Coastal Processes Manual

How to Estimate the Conditions of Risk to Coastal Property from Extreme Lake Levels, Storms, and Erosion in the Great Lakes Basin

2nd edition

by J. Philip Keillor

University of Wisconsin Sea Grant Institute WISCU-H-98-003

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How to Estimate the Conditions of Risk to Coastal Property from Extreme Lake Levels, Storms, and Erosion along Great Lakes Shores

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Table of Contents

Figures and Tables

Figures

Tables

INTRODUCTION

This is the second edition of a 1987 manual, updated to contain new material on estimating low and high water levels, the risks of urban flooding, estimating stable slope ratios, and lakebed erosion. This edition also has preliminary information on estimating the probabilities of flooding and erosion risks to coastal investments. It contains numerous examples, a supplemental workbook section with worksheets, and appendices with additional information. The loose-leaf format allows the manual to be easily updated and expanded.

A. The Benefits of Using This Manual

Many people who consider investing in coastal property are familiar with stable hillsides that remain in place and small lakes that retain their present shorelines. They are drawn to Great Lakes shores by the same attractive features that are offered on small lakes without realizing that many of the 10,579 miles of Great Lakes shoreline are not stable, but retreating.

This manual is for making estimates of the conditions of risk at particular sites on Great Lakes coasts. It will help prospective buyers, insurers, and lenders make or influence decisions about investing in Great Lakes coastal property; realtors make better hazard disclosures to prospective buyers; appraisers improve their valuations of coastal property; and developers, local officials, planning and zoning commissions, and boards of appeal make more informed decisions on the development of coastal properties.

The manual describes some of the natural processes at work along the Great Lakes shoreline that may adversely affect investments in coastal property. Information and advice are provided on how to evaluate the likely effects of changing lake levels, storm surges, wave runup, lakebed erosion, and shoreline recession on particular coastal properties.

The simplest methods described here can be used to identify sites that are *obviously at risk* of flooding and/or erosion. More complex use of the same methods will help identify what site conditions cause an *apparently low risk* of flooding and/or erosion. Professional help is often necessary in evaluating situations of apparently low risk; this manual helps define these situations.

B. Adapting to a Dynamic Coastal Environment

Ocean coasts have twice-daily tides that leave telltale marks on beaches, rocks, and piers as reminders of "normal" water level ranges. A Great Lake "normal" range of water levels, similar to many ocean tidal ranges, may occur only once or twice in a long period of property ownership. In 1985 and 1986, Great Lakes coastal residents were surprised by record lake levels for this century, high levels not seen since the 1880s. These high water levels washed away an assumption that lake level regulation and human modifications of the lakes, such as interconnecting channels, offer enough control to prevent any reoccurrence of nineteenth-century record lake levels. The new record water levels brought flooding and impaired operation to homes, businesses, utilities, and other facilities.

C. Some Limitations of This Manual

The methods used here are primarily intended to identify conditions of risk at particular sites that are obviously at risk of flooding, erosion, or impaired operation at low water levels. The manual has a secondary and less adequate use in identifying sites with conditions that give them an apparently low risk of flooding or erosion. This second category, and the large "gray area" between these two categories, requires the additional analysis and judgment of skilled professionals.

In many cases, the cost of a detailed engineering study is out of proportion to the investment. This manual is designed to fill the gap between mere guessing and an engineering study. Choosing to use the generalized procedures in this manual instead of an engineering study increases the risks and uncertainties involved in estimating storm water levels, adequate home elevations, and adequate setback distances.

The methods described in the manual are not adequate to anticipate flooding from rapidly moving weather fronts, rapid atmospheric pressure changes, or thunderstorms. Nor are they adequate to predict catastrophic erosion caused by factors such as coastal "washouts" resulting from extreme rainfall events and runoff. The methods are also inadequate for such locations as:

- Exposed points of land subject to wave action from several directions.
- Land inshore of large shoals.
- Shallow water bays exposed to long overwater distances on the lakes.
- Shores affected by significant lakebed erosion.
- Shores with nearshore lakebed slopes steeper than 50:1 (horizontal:vertical).

This manual is not intended to provide a standard for professional practice. It does not contain descriptions of all the processes, factors, and site conditions that can contribute to the risks of flooding and erosion. The stable slope tables apply only to Wisconsin's Great Lakes shores for simplified bluff/bank soil conditions and soil properties on undeveloped properties. The procedures described here can be applied to other areas by using equivalent, appropriate local information. Consult an engineer or geologist about the need for an on-site investigation.

D. How This Manual Is Organized

"Evaluating the Risks from Natural Hazards" (pages 5-6) is important background reading for everyone using this manual. "Evaluating the Risks of Flooding," "Evaluating Conditions of Risk from Low Water Levels," "Coastal Erosion and Construction Setbacks," and "Evaluating Conditions of Risk from Erosion" can be used independently, depending on whether the risks of flooding, low water, or erosion are of concern. Within each of these latter four sections, the material begins with the basic methods needed to estimate if a site is obviously at risk. The material and examples become progressively more complex within each section paced to match a need to know more about the risks at a site. Some of the data needed to make these more complex evaluations of sites with apparently low risks are located in the appendices. One of the appendices lists additional data sources. A tabbed workbook section contains a few worksheets and examples along with the minimal charts and graphics needed to carry out simple risk evaluations.

Measurements are given in U.S. units, with metric equivalents in parentheses. For clarity, U.S. units are used in the examples, with the exception of Examples 3 and 4.

EVALUATING THE RISKS FROM NATURAL HAZARDS

A. Options for Protecting Coastal Property Value

1. Going without Shore Protection

For undeveloped and many developed properties, the best economic choice is to allow natural erosion and flooding processes to proceed. This option should be seriously examined before deciding to construct new buildings for at least two reasons:

- Many shore protection structures have shorter than anticipated lives because of poor-quality materials and construction, lack of proper design, or lakebed erosion (which undermines most structures).
- The expense of installing and maintaining shore protection is about the same order of magnitude as the cost of coastal land whether or not the protection is an expensive relatively durable system or a cheaper system that needs frequent repair and replacement.

2. Relocation of Buildings

Where existing coastal buildings are threatened by erosion or flooding, relocation is a prudent, and often most economical, option. The feasibility of relocation depends, in part, on a) structural integrity and complexity of the building, b) landward depth of the lot, c) suitability of the soil for relocating the septic system, and d) sufficient land between the building and the edge of the bluff or bank edge for house moving equipment to be used safely. Decisions on what to do about coastal erosion need to be made long before the edge of a bluff or bank has retreated to the front steps of an existing building. Erosion is not always slow and orderly.

3. Preserving and Improving Natural Shore Protection

Natural defenses against coastal erosion include nearshore shoals and/or beaches of boulders, sand, bedrock, and gravel, which cause storm waves to break and lose most of their energy before reaching the land. Other natural coastal defenses include wetlands, sand dunes, or beach ridges, which provide buffers that absorb wave energy. Wetlands, dunes, and ridges should not be altered because that will diminish their coastal defense function. Don't remove, cut into, or use dunes and ridges on the shore for building sites or access roads. Plant beach grasses on barren ridges and dunes. Augment natural cobbles and boulders on rocky shores. Some new shore protection designs incorporate habitat creation or recreational functions as ways to justify the expense of shore protection.

4. Building and Maintaining Shore Protection Structures

Stable, effective, well-maintained shore protection structures are needed for coastal properties where erosion cannot be allowed to continue uninterrupted. Some information on evaluating shore protection structures is included in this manual. Unfortunately, there are no current, authoritative guides for constructing small-scale shore protection structures for residential homes on the Great Lakes.

Since the first edition of this manual was published in 1987, the importance of lakebed erosion has become apparent. Where significant lakebed erosion is occurring, most shore protection structures will suffer loss of foundation support and their useful lives will be severely shortened. There are presently few (if any) forms of structural shore protection that are believed to be durable for sites with significant lakebed erosion.

B. A Sunset on Estimates of Vulnerability

Any estimate of vulnerability to natural hazards should be time-limited. Coastal properties are dynamic places where bluffs are becoming more or less stable; where lakebed erosion diminishes natural defenses from destructive wave energy; where the effects of climatic change are felt in terms of changes in the intensity and frequency of storms. New estimates of vulnerability of particular coastal properties to flooding and erosion should be made whenever properties change ownership and no less than every 10 years.

Flooding

EVALUATING RISKS OF FLOODING

The following section describes how to decide if specific sites are obviously at risk of flooding and includes some information on the more difficult task of determining if particular sites have an apparently low risk of flooding. A coastal site at risk of flooding has land and/or building elevations that are not as high as a particular *storm water level* or *wave runup elevation.*

A. Definition of a Storm Water Level and Wave Runup Elevation

A *storm water level* is:

lake level elevation
\+
storm surge

A *wave runup elevation* is:

lake level elevation
\+
storm surge
\+
storm wave runup

These three elements are shown in Figure 1. Each of the three elements has a different duration:

- Lake levels—durations of days to months.
- Storm surges—durations of hours to a day.
- Storm wave runups—durations of seconds (an occasional extreme wave) to hours (a prolonged period of high waves).

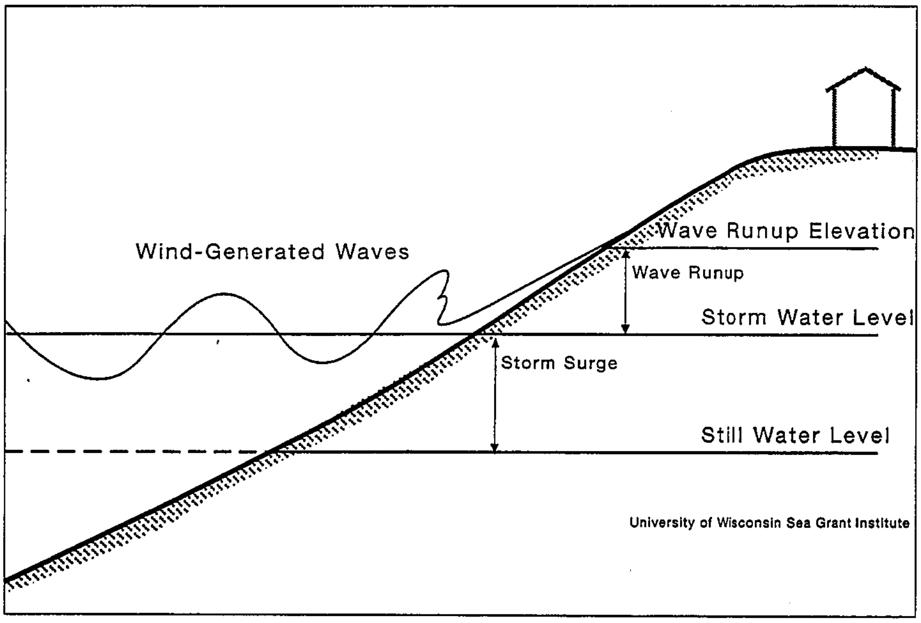


Figure 1. Water level, storm surge, and wave runup

B. Seasonal and Long-Term Changes in Great Lakes Water Levels

The water levels of the Great Lakes respond to seasonal changes in climate. Lake levels rise in the spring due to precipitation entering the lake directly from the atmosphere and indirectly as runoff from spring rains, melting snow, and ice on land and inland waters. Lake levels decline in the fall, when conditions generally favor evaporation as cold, dry air blows across the warmer water of the lakes. The long-term seasonal range of lake levels vary from lake to lake: Superior, Michigan, and Huron (1 foot, 0.3 meters); Erie (1.2 feet, 0.4 meters); and Ontario (1.7 feet, 0.5 meters). On average, seasonal high levels occur in mid- to late summer and seasonal low levels occur in mid- to late winter or early spring. Seasonal variations and extreme lake levels are shown in Figure 2 and Table 1 (page 13).

C. Datums: Reference Elevations

The U.S. Army Corps of Engineers' (USACE) *Monthly Bulletin of Lake Levels for the Great Lakes* and the Canadian *Monthly Water Level Bulletin* give monthly mean lake level information in terms of feet or meters above or below a *chart datum*, or *low water datum* (LWD), for each lake. A sample lake level forecast bulletin is shown in Figure 2. The chart datum is zero feet or zero meters on the vertical scale of these bulletins. A *vertical datum* is a measured elevation at a particular location that is used as a reference elevation at other locations. A vertical datum is a handy reference elevation from which to measure and compare lake level changes with land elevations and harbor water depths.

Most of the Great Lakes have a unique chart datum from which water levels are measured. The exceptions are Lakes Michigan and Huron, which share a common chart datum. Because these two lakes are connected by the broad, deep Straits of Mackinac, they rise and fall as one body of water. Recent charts provide elevations above the *International Great Lakes Datum, 1985* (IGLD 1985). Older charts provide elevations above the IGLD 1955.

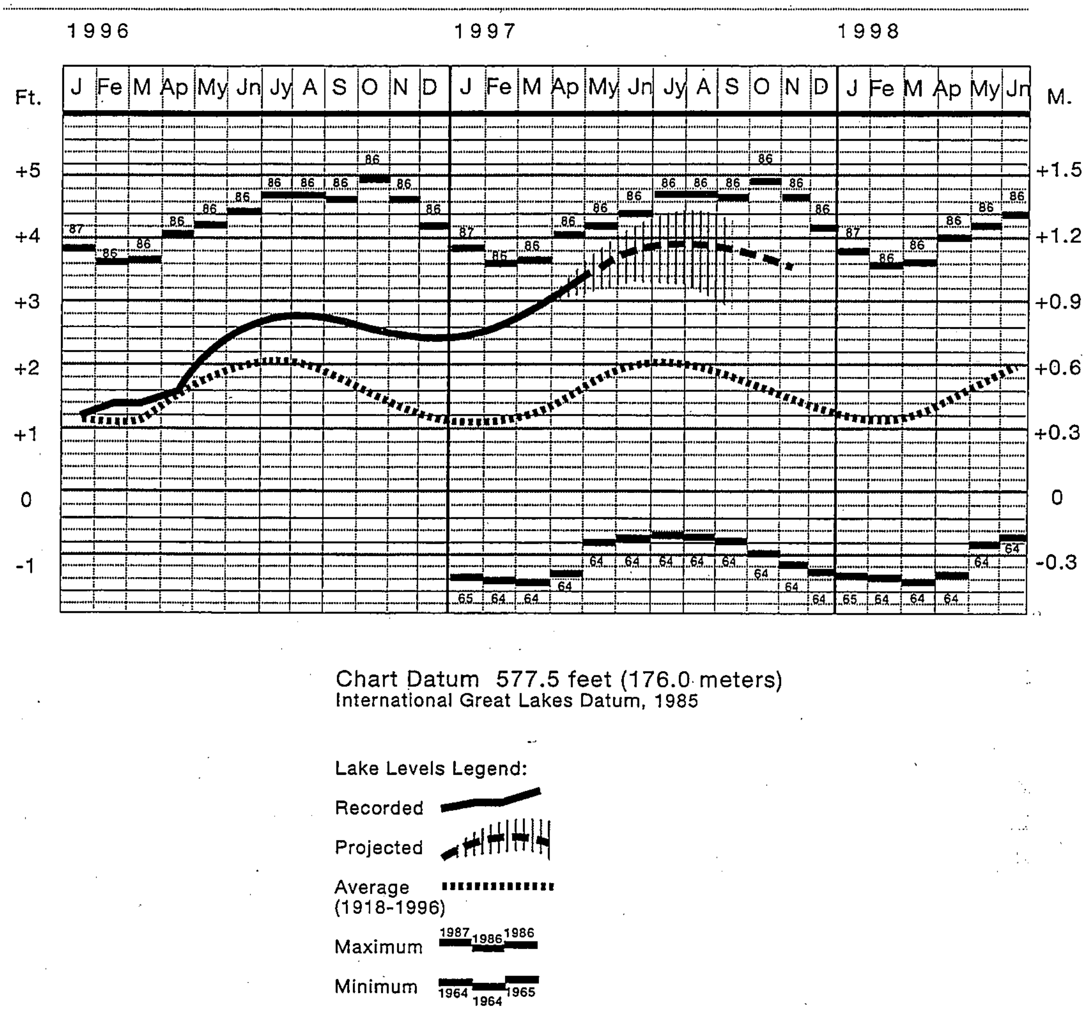


Figure 2. Monthly bulletin of lake levels for Lakes Michigan and Huron (Source: U.S. Army Corps of Engineers)

1. Using Datums to Compare Land and Lake Elevations

An evaluation of a site's susceptibility to flooding requires a comparison of the estimated storm water elevation or wave runup elevation with the elevation of the land or the crest elevation of a shore protection structure. For these comparisons, the water level elevation needs to be converted to the same datum measurement system that is used for land elevations.

The most current vertical land datum in the Great Lakes Basin is the *North American Vertical Datum, 1988* (NAVD 1988). Older U.S. topographic maps will show elevation in feet above National Geodetic Vertical Datum, 1929 (NGVD 1929) or in feet above mean sea level (MSL 1929, or simply MSL). NGVD and MSL are different names for the same datum. Canadian land elevations are referenced to Canadian Geodetic Datum (CGD) as determined by the Geodetic Survey of Canada. Coastal property within city limits may have elevations referenced to the city datum. For more information on datums, see Appendix 1.

Table 2 (page 14) shows each lake chart datum in approximate relationship to the IGLD (1985), NAVD (1988), NGVD (1929), and CGD datums on each of the lakes. Table 2 can be used to make a simple conversion of estimated water level elevations to the land-based datum system so the highest (or lowest) water and land elevations can be compared. The differences between the IGLD, NAVD, NGVD, and CGD datums vary slightly from location to location throughout the Great Lakes Basin. Engineers and surveyors who need to know the exact differences between these datums at particular sites should see Appendix 1 for sources of data about benchmark elevations.

D. Storm Surges and Seiches

As storm winds blow across many miles of open water on the Great Lakes, they drag some water towards the downwind side of the lakes, causing a build-up in water level along the downwind shore and lowering the water on the upwind shore (Figure 3). The temporary rise in water level is called a *storm surge, storm set-up*, or *storm-induced rise*. The drop in water level is a *set-down*. A storm surge lasts about as long as the storm wind lasts, rising quickly with wind velocity and dropping after the wind speed falls or the wind changes direction. A storm surge may last all day. Similar, but shorter, periodic oscillations of lake levels are called *seiches*.

Seiches last seconds to minutes. One or more seiches following a storm may cause repeated flooding of low-lying property. They will have less effect on coastal erosion. Their elevations are not as high as the original surge, and they are not accompanied by waves as high as the waves that come with the storm surge. Small seiches (less than a foot) are a normal everyday result of weather systems passing over the Great Lakes.

Storm surges occur on all of the Great Lakes shoreline. The greatest storm surges occur in shallow bays exposed to long distances of water surface. The smallest surges occur on islands and on the ends of peninsulas or points of land. Typical storm surge values for some coastal sites are shown in Figure 5 (page 15). Appendix 2 contains tables of storm-induced rises and tables of wind setup or surges with their probabilities of occurrence.

Figure 5 and the tables in Appendix 2 cannot be used to estimate storm surges where coastal waters are confined by bays or where there are islands or large shoals. Localized storm surges caused by rapidly moving weather fronts, thunderstorms, or large pressure changes can be quite large (2–5 feet, 0.6–1.5 meters) but cannot presently be calculated or forecast.

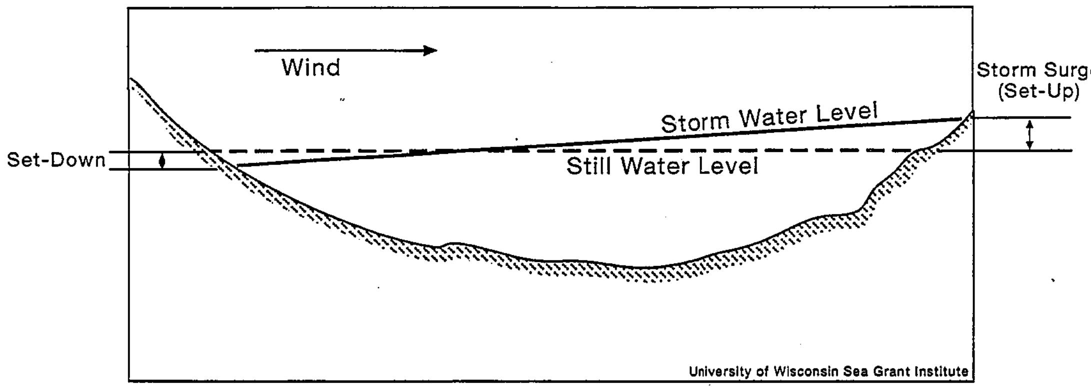


Figure 3. Storm surge

E. Shoaling Storm Waves

During storms, waves have a range of heights at each location. Maximum storm wave heights vary from site to site and from lake to lake. Deep water storm waves as high as 25 to 30 feet (7–9 meters) have been reported on the Great Lakes. Fortunately for coastal property owners, shallow nearshore water depths are typical of most coastal sites, which helps protect the shoreline. As waves approach the shore and travel over decreasing water depths, they begin to dissipate their energy, first by partial spilling of the wave at the crest, followed by complete spilling as the wave surges to shore, or complete collapse in the form of plunging breakers.

Before waves reach the shoreline, the largest waves have broken. This is a very important form of protection, since the amount of wave energy that breaks against the shoreline is proportional to the wave height squared. This is why rising lake levels, lakebed erosion, and storm surges have such a large effect; they create deeper water near the shore and allow larger waves to break against the shore. This increases shoreline recession and damage to coastal shore protection structures.

Each wave has a limiting water depth below which it will break, retaining some of its energy. As a rule of thumb, severe storm wave heights on the Great Lakes are limited to 60% to 80% of the **storm** water depth on gentle lakebed slopes (gentler than 1:50, vertical: horizontal distance) in water depths of less than 15 feet (5 meters) (Goda 1985). For steeper-sloped lakeshores, this generalization does not apply. Wave heights can exceed water depths on some very steep lakebed slopes.

F. Estimating Storm Wave Runup

Wave runup is the vertical distance a wave will rise when washing up on a beach or on a shore protection structure (Figure 1). This distance depends on wave characteristics, nearshore lakebed form and slope, porosity, roughness, and slope of the beach or shore protection structure. Generally, because a cobble beach or rubble revetment is more porous, it will absorb more of a wave and have less runup than a sandy beach or a sloping concrete slab revetment. A wave will run higher up a steeply sloping structure than a gently sloping structure. Wave runup on beaches or coastal structures is proportional to the wave height. Some minimum values for wave runup are given in Table 3 (page 14).

