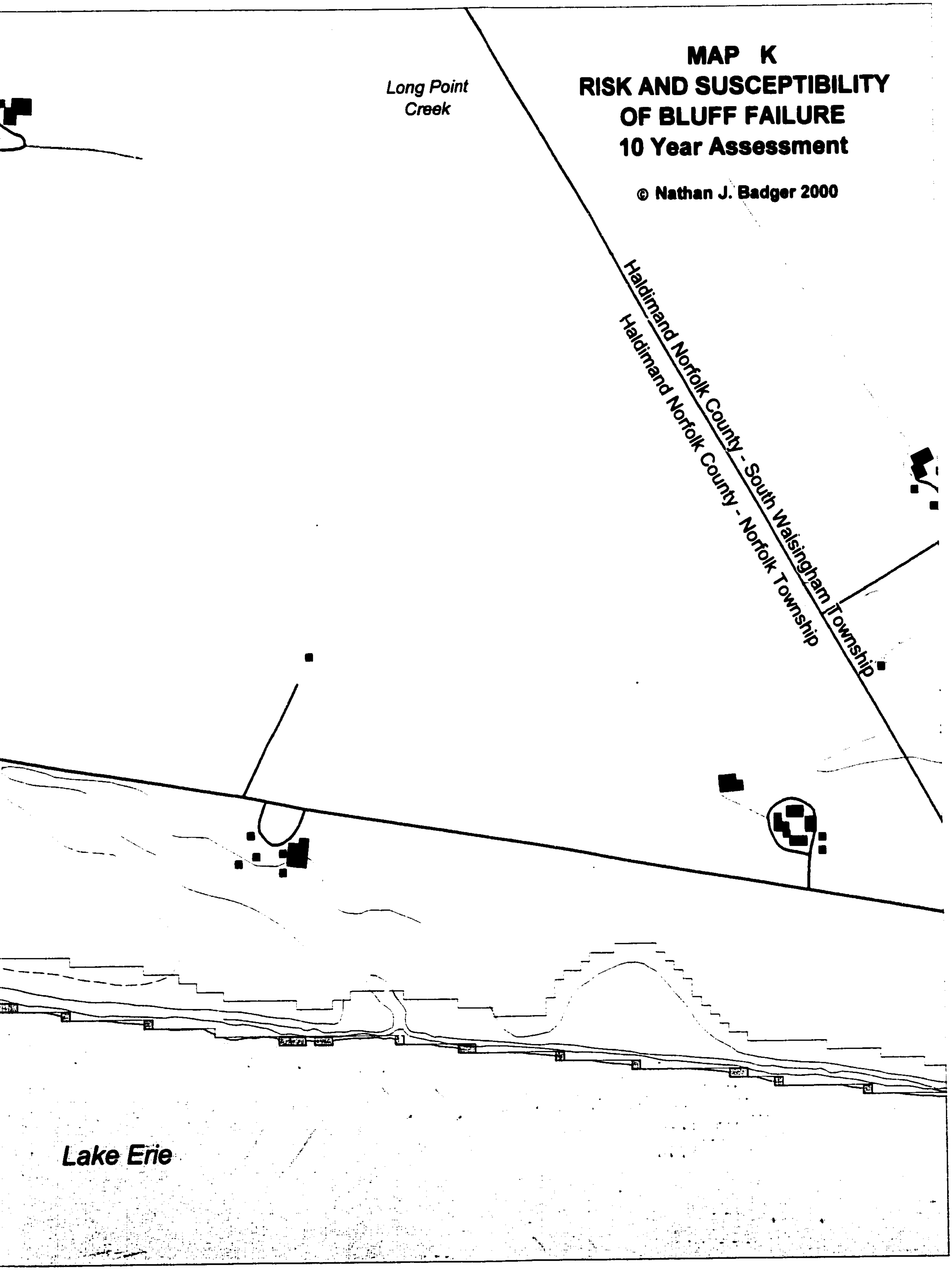
MAP K
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10 Year Assessment
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