Calculating maximum wave runup is a complicated process best left to a professional engineer. A set of maximum wave runup values for particular wave and coastal conditions is shown in Table 4 (page 19) as an example of the possible variations in wave runup.

G. Identifying Sites *Obviously at Risk* of Flooding

This evaluation can be done by nonprofessionals at specific sites. It will be subjective, but informed. A step-by-step example of such an evaluation is given at the end of this section. Although what seems obvious to one person may not seem obvious to another, there is a sound basis for the conditions of risk that make some sites obviously at risk. For example, experts agree that a house located within a 100-year floodplain has an obvious long-term risk of flooding.

Some of the ways in which coastal land may flood are shown in Figure 4. Two assumptions are used here to make this type of evaluation:

Assumption 1—Sites that are obviously at risk will be flooded with a combination of record-high monthly mean lake level, moderate storm surge, and minimum storm wave runup.

Assumption 2—Sometime within a few decades, most coastal properties will experience a high water elevation equivalent to the elevation in Assumption 1. It may also be due to a combination of moderately high lake levels, severe storm surge, and major storm wave runup.

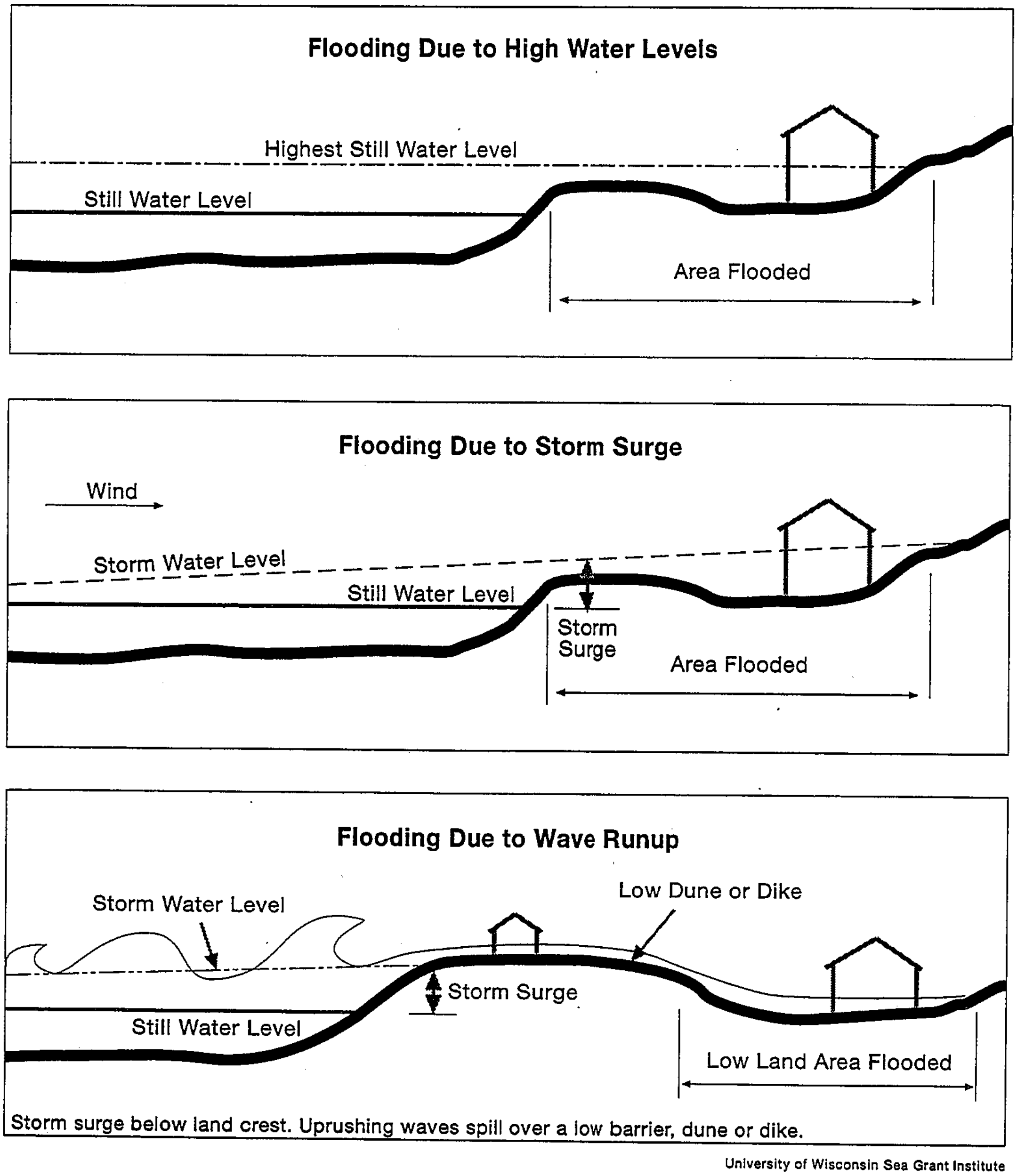


Figure 4. Types of coastal flooding

1. Calculating a Storm Water Level or Storm Wave Runup Elevation

Sites obviously at risk of flooding are sites with land elevations at or below the sum depicted in Assumption 1:

highest 20th century mean monthly lake level elevation
+
moderate storm surge
+
minimum storm wave runup

Lake level and storm surge make up the storm water level (Figure 1). Add wave runup to get the storm wave runup elevation.

It is important to recognize that other combinations are sometimes more appropriate to use, depending on what is at risk. For an electrical substation sited near the coast, a higher combination of lake levels, storm surges, and wave runups should be used.

2. Converting Lake Level Elevations to Land Elevations

Use Table 2 to convert lake levels from Table 1 to equivalent land elevations. Then comparisons can be made between highest storm water elevation and land elevations of buildings and property. The equivalent elevations in Table 2 are only true for U.S. and Canadian master lake level gauging stations on each lake and for the chart datums used on the monthly lake level bulletins. However, the equivalent elevations in Table 2 can be used as approximations of the equivalent elevations between datums at other locations within less than a half-foot (a few tenths of a meter) error. The NGVD elevations are the same as MSL elevations.

Table 1. Record Great Lakes Water Levels 1918-1998 (Relative to IGLD 1985)

Lake	Record High Levels, Monthly Mean (above Chart Datum)			Record Low Levels, Monthly Mean (below Chart Datum)		
	Feet	Meters	Year	Feet	Meters	Year
Superior	+2.3	+0.7	1985	−1.6	−0.5	1926
Huron	+4.9	+1.5	1986	−1.4	−0.4	1964
Michigan	+4.9	+1.5	1986	−1.4	−0.4	1964
St. Clair	+5.0	+1.6	1986	−1.8	−0.5	1936
Erie	+5.1	+1.5	1986	−1.0	−0.3	1936
Ontario	+5.3	+1.6	1952	−1.4	−0.5	1934

Source: U.S. Army Corps of Engineers 1998.

3. Moderate Storm Surges

For a moderate storm surge, pick the storm-induced rise (storm surge) on Figure 5 at the location closest to the site being evaluated. The tables in Appendix 2 provide some indication of how often such a storm surge is expected to occur.

Table 2. Approximate Land Elevation Equivalents for Great Lakes Chart Datums

	Chart Datum[1]		Equivalent Land Elevation		
Lake	Feet[2]	Meters[2]	NGVD 1929[3] Feet	NAVD 1988[4] Feet	CGD[5] Meters
Superior	601.1	183.2	601.0	601.0	182.9
Michigan	577.5	176.0	578.1	577.6	N/A
Huron	577.5	176.0	578.1	577.6	176.0
St. Clair	572.3	174.4	573.1	572.5	174.4
Erie	569.2	173.5	570.1	569.4	173.5
Ontario	243.3	74.2	244.0	243.4	74.2

1). IGLD 1985. Sources: 2) Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1992, 3) U.S. National Ocean Service 1987, 4) National Geologic Survey 1998, and 5) Canadian Geodetic Datum (CGD or GSC) Canadian Hydrographic Service 1987.

4. Minimum Wave Runup

A value for a minimum wave runup can be selected from Table 3. *At sites where there is evidence of (or suspected) significant lakebed erosion in front of a shore protection structure, double the runup values given in the table.* This is a precaution against anticipated deeper water in front of the structure in the future. For most beaches, lakebed erosion will shift the beach landward, and the wave runup is not likely to change. Lakebed erosion is discussed on page 36.

Table 3. Minimum Wave Runup Values for Open Coasts of the Great Lakes

Minimum Wave Runup Values in Feet above a Storm Surge Elevation	
Beaches	2.0 feet (0.6 meters)
Riprap Revetments	2.0 foot (0.6 meters)
Vertical Seawalls*	3.0 feet (0.9 meters)

*Runup on seawalls is treated differently than runup on beaches or revetments. The values given in the table are for the seawall crest elevation above the storm water elevation. See section 5, page 16.

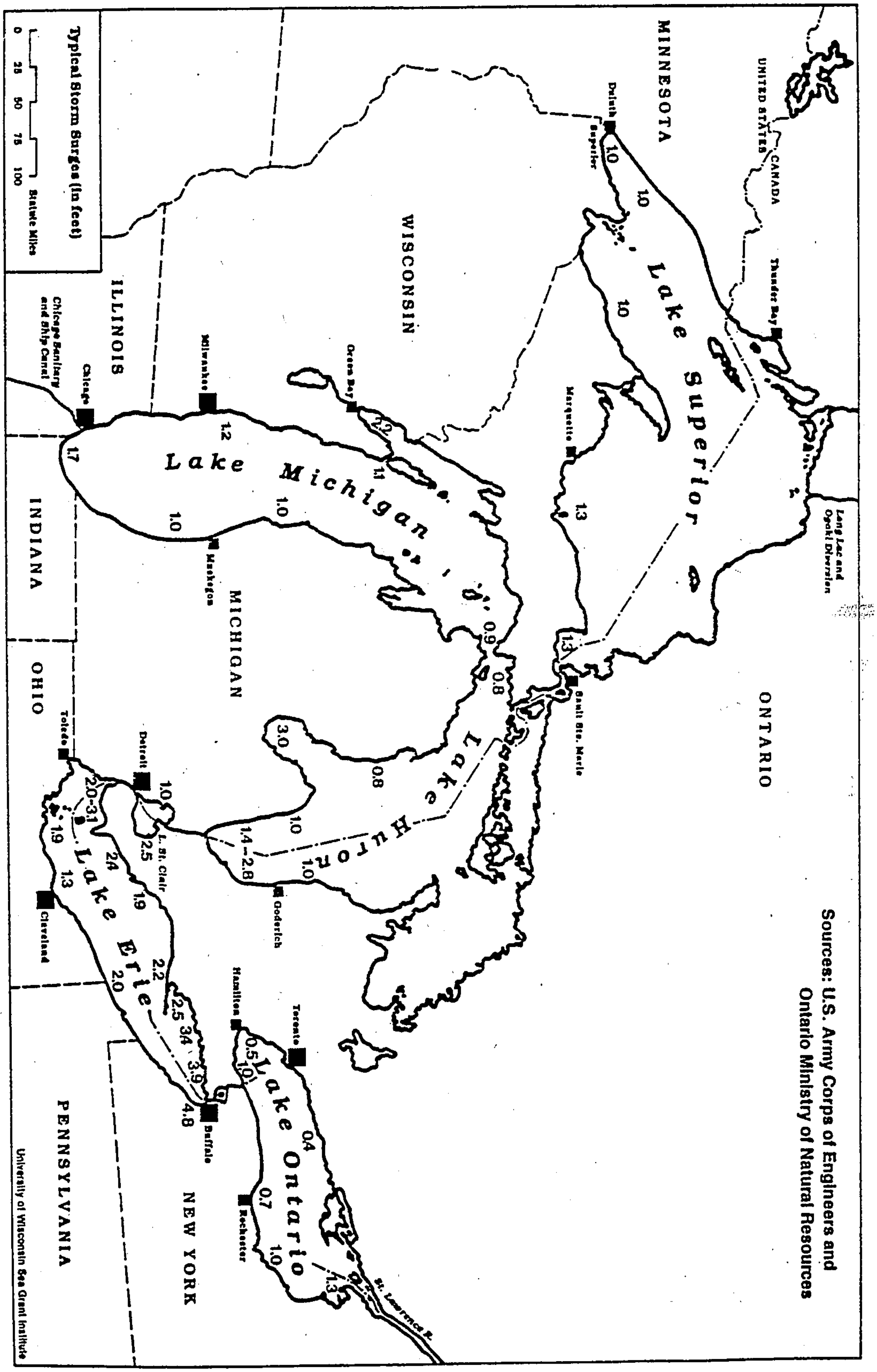


Figure 5. Generalized storm surges in the Great Lakes (Sources: U.S. Army Corps of Engineers and Ontario Ministry of Natural Resources)

5. Wave Runup on Seawalls

Wave runup on seawalls is treated differently than for other structures. The runup value is the height of the seawall crest above storm water levels (*freeboard*) that is estimated to be adequate for storm wave overtopping rates of 4.5 gallons per minute per foot of shoreline (or 3.5 cubic meters per hour per meter of shoreline) (Goda 1985). This value is appropriate where the land behind the seawall is not prepared to handle large volumes of runoff from wave overtopping. Examples are most residential and commercial properties where there are no sloped concrete surfaces, retaining walls, and large-capacity drainage systems to handle storm water drainage.

Example 1: Estimating Storm Water Level and Wave Runup Elevation

A 30-year-old house is on a coastal lot in Sheboygan County, Wisconsin, on Lake Michigan. The elevation of the first floor is about 3 feet above ground level, and the elevation of the basement floor is about 6 feet below ground level. A topographic map of the area indicates that the ground around the house is about 588.5 feet above sea level (NGVD 1929). The shore is a beach. There is no sign of lakebed erosion. Is the building obviously at risk of being flooded?

Step 1: Determine the highest historic or predicted lake level.

First, find the highest monthly mean lake level for Lake Michigan from Table 1. This is 4.9 feet above chart datum. Round up this value to the next highest whole number: 5.0 feet.

Step 2: Determine a local moderate storm surge.

The open coast at Sheboygan has a typical storm surge of 1.2 feet (Figure 4). Check Appendix 2 for a moderate storm-induced rise (storm surge) with a 20% possibility. Sheboygan is between Kewaunee (0.8 foot rise) and Milwaukee (1.0 foot rise). Use the highest of the three values: 1.2 feet.

Step 3: Select an appropriate minimum wave runup value.

From Table 3, the minimum wave runup on a beach will be 2.0 feet.

Step 4: Estimate a wave runup elevation.

Highest still water level (Step 1)	5.0 feet above chart datum
Typical storm surge (Step 2)	1.2 feet
Minimum wave runup (Step 3)	2.0 feet
Lake Michigan elevation (Table 2)	+578.1 feet above NGVD 1929
Estimated wave runup elevation	= 586.3 feet above NGVD 1929

Step 5: Compare the wave runup elevation with the building site elevation.

Building site ground elevation	588.5 feet above NGVD 1929
wave runup elevation (Step 4)	−586.3 feet above NGVD 1929
Difference	= 2.2 feet

Since the first floor of the house is 3 feet above ground level, the wave runup elevation is 5.2 feet below the first floor elevation.

Step 6: Compare the basement floor elevation with the highest still water elevation.

Highest still water level (Step 1)		5.0 feet above chart datum
Lake Michigan elevation (Table 2)		+578.1 feet above NGVD 1929
Highest still water elevation		583.1 feet above NGVD 1929
Basement floor elevation	(588.5 – 6.0)	–582.5 feet above NGVD 1929
Difference		= 0.6 feet

Answer: The land around the building is about 2 feet above the estimated wave runup elevation, so the building is **not** obviously at risk of being flooded. The basement is 0.6 feet below the highest still water elevation. The basement could flood if substantial water seepage through the ground from the lake occurred, or if a storm surge and storm wave runup is much higher than estimated and the yard becomes flooded.

This example demonstrates the judgment used in picking lake level and storm conditions "likely" to be encountered. In this example, an evaluator may consider: a) installing a larger basement sump pump, b) installing a storm water drainage system in the yard, c) installing a raised berm behind the beach, or d) getting an estimate of **highest** storm water elevation. There is a possibility that the storm water level could exceed the value estimated in the example. This issue is covered in the following section on making estimates for sites with an apparently low risk of flooding.

H. Identifying Conditions for a Lesser Risk of Flooding

An evaluation of the conditions of an apparently low risk will be more difficult, more subjective, with more differences of opinion than an evaluation of a site that is obviously at risk. There are more frequent observations and agreement about typical storm surge, minimal wave runup, and common storm conditions. Knowledge of the conditions of extreme events is rare. Such extreme events are so rare and the lakeshore conditions so miserable that trained observers are rarely present and able to make careful observations. Therefore, professional judgment is needed in picking realistic combinations of water levels, storm surges, and wave runup. Here are a few assumptions to demonstrate the procedures involved:

> **Assumption 3**—Sites that have an apparently low risk of flooding are sites that would be flooded *only* with a combination of record high water levels (in the twentieth century), extreme storm surge, and high wave runup.
>
> **Assumption 4**—Sometime within a long period of ownership, a coastal property will experience a very high storm water elevation. This elevation may be due to a combination of a moderately high lake level, extreme storm surge, and extreme wave runup values.

The United States and Canada use slightly different methods for estimating extreme storm water rises, so two slightly different approaches are described in the following two sections.

1. Estimating a Highest Storm Water Level Elevation along U.S. Shores

Sites with an apparently low risk of flooding, according to Assumption 3, are sites with land elevations at or above the sum of:

highest water level elevation
+
extreme storm surge
+
high wave runup

Highest water level elevations in this manual are record high twentieth-century mean monthly lake levels. Other highest elevations are possible and may sometimes be preferable (such as the highest daily average water level recorded at the gauge nearest the site). However, the USACE's tables of storm surges used in this manual are meant to be used with forecasted monthly mean lake levels. These storm surge values should work as well with historic mean lake levels in the same months of the year.

2. Selecting a High Storm Surge

Appendix 2 has tables of storm surges for each month, selected sites, and various probabilities of occurrence during the month. These tables have been prepared by staff at the Detroit District, USACE. The storm surge values are meant to be used with a monthly mean lake level forecast published in the District's *Monthly Bulletin of Lake Levels for the Great Lakes* (see Appendix 1 for how to obtain this bulletin).

When you select a storm surge value with an X% chance of occurrence from Appendix 2, you are engaged in *probabilistic thinking*. Probabilistic thinking introduces to hazard evaluation some notion of the likelihood of an event occurring. In seeking to know if a particular coastal site has an apparently low risk of flooding or storm wave damage, you need to seek an answer to these questions:

What is the probability of occurrence of an extreme storm that would cause flooding and storm wave damage to a particular property? Is this probability high enough to take action?

The previous questions are like these familiar questions: *What is the percent chance of rain tomorrow? Is the chance of rain enough to warrant taking my umbrella to work?*

A storm-induced rise is the difference between the instantaneous maximum water level during a month and the mean water level for the same month. This is not the same as a storm surge value, which is the difference between the instantaneous maximum water level during a storm and the mean water level in the days before and after the storm. However, a large record of these rises should provide statistical values that approximate storm surge values because the differences should cancel out.

Caution: The storm-induced rise values and instantaneous peak water level elevations in Appendix 2 understate the possible magnitude of *localized* storm surges in shallow bays and surges caused by rapidly moving weather fronts, rapid atmospheric pressure changes, or thunderstorms.

3. Selecting a High Storm Wave Runup Value

There are no published tables for extreme wave runup on the Great Lakes as there are for storm surge (storm rise) values. Wave runup depends upon a number of factors, including water depths at the bases of shore protection structures, physical characteristics of beach and structure slopes, nearshore lakebed slopes, and storm wave conditions.

Table 4 was compiled from Tables 4–7 in the 1987 *Coastal Processes Manual* to demonstrate the variability in wave runup values that are possible (Keillor and Miller 1987). It is feasible to make similar tables, using updated methodology, engineering runup formulas, or field verification of storm wave runup at coastal sites for each type of shoreline and structure.

Table 4 is evidence of the need for a professional engineering evaluation *if* storm wave runup is an important factor in deciding whether or not a particular property has an apparently low risk of damage from flooding and storm wave damage.

One example of a coastal engineering approach to wave runup on beaches can be found in a recent paper by Ahrens and Seelig (1996). They developed formulas to estimate the approximate upper limit of wave runup on sand and gravel beaches, using data from real sand beaches and laboratory models of gravel beaches. They defined *extreme wave runup* as the elevation above the still water level that was exceeded by 2% of the wave runups.

This extreme wave runup is dependent on

- Deepwater significant wave height (average height of the highest one-third of the waves).
- Deepwater wave length (distance between wave crests).
- Beach face slope.
- Slope of the lakebed in the *surf* zone.
- Difference between sediment size in the surf and *swash* zones.

Table 4. Maximum Wave Runup and Freeboard for a Set of Great Lakes Conditions[1]

Site Conditions	Beach Runup[2,5]	Riprap Runup[2,3]	Seawall Freeboard[2,4]
Beach slope: 1:10	4–8 ft. (1.2–2.4 m)		
Beach slope: 1:20	2–5 ft. (0.6–1.5 m)		
Max. water depth at base of riprap: 1–2 ft. (0.3–0.6 m)		2–4 ft. (0.6–1.2 m)	
Max. water depth at base of riprap: 2–4 ft. (0.6–1.2 m)		3–8 ft. (0.9–2.4 m)	
Max. water depth at base of riprap: 4–5 ft. (1.2–1.5 m)		6–10 ft. (1.8–3.0 m)	
Max. water depth at base of seawall: 1–2 ft. (0.3–0.6 m)			2–4 ft. (0.6–1.2 m)
Max. water depth at base of seawall: 2–4 ft. (0.6–1.2 m)			4–6 ft. (1.2–1.8 m)
Max. water depth at base of seawall: 4–5 ft. (1.2–1.5 m)			6–8 ft. (1.8–2.4 m)

1. "10-year" storm wave conditions, Wisconsin coasts, Lakes Michigan and Superior. Wave periods of 7-10 seconds, deepwater wave heights of 12–18 feet (3.7–5.5 meters).
2. Measurements are given in feet (meters).
3. Riprap slopes of 1:2 (vertical:horizontal distance).
4. Acceptable overtopping rates: 4.5 gallons/minute/shoreline foot. Nearshore slope: 1:30.
5. Minimum runup values for nearshore lakebed slopes of 1:50 inshore of 10-foot (3-meter) water depths. Maximum runup values for nearshore lakebed slopes of 1:10 inshore of 5-foot (1.5-meter) water depths.

> High storm wave runup values used in this manual are intended only for the purpose of illustration. These values approximate extreme wave runup under common storm and shoreline conditions on the western Great Lakes and may not be adequate for uncommon conditions. This is a subject that needs a thorough review. When such a review is done and suitable methods and field verifications are found for calculating wave runup, a revision will be made to this section of the present manual.

Example 2: Estimating an Extreme Storm Wave Runup Elevation on U.S. Shores

This is the same site as in Example 1, except a riprap revetment with a 1:2 slope (vertical:horizontal) has been built on the lakeshore of the property. Recall that this is a house on a coastal lot in Sheboygan County, Wisconsin, on Lake Michigan. The elevation of the first floor is about 3 feet above ground level, and the elevation of the basement floor is about 6 feet below ground level. A topographic map of the area indicates that the ground around the house is about 588.5 feet above sea level (NGVD 1929). The shoreline is a gravelly beach about 20 feet wide with a slope of 20:1 (horizontal:vertical) to the water's edge. The back of the beach at the base of the low bank is about 5 feet below the ground elevation around the house. There is no evidence of lakebed erosion, based on wading near shore and probing the lakebed with a steel rod. (See a later section for more on lakebed erosion.)

Is the first floor of the building apparently safe from being temporarily flooded by high storm water levels?

The simplest way to answer this question is to obtain the *100-year flood elevation* from the Sheboygan County Planning and Zoning office. This is an elevation expected, on average over a long period of time, to occur and reoccur once in 100 years. It is an important and authoritative elevation because it is established by the Federal Emergency Management Agency (FEMA) and used to determine eligibility for flood insurance. Some FEMA 100-year flood elevations are shown in Appendix 2.

Step 1: Obtain the 100-year flood elevation for Sheboygan County.

100-year flood elevation	584.3 feet MSL 1929

Step 2: Compare the 100-year flood elevation with the property elevation.

Yard elevation around the house	588.5 feet NGVD 1929 (same as MSL)
Minus 100-year flood elevation	−584.3 feet MSL 1929
Ground elevation above 100-year flood water level	= 4.2 feet

The 100-year FEMA flood elevation includes a storm surge of unknown magnitude.

Step 3: Estimate the range of wave runup values.

In Table 4, ranges of wave runup values depend on the water depth at the base of the slope. Assume the elevation of the revetment base equals the beach elevation at the water line.

Elevation, base of revetment = 588.5 feet − 5 feet − 1 foot = 582.5 feet

100-year flood elevation	584.3 feet NGVD 1929
Elevation, base of revetment	–582.5 feet NGVD 1929
100-year flood water depth at base of revetment	= 1.8 feet

From Table 4, wave runup on the revetment is likely to be: 2–4 feet for water depths of 1–2 feet. Assume the higher value of 4 feet for wave runup.

Step 4: Calculate the wave runup elevation.

Wave runup elevation = 584.3 feet + 4 feet = 588.3 feet NGVD 1929

Step 5: Compare the freeboard (height of the yard above the 100-year flood) of the ground elevation to the wave runup elevation value.

The wave runup elevation of 588.3 feet is about the same as the ground elevation around the house (588.5 feet). Wave runup seems likely to reach the yard if a *ten-year* storm (assumed in Table 4) coincides with a *100-year flood* at this property.

Step 6: Check this conclusion against an alternative approach of using maximum published values for mean monthly lake levels, storm surges and wave runup (from Table 4).

From the Corps web site, or from the Lake Michigan at Kewaunee, Wisconsin, table and the Lake Michigan at Milwaukee, Wisconsin, table in Appendix 2, pick a storm surge with a 1% possibility of occurrence in October. Sheboygan is between Kewaunee (1.0 foot rise) and Milwaukee (1.6 foot rise). Use the higher of the two values.

Highest mean monthly water level (Table 1)	4.9 feet above chart datum
Maximum storm surge (Appendix 2)	1.6 feet
Lake Michigan chart datum elevation (Table 2)	+578.1 feet above NGVD 1929
Estimated storm surge elevation	= 584.6 feet above NGVD 1929
Elev., base of revetment = 588.5 feet – 6 feet =	– 582.5 feet NGVD 1929
Maximum water depth, base of the revetment	= 2.1 feet

Wave runup value (Table 4): 4 feet.

Wave runup elevation = storm surge elevation plus wave runup

Wave runup elevation = 584.6 feet NGVD (1929) + 4 feet = 588.6 feet NGVD (1929)

Using the maximum combinations of record high mean monthly lake level, storm surge, and wave runup, the wave runup elevation barely reaches the yard elevation of 588.5 feet, NGVD 1929. This conclusion agrees with the conclusion reached by considering the FEMA 100-year flood elevation.

Do the two conclusions satisfy the condition of risk that there is an apparently low risk of flooding at this property?

If a subjective judgment of the conditions of risk is satisfactory, one need go no further with Example 2. If there is a need to define *low risk*, one must consider probabilities of occurrence of the water level and storm conditions used in the example. The wave runup value used in Example 2 is the weakest element in the example because it is just "tacked on" and not associated with either the storm surges that are part of the FEMA flood elevation history or the storm rise values selected from Appendix 2. The estimating of probabilities is described after Example 3.

4. Estimating Highest Storm Water Elevations along Canadian Shores

Determining conditions of risk for Canadian sites with an apparently low risk of flooding can be done as illustrated in Example 2, substituting the appropriate 100-year peak instantaneous water level developed by the Ontario Ministry of Natural Resources (OMNR 1989) from Appendix 2 for the FEMA 100-year elevation.

Example 3: Estimating an Extreme Storm Wave Runup Elevation on Canadian Shores

There is a house on a coastal lot east of Port Colbourne, Ontario, on the northern shore of Lake Erie. The first floor of the house is about one-half meter above a ground elevation of 178 meters, CGD. There is no basement. A topographic map of the area indicates that the yard around the house varies from 178 to 179 meters, CGD. The shoreline is a sandy beach. The back of the beach at the base of the low bank is about 1.5 meters below the first-floor elevation of the house.

Is the first floor of the building apparently at low risk from temporary flooding by high storm water levels? Will the yard be flooded?

Step 1: Obtain the 100-year peak instantaneous water level from Appendix 2.

The 100-year water level at Port Colbourne is 176.8 meters CGD

Step 2: Compare the 100-year water level with the property elevation.

First-floor elevation of the house = 0.5 meter + 178.0 meters =	178.5 meters CGD
Minus 100-year level	− 176.8 meters CGD
First-floor elevation above 100-year water level	= 1.7 meters

Step 3: Estimate the range of wave runup values.

Table 4 (derived for conditions in Lakes Superior and Wisconsin) indicates ranges of beach runup of 1.2–2.4 meters and 0.6–1.5 meters depending upon the beach slope. Since the property elevation is quite low, it is worth the effort to measure or estimate the beach slope. The beach slope appears to be gentler than 1:20 (vertical:horizontal). Therefore, the appropriate range of wave runup is 1.5 meters for similar wave conditions as those used to develop Table 4.

Step 4: Calculate the wave runup elevation.

100-year water level at Port Colbourne	176.8 meters, CGD
Add wave runup	+ 1.5 meters
Wave runup elevation	= 178.3 meters, CGD

Step 5: Compare the ground elevation to the wave runup elevation.

Elevation of the yard	178 to 179 meters CGD
Wave runup elevations	178.3 meters CGD

If the wave runup values in Table 4 are appropriate for this site, the lowest areas of the yard would be flooded from wave runup if the storm wave conditions used in Table 4 coincided with the 100-year water elevation at this site.

The primary weaknesses with the information available for use in this example are similar to the weaknesses seen in Example 2: wave runup information not derived for this site and storm wave conditions not matched to storm surge conditions. Professional engineering help is needed to isolate the storm surge component in the 100-year water elevation information, match storm wave to storm surge wind conditions, and estimate the storm wave runup elevation.

5. The Probabilities of Flooding and Storm Wave Damage

Is there a need for information about the probabilities of flooding and storm wave damage?

If the answer to this question is "yes," Example 4 (page 25), plus a few examples from published studies (Section 7, page 24), show the kind of information that results from professional efforts to estimate probabilities of storms and their consequences. Professional engineering firms can develop site-specific probabilities of high storm water elevations and wave conditions. Published information on the probabilities of storm wave damage to shore protection structure or bluffs and banks from storm conditions is rarely found. The likelihood of storm wave damage is a matter of professional engineering judgment.

6. What is the Probability of Another Storm Like the One That Sank the *Edmund Fitzgerald*?

What is the chance that coastal property on the southeast coast of Lake Superior will again experience a storm like the storm that sank the *Edmund Fitzgerald*? This now-legendary Great Lakes ore carrier sank near Whitefish Bay in the tremendous gale of November 10, 1975. Waves as high as 25 feet (7.4 meters) and steady winds of 43 to 58 knots (50–67 miles/ hour or 22–30 meters/second) were reported by a nearby vessel, the *Anderson*, around the time of the disaster (Trimble 1977).

The *return period* is a common term used by flood planners and coastal engineers to define extreme flood and storm events on rivers and along coasts. It is the expected time (on average) between extreme events of the same magnitude over many decades. The *Fitzgerald* storm in the previous example was probably a 50-year storm event, according to extreme wave height tables (Driver et al. 1992). In the area of Lake Superior where the *Fitzgerald* sank, extreme wave heights of 28.2 to 29.5 feet (8.6–9.0 meters) have a 2% chance of being equaled or exceeded at least once a year, an 18% chance at least once in 10 years, a 40% chance in 25 years and a 61% chance in 50 years (Driver et al. 1992).

Is this is a frequent enough occurrence for an insurer, lender, or property owner to be concerned about particular coastal properties during such extreme storm conditions?

Over the multiple decades of a home mortgage, the FEMA 100-year flood elevations give a good indication of the probability of occurrence: 1% in any given year, 26% in a 30-year time span.

However, during a period of high lake levels, the risk of reaching and exceeding the 100-year flood elevation within the coming year rises considerably above 1% as shown in the next section and Example 4: *Conditional Probability of Flooding at Cleveland, Ohio.*

7. A Few Samples of Probabilistic Analyses of Flood and Storm Damage

It is helpful for investment and insurance purposes to know the probability that a particular coastal property or structure will suffer damage within the period of investment or coverage. Here are a few samples of engineering work where this information was obtained.

- *The probability of a storm surge flooding a city.* Erich Plate (1994) calculated the probability of an extreme storm surge traveling 100 km up the Elbe River from the North Sea and overtopping dikes protecting the city of Hamburg, Germany. Results indicated a 1.2% annual probability of overtopping and dike failure for climatic conditions in 1990. Raising of the dikes by 3.9 feet (1.2 meters) would lower that annual probability to 0.21%. The acceptable condition for this risk in Hamburg, reached by social consensus, is an annual probability of flooding of 0.1% (a one-in-1,000-years event). The standard could be met for 1990 climatic conditions only by using all of the freeboard of the raised dikes (leaving no margin for error in the estimate).

- *Reduction of the probability of unsatisfactory performance of a harbor breakwater.* Moritz et al. (1994) studied the present condition and rehabilitation options for a breakwater protecting Burns Harbor on Lake Michigan. The breakwater was structurally and operationally unreliable. More than half of the armor stone had settled or toppled to the lakebed. Harbor waters were not calm enough for unloading ships, and damage to ships and docks was substantial. The optimum economic option for rehabilitation reduced the annual probability of instability of the breakwater armor stone from 61% to 0.01% on the lake side of the breakwater and from 87% to 8% on the harbor side. This option would reduce the annual probability of unsatisfactory wave transmission from 94% to 43%.

- *Prediction of the probability of damage to a shore protection structure from a particular storm.* Meadowcroft et al. (1994) predicted a 16% chance of more than moderate damage and a 3% chance of severe damage from a *design storm* and water level. The chance of occurrence of the design storm and water level event were not stated.

- *Reduction of the probability of water overtopping a coastal structure by raising the crest elevation.* Meadowcroft et al. (1994) determined that the annual probability of severe damage from overtopping water is 72% with a crest elevation at 47 feet (14 meters). Raising the crest elevation by 20 feet (6 meters) would reduce the probability to 3%.

- *The probability that a coastal dike is unstable.* Meadowcroft et al. (1994) calculated a factor of safety of 1.6 from the mean values of the slope properties. This indicates the resistance to failure in the slope is 60% greater than the forces acting on the slope. Given the variability assumed in the slope properties, there is a 3% probability that the factor of safety is less than 1.0, indicating potential failure of the slope.

8. The Conditional Probabilities of Lake Levels

The *conditional probabilities* of extreme water levels are partly dependent on the present lake level. There is a greater probability of record water levels occurring next year if this year's water levels are high. Conversely, there is a lower probability of record water levels occurring next year if this year's water levels are average. Potter (1992) demonstrated such a conditional probability using annual maximum water levels in Lake Erie at Cleveland, Ohio.

Potter suggested that a probabilistic approach could be used to adjust insurance premiums annually to reflect the full risk of loss during the coming year. When lake levels are very high, this rate would be higher. With such a floating insurance rate, the coastal homeowner would be paying the "true current cost of insurance."

Example 4: The Conditional Probability of Flooding at Cleveland, Ohio

The 100-year flood elevation at Cleveland, Ohio, is 175.5 meters above IGLD 1985. The record-high monthly mean lake level for Lake Erie occurred in July 1986, at an elevation of 175.0 meters above IGLD 1985. The long-term (twentieth century) mean lake level for Lake Erie in July is 174.4 meters above IGLD 1985. Table 5 compares the probabilities of equaling or exceeding the 100-year flood event computed from Potter's paper with the unconditional probabilities computed as if flood levels on Lake Erie were random events (Markowitz 1971).

The unconditional probability of a 100-year flood occurring within the next year remains constant at 1%. In contrast, the conditional probability of this flood occurring within the next year dropped from 10% at the time of highest lake levels to 0.4%, three years later, when lake levels had declined. Declining lake levels altered only the short-term risk of flooding.

In July 1986, the regional climate shifted from a wet to a dry period. Lake Erie's water level started to decline, which reduced the probability of exceeding the 100-year flood level at Cleveland. By July 1987, Lake Erie had dropped 0.2 meters from the record high level of 1986. The probability of flooding the next year (in July 1988) had dropped to less than 5%. In July 1989, lower lake levels (0.5 meters below the record high level) reduced the probability of the 100-year flood for the next 12 months to 0.4%.

Table 5. Probability in July 1986 of the One-Hundred-Year Flood Level at Cleveland, Ohio

Future Time Span (years)	100-Year Event, Conditional Probability[1]	100-Year Event, Unconditional Probability[2]
1	10%	1%
3	5%	3%
10	2%	10%
30	not relevant	26%
70	not relevant	51%

Sources: 1) Potter 1992 and 2) Constructed from Reich (1973), Markowitz (1971) and USACE (1979).

The risk to investment is a long-term risk with a short-term variable risk component. With the conditional probabilistic approach, an investor in coastal property at Cleveland in 1986 would have seen the greatest risk to investment from high water levels in the year ahead, a level of risk not approached again for another decade. Four or five years in the future, the risk would have appeared to be the same for both conditional and unconditional probabilistic approaches.

If future climatic conditions are like those of the past, over a time span of more than 5–10 years, the relatedness of lake levels from one year to the next becomes less important and the risk to investment seems more likely to approach the risk calculated with the unconditional approach used by FEMA. *If significant climatic change occurs, predictions about water levels based on historical records will be misleading.* The FEMA method assumes a future climate like that of the past.

The FEMA flood frequencies and the Canadian instantaneous peak water elevations combine high lake levels and storm surges. If the probabilities of wave runup and resulting damage from wave runup are important, the estimation of such probabilities is complex. There are many possible combinations of lake levels and storm conditions that will produce the wave runup elevations used in Examples 2 and 3. The probability of water reaching those elevations is the sum of many *joint probabilities* for storm and high lake levels occurring at the same time.

The method demonstrated in Examples 2 and 3 does not contain an estimate of the likelihood and severity of storm wave damage to the revetment and the bank behind the beach. Such an estimate is made on the basis of engineering judgment. More specific information requires scaled physical model studies, which are run only for engineered shore protection structures on major projects. Many shore protection structures in front of private homes bear little resemblance to the few engineered structures that have been tested in laboratories.

9. Urban Flooding

In urban areas, manufacturing plants, office buildings, wholesale and retail buildings, hotels, and residences may be built on low ground with building services located in the basement. These flood problems occurred in Milwaukee in 1986, the year of highest twentieth-century lake levels. Similar problems could occur during high lake levels in any coastal town or city on the edge of the Great Lakes.

- Basements in low-lying areas were flooded because of water infiltration due to elevated groundwater or through sewer backup.
- Structural damage occurred to building foundations because of hydrostatic pressure from an elevated groundwater table.
- Steam distribution tunnels and underground electrical vaults were flooded and damaged from groundwater intrusion.
- Sewage system lift stations and treatment plants suffered impaired performance because of increased infiltration of clear groundwater and reduced outflow rates.
- Stability of supporting soils under buildings and foundations was reduced.

10. Why Are Urban Facilities Vulnerable to Flooding?

Lake level elevations used for designing and building coastal and estuarine facilities have changed over time, as shown in Table 6. The lake elevations used by USACE for design and construction, and by FEMA for flood insurance, are probably the principal influences on the siting decisions made by municipal, corporate and private planners, engineers, and contractors on the U.S. coasts of the Great Lakes. When lake levels exceed the anticipated elevations, flood damage occurs.

In 1986 and 1987, Lake Michigan water levels exceeded design elevations used by the USACE at Milwaukee since World War II. The record high monthly mean lake level in October 1986 was 4.8 feet (1.5 meters) above LWD. This level was 2.7 feet (0.8 meters) above the design lake level elevation used in the 1950s and 1960s. During a March 9, 1987, storm surge at Milwaukee, the local storm water elevation rose 6.2 feet (1.9 meters) above LWD, even though the mean monthly lake level had dropped 1.3 feet (0.4 meters) from October's century record level.

Lake Michigan water levels have also exceeded elevations used by FEMA at Milwaukee for flood insurance purposes. Three times during the recent high water level period (November 9, 1985; October 4, 1986; and March 9, 1987), water levels at Milwaukee reached or exceeded the FEMA lake level elevation of 5.6 feet (1.7 meters) above LWD, expected to occur (on the average) once in 100 years (USACE 1988a, SEWRPC 1989b). Because of a prolonged period of high water levels and a longer period of record, FEMA raised the 100-year flood elevation at Milwaukee in 1988 by 0.18 meters to a new elevation based on a new statistical analysis by the USACE. The new flood elevation also happened to equal the 1838 maximum monthly mean lake level and the March 9, 1987, storm level.

Table 6 gives historic monthly mean water elevations. FEMA flood elevations are instantaneous water elevations.

Table 6. Historic Lake Michigan Elevations Used for Design at Milwaukee, Wisconsin

Above LWD		Description
Feet	Meters	
7.2	2.2	1838 highest lake level. Federal design level used until WWII for harbor structures on Lake Michigan (3).
6.2	1.9	Open-coast flood level used by FEMA at Milwaukee as of 1988 (1).
5.6	1.7	Open-coast flood level used by FEMA at Milwaukee as of 1977 (1).
3.7	1.2	Federal design level used in the early 1970s for design of the Milwaukee Confined Disposal Facility for dredged material (2).
2.1	0.7	Federal design level used in the 1950s and 1960s for design (2).

Note: low water datum (LWD) is 176.0 meters (577.5 feet) above the International Great Lakes Datum 1985 (IGLD). Sources: 1) U.S. Army Corps of Engineers 1988a, 2) Johnson 1997, and 3) Johnson 1998.

In 1987, the city of Milwaukee had 168 structures completely or partially within the 211 acres (85 hectares) of a newly-revised flood plain elevation of 6.4 feet (2.0 meters) above LWD (SEWRPC 1987). If lake levels rise 1.4 feet (0.4 meters) above this new 100-year flood elevation, an additional 217 structures on an additional 283 acres (115 hectares) of urban land will be flooded. Similar situations probably exist in other Great Lakes cities and towns.

Low Water

EVALUATING CONDITIONS OF RISK FROM LOW WATER LEVELS

A. Sites Obviously at Risk

An approach similar to that used in the previous chapter can be used to investigate this risk.

Assumption—Sites that are obviously at risk from low water are sites where problems are expected to occur when a temporary water level is as low as:

lowest lake level elevation
minus
moderate *set down*

The same moderate storm that brings a temporary rise in water level (storm surge) to one side of a lake will bring a comparable temporary drop in water level (set down) at the other side. If the coastal facility under consideration can withstand a temporary drop in water level ranging from hours to a day, discard the set down value from the calculation. This type of low lake level calculation is useful for evaluating the water levels that could impair operation of a marina or a nearshore water intake.

Example 5: Estimating a Low Water Level for a Marina

A new marina is planned for Lake Michigan at Sheboygan, Wisconsin. In determining how much dredging is required to ensure suitable water depths in the marina at all likely lake levels, it is necessary to calculate a low lake level. The land elevation datum being used by the marina design engineering firm is NGVD 1929.

Step 1: Determine the lowest predicted water level.

Find the lowest monthly mean water level for Lake Michigan from Table 1:
1.4 feet below chart datum.

Step 2: Determine the local storm surge (1.2 feet) from Figure 5 (page 15) (or Appendix 2). Assume an occasional comparable local setdown in water level of 1.2 feet.

Step 3: Estimate the low storm water elevation.

Land elevation of the lake chart datum (Table 2)	578.1 feet (NGVD 1929)
Lowest monthly mean lake level (Table 1)	−1.4 feet
Moderate local water setdown	−1.2 feet
Low storm water elevation	= 575.5 feet (NGVD 1929)

Step 4: Determine the required elevation of the lakebed in the marina needed for continued boat operation during the set down event at low lake levels.

Low storm water elevation	575.5 feet NGVD 1929
Desired depth of water for safe navigation	−11.0 feet*
Clearance between boat and harbor bottom	−1.0 feet
Dredged elevation of marina basin and entrance	= 563.5 feet NGVD 1929

* The desired depth of water is for sailboats that are 40 feet or less in length. The desired depth was selected from Tobiasson and Kollmeyer (1991, Table 12-1, page 280).

B. Identifying Conditions of Lesser Risk

This type of evaluation involves consideration of the probabilities of *lowest* water elevations. In some cases, as with water intakes, an evaluation is simplified by not having to consider storm waves. Lee and coauthors (1997) demonstrated the use of probabilistic lake level forecasts to determine the probabilities of lake levels so low as to impair the operation of a water intake. Their demonstration is used in Example 6.