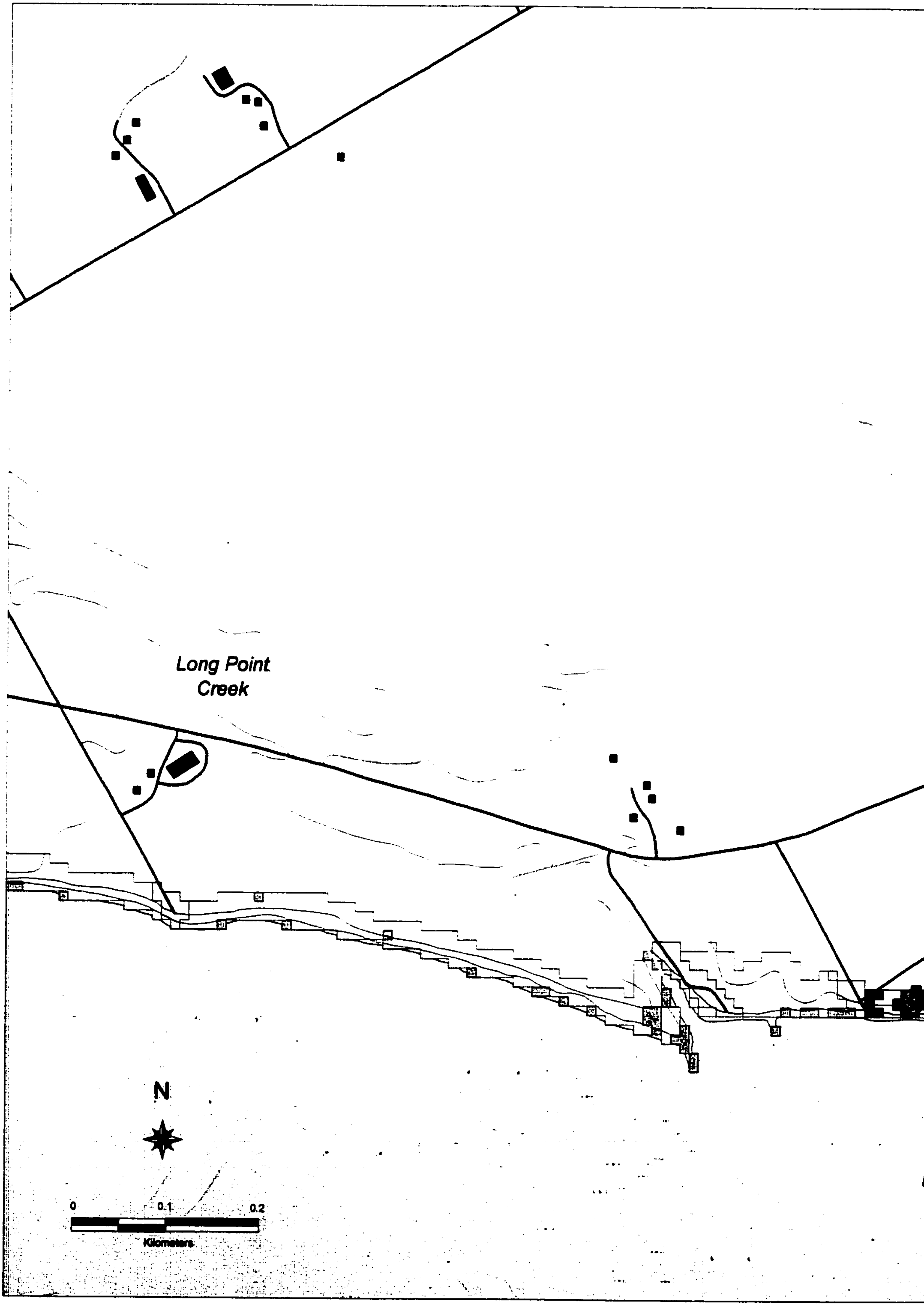
Lake Erie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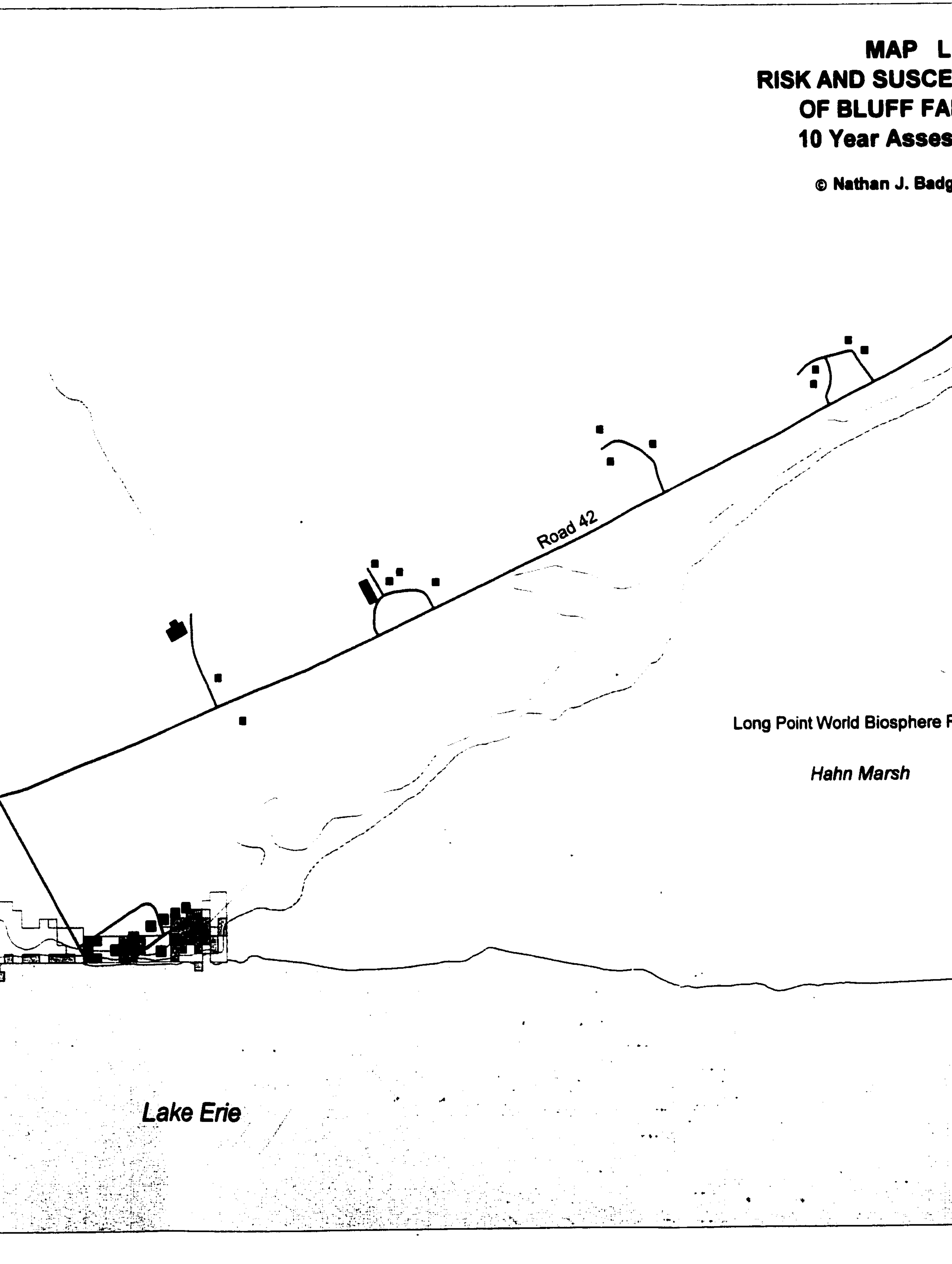
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