Example 6. Estimating a Lowest Water Level for a Water Intake

In 1964, Lakes Michigan and Huron began setting record low levels and Lakes Erie, St. Clair, and Ontario were approaching record low levels set in the mid-1930s. At that time, the municipality of Port Colborne, Ontario, on Lake Erie reported to the Ontario Water Resources Commission that the community's water intake could not meet maximum demand at a lake elevation of 570.0 feet (173.7 meters) above IGLD 1955. The community had been experiencing water pumping problems since 1955 because Lake Erie had been below this critical level for some months of each year and continued to decline.

What were the probabilities in July 1964 that Port Colborne would continue to be unable to meet maximum water demand over the next year?

Lee and coauthors (1997) developed a probabilistic lake level forecast based on the information about past lake levels and inter-lake flows that was available in July 1964. Their forecast for 1965 showed a greater than 70% chance that lake levels would be lower than the water level of 570 feet (173.7 meters) (IGLD 1955) at the Port Colborne intake that impeded maximum demand (Figure 6). What happened at Port Colborne? Late in 1964, Lake Erie's mean monthly level dropped to 568 feet

(173.2 meters), a record low level that still stands. The monthly mean level did not rise above the elevation that Port Colborne needed to meet maximum demand until April 1966. The monthly mean elevation did not stay above 570 feet (173.7 meters) until April 1967.

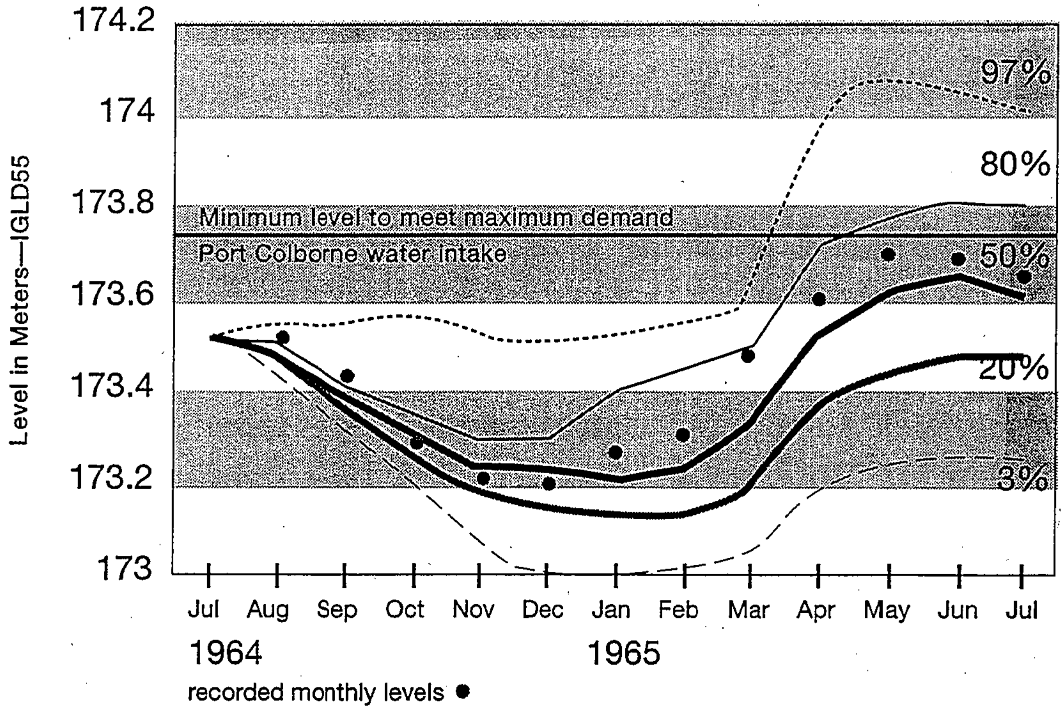


Figure 6. Lake Erie nonexceedance probabilities in 1964 and 1965 (Source: Lee et al. 1997)

The Great Lakes can respond to dry conditions faster than predicted to date by computer modeling. In 1986 computer simulations predicted that if temperature and precipitation in the Great Lakes region return to average conditions, Lake Michigan and Lake Huron will return to average water levels in 6 to 10 years (Hartmann 1987). If the region has very dry conditions like those during 1961–64, the water level of these two lakes will return to average levels in only three or four years. The prolonged wet period that climaxed with the very wet years of 1985 and 1986 was followed by a dry period, including the drought of 1988. Lakes Michigan and Huron declined to average levels 1.7 years after the peak level reached in October 1986.

Erosion Setbacks

COASTAL EROSION AND CONSTRUCTION SETBACKS

It is important to determine if an existing or proposed building is set back far enough from the lake to prevent damage or loss of the building due to erosion during the life of the mortgage or the projected life of the structure.

A. Bluff and Bank Erosion

Erosion and recession of bluffs and banks is the rule for most coastal properties. From a geological perspective, the Great Lakes are relatively young, and erosion of their shores is an active natural phenomenon.

Bluffs recede as the bluff face weakens and collapses, as waves chew away at their bases and erode soft nearshore lakebed sediments, and as the exposed bluff face is washed, grain by grain down the slope and into the lake. Over the years, these actions cause the shoreline to move inland continually—a process known as *shore recession,* or *shore erosion.* The various ways in which coastal bluffs and banks erode are shown in Figure 7. Lakebed erosion is not shown but is discussed in a later section.

Bluffs and banks are stable as long as the soil's resistance to failure remains greater than the forces that can cause failure. Generally speaking, stable slopes have fairly uniform faces and are likely to remain stable as long as a) the toe is protected from wave attack, b) the face of the slope is protected from surface erosion by vegetation, c) the bluff or bank is well-drained and groundwater pressure does not build up behind the slope, and d) the nearshore lakebed is not eroding. There are many Great Lakes slopes where these conditions are not met, and slopes fail.

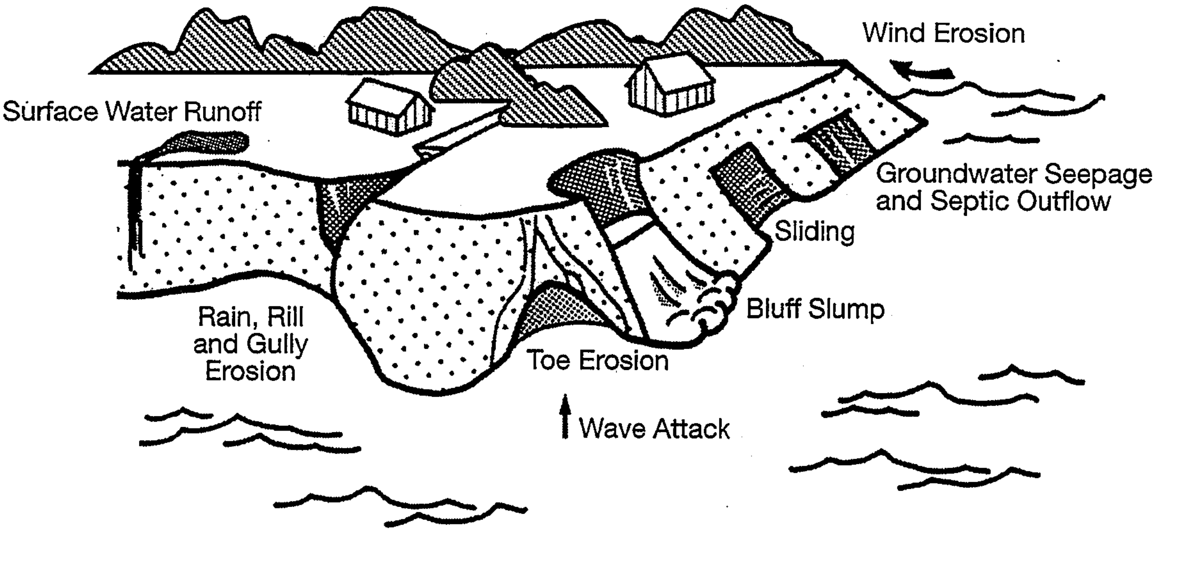


Figure 7. Coastal erosion problems

1. Causes of Bluff/Bank Failure

The forces that can cause the collapse of a bluff include the weight of the soil and groundwater in the bluff and the weight of buildings or heavy machinery on top of the bluff. Bluffs often fail in a sequence of events. The events may include some or all of the following factors in various different time sequences:

- Heavy rains or melting snow.
- Elevated groundwater levels.
- Increased bluff top load (buildings, machinery, etc.).
- Decreased soil strength.
- Loss or removal of vegetation on the slope.
- Erosion of the bluff toe during storms.

The presence of groundwater in the bluff weakens the frictional forces that hold soil particles together and give the soil its strength. Soil drying and cracking, freezing and thawing, as well as water saturation, are other factors that reduce bluff soil strength.

2. Surprising Bluff Failures

Coastal erosion does not always proceed in an orderly predictable fashion. Occasionally, a large section of bluff will suddenly fail, thundering down the slope to pile up on the beach, shaking the ground like an earthquake. Sometimes these failures are preceded by warning signs, beginning with a small movement that lowers the top surface of the bluff a few inches to a few feet until the displaced block of soil encounters enough resistance to halt its movement. Further movement can be slow or sudden. Storm waves attacking the base of the bluff or rainfall seeping into bluff soils triggers further movement of the sliding block of bluff material.

3. Unspectacular Bluff Failure

Significant but less obvious coastal erosion occurs as shallow slides, surface water runoff, and mudflows. The faces of bluffs may wash away in small clumps and individual grains (rain, rill, and gully erosion). As much as half of the long-term erosion of some bluffs is caused by these almost invisible forms of erosion. Slow failure may occur via *bluff creep* (see box).

4. Evolution of Bluff Faces

A coastal bluff may not remain in the condition it was in when the property was inspected and a decision was made to invest in the property. Bluffs need to be monitored for changes that are likely to increase the risk to investment. It is important to recognize the signs of active bluff erosion and failure (see the box below). Some slopes are becoming steeper and less stable. These slopes need to be carefully watched.

Visual inspections of bluff tops and bluff faces should be done at least twice a year: spring and fall. Significant signs of impending rapid failure should be followed up with an evaluation by an expert. Some of these signs of impending rapid failure are

- A lowering (slumping) of part of the bluff top, forming a ledge lower than the bluff top.
- Cracks developing or opening up in the bluff top.
- Unexpected water seepage from the face of the bluff.
- A major loss of vegetation from the bluff face.
- Loss of a significant portion of the lower part of the bluff face.

Some signs of ongoing bluff creep (Terraprobe 1994) are

- Trees with curved trunks that are concave in the upslope direction.
- Displaced posts, poles, retaining walls, foundations, roads.
- Turf rolls downslope of creeping boulders.
- A "stone line" at the base of a creeping soil mass.

5. Bank Erosion

In this manual, banks are defined as low shorelines (generally 10 feet or less above beaches) that have less complex structure than bluffs. In Wisconsin, there are numerous sandy banks that are remnant beaches from a distant period of very high lake levels. Bank erosion is less complex but sometimes more dramatic than bluff erosion. In 1985, storms caused rapid erosion on Wisconsin's Lake Michigan coast where the combination of high lake levels and storm surges allowed storm waves to break against unprotected, highly-erodible sand banks. Some of these banks, 2 to 6 feet high, retreated 10 to 50 feet in a single storm.

6. Rock Bluff Erosion

Recession is not limited to clay bluffs and low sandy banks; rock terraces and bluffs also recede. Over decades, wave action and the ceaseless wash of gravel and cobbles against rocky ramparts of the coast undercut the rock. Storm waves and water draining from overlying topsoil fill cracks in the rock. In cold weather, this water freezes and expands, applying large separation forces to the rock along the sides of the cracks. Eventually, blocks of rock fall from the face of the bluff.

B. Recession and Water Level Change

Up to half of the material loss in bluffs or banks with raw, unvegetated slope faces may come from the slow processes of surface erosion as water flows over the faces of the slopes. Recession of coastal banks and bluffs, in theory, also occurs in direct proportion to rises in lake level as bluff soil and lakebed sediment are removed and where the shore is no longer in equilibrium with the lake (Bruun 1962, Kamphuis 1987). Fine sediment gradually moves offshore to eventually settle in deep, depositional basins. Coarse sand and gravel from the land join nearshore sediments. As long as water levels continue to rise or the lakebed continues to erode, a state of equilibrium between the land and the lake—and therefore a slowing or halting of recession—will not occur.

During a period of rising lake levels (1967–76), a 31-mile stretch of sandy beach along Michigan's Lake Michigan coast was observed as it responded to rising lake levels (Hands 1980). As the water level rose, the nearshore sandbars moved up the beach slope and shore recession increased, though at a rate that depended on storm events. The sandbars continued to migrate shoreward even under relatively mild wave conditions. Shoreline retreat lagged behind rising lake levels, ultimately reaching a new position and reestablishing a series of stationary sandbars in equilibrium with the lake levels about three years after lake levels stabilized.

Many Great Lakes shores are different from Michigan's Lake Michigan coast, lacking either the extensive dunes and sandy beaches or the prevailing onshore winds common on the east side of the lake. Where little or no sand beach and sandbars exist in front of a bluff to absorb wave energy, yet mobile sand is present as an abrasive agent, the recession rate will be related to the long-term average wave energy striking the bluff (Kamphuis 1987).

As lake levels stabilize or decline, beaches may rebuild with sediments brought ashore by waves. The new beaches protect the base of banks and bluffs from all but the largest storm wave runup. With protected toes, banks and bluffs recede to ultimately stable slopes if the slope face revegetates. The resulting new equilibrium between the land and the lake occurs where there is sufficient sand and gravel for effective beach building and where there is little or no net movement of nearshore sediment out of a coastal reach where the beaches are being built. The return of high water levels or extreme storms breaks up this equilibrium.

Bishop et al. (1992) and Nairn and Riddell (1992) showed the effect of a prolonged period of high water levels on the Scarborough Bluffs and nearshore lakebed of Lake Ontario (Figure 8). During the 37 years between lakebed profile measurements, the monthly mean lake level was above the long-term (1900–1989) average lake level for the entire year in each of 20 years. The result was that waves eroded the upper, inshore part of the profile more than the lower part of the profile and contributed to the recession of the bluff. Over decades, the profile deepened with deeper water close to shore, as the lakebed eroded. Lakebed erosion is described in the following section.

C. Lakebed Erosion

During the 10 years since the first edition of this manual, lakebed erosion has been measured in places as diverse as the eastern coast of Lake Michigan and the shallow waters of Maumee Bay on Lake Erie. Lakebed erosion is shown in Figure 8. Average short-term and long-term rates of 0.5 to 6 inches (1–15 centimeters) per year have been measured.

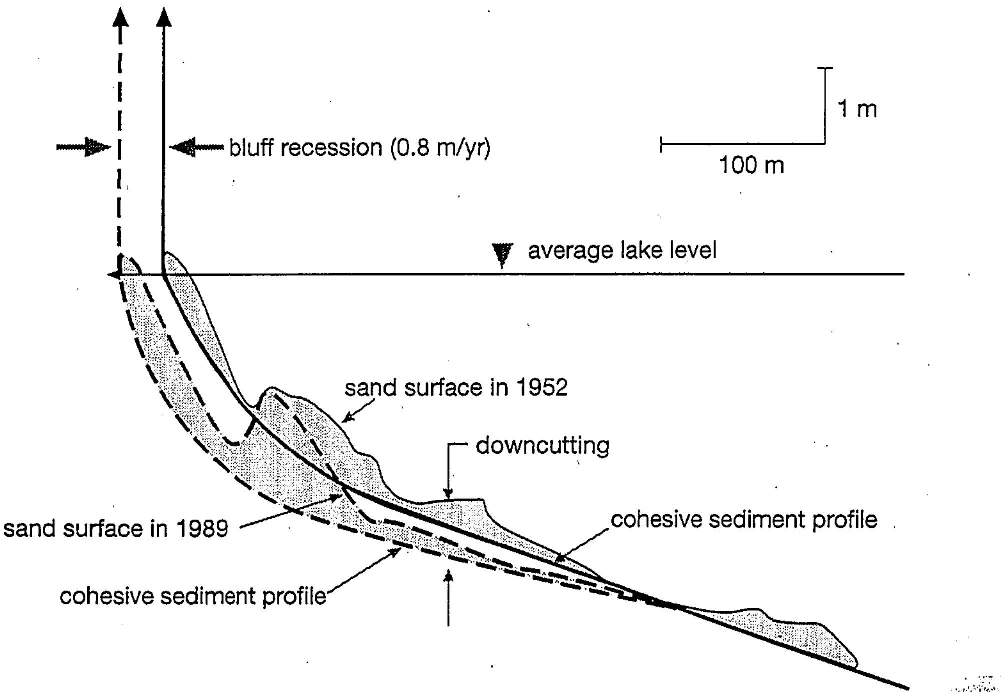


Figure 8. Cohesive bluff recession and lakebed erosion 1952-1989, at Scarborough Bluffs, Lake Ontario. Note: Vertical exaggeration is 100 times. (Sources: Bishop et al. 1992 and Nairn and Riddell 1992.)

1. What Is Lakebed Erosion?

Lakebed erosion (or downcutting) is abrasion of erodible nearshore lakebeds by the motion of small amounts of sand and gravel over the lakebed. The motion of these particles and their abrasive action is caused by waves and currents. Lakebed erosion seems to be a continuous process, even though major storms cause a lot of the erosion. Even during low water level periods and during low wave conditions, the abrasion goes on. Lakebed erosion occurs from the shoreline out almost to the 34-foot (10 meter) water depths reached by harbor breakwaters, according to Nairn (1993) and Johnson (1994).

2. Consequences of Lakebed Erosion

This invisible hazard can surprise shoreline property owners and prospective buyers of shoreline property with unexpected damage to property by recession rates and by shortening the effective lives of shore protection structures. Lakebed erosion will most adversely affect seawalls and revetments, undermining them by erosion in front of the structure toe and base.

3. The Significance of Lakebed Erosion

Lakebed erosion can be a major factor in increasing the wave energy that impacts on shore protection structures. The magnitude of this factor can be seen by considering a hypothetical shore protection structure on the Lake Erie coast where the clay till lakebed is being eroded at an average of 3.9 in/year (10 cm/year) from October 1986 to October 1996, a maximum rate observed in Maumee Bay of Lake Erie (Fuller 1995). The lakebed in front of the structure would be one meter lower in 1996 than it was in 1986. Assume that the structure had a maximum of 2-foot (0.6-meter) water depth at its base (and a maximum wave height of 1.2 feet (0.4 meters), striking the structure) during the highest water levels of the twentieth century in October 1986. Then, the same water level returning in October 1997 would cause a maximum water depth of 5.3 feet (1.6 meters) at the base of the structure (and allow a maximum wave height of 3.2 feet (0.9 meters) to strike the structure). The effect of one meter of lakebed erosion in this case is to multiply the maximum wave energy striking the structure by seven times. Wave energy is proportional to the wave height squared.

Now assume the same amount of lakebed erosion in front of the same structure but a maximum of 4-foot (1.2-meter) water depth at its base (and a maximum wave height of 2.4 feet [0.7 meters], striking the structure) in October 1986. A return of the same water level in October 1996 would cause a maximum water depth of 7.3 feet (2.2 meters) at the base of the structure (and a maximum wave height of 4.4 feet [1.3 meters], striking the structure). The effect of the lakebed erosion in this latter case is to multiply the maximum wave energy striking the structure by more than three times.

4. Susceptibility of Lakebeds to Erosion

Lakebed erosion is likely to be greatest on nearshore lakebeds of exposed, erodible *glacial till* that have thin, scattered deposits of sand and gravel. Over time, lakebed till deposits soften, becoming more susceptible to erosion. On gently sloping lakebeds, a thin veneer of sand is required to initiate erosion. On steeply sloping lakebeds, and in front of steep-sloped shore protection structures, turbulence from plunging breakers can erode the lakebed without the presence of sand (Nairn 1991). The problem of lakebed erosion is worsened where the supply of sands and gravels to the littoral transport system has been reduced by harbor dredging, coastal shore protection structures, and erosion control measures in tributary watersheds. There is insufficient sand and gravel in the littoral transport system to protect the erodible lakebed from wave action or to compensate for the irreversible loss of eroded lakebed materials.

5. How Much Coarse Sediment Will Protect a Lakebed from Erosion?

A layer of cobbles or boulders a few rock diameters thick should be sufficient to protect an erodible lakebed from erosion. Under laboratory conditions, less than 1 centimeter of sand appeared sufficient to protect clay tills when the significant wave height was 1 foot (30 centimeters). Coastal sites with enough sand to form a modest bar may have the lakebed erosion process inhibited by the bar, but migrating sand bars can "shave" the soft till.

6. Detecting Lakebed Erosion

Some coastal features that indicate possible lakebed erosion are

- Lakebed of glacial till overlaid with thin sand deposits (less than a few inches thick).
- Narrow beaches during average as well as high water levels.
- Lakebed profile is concave upward, steeply inclined near the water's edge.
- Soft, watery clay lakebed, easily penetrated with a probing rod.

Find out whether or not the lakebed in front of a particular coastal site is "soft" with sparse or thin protective layers of cobbles, gravel, or sand. Probe the lakebed in a number of places with a steel rod to locate the elevation of the "hard bottom" (presumably erosion-resistant). If there is soft till present, the rod will penetrate it, and a telltale coating of clay will be left on the rod when it is extracted. It can be assumed that such soft material will be eroded by waves. Engineering tests of the lakebed should be done for large, expensive shoreside structures. Set up a series of lakebed monitoring sites where lakebed erosion is suspected (Askin and Davidson-Arnott 1981).

7. Evidence of Lakebed Erosion

Fuller (1995) reported erosion of a glacial *lacustrine* lakebed on Maumee Bay, Ohio, measured along four nearshore profiles over a 10-year period (1981–90). This lakebed erosion occurred in a shallow water environment with less than 6.6 feet (2 meters) depth and 31 miles (50 kilometers) of open water exposure to the northeast. Davidson-Arnott (1993) reported on short-term lakebed erosion rates measured by divers in exposed clay till during the mild wave climate months of May to October along the southwest shore of Lake Ontario near St. Catherines and Grimsby, Ontario. Foster et al. (1992) told of lakebed surveys and erosion discovered within 100 feet (30.5 meters) of shore off Berrien County south of St. Joseph, Michigan. The lakebed had eroded as much as 13.5 feet (4.1 meters) between 1945 to 1991. The rates of erosion at these varied sites are shown in Table 7.

Table 7. Some Reported Lakebed Erosion Rates for the Great Lakes

Location	Erosion Rate (in./yr)	Erosion Rate (cm/yr)	Reference
L.Michigan, Berrien County, Michigan	3.5 (over decades)	9	Foster et al. 1992
L. Erie, Maumee Bay	1.6–3.8 (within a decade)	4–10	Fuller 1995
L. Michigan, Illinois Coast S. of Waukegan	0.5 (over a century)	1	Illinois DOT 1980, cited by Shabica and Pranschke 1994
L. Ontario, SW coast	1.3 to 5.8 (within a year)	3–15	Davidson-Arnott 1993

The irregular nature of lakebed erosion and the creation of "holes" and "troughs" are shown in Figure 9 from the Berrien County lakeshore work reported by Foster et al. Lakebed erosion has been studied in the laboratory by subjecting blocks of cohesive, glacial tills to random breaking waves, various water levels, and different amounts of sand cover (Bishop et al. 1992). Raising or lowering water levels shifted the zone of erosion activity up or down the till profile. In the laboratory, *scour holes* formed near the waterline when the lakebed slope had a steepness of 1:5 (vertical:horizontal) and plunging breaker energy was concentrated. Scour hole formation didn't occur with more dispersed wave breaking on a slope of 1:10.

8. Coping with Lakebed Erosion

Take precautionary measures as though lakebed erosion were a confirmed, significant hazard. Place primary reliance on a large setback distance from the bluff/bank edge for shoreland buildings and other structures on coastal sites. Plan on a need to repair or replace shore protection structures every 5 to 10 years. Placement of protective armor stone in front of an imperiled bulkhead or sea wall is likely to transfer the problem from the wall to the armor stone.

Beach nourishment with stone and/or gravel, particularly captive beaches retained with appropriate structures, is likely to be an effective form of constructed shore protection. Some coastal sites will have a glacial till lakebed with sufficient cobble and boulder-sized stone content that has formed a natural protective layer of stone during centuries of lakebed erosion. These sites are not likely to be subject to additional erosion.

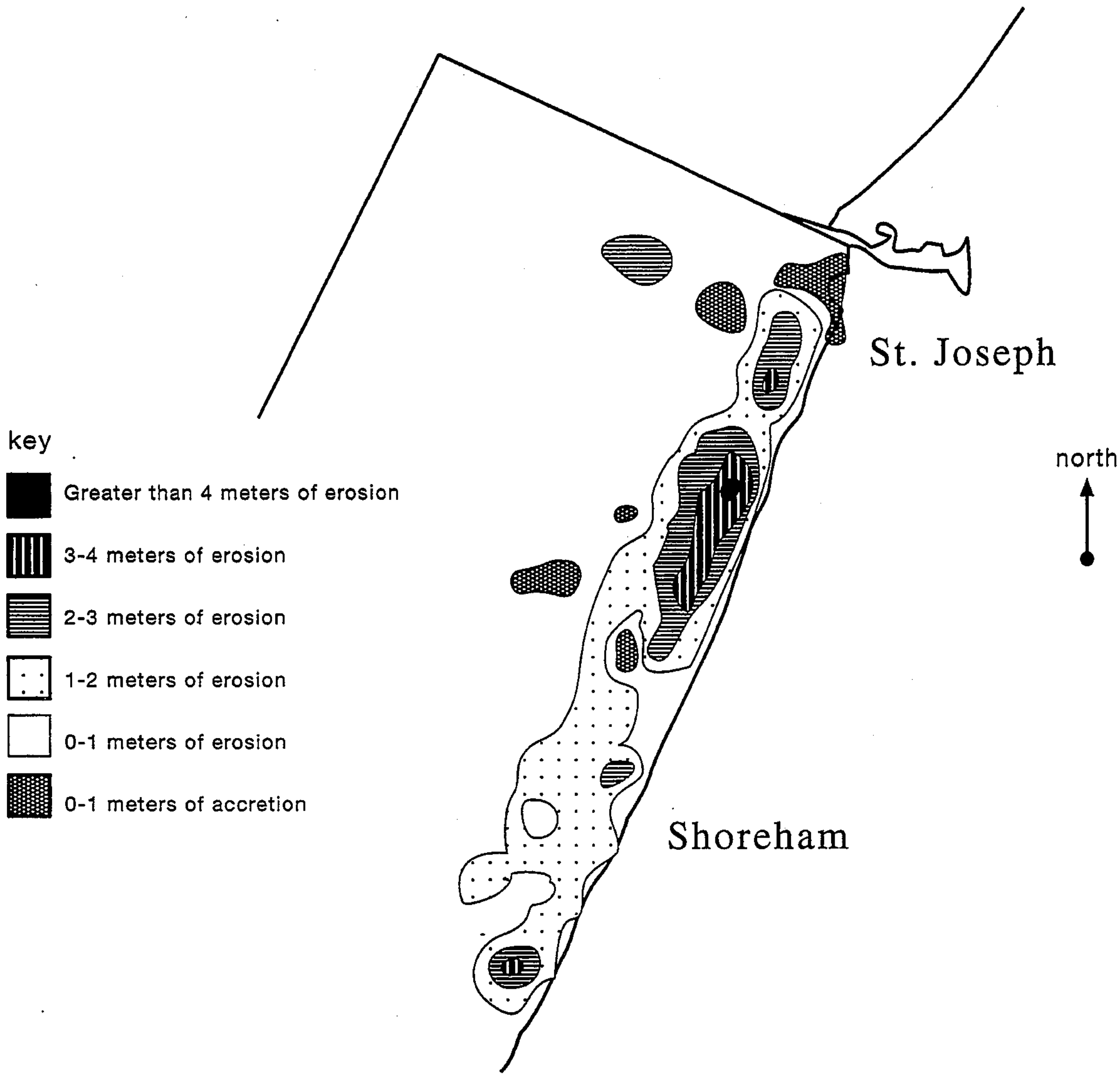


Figure 9. Lakebed erosion near St. Joseph, Michigan, 1945-1991. The scale was not given on the original chart. There is about three miles between the harbor at St. Joseph and Shoreham. (Redrawn from Foster et al. 1992)

D. Estimating Construction Setbacks

An estimate of a construction setback is an estimate of adequate distance between a building and the edge of a bank or bluff so that the building is unlikely to be endangered by erosion during its useful life. Three factors are involved in estimating construction setback:

- *Recession setback*: The horizontal distance a bank or bluff edge is expected to recede during a selected period of time.
- *Stable slope setback*: The horizontal distance a bluff edge is expected to recede to a stable slope condition after the toe of the slope is stabilized, or the horizontal distance a bluff top is to be regraded in order to achieve a predicted stable slope condition with slope toe stabilization.

- *Minimum facility setback*: an allowance for uncertainties about future bluff soil conditions, bluff soil properties, stable slope angles, and effect of proposed building construction on bluff stability. Includes space for equipment needed to relocate a building.

The first element is shown in Figure 10, the second element is shown in Figure 11, and the third element is shown in both figures.

The combination, or omission of, any of the three elements (recession, stable slope, and minimum facility setbacks) depends upon the logic an investor or regulatory agency chooses to use in defining a prudent construction setback distance.

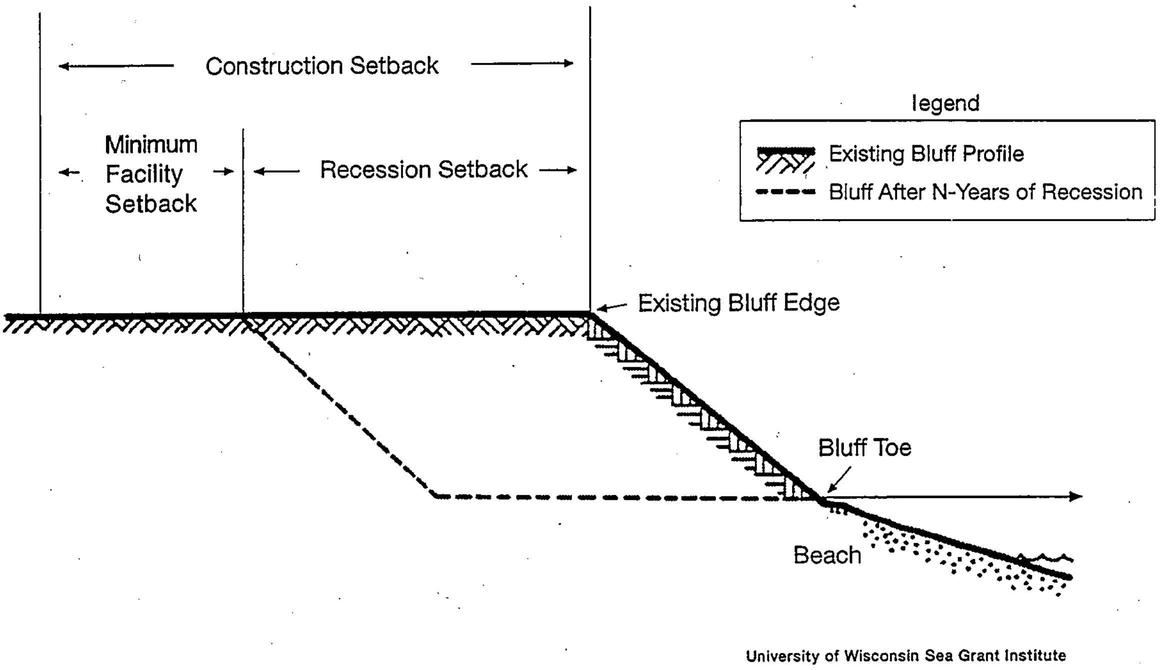


Figure 10. Construction setback distance for property without shore protection

A recession setback is appropriate where there is no confidence that the toe of a bluff or bank will remain in a fixed location. Shore protection structures may not exist, may not be planned, or may not appear to be effective. A recession setback is appropriate for eroding shorelines that are **not** of the types for which bluff stability analysis can be used to estimate stable slope angles and ratios.

A stable slope setback is appropriate where bluff stability methods are applicable and where there are (or will be constructed) effective, well-maintained shore protection structures. A stable slope setback is also appropriate where there is a natural feature (such as a bedrock terrace) to anchor the base of an erodible slope in a fixed position.

A minimum facility setback distance is needed in all situations to account for uncertainties and to allow house movers to relocate a building safely after recession has occurred.

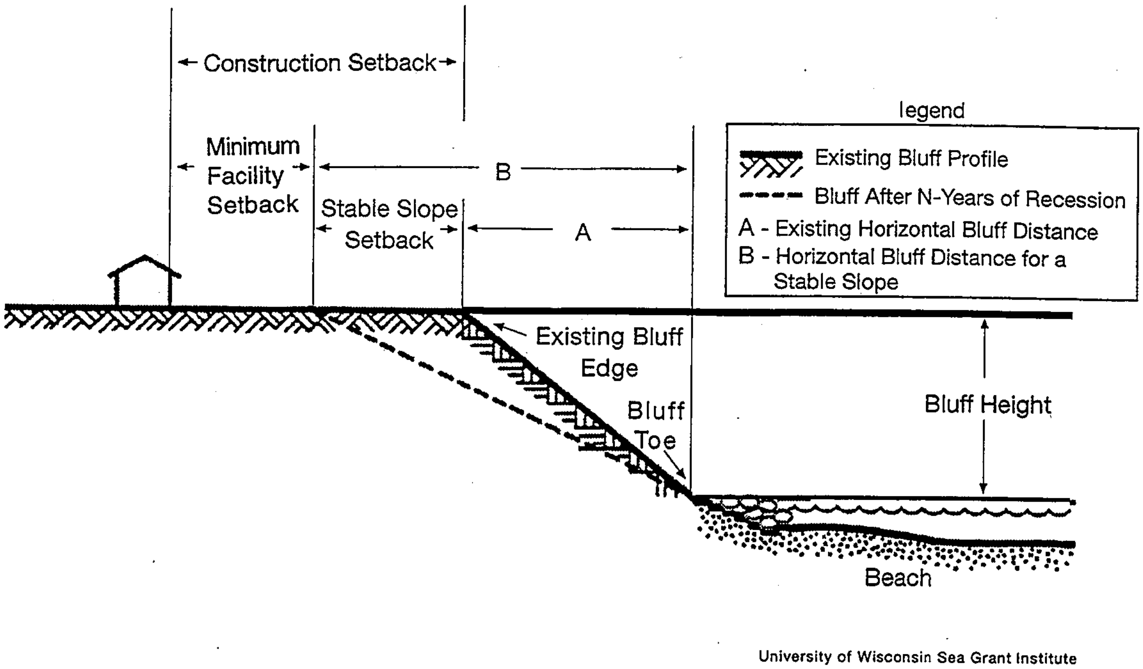


Figure 11. Construction setback distance for property with shore protection

1. Recession Setbacks

Estimating a recession setback is a matter of determining the property's average annual recession rate and multiplying it by the desired number of years of site occupancy. While the arithmetic is easy, picking an appropriate recession rate is likely to be an educated guess, at best. Recession rate information usually originates from the analysis of aerial photos or maps. There are errors associated with this type of analysis.

Influence of Changing Conditions on Recession Rates

Whether recent, short-term rates (a decade or less) are better to use than long-term rates (more than two decades) depends upon whether conditions are varying about some normal conditions or changing to some different conditions. Recession rates may increase with a long-term reduction in supplies of sand and gravel from beaches and protective nearshore shoals and bars. The absence, presence, and failure of shore protection structures can change recession rates over time. Recession rates may also change due to climate change, a subject covered on pages 63-64.

Caution: Although we assume average annual recession rates, recession often proceeds sporadically. A bluff may be stable for one or two decades, then lose 20 feet of bluff top in a few seconds. A low sandy bank may be stable for years until a rising high lake level and an unusually severe storm erode the bank landward 30 to 50 feet. This erratic behavior of much erosion provides an additional rationale for generous setback distances when a new coastal investment, including new construction, is contemplated.

Recession Rates in Varying but Stable Climate Conditions

Where storm, water level, and sand supply conditions fluctuate without a trend, average long-term recession rates determined for multiple decades are preferred to short-term recession rates measured over periods of 10 years or less. Long-term rates usually cover several high and low water periods and short-term decadal shifts in storm conditions, so they are more appropriate for siting of longlived facilities. In long-term rate measurements, the significance of translational errors in the measurements is diminished by averaging the errors over longer time periods.

Recession Shaped by a Changing Slope

Erosion that causes a bluff or bank slope to become more gentle and more stable should cause the future recession rate to be lower than the recent recession rate. Such slopes need infrequent monitoring to see if conditions have changed to alter this trend. Erosion that causes the slope to become steeper and less stable may cause future recession rates to be higher than recent recession rates. Such slopes need more frequent monitoring to avoid unpleasant surprises. Slopes that have parallel retreat should have future recession rates that are similar to recent recession rates.

Recession Rate Errors

There are three kinds of unavoidable but predictable errors in estimating recession rates that are usually either unstated or guessed:

- Translation error. Errors in accurately determining historic positions of shorelines or bluff edges from aerial photos and maps.
- Temporal error. The measured recession rate from the past does not represent the future recession rate.
- Spatial error. The measured historic recession rates at nearest locations X and Y are not the recession rate that has occurred at location Z in which you are interested.

> CAUTION: Look for estimates of translation, temporal, and spatial errors with any recession rate information you find. Since the recession rate is critical to ensuring adequate setback distance for the desired time period, it is worth a significant effort to get the best available information (including information from prior owners and neighbors). Then allow a generous extra recession setback distance in case future recession turns out to be greater than expected.

Studies of Recession Rate Errors

In the later examples in this manual, a minimum recession rate of 1 foot per year is used in estimating setback distances for sites at obvious risk of erosion, based on these studies:

Jibson et al. (1990) estimated a measurement location error of ±19.7 feet (6 meters) for measurements of bluff edge location spanning 50 years (equivalent to ± 0.3 feet, or ± 0.1 meters, per year). Over a span of 17 years instead of 50 years, this error would result in a recession rate error of ±1 foot per year. Thieler and Danforth (1994) concluded that frequently ignored sources of error in shoreline recession rate measurements from aerial photographs often represent ground distances of 33 feet (10 meters). Over a time interval of 33 years between aerial photo dates, this would result in an annual recession rate error of 1 foot per year.

Keillor and DeGroot (1978) estimated that the maximum error possible for any recession rate in their Racine County (Wisconsin) study would be ±0.8 feet (0.2 meters) per year for time spans between measurement of as short as four years. They estimated a maximum **likely** recession rate measurement error of ±0.3 to 0.6 feet (0.1 to 0.2 meters) per year. Photogrammetric errors were not considered. The major errors were cartographic errors and errors in definition of the bluff and bank edge.

Peters (1982) estimated maximum recession rate measurement errors in his Manitowoc County (Wisconsin) study: ±0.7 feet (0.2 meters) per year for the 37-year period of 1938 to 1975 and recession rate errors of at least ±0.2 to 0.3 feet (0.06 to 0.09 meters) per year for 100-year recession rate measurements. Peters considered these sources of errors: use of nonrectified photos and lack of good control points or accurate locations of good control points, definition of the bluff/bank edge, and finding the distance between historic edge locations at the same site.

Predicting Future Recession from Bluff Stability Analyses

Even detailed engineering analyses of bluff stability will not always provide reliable indicators of future bluff recession. A recent study looked at how well bluff stability analyses made on Wisconsin's Lake Michigan bluffs 19 years ago predicted the amount of recession that has occurred since then (Chapman 1996, Chapman et al. 1996). The bluff stability analysis was considered to be a successful predictor if the distance between the old bluff edge and the most landward intersection of a failure surface with the bluff top was within 10% of the actual distance the bluff retreated. The method was successful for 55% of the 91 bluff profiles evaluated. This is better than guessing, which should have resulted in a 33% success rate because there were three possibilities: underpredicting, overpredicting, and correctly predicting the extent of recession.

2. Stable Slope Setbacks

Figure 11 shows that a construction setback distance for a property with a maintained shore protection structure includes a stable slope setback distance representing the amount of additional erosion that is likely to occur before the slope becomes a stable slope.

What Is a Stable Coastal Slope?

- A stable slope is one that is no longer likely to fail by slumping or sliding, though surface erosion will continue unless the slope is well vegetated and surface water runoff on the slope is minimized. Slope stability depends on the properties of the bluff soil, on loads placed on the bluff top or slope, and on the presence or absence of water in the bluff soil.

- A stable slope angle is the natural angle to which a slope would erode if the toe of the slope stabilized and no longer continued to recede. Such stabilization of the toe could occur naturally if lake levels drop and sand or gravel forms a protective beach. Stabilization of the toe of the bluff or bank can also be done by building and maintaining effective shore protection at the toe.

- A stable slope is one that has stopped evolving. Slopes evolve in different stages: steepening and failing, becoming less steep and stabilizing, or receding more or less uniformly from top to bottom. If the cycle is stopped, the slope is stable.

- A stable slope is a slope that will support a building or other structure placed on the land above and behind the slope.

When Stable Slopes become Unstable

Slope stability does not last forever. A stable natural slope may no longer be stable when a building is constructed on the land above and landward of the slope. A stable natural slope may become unstable when rare precipitation events saturate bluff soils. Mudslides and hillside home destruction in California during El Niño years provide dramatic examples. In some bluffs, fractured till in the top portion of the bluff allows rainwater and snowmelt to penetrate bluff soils rapidly and raise the groundwater table within the bluff. This process reduces bluff soil strength and can lead to either deep-slip failures or sliding surface failures on the bluff face. Stable slopes may become unstable when prolonged periods of high water levels allow storm waves to erode the upper portions of protective beaches and attack the lower sections of bluffs.

Unstable Slopes in Disguise

The easiest way to recognize a stable bluff is to examine whether the slope above the beach has mature vegetation or not. If the vegetation is mature shrubs or trees and if there are no signs of slump blocks, the slope has probably been stable for as long as the vegetation has been there. A close look is required because unstable slopes sometimes look like stable slopes in disguise. North of Sheboygan, Wisconsin, on Lake Michigan, there is a gentle slope covered with tall grass, with an odd, rough appearance: undulations in the slope face, parallel to the shoreline. Multiple segments of this apparently stable slope have been slowly creeping toward the water's edge for decades. The slump block scarps are hidden in the grass.

Estimating a Stable Slope Setback Distance

Calculate a stable slope distance, using information similar to the data in Table 8 (page 41) and the vertical bluff height at the site.

A stable slope setback distance is:

stable slope ratio
×
bluff height
minus
horizontal bluff distance (Figure 10)

Using Information on Stable Slopes

The suggested approximate stable slope ratios given in Table 8 are based on ultimate stable slope inclination angles, measured from a horizontal reference plane, below which rapid soil movements are not expected to take place. Table 8 was mainly developed from Wisconsin coastal bluff studies. The listed Wisconsin sources indicated that the information can be more generally used as a rapid method of assessing the conditions of risk for natural slopes that have material and geometric characteristics within the range of bluff conditions and properties covered in the table. Table 8 demonstrates the variability in stable slope ratios by location and effective internal friction angle (due to differences in soil properties) as well as groundwater conditions. Example 7 (page 51) and Example 8 (page 53) show how to use Table 8.

Stable slopes can be described with *safety factors* (SF). For a bluff this can be stated as:

$$\text{Safety Factor} = \frac{\text{forces resisting failure}}{\text{forces leading to failure}} = \frac{\text{bluff strength}}{\text{bluff load}}$$

Bluff soil strength parameters include soil cohesion and soil friction angle. Bluff soil loads include soil weight, pore water pressures, and bluff top loads.

The stable slope ratios for Wisconsin slopes in Table 8 were calculated with a factor of safety of 1.0. A factor of safety of 1.0 is a precariously balanced situation where the bluff strength exactly equals the load on the bluff. A change in conditions or an error in calculation will tip the balance one way or the other.

Bluff stability analysis by experts can be a good indicator of future bluff stability over several decades or more. Chapman (1996) reported that a combination of methods for determining landslide potential resulted in correct predictions of future bluff stability at 90% of 115 analyzed sites on Wisconsin's Lake Michigan coast. The methods were applied to bluff conditions in the mid-1970s, and predictions were compared to bluff conditions in 1996 and 1997.

Table 8. Ultimate Stable Slope Ratios for Wisconsin Great Lakes Coastal Bluffs with Stabilized Bases

Location on Wisconsin Great Lakes Coastlines	Max. Height of Groundwater in Bluff (measured from base) H = bluff height	Stable Slope Ratio[1] Horizontal Feet: Vertical Foot efa[2] = 30°	Range[3]
Lake Michigan	base of bluff	1.7:1	2.1:1 to 1.4:1
	1/4H	1.8:1	2.5:1 to 1.5:1
	1/2H	3.0:1	3.4:1 to 2.2:1
	3/4H	3.5:1	4.3:1 to 2.6:1
	H	3.5:1	5.4:1 to 2.9:1
Lake Superior		min. ratio	
Douglas County	1/2H	3.4:1	3.4:1 to 2.2:1
W. Bayfield County	1/2H	3.6:1	3.6:1 to 1.8:1
E. Bayfield County	base of bluff	2.2:1	2.2:1 to 1.3:1
Madeline Island	base of bluff	2.6:1	2.6:1 to 1.5:1
Ashland/Iron counties	1/2H	3.7:1	3.7:1 to 2.0:1
Ontario, Canada bluffs (Terraprobe, 1994)	unstated conditions	2.75:1	
	unknown soil conditions	3:1 or flatter[4]	
	heavy groundwater seepage	4:1 to 5:1	

Sources: Vallejo and Edil 1979, Edil and Vallejo 1980, Schultz et al. 1984, and Terraprobe, 1994.