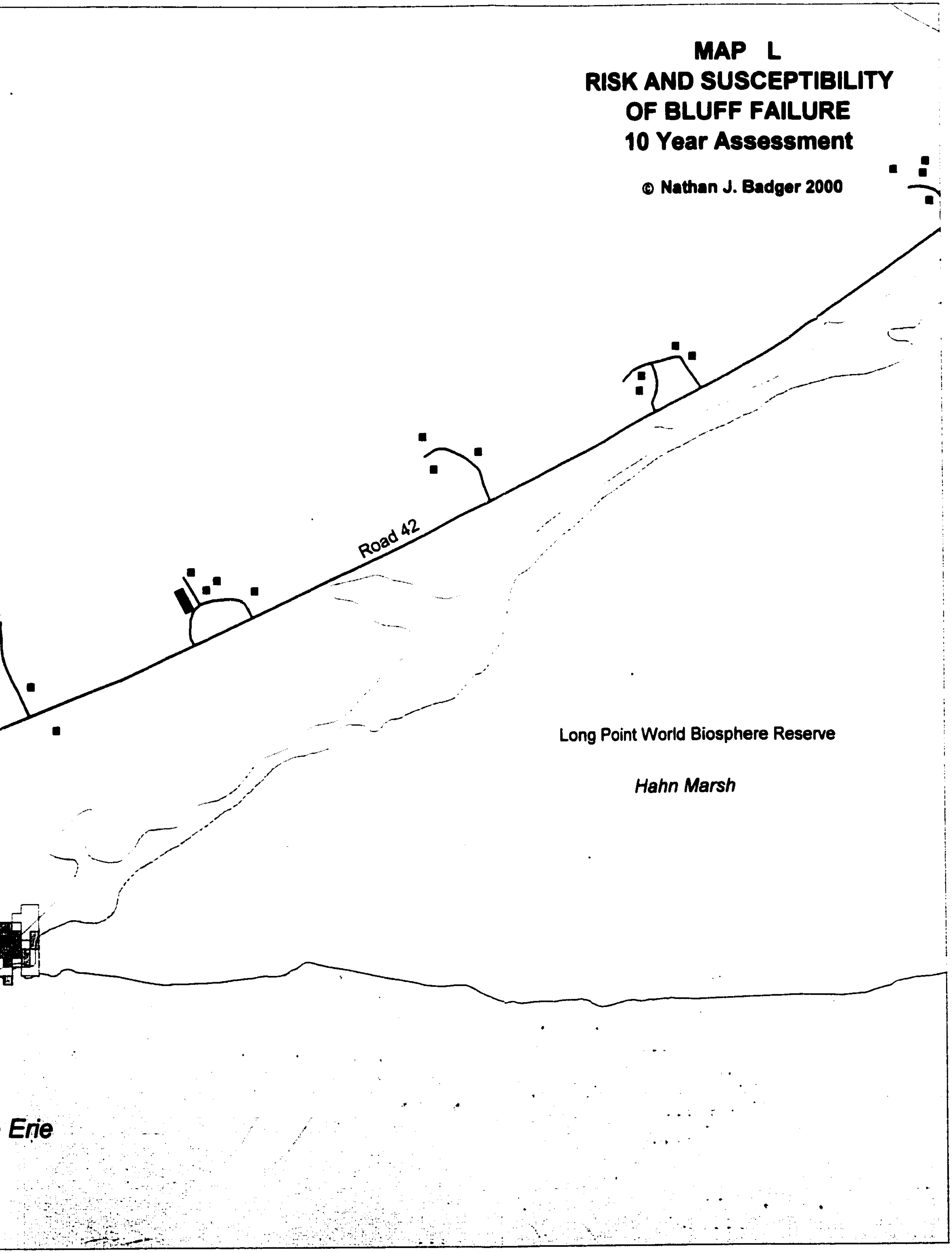
MAP L
RISK AND SUSCEPTIBILITY
OF BLUFF FAILURE
10 Year Assessment
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Road 42
Long Point World Biosphere Reserve
Hahn Marsh
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plantek@lprca.on.ca

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