1. The stable slope ratios are derived from ultimate stable slope angles below which rapid soil movements on slopes are not expected to occur, but slow creep may occur. The angles were developed for weathered natural slopes having a bulk unit weight of 21 kN/cu.m. The stable slope ratios were derived for safety factors of 1.0 and are therefore *not conservatively safe*.
2. The slope ratios for an effective angle of internal friction (efa) of 30°.
3. The range of slope ratios for the Lake Michigan coast represents efas of 25° (lower limit) and 35° (higher and steeper limit). The ranges of slope ratios for the Lake Superior coast are for measured ranges of efas in the respective locations between 19° and 40°.
4. The Terraprobe report passes along the recommendation of many Regional Conservation Authorities for slopes where there is little or no information on subsurface conditions. No citation is given.

Caution about Table 8: Use of the stable slope ratios is no guarantee of future bluff stability at any particular coastal site. Table 8 illustrates stable slope ratios for bluffs with particular uniform cohesive soil properties. Bluff soils are typically nonuniform.

The stable slope ratios are appropriate for cohesive bluffs 60 feet (18 meters) or more in height but were not developed for lower bluffs and banks. These values were intended to be used with natural slopes having the same properties as measured in Wisconsin coastal bluffs. The stable slope ratios were derived for safety factors of 1.0 and are therefore not conservatively safe.

At some coastal bluff sites, slow creep and shallow slides may take place at the stable slope ratios given in Table 8. External alterations to a bluff can invalidate the ratios given in the table: alterations such as adding a building to the top of the bluff or wave erosion of the base of a previously stable bluff. Conservatism can be practiced by choosing greater stable slope ratios and by adding additional setback distances in working with the stable slope ratios. Such choices are best made by trained professional geologists or engineers.

The variability in stable slope ratios can make a big difference in the size of a stable slope setback distance. For example, on a Wisconsin bluff along Lake Michigan that is 60 feet (18.3 meters) high with an efa of 30°, the stable slope ratio can range from 1.7:1 to 3.5:1, depending on whether or not the bluff is always free of groundwater or sometimes has groundwater as much as three-fourths of the way up the bluff face. The difference in stable slope setback distance for these two stable slope ratios is 108 feet (32.9 meters). For a bluff that is 110 feet (33.5 meters) high, the difference would be 198 feet (60.4 meters). These differences because of groundwater levels might make some coastal lots unbuildable.

Uncertainty or variability in average bluff soil properties can also make a big difference in the size of a stable slope setback distance. For example, using the same Wisconsin bluff mentioned in the previous paragraph and assuming a nearly fully saturated bluff condition, the stable slope ratio will be somewhere between 5.4:1 and 2.9:1 if the representative effective friction angle of the bluff soil is somewhere between 25 and 35 degrees. The difference in stable slope setback distance for these two ratios is 150 feet for a bluff that is 60 feet high. If the bluff were 110 feet high, the difference would be 275 feet. Table 8 indicates that the difference in effective friction angles could be more than the 10 degrees used here.

Improving Slope Stability

In situations where groundwater threatens bluff stability, dewatering of the bluff with a curtain drain, or a series of shallow wells, might be needed for slope stabilization in addition to toe stabilization and vegetation of the bluff face. Table 8 can be used to get some idea of how much reduction in a stable slope setback distance can be accomplished by dewatering a bluff. Groundwater elevations in bluffs can often be reduced by intercepting surface water runoff before it gets to the bluff vicinity and installing shallow vertical wells or curtain drains.

Property with Effective and Maintained Slope Protection

The key to estimating the appropriate construction setback for properties with stabilized slopes is to estimate the effectiveness of the *slope protection system* correctly. This includes surface water drainage control, groundwater interception and drainage, slope protection, and shore protection structure. Each element of a slope protection system has strategic importance and must be maintained. Neglect one element and the whole system is in danger of failure. There is little general guidance available on evaluating shore protection structures. Consult a professional engineer.

A Traditional Engineering Approach to Bluff Stability

Typically, engineers use a *deterministic* approach in evaluating slope stability. This involves using professional judgment in selecting reasonably conservative mean values for important bluff properties (often by sampling and testing). These data are used to compute both the stress (or load) on the bluff and the strength of the bluff along potential failure surfaces. There are two types of slope failure that are evaluated in a traditional engineering analysis: *rotational sliding* and *translational sliding* (Figure 12).

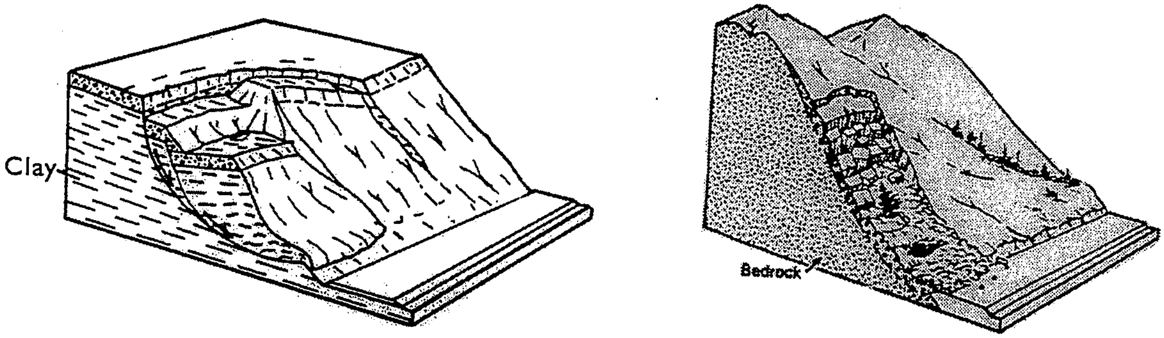


Figure 12. Rotational and translational sliding (Source: Varnes 1978)

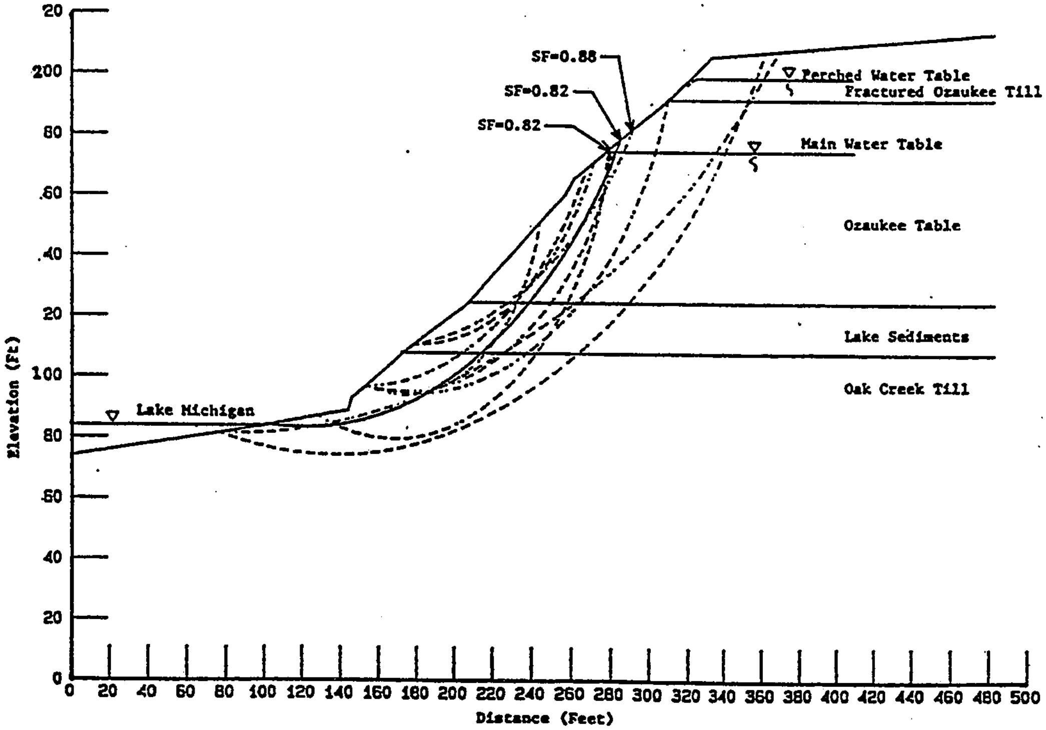


Figure 13. A typical bluff profile from northern Milwaukee County (1 ft = 0.305 m). (Bosscher et al. 1988.) Reprinted with permission from Springer-Verlag New York, Inc.

Figure 13 shows nine potential bluff failure surfaces for rotational sliding on a typical bluff profile in northern Milwaukee County. Only three of the safety factors are shown for clarity, but each potential failure surface within a bluff has an estimated safety factor. The factor of safety is the ratio of shear strength (resisting forces) to shear stress (driving forces). A value greater than 1.0 means that the forces resisting failure are greater than the forces promoting failure. The greater a factor of safety, the "safer" the bluff. Factors of safety are sometimes used to "grade" bluffs in terms of their degree of hazard. A few examples of the use of factors of safety in bluff stability analysis are given here:

- For Wisconsin's Lake Michigan bluffs less than 60 feet (18.3 meters) in height, the factor of safety that best divides stable from unstable bluffs is 2.0 (Chapman et al. 1996).

- For Wisconsin's Lake Michigan bluffs more than 60 feet (18.3 meters) in height, a 1.1 factor of safety works better than the theoretical 1.0 factor of safety (Chapman et al. 1996).

- In general, factors of safety less than 1.2 indicate high hazard areas for landslides; values in the 1.2 to 1.7 range indicate moderate hazard (Ward 1978, as cited by Schultz et al. 1984).

- Wisconsin's bluffs in northern Milwaukee County were generally classified as stable if the lowest factor of safety was more than 1.0, marginal if the lowest factor of safety was between 0.9 and 1.0, and unstable if the safety factor was less than 0.9 (Southeastern Wisconsin Regional Planning Commission 1988).

- Design minimum factors of safety recommended for Ontario, Canada, bluffs are 1.10 for passive land use (no buildings), 1.20 to 1.30 for nonhabitable buildings near the slope, 1.30 to 1.40 for habitable or other human-occupied structures near the slope, and 1.40 to 1.50 for public use structures such as hospitals, schools, and utilities (Terraprobe 1994).

The setback distance from the bluff edge is computed for construction of a building or other structure so that the structure is comfortably landward of any potential failure surface with a safety factor judged to be too low. In a professional analysis, this selection of a safe distance is a matter of best professional judgment on the part of an engineer or geologist, taking into account the weight of the proposed new building or other structure. *Such an analysis is not good forever.* The location of potential failure surfaces will change over time as the bluff face recedes and evolves into a different form of retreat or as major additions are made to the building.

Erosion Risk

Evaluating Conditions of Risk from Erosion

This section describes deterministic approaches to use in making qualitative evaluations of two different degrees of risk from erosion: obvious risk and lesser risk. The latter category was called "apparently safe from erosion" in the first edition of this manual. Some samples are also given of quantitative risk determination using probabilistic methods.

A. Building Sites with an Obvious Risk of Bluff/Bank Erosion

These are sites where a building is threatened by erosion at the lowest recession rates and the most favorable (steepest) stable slope angles. The logic is similar to that used in estimating an obvious risk of flooding. *A reasonable minimum recession rate is 1 foot per year.* This is about the measure of uncertainty and error inherent in the measurement of bluff/bank edges shown on aerial photos or maps from which recession rates are determined.

For sites with apparently adequate shore protection structures, pick a steepest stable slope angle. For a Wisconsin coastal site on Lake Michigan, Vallejo and Edil (1979) indicated a steepest stable slope would be 1.7:1 (horizontal:vertical) for a bluff soil with an effective internal friction angle of 30° and no groundwater elevated within a bluff (Table 8, page 46).

Example 7. A House Obviously at Risk of Loss from Erosion

The property is located in Racine County, Wisconsin. The lakeward side of the house is 30 feet from the edge of a 60-foot-high bluff. There is no shore protection structure at the base of the bluff, and the bluff face is mainly free of vegetation and seems to be actively eroding. The bluff edge appears to be as far horizontally from the bluff toe as it is vertically from the bluff toe. A local house mover states that a minimum of 25 feet between the house and the bluff edge *at this site* is needed to move in heavy equipment safely and relocate the house if that should become necessary.

Is the house at obvious risk of loss from erosion?

Step 1: Estimate the maximum time before relocation must occur, assuming erosion continues.

Available recession distance = 30 feet – 25 feet = 5 feet. At a minimum recession rate of one foot per year, relocation must occur in less than five years.

Step 2: Estimate a minimum stable slope setback distance.

Assume the toe of the bluff can be stabilized and a steepest stable slope of 1.7:1 is adequate.

Stable slope horizontal distance from bluff toe (1.7 × 60 feet)	102 feet
Minus the existing horizontal distance from bluff toe to bluff edge	– 60 feet
Additional setback distance to achieve a stable slope	= 42 feet

The distance from the house to the bluff edge is 12 feet short of the distance needed to get a stable slope: 30 feet – 48 feet = –12 feet, or 12 feet short of the distance needed.

Answer: This house has a pending and obvious risk of loss from erosion. Relocation of the house within a few years seems necessary. There is not enough room between the house and the bluff edge to allow for any margin of error in assuming groundwater conditions in the bluff and in selecting the correct stable slope angle.

Note: Even with a *most favorable* stable slope ratio of 1.4:1 from Table 8, there would only be 6 feet between the house and the edge of a stable slope. This increased distance is not enough to allow for instability from the elevation of groundwater in the bluff or to bring in equipment for house relocation.

There are some weaknesses in Example 7. This evaluation for obvious risk of erosion is more uncertain than an evaluation for obvious risk of flooding because of the site-specific variability in bluff properties and the complexities of recession sequences. The risk factors and their values are not always obvious:

- A bluff composed of many layers of different soil types can suffer a massive failure due to one weak layer.
- A slope may evolve into a different form of retreat, perhaps to become steeper over time.
- It is difficult to choose a minimum period of recession.
- Lakebed erosion may threaten the stability of a shore protection structure on the site.

B. Identifying Building Sites with a Lesser Risk of Bluff/Bank Erosion

The bottom line for a prospective or present coastal property owner, a banker, or an insurer is a need to lessen the risk from erosion as much as possible, to make the property investment apparently safe. Example 8 addresses this need in solving the relocation problem for the house in Example 7.

Example 8. Relocating a House to Lessen a Risk from Erosion

The property is located in Racine County, Wisconsin. The lakeward side of the house is 30 feet from the edge of a 60-foot-high bluff. There is no shore protection structure at the base of the bluff, and the bluff face is mainly free of vegetation and seems to be actively eroding. The bluff edge appears to be as far horizontally from the bluff toe as it is vertically from the bluff toe. A local house mover states that a minimum of 25 feet between the house and the bluff edge *at this site* is needed to safely move in heavy equipment and relocate the house. The calculations done in Example 7 indicate that the house should be relocated as soon as possible to protect it from loss as the bluff recedes or in case of sudden, massive bluff failure.

CAUTION: Don't assume that 25 feet between a building and a bank/bluff edge is adequate for bringing in heavy house-moving equipment. Get an estimate from a local contractor familiar with the bluffs at the site and willing to hold the property owner harmless of consequences arising from bluff failure during the building move.

How far back should the house be relocated to change the conditions of risk to apparently low risk of loss from erosion?

Answering this question involves more work than was involved in Example 7 because some uncertainties about the bluff properties and future conditions affecting bluff stability need to be evaluated.

Step 1: Estimate the stable slope setback distance for a maximum stable slope angle.

Table 8 shows a stable slope ratio of 3.5:1 for the Lake Michigan coast of Wisconsin if the groundwater seepage from a bluff is three-fourths of the bluff height to the full bluff height, measured from the base of the bluff with an efa value of 30°.

Stable slope distance (Figure 10) = 3.5 × 60 feet (bluff height)	210 feet
Minus existing horizontal bluff distance (A)	−60 feet
Stable slope setback distance	= 150 feet

Step 2: Estimate a house relocation distance (relocated house to the bluff edge).

Stable slope setback distance (from Step 1)	150 feet
Plus room for equipment to make a *second* relocation	+25 feet
House relocation distance	= 175 feet

The house needs to be moved back 175 feet − 30 feet = 145 feet from its present location.

Effective, adequate toe protection needs to be constructed at the base of the bluff.

If the soil strength is less than the 30° (efa), the stable slope ratio will be different. The worst case condition in Table 5 for a Lake Michigan site would be a stable slope ratio of 5.4:1 (for an efa of 25°), although the combination of high groundwater in the bluff and this soil condition is probably uncommon on the Wisconsin coast. A repetition of Steps 1 and 2 for this extreme condition indicates that the house would have to be moved back 259 feet instead of 145 feet for a house relocation distance from the bluff edge of 289 feet.

How long will the relocated house be safe if the bluff is allowed to continue to erode indefinitely without shore protection being added?

Step 3: Estimate the time before a second relocation of the house becomes necessary.

Current recession rate information is not available for the Racine County shoreline. However, information from the county's planning and zoning office indicates that the section in which the house is located had a long-term recession rate until the late 1970s that varied between 2 and 4 feet per year, depending on location.

Recession setback distance = 175 feet – 25 feet = 150 feet

If the long-term recession rate in the future at this site will average 2 feet/year, the house doesn't have to be relocated again for: $\frac{150 \text{ feet}}{2 \text{ ft./yr.}} = 75$ years.

If the long-term recession rate in the future at this site will average 4 feet/year, the house doesn't have to be relocated again for: $\frac{150 \text{ feet}}{4 \text{ft./yr.}} = 37.5$ years.

The 38-year time span until the second relocation must occur is rather short. It is better to increase the first house relocation distance, if possible. Assume that there is plenty of room on this coastal lot for a greater initial relocation of 195 feet.

Recession setback distance = 30 + 195 – 25 = 200 feet

Calculate the years until the relocated house needs to be moved again.

recession setback distance divided by recession rate: $\frac{200 \text{ feet}}{4 \text{ft./yr.}} = 50$ years

The approach used in the last part of this example may (or may not) instill confidence that the greater relocation will provide an apparently low risk of loss.

The weaknesses of Example 8 are:

- Uncertainty about the stable slope ratio, bluff groundwater conditions, bluff soil strength, and future recession rate most appropriate for the site.
- Uncertainty about the confidence level in achieving the targeted condition of risk.

The apparently low risk (or apparently safe) evaluation needs the services of a trained professional to use a probabilistic approach.

C. A Probabilistic Approach to Identify Low Risk of Erosion

A probabilistic approach should take into consideration uncertainties about recession rates, stable slope ratios, bluff conditions, and effects of high lake levels, storms, and erosion events. These things are all elements of the risk. Here are some of the questions that an investor could answer with a probabilistic analysis of risk:

What is the percent probability (or likelihood) that a coastal property will suffer serious erosion damage from particular combinations of extreme water levels and storm conditions in the time period of concern?

What is the percent probability that a building placed on a coastal bluff or bank will be jeopardized by slope failure in any year?...during the expected years of ownership?...during the period of the mortgage?...during the life of the building?

A *probabilistic* approach to bluff stability takes uncertainty about bluff conditions into account and can be quite important in trying to estimate whether or not a particular site is apparently safe from bluff failure and erosion.

1. Samples of a Probabilistic Approach to the Risk of Bluff Erosion

Probability of Landslides on Coastal Bluffs, Southern Coast, Lake Superior
Edil and Shultz (1983) studied the rotational sliding type of bluff failure along the southern Lake Superior shoreline in Wisconsin. The probabilistic analysis was required to detect and evaluate the potential hazard. The results from their scatter diagram of landslide probability vs. deterministic safety factor are shown in Table 9 for 48 sites scattered along Wisconsin's Lake Superior coast. The landslide risk is from the rotational type of bluff failure (a common form of failure on this coast) but not from shallow slides. The table shows some tendency for bluffs with higher factors of safety to have lower probabilities of failure, as one might expect. However, there is a lot of scatter in the lowest two factor of safety ranges, and a very small sample size in the two higher factor of safety ranges. A table like this, with more sites analyzed, could be used to develop criteria for bluffs with a low risk of failure. For example, bluffs with a deterministic safety factor greater than 1.7 and a low and narrow range (10-15%) for probability of failure could be called "safe" or "stable," if there were a significant number of sites analyzed. Such criteria were developed in the next example.

Table 9. Stability of Coastal Slopes on Wisconsin's Lake Superior Shore [1]

Deterministic factor of safety	Number of slopes analyzed	Percent probability of slope failure [2]
less than 1.4	36	25 - 80
1.4 - 1.7	9	0 - 40
more than 1.7	3	10 - 15

1. Analysis conducted for rotational sliding type failure on 48 slopes.
2. Probability of failure defined as occurring when the probabilistic factor of safety is less than one.
Source: Edil and Schultz 1983.

Classifying Stability of Coastal Bluffs, Western Coast, Lake Michigan
The Southeastern Wisconsin Regional Planning Commission made a study of shoreline erosion along a 7.3-mile (11.7-kilometer) length of the northern Milwaukee County shoreline on Lake Michigan (SEWRPC 1988, Bosscher et al. 1988). Bluffs with less than a 25% probability of failure were called stable. Bluffs with more than a 75% probability of bluff failure were called unstable: In between these values were bluffs with marginal stability. Deterministic and probabilistic slope stability calculations were made at 30 locations. A few of the potential failure surfaces at one site are shown in Figure 13 (page 48). At least 25 slope stability analyses were required at each site, and each analysis used a different combination of variables defining possible slope properties and conditions. One hundred random failure surfaces were considered in each analysis. Therefore, for the site shown in Figure 13, 2500 potential failure surfaces were considered.

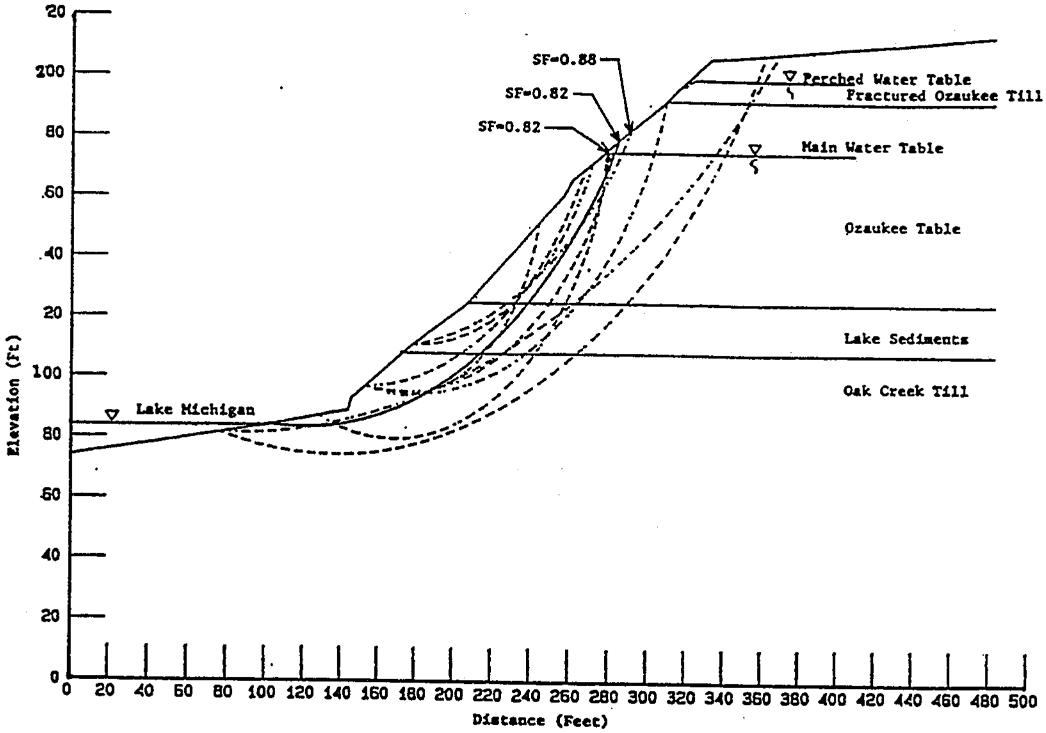


Figure 14. Bluff profile in northern Milwaukee County used in probabilistic analysis. (Bosscher et al. 1988.) Reprinted with permission from Springer-Verlag New York, Inc.

The previous two samples are examples of probabilistic thinking because the study authors didn't use a completely probabilistic approach. Three elements were lacking:

- The percent chance of bluff failure in *X* years was not determined because of insufficient information on the destabilizing role of storm wave attack at the base of the bluff, no information on lakebed erosion, and a lack of information relating rainfall to changes in groundwater elevation within the bluffs.

- The two studies equated percent probability of failure with the percentage of factors of safety having values less than 1.0, implying perfect correspondence between failure and the factor of safety threshold. However, Table 9 indicates that bluffs with a factor of safety greater than 1.0 can have a significant chance of failure. Chapman (1996) pointed out that at least 10% of bluff stability conditions were not predicted on Wisconsin's Lake Michigan coast over 19 years, even with a combination of four stability methods.

- The methods used in the two samples could not account for the role of shore protection structures in stabilizing bluffs. A key issue is the degree of confidence in the reliability of a maintained shore protection system protecting the base of the bluff or bank from toe erosion. Some examples of probabilistic methods applied to shore protection structures were given in the earlier section on the probability of flooding.

The Probability of Landslides on Forested Inland Slopes, Western United States

Chandler (1996) made a probabilistic analysis of slope stability in mountain forest areas with thin soils where timber harvest was being considered. A minimum safety factor of 0.38 was found. The probability of failure due to landslides in these small areas ranged from zero to 26%. Chandler used *Monte Carlo simulation* in a very detailed slope stability analysis. He divided slope areas into grids with cells that had dimensions of 16.4 to 32.8 feet (5 to 10 meters). Safety factors were calculated for each grid cell for each year of the trial period, using data from the largest 24-hour precipitation event of each year.

Probabilistic analysis requires work by qualified professionals. Probabilistic analysis of natural coastal hazards is beginning to appear in professional journals and is an important part of the new *Coastal Engineering Manual* produced by the USACE. More information about this manual is provided in Appendix 1.

2. How Well Do Bluff Stability Analyses Predict Future Recession?

Bluff stability analyses do not necessarily indicate how far future bluff failures will progress. In a recent appraisal of bluff stability analyses made in 1976-77, Chapman and coauthors (1996) determined that 55% of 91 deterministic bluff stability analyses for rotational sliding correctly predicted the amount of bluff top recession within 10% of the actual recession that occurred over the following 19 years. Bluff stability analyses are better at predicting other measures of bluff failure (Table 10). Predicted failure surfaces are shown in Figure 14.

Table 10. Predictive Capability: Rotational Failures, Wisconsin's Lake Michigan Bluffs

Category of Correct Predictions	Profiles Matching Deterministic Predictions	Number of Profiles with Available Data
Failure/Nonfailure	68%	115
Magnitude of failure	70%	94
Failure location in the slope	79%	96
Extent of bluff top recession	55%	91

Sources: Chapman et al. 1996 and Chapman 1996.

The modified Bishop's method rated in Table 10 worked well for deep rotational sliding and for translational sliding on high bluffs. Poor predictions happened where translational or shallow rotational failures occurred on bluffs under 60 feet (20 meters) in height. Some of the poor predictions may represent imminent failure of presently stable bluffs whose safety factors were low. Predictive ability could be improved slightly by several percent if the failure criteria of the safety factor were shifted from 1.0 to 1.1.

Chapman and coauthors (1996) achieved significantly better predictions of translational failures using a deterministic infinite slope analysis method with soil cohesion corrected for desiccation (drying). About 85% of 115 profiles were correctly interpreted, with about two-thirds of these profiles having translational failures. Slightly more than half of nine stable profiles were correctly predicted.

3. Reliability of Building Sites on Coastal Land

Engineers prefer to talk about *reliability* rather than probability of failure. Reliability is the positive side of the risk assessment coin. This indicator of slope stability has not yet been widely applied to coastal slopes in the Great Lakes.

One measure of reliability is the reliability index. It is defined as:

$$\text{Reliability index} = \frac{Sf_m - 1}{S.D.}$$

Sf_m = arithmetic mean of recorded, probabilistic safety factors

S.D. = the standard deviation of the recorded safety factors

The reliability index has an infinite range of values (Chapman 1996). A bluff slope at *equilibrium* between bluff strength and bluff load (SF = 1.0) and a standard deviation of 1.0, has a reliability index of zero. A positive value represents a slope that is unlikely to fail; a negative number represents a slope that is likely to fail. There is no broad, professional consensus about an acceptable range of values for stable or unstable natural slopes because of a lack of sufficient experience with probabilistic methods of slope stability.

For designed, constructed slopes there is more experience and agreement (Wolff 1996):

- Stable slopes. A reliability index of 4.0 or greater.
- Marginally stable slopes. Reliability index of 2.5 to 3.9.
- Unstable slope requiring immediate corrective action. Reliability index less than 2.5.

The recent probabilistic analyses of Wisconsin's Lake Michigan bluffs, done with the best conditions, indicated that slopes with a reliability index value (beta value) of 1.1 have a 50% chance of a rotational slipping failure. This appeared to be the dividing line between failing and nonfailing slopes. Slopes with a beta value greater than 3.0 had a 1% chance of rotational slipping failure (Chapman et al. 1996). In the same study, a beta value of zero was the dividing line between bluffs failing and not failing due to translational sliding, when soil cohesion was corrected for weathering to get the best predictability.

Disadvantages and Advantages of Reliability Indices

The chief disadvantage of using a reliability index is that it is not as well known or as well understood as factors of safety. Engineers and geologists have less experience with the index and little agreement on acceptable values for planning and design. There are additional costs involved in obtaining the added information needed to calculate a reliability index. However, the work involved provides a lot more information about the stability of a slope than does the work involved in calculating a set of safety factors. This information reveals to the geologist or engineer which slope parameters contribute most to the uncertainty in computing a factor of safety.

> "A final comment on reliability analysis is that it does not by itself reduce the uncertainties in slope stability analysis but it does provide a rational way to deal with the uncertainties explicitly and coherently." (Christian 1996)

D. Adequacy and Maintenance of Shore Protection Structures

A thorough evaluation of existing or proposed shore protection structures requires a professional coastal engineering analysis. Where this assistance is unavailable, follow this general advice:

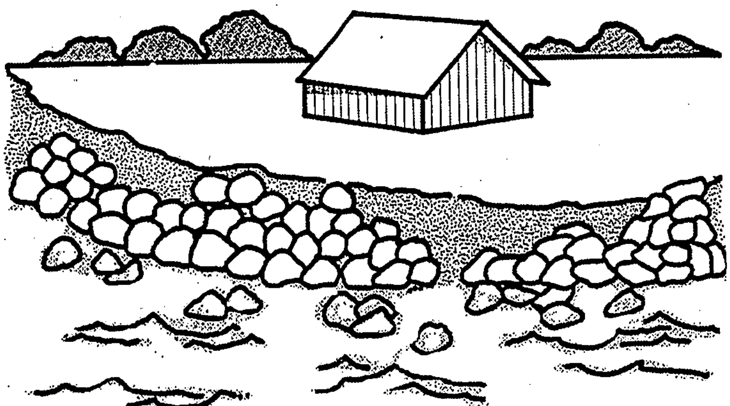
1. Adequacy of Existing Structures

The simplest indication of the adequacy of an existing shore protection structure is the test of time: Has it protected the property from erosion? Is the structure old enough to have survived severe storms successfully over many years? If so, how much and what kind of maintenance was required? A written performance history of such structures is worth acquiring and keeping because the issue should be important to the next property owner. A partial indication of the adequacy of a planned shore protection structure can be obtained by comparing a proposed design with nearby shore protection structures that have successfully protected property and survived severe storms at high lake levels. Some ways in which shore protection structures fail are shown in Figures 15a-15d.

2. How Structures Fail

No shore protection structures are invulnerable to failure. Shore protection structures most often fail incrementally, not catastrophically, during storms. Exceptions are some harbor breakwaters and riprap revetments with *single* layers of armor stone. In model tests, catastrophic failure has been found to occur due to sliding of the armor layer and exposure of the lighter weight core material to rapid washout by storm waves (Davies et al. 1994). Similar sudden failure can occur with a weakened seawall as storm waves remove remnant toe protection or overtop the crest and wash out tierod anchors. An intense storm with big waves rolling into the harbor at Port Washington, Wisconsin, in the 1980s ripped out a hundred feet of sheetpile wall and carved out a basin in a paved parking lot between a motel and a restaurant.

If shore protection structures fail catastrophically during storms, the failure can allow storm waves to attack the base of a bluff and precipitate a major bluff failure, which can cause structural damage to a building located too close to the bluff edge. Similarly, coastal dikes can fail catastrophically, causing flooding. Proper maintenance and prompt repair after damaging storms is the key to continuity in the protection of coastal bluffs, banks, homes, and other buildings.



Shore Protection Failure
Gaps in the Structure

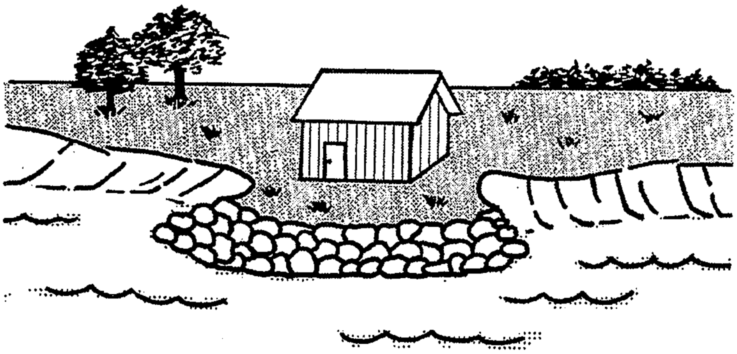
Failure: Gaps in the Structure

Causes: Wave Forces Too Great for the Structure to Withstand, or Large Spaces Between Stone

Correction:

- Add Structural Material Adequate in Size and Density to Withstand Wave Forces
- Fill Spaces Between Stones

Figure 15a. Shore protection failures: Causes and corrections



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Shore Protection Failure
Flanking

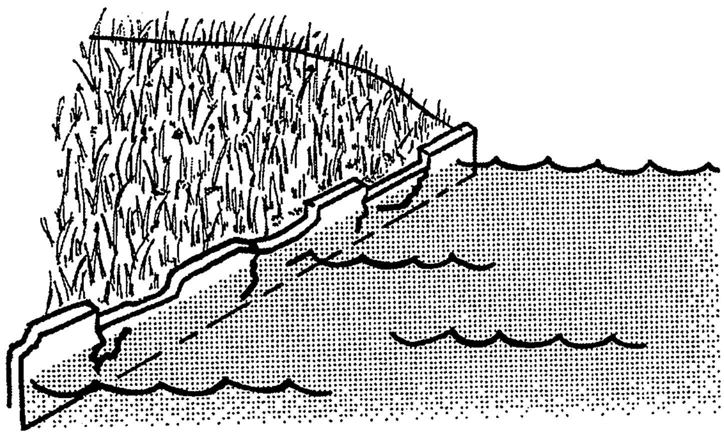
Failure: Flanking Erosion Around the Ends of the Structure

Causes: Wave Action and/or Bluff Slumping Adjacent to Stabilizing Bank

Correction:

- Add Structural Elements at Structure Ends
- Tie Structure Ends Back into the Bank
- Stabilize Adjacent Banks

Figure 15b. Shore protection failures: Causes and corrections



University of Wisconsin Sea Grant Institute

Shore Protection Failure
Settling or Slumping

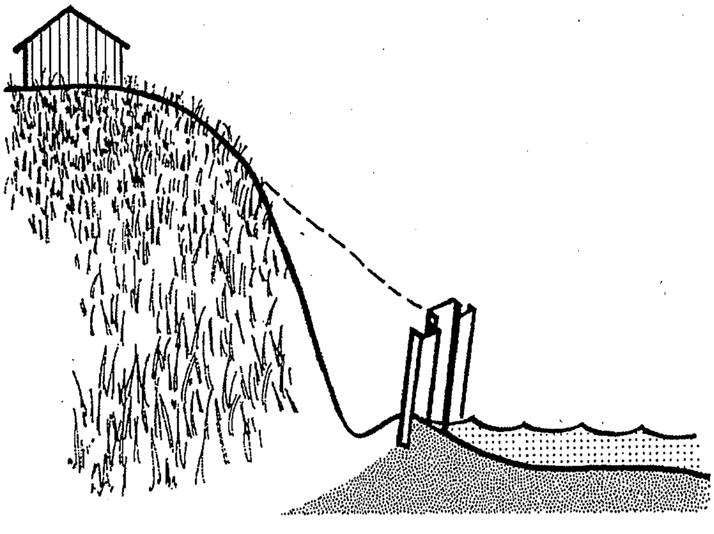
Failure: Settling or Slumping of the Structure

Causes: Soft or Unstable Foundation Soil, and/or Excessive Groundwater Pressure

Correction:

- Remove Unsuitable Foundation Material and Replace with Stable Material
- Stabilize the Bank Behind the Structure
- Dewater the Bank Behind the Structure
- Rebuild the Structure

Figure 15c. Shore protection failures: Causes and corrections



Shore Protection Failure

Overtopping, Scouring and Undermining

Failure: Undermining and Scour at the Base of the Structure and Erosion Behind the Structure

Causes: Waves Eroding Lake Sediments in Front of the Structure and Washing Out Soils Behind the Structure

Correction:

- Build the Structure High Enough to Avoid Wave Overtopping, and Pile Stone at the Base to Prevent Scour of Sediments

Figure 15d. Shore protection failures: Causes and corrections

3. Design Guides for Shore Protection

There are no up-to-date design guides for shore protection on the Great Lakes. Some general design guidelines for property owners to use for shore protection structures were the USACE's *Help Yourself* brochure and the OMNR's booklet, *How to Protect Your Shore Property*. Both of these publications are somewhat out of date because they do not take into consideration features including

- Bermed revetments of stone smaller than conventional armor stone.
- Captive, artificial beaches of sand or gravel.
- Cobble aprons or pavement as toe protection from lakebed erosion.
- Hybrid structures such as seawalls with revetments built in front of them.
- Poor stone quality, which leads to fracturing and break up by freeze/thaw.
- Dumped stone ridges (a common form of shore protection).

Engineered shore protection structures have been typically designed with formulas and safety factors to ensure stability and adequate performance of the structures under selected combinations of water level and storm wave conditions. The main reference for design of shore protection structures has been the *Shore Protection Manual* (SPM) produced by the USACE (1984). The replacement for the SPM is a new *Coastal Engineering Manual* (CEM) currently being written and internally reviewed by the Corps. The availability of the CEM is described in Appendix 1.

4. Probabilistic Design of Shore Protection Structures

Engineered shore protection structures have typically been designed with formulas to ensure stability and adequate performance of the structures under selected combinations of water level and storm wave conditions. This is called a deterministic approach. Deterministic methods do not allow a designer to estimate the risk of failure for a structure or the confidence limits for the design. The reliability of a design and the degree of uncertainty about conditions that might lead to failure of a structure are expressed in the selection of safety factors.

The new CEM will describe both deterministic and probabilistic approaches to the design of shore protection structures so that reliability and risk of failure can be estimated (Melby and Mlakar 1996). The CEM will describe methods for three different levels of design effort:

- Level I. Coefficients in design equations are used to account for uncertainty in design. This is a deterministic approach.
- Level II. Approximations of reliability are obtained by assuming normal distributions of variable properties that determine the strength of the structure.
- Level III. The actual distributions of the random property variables important in the design are used to compute the reliability of the design.

The Corps of Engineers presently uses reliability methods as standard practice in design. Once the CEM is distributed, these methods will probably gain common acceptance in the engineering of major shore protection structures. Reliability methods necessarily involve property owners because there are important decisions to be made about the acceptable level of risk in constructing shore protection to meet a particular design standard. Reliability-based design of shore protection structures requires a decision on the trade-off between cost and risk.

Accounting for Climate Change

Climate change issues featured prominently in the news in 1997—the onset of a new El Niño event in the southern Pacific Ocean, global warming, and drought with forest fires in Southeast Asia. El Niño brought regional short-term (months to a year) climatic shifts to regional weather patterns in the Americas. Global warming due to the atmospheric accumulation of carbon dioxide and other *greenhouse gases* became more widely recognized as a long-term (decades to centuries) climatic change already underway, boosted by the products of combustion in the industrialized nations.

Climate change alters natural coastal hazards. El Niño brings heavy rains and damaging surf to southern California. Global warming is expected to bring sea level rise to ocean coasts and either lower lake levels or a broader range of lake levels (higher and lower than record levels) to the Great Lakes. Regional areas may experience greater or lesser intensity and frequency of storms with either El Niño or global warming. Climate change is important to coastal investors around the Great Lakes because of potential significant changes in the paths, number, and strength of storm events and potential changes in typical and extreme lake levels.

A. Recession Rates during Changing Climate Conditions

Recession rates may shift from decade to decade as climate shifts occur along with long-term changes in lake levels, storm frequency, storm intensity, and storm direction. Fenster et al. (1993) demonstrated how to use statistical techniques to identify significant changes in trends. When such changes have occurred, recent recession rates are preferred to long-term recession rates. Large, regional climate changes could occur even if global climate changes are small. The situation of Hamburg, Germany, demonstrates the significance of regional climate change.

1. Climate Change and Changes in Storm Surges at Hamburg, Germany

Dr. Erich Plate (1994) described the effect that a modest climate change made in the magnitude and frequency of storm surges traveling up the Elbe River to Hamburg, Germany, from the North Sea. Storm surges in the Elbe are usually caused by low-pressure cyclones originating near Iceland, traveling eastward over the North Sea, steered by a stable high-pressure area located over southern

Europe. Many cyclones may follow in succession. Plate concluded that climate changes from 1980 to 1990 caused a 45% increase in the frequency of storm-producing weather patterns. He demonstrated that the elevation of a 100-year storm surge at the mouth of the Elbe River (and at the upstream city of Hamburg) was significantly higher in 1990 than in 1980 due to these climatic changes. He concluded that Hamburg needed to reinforce its protective dikes and raise some dike tops to a uniform design elevation in order to reduce the flooding risk to an acceptable standard.

The acceptable standard reached by "social consensus" in Hamburg is an annual probability of flooding of 0.1% (a one-in-1000-years event). This standard could be met for 1990 climatic conditions only by using all of the freeboard of the dikes. Even with this work on the dikes, such a flood level would bring waters lapping at the crests of these dikes, with no extra dike height to provide a safety margin.

2. Climate Change in the Sprawling Great Lakes Basin

The Great Lakes Basin's half million square kilometers sprawls across many dominant storm tracks of North American weather systems. Within the past 140 years, the basin's location provided consistent and reliable precipitation, and relatively infrequent and short episodes of unusually dry or wet, cold or warm years. The large water storage capacity of the lakes and the moderately varied climatic conditions of this century provided a relatively narrow range of water levels (less than 6.6 feet, 2 meters). This range of levels was used by coastal property owners, urban planners, engineers, and industrialists in siting coastal development, but it may not be representative for the future.

The most urgent consideration is to re-examine assumptions about how likely or unlikely there will be water-saturated coastal bluffs in the Great Lakes with adverse effects on bluff stability. There are plenty of warnings that climate change brings the unexpected.

The Mississippi River had an unprecedented long-duration flood in 1993. In the upper Mississippi River basin there were 187 heavy rain events for each 100 recording stations during the 12-month period of October 1992 through September 1993 (Kunkel 1996). A heavy rain event is a seven-day event producing four or more inches of rainfall. On average, one of these events is expected to occur about once a year at any given point in this basin. Twenty-four stations received seven-day rainfall in excess of 10 inches during June and July 1993. Six such events occur in the basin in an average year.

The El Niño events in the mid-1980s and in 1997-98 brought unusually severe sequences of storms with massive rainfall and high waves to West Coast shores and inland properties, triggering landslides and severe property damage.

It is prudent to assume that climate change within the Great Lakes Basin will occasionally produce extreme rainfall events that will cause fully saturated soil conditions in poorly drained coastal bluffs and banks sometime during multiple decades of property ownership. Climate change alters dominant storm tracks across the basin. The major El Niño event of 1997-98 brought greatly increased precipitation to the lakes below Lake Superior. In the first three months of 1998, precipitation was 38% above average across the basin (USACE 1998): By lake basin, the above average percentages were: Superior (2%), Michigan-Huron (56%), Erie (40%); Ontario (36%).

A localized example of a possible climate shift or change may have occurred in southeastern Wisconsin in the 1980s and 1990s. SEWRPC (1997) documented four extreme and local rainfall events in the twentieth century that did not coincide with snowmelt: August 3-6, 1924; August 6, 1986; June 16-18, 1996; and June 20-21, 1997. At gauging stations in the areas of most intense rainfall, all four events reached or exceeded the hypothetical "500-year event." Although extrapolations of rainfall amounts to 500-year frequencies of occurrence from records less than a century old are highly questionable, the 500-year hypothetical event is a useful definition of a "rare event." It is significant that one of these rare events occurred in the 60 years from 1924 to 1984, and three of these events in the 12 years of 1986 through 1997. This is one of the types of change that can occur with climate change.

B. Making Decisions in Anticipation of Climate Change

New methods are needed to estimate the joint probability of extreme lake levels and storms occurring and to assess the future risks of coastal hazards in the Great Lakes that come with climate change. Making decisions in anticipation of climate change requires some information on how the Great Lakes responded to past climatic changes and how the lakes might respond to future climate changes. This subject is beyond the scope of this manual, but some references are included in Appendix 1.

One way to cope with climate change is to plan a periodic review of the risks to urban and coastal investments from natural coastal hazards. The probabilities of extreme lake levels, extreme storm surges, and extreme wave changes are likely to change over time as the climate changes, for whatever reasons.

The view that data on storms and water levels occurring in the first three-fourths of this century are adequate for predicting future storms and water levels on the Great Lakes was a casualty of the high water level crisis in 1985 and 1986. As new information and new models for predicting climate change emerge, that view is likely to suffer further.

SUMMARY

The process of estimating storm water levels, wave runup elevations, and adequate construction setback distances on a coastal property can help reduce the risk of investment.

It is important to consider all elements that can affect coastal properties, including

- Future lake levels.
- Storm surges.
- Extreme wave runup.
- Land elevation.
- The adequacy of shore protection structures.
- Recession rates.
- Factors that make bluffs unstable.
- Lakebed erosion.
- Stable slope angles.
- Regional climate change.

Every coastal property should be evaluated to estimate how vulnerable or safe it appears to be in the face of uncertainties about future lake levels, storms, and erosion.

Each property should be considered in terms of the contingencies available to the property owner. Some of these contingencies require consultation with a professional engineer or contractor.

The following questions are some of those that need to be answered in evaluating contingencies:

- Do natural defenses (building setback distances, nearshore shoals, exposed bedrock, beaches, etc.) seem adequate to protect the property from all possible combinations of high water and storms?

- Is there significant lakebed erosion in front of the property?

- Is the lot size adequate for relocating the house if the property's recession rate is greater than estimated?

- Can an existing shore protection structure be reinforced or its crest elevation be raised if lake levels or storm wave runup are higher than expected? What will lakebed erosion do to this structure?

The steps outlined in this manual offer a careful way of thinking about coastal property. The steps for identifying properties that are obviously at risk from flooding and erosion can, with practice, help improve decisions involving coastal property with a minimal expenditure of time, money, and effort. Identifying site conditions that have an apparently low risk of flooding and erosion usually requires professional assistance.

The steps for identifying properties that have an apparently low risk of flooding and erosion need additional methods developed to put such estimates on a firm, probabilistic foundation. There is a need for a tested methodology for making a thoroughly probabilistic slope stability analysis by relating bluff/bank failure to lakebed erosion and to storm wave energy. There is a need for hydraulic model tests on common types of shore protection structures to learn their probabilities of failure under selected combinations of lake levels and storms.

An estimator of risk must rely on professional judgment in selecting extreme values for lake levels, storm surges, storm wave runup, recession rate, and stable slope angles.

An estimate of vulnerability to natural coastal hazards is time-limited. New estimates should be made when properties change ownership or at least every ten years. Coastal properties are dynamic places where bluffs are becoming more, or less, stable; where lakebed erosion diminishes defenses from destructive wave energy; where the effects of climatic change may be experienced as changes in the intensity and frequency of storms.

Several ways to cope with climate change include the following steps:

- Assume that climate change will occasionally bring extreme rainfall and saturated bluff conditions to poorly drained bluff soils with a resulting decrease in bluff stability.
- Assume a wider than historic range of extreme lake levels, storm surges and wave conditions over multiple decades of coastal property ownership.
- Review the risks to coastal investment from natural hazards when indications of climate change appear.
- Promote the development of probabilistic methods of natural hazard risk assessment and research on the likely responses of the Great Lakes and its regional climate to global climate changes.

Glossary

Accretion — A net accumulation of materials such as sand and gravel that builds up on beaches.

Bank — The edge and face of land closest to a body of water, generally less than 10 feet above water level, containing a few simple soil layers and no groundwater. Often a bank is located landward and above a beach.

Bar — A submerged linear mass of sand and gravel in shallow water built by waves and currents.

Beach Ridges — A series of elongated sand ridges parallel to the shoreline formed by wind and waves during past periods of high lake levels.

Berm — A low linear ridge of land.

Bluff — The edge and face of land closest to a body of water, generally higher than 10 feet and high enough to contain complex, multiple layers of soil and groundwater.

CGD — Canadian Geodetic Datum.

Cobble — Stones that are larger than gravel but small enough to be lifted and thrown. The size of tennis balls to footballs.

Cobble Apron — One or more layers of moderate-sized stone (typically six inches to a foot in diameter) extending lakeward from the base of a shore structure to provide protection from the scouring effects of breaking waves on an erodible lakebed.

Creep — The slow movement of large masses of soil.

Datum	A convenient accurately known elevation at a particular geographical location from which other elevations are measured. A common reference elevation. A datum can be selected for a town, a region, or a nation.
Design Storm	A particular recognizably, generally acceptable set of storm conditions used for design of structures that has particular and expected frequency of reoccurrence.
Deterministic	Methods by which precise values are calculated. Uncertainty is dealt with by using factors of safety.
Downcutting	The irreversible abrasion and wearing away of the nearshore bed of a body of water by suspended particles moved by currents or waves. Sometimes referred to as *lakebed erosion.*
Effective Friction Angle (efa)	A property of soils that helps give the soil strength, or resistance, to shearing forces. The larger the angle, the greater the strength. Angle values are typically 19° to 37° in Wisconsin's coastal bluffs.
Equilibrium	A stable balance as in soil loads matched by soil strength.
Evapotranspiration	The moisture absorbed by plants from soil and then passed into the atmosphere.
Extreme Wave Runup	The relatively large and unusual vertical distance sometimes covered by waves washing across a beach or shore protection structure.
FEMA	Federal Emergency Management Agency.
Floodplain	The land covered during a flood. Commonly used as the land covered by a flood expected to occur on average only once in 100 years.
Freeboard	The distance that the crest of a shore protection structure exceeds a particular water level.
GSC	Geodetic Survey of Canada.
Greenhouse Gas	Gases in the atmosphere such as carbon dioxide and methane of increasing concentration that aid in trapping heat and raising atmospheric temperature.
Groundwater	Water within the bluff soils that is slowly moving toward the bluff face.
Hydrostatic Pressure	Pressure caused by the weight of water.
IGLD	International Great Lakes Datum.

Joint Probability	The probability that a particular combination of events will occur at the same time. Each event is of a different type with its own probability of occurrence. One combination of three types of events is: high water level, storm, and bluff response to storm wave attack.
Lakebed Erosion	The irreversible abrasion and wearing away of the surface of a lakebed. Also referred to as *downcutting*.
Lacustrine	Soils deposited as sediments by lake processes.
Littoral Transport	The movement of sand and gravel along the water's edge of the shore by waves and currents.
Low Water Datum	Referred to as LWD or Chart Datum. A reference elevation from which water elevations are measured.
Monte Carlo Simulation	A method of artificially deriving the probability distribution of outcomes based upon the probabilistic nature of input variables. A useful tool where neither bluff soil properties nor present and future bluff soil conditions can be known with adequate certainty.
MSL	Mean sea level.
NAVD	North American Vertical Datum.
NGVD	National Geodetic Vertical Datum.
OMNR	Ontario Ministry of Natural Resources.
100-Year Flood Elevation	This is an elevation expected, on average over a long period of time, to occur and reoccur once in 100 years.
Probabilistic	Methods in which calculations of values are stated in terms of probability of occurrence, probability of failure or reliability. Also known as *reliability-based methods*.
Probabilities	Likelihood of occurrence or exceedance of an event, stated either as a decimal fraction (1.00 meaning absolute certainty) or as a percentage (100% meaning absolute certainty).
Profile	The outline of a bluff, beach, and nearshore lakebed in vertical cross section.
Reach	A section of coastline with common characteristics.
Recession	The landward movement of a shoreline caused primarily by erosion of the shore.
Reliability-Based Methods	Methods in which calculations of values are stated in terms of reliability where reliability = 1- probability of failure (stated as a decimal fraction), or percent reliability = 100% chance of failure.

Reliability Index A measure of satisfactory strength. The reliability index is the mean factor of safety divided by the standard deviation of the factor of safety.

Return Period The average interval (years to decades) between occurrences of storms or water levels of the same magnitude.

Revetment A sloped structure of stone or concrete designed to protect a bluff or bank from recession.

Rill An erosional process on a slope where running water carves small channels in the slope.

Riprap One or more layers of stones on an embankment slope to prevent erosion; a type of *revetment.*

Rotational Sliding Failure of an intact mass of a slope that causes mass slippage along a curved failure surface within the slope.

Runoff Water from precipitation, flowing over land surfaces to streams, lakes, and oceans.

Safety Factor A measure of adequacy used in design calculations. The safety factor is the ratio of strength to load. A value greater than 1.0 means that the forces resisting failure are greater than the forces promoting failure. The greater a factor of safety is for a bluff, the safer the bluff is from failure.

Scarps A bare portion of a slope where a section of the slope has been removed by slope collapse or wave attack.

Scour Holes Depressions in the nearshore lakebed caused by the scouring action of breaking waves.

Seawall A vertical structure—usually made of concrete, steel, or wood beams—installed to protect a bluff or bank from erosion.

Sediments Residual soil repeatedly moved and deposited by water in water bodies.

Seiche Pronounced "saaysh." Seiches are a back-and-forth sloshing of water in a lake caused by a disturbance from a storm, wind shift, or rapid atmospheric pressure change. Small seiches are occurring all of the time on the Great Lakes.

Setback Part or all of the distance between a building and the edge of a bluff or bank.

Set-Down A drop in water level along a shore due to a strong wind blowing off the shore (away from the shore).

Shear Stress A combination of forces promoting soil failure along a potential failure surface in a slope.

Shear Strength	Soil properties that combine to resist shear stresses along a potential failure surface.
Shoal	An offshore lakebed feature that is an area of shallow water.
Shore Erosion	The process by which soil moves down coastal slopes and away from coastal boundaries.
Shore Recession	The movement of coastal landforms retreating from the shore.
Slip Failures	Failure along a surface within a bluff or bank because the load exceeded the resistance to failure at that surface.
Slope Failure	The collapse of coastal bluffs and banks where loads on them exceed soil strength and resistance to failure.
Slump Block	An intact block of earth that has slipped down the face of a bluff or bank.
Stable Slope	The natural angle to which a coastal bluff or bank will erode if erosion at the base is halted.
Standard Deviation	A statistical indicator of the spread of measured values about a mean value.
Still Water Level	The normal level of a lake when it is unaffected by winds, storms, or seiches.
Storm-Induced Rise	A term used by the USACE to indicate the difference between a monthly maximum water elevation recorded at a gauging station and the mean water level for the same month as computed from average daily water levels at the gauge. The rise is not the actual change in water levels caused by a storm at a water level gauge site.
Storm Set-Down	A drop in water level at the shore because of storm winds blowing offshore.
Storm Set-Up	The same process as storm surge.
Storm Surge	A temporary rise in water levels along a downwind coast caused by the drag of storm winds on the surface of a lake or ocean. Also known as *wind setup*.
Storm Water Level	The water elevation at the coastal boundary of a storm-driven body of water. On the downwind coast, the storm water level is the still water level plus the storm surge. On the upwind coast, the storm water level is the still water level minus the storm set-down.
Surf Zone	The shallow water near shore where most wave breaking occurs. Typically, water depths are less than 30 feet (10 meters) on the Great Lakes.
Swash Zone	The area of the beach wetted by broken waves.

Till	The combination of re-worked clay, sand, silt and stone formed by glacial action and left behind as soil when the glacier retreated.
Toe	The base of a bluff or bank. The lakeward base of a shore protection structure.
Translational Sliding	Failure of a relatively thin section of a bluff face along a failure surface that is approximately parallel to the bluff face.
USACE	U.S. Army Corps of Engineers.
Washout	A section of a bluff or a bank that has been lost to erosion.
Wave Climate	The distribution of waves by frequency of occurrence, wave height, wave period, and direction of travel.
Wave Height	The vertical distance from the trough to the crest of a wave. A trough is the depression between the highest parts (crests) of adjacent waves.
Wave Period	The time in seconds for two wave crests to pass a fixed point.
Wave Runup	The vertical distance that waves will rise while moving up a beach or sloped shore protection structure.
Wave Runup Elevation	The highest elevation on shore reached by a wave running up the shore. It is the sum of the still water elevation plus the storm surge plus the wave runup value.
Wind Setup	A temporary rise in water levels along the downwind coast of a body of water caused by surface drag of the wind on the water surface. Also called a *storm surge*. Wind setup is recorded by water level gauges.

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Appendix 1

Appendix 1
Sources of Information

Updated 10/12/99

A lot of new information has become available since the first edition of this manual was published in 1987, and new information appears since this second edition was published in 1998. Revisions to this manual are published on Wisconsin Sea Grant's web site at the following address:
http://www.seagrant.wisc.edu/advisory/coastal_engr/index.html
Under What's New? Check out the CP Manual Update.

New, and changed Internet sites appear at the same site under Wet Net Notes.

The following sources of information are not comprehensive.

Please send information about new sources to the author, Philip Keillor, University of Wisconsin Sea Grant Institute, 1800 University Avenue, Madison, WI 53705-4094, Fax: 608-263-2063, Email: jkeillor@seagrant.wisc.edu

Guides for Owners and Buyers of Shore Property

Living with the Lakes. First edition. August 1999. A 40-page illustrated booklet offers advice on Great Lakes water levels and shoreline protection to boaters and shoreline owners, as well as prospective shore property owners. The booklet was jointly produced by the U.S. Army Corps of Engineers and the Great Lakes Commission. It is available from the Great Lakes Commission upon request. Send $3.00 (U.S.) to cover shipping and handling to: Great Lakes Commission, Argus II Building, 400 Fourth Street, Ann Arbor, MI 48103-4816. There is a discount of 10 percent on quantities of 10 or more. Allow six to eight weeks for delivery. (Source: press release of 8/6/99).

Buyers Guide to Shoreline Property, Great Lakes, and St. Lawrence River. First edition, August 1995. A 12-page, illustrated booklet for prospective buyers of shoreline property on how to make an informed decision and get the most from their investment by avoiding or minimizing hazards of flooding and erosion. Prepared as a joint project of the Great Lakes-St. Lawrence Water Level Information and Geomatics Office of Environment Canada-Ontario Region and the Association of Conservation Authorities of Ontario. Individual copies are available at $3 (Canadian) per copy (GST tax included). Order from: Marian Pacey, Water Issues Division, Environment Canada-Ontario Region, P.O. Box 5050, Burlington, Ontario, L7R 4A6. Phone: 905-336-4712, Fax: 905-336-8901. Make check or money order payable to: "Receiver General for Canada." Payment by VISA or MasterCard is also accepted. Bulk orders are also available.

Help Yourself. Published in 1973, revised in 1978. Prepared by the former North Central Division (now the Ohio River and Great Lakes Division), USACE. A 24-page general information pamphlet about erosion problems on the Great Lakes and alternative methods of shore protection. Includes relatively detailed construction and design features of selected types of shore protection structures with listed advantages and disadvantages. This unique pamphlet is somewhat out of date, in very limited supply, and in need of revision. Limited copies are available from Philip Keillor, University of Wisconsin Sea Grant Institute, 1800 University Avenue, Madison, WI 53705-4094. (Email: jkeillor@seagrant.wisc.edu).

Great Lakes-St. Lawrence River System and Large Inland Lakes Technical Guide (1998). The Province of Ontario has developed information on natural coastal hazards along the Ontario shores of the Great Lakes, including storm surge values and their estimated frequencies of occurrence and flood elevations of various estimated frequency of occurrence. This information is part of the Ontario Ministry of Natural Resources' support of the Public Health and Safety Policies, Provincial Policy Statement, Section 3, Planning Act. The technical guide will be available only as a CD-ROM. As of August, 1999, the production of the technical guide was on hold for lack of funding. The price is expected to be in the range of $250 to $300, Canadian dollars. Source: Ms. Ala Boyd (boyda@gov.on.ca)) on 8/16/99.

Coastal Geographic Information Systems (GIS)

The University of Wisconsin Sea Grant Advisory Services is developing a GIS that incorporates much of the information needed to make an evaluation of natural coastal hazards. This work is an ongoing activity, using ArcView software. There is a demonstration model coastal GIS in continuous development for the Town of Mosel in Sheboygan County, Wisconsin.

For further information on this coastal GIS, contact Mr. Allen Miller, Assistant Director for Advisory Services, University of Wisconsin Sea Grant Institute, 1800 University Avenue, Madison, WI 53705-4094. Phone: 608-262-0644, Fax: 608-263-2063, Email: ahmiller@seagrant.wisc.edu. Or contact: David Hart, Geographic Information Systems Specialist, Land Information and Computer Graphics Facility, University of Wisconsin-Madison, B-102, Steenbock Library, Madison, WI 53705. Phone: 608-263-5534, Fax: 608-262-2500, Email: dhart@macc.wisc.edu

Internet Sites

Coastal Shorelines on the Web

NOAA Coastal Shoreline Information. This site contains a history of shoreline mapping, glossary, frequently asked questions, a bibliography and shoreline-related links.

Address: http://www.csc.noaa.gov/shoreline/index.html

Canadian Great Lakes Shoreline Classification. This site includes a description of the classification scheme and summaries of shoreline by type.

Address: http://www.cciw.ca/glimr/metadata/great-lakes-shore-class/intro.html

U. S. Great Lakes Shoreline Classification Update. This site includes a description of the U. S. Army Corps of Engineers' Lake Michigan Potential Damages Study and a re-classification of U. S. shores of the Great Lakes.

Address: http//orcatec.com/LMPDS/Coastal/coastal.htm

Coastal Hazards on the Web

Federal Emergency Management Agency (FEMA). This site includes information about the National Flood Insurance Program: NFIP (select Flood Insurance) and information on how to obtain flood hazard maps (select Maps).

Address: http://www.fema.gov/

Ontario Information on Natural Hazards on the Great Lakes. The Ontario Ministry of Natural Resources' Conservation Authorities and Water Management Branch has published a natural hazards training manual. On the site below, select Publications Online.

Address: http://www.mnr.gov/on.ca/MNR/lio/contact.html

Visualizing coastal erosion. University of Wisconsin Land Information and Computer Graphics Facility. Animated fly-over and erosion on a coastal bluff.

Address: http://www.lic.wisc.edu/coastgis/visualization/visualization.htm

Weather Information on the Web

National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA). NEXRAD radar images of precipitation and storm systems, satellite images for the continental U.S. plus the following information for each state and for selected locations within each state: forecasts, warnings, advisories, watches, weather summaries, and climatic data.

Address: http://iwin.nws.noaa.gov

NWS Marine Weather. This site provides worldwide coverage of marine weather forecasts for open waters. Weekly forecasts of Great Lakes water levels are also included.

Address: http://www.marineweather.com

Great Lakes Information on the Web

Great Lakes Information Network (GLIN), Great Lakes Commission. A primary source of information by lake and by subject for a range of Great Lakes subjects.

Address: http://www.great-lakes.net

Our Great Lakes. Replaces GLIMR. Environment Canada. A Canadian web page partner to GLIN. An alternate primary source of Great Lakes information including weather, climate, lake levels, environmental health of the lakes, educational resources, and Environment Canada's Great Lakes 2000 Program. a Great Lakes Atlas, Great Lakes facts and figures, directories, weather forecasts, and references.

Address: http://www.cciw.ca/glimr/intro.html

Lake Level Information on the Web

Ocean and Lake Levels Division, National Ocean Service, NOAA. Recent (unverified) and verified historic lake levels (at 6 minute or hourly intervals) for the date and period of choice for selected U.S. recording sites on the Great Lakes and interconnecting waterways.

Address: http://www.opsd.nos.noaa.gov/data_res.html

Great Lakes Environmental Research Laboratory (GLERL)- NOAA (an alternative site to the previous NOAA site). Select from Great Lakes Water Levels; historic water level data or preliminary current water level data.

Address: http://www.glerl.noaa.gov/data/data.html

Detroit District, USACE. Six-month lake level forecast for each of the Great Lakes in a graphical format plus Great Lakes Basin hydrologic data by month (for the past 5 months) in a tabular format.

Address: http://www.lre.usace.army.mil/hmpghh.html

Canadian Hydrographic Service, Department of Fisheries and Oceans, Canada. Lake level forecast for the next six months in a table format: high, most probable, and low forecast lake levels.

Address: http://chswww.bur.dfo.ca/danp/glfcst.html

Marine Environmental Data Service, Department of Fisheries and Oceans, Canada. Most recent daily and weekly mean, highest and lowest water levels at master water level gauges for each lake.

Address: http://www.meds-sdmm.dfo-mpo.gc.ca

Buffalo District, U.S. Army Corps of Engineers. Select: 1) water levels, 2) Great Lakes. Choose from Lake Ontario or Lake Erie forecasts, hydrology information. Links are provided to other sites for water level data, weather, and climate information.

Address: http://www.lrb.usace.army.mil/

Detroit District, U.S. Army Corps of Engineers. A periodic newsletter summarizing information related to Great Lakes water levels and the regulatory system for adjusting lake levels.

Address: http://www.lre.usace.army.mil/levels/tnewsletter.html

Graphs of historic lake levels can be found at the GLIN site. Select: 1) Great Lakes, then 2) hydrology:levels.

Address: http://great-lakes.net **or** http://great-lakes.net/envt/water/levelsh.html

Lakebeds on the Web

Contact this National Geophysical Data Center (NGDC) web site below and select: 1)Marine Geology and Geophysics (MGG), 2) bathymetry, then 3) Great Lakes bathymetry. For updates, check What's New in MGG.

Address: http://ngdc.noaa.gov

New bathymetric maps of Great Lakes lakebed forms are being generated as both posters (approximately 33 inches wide by 44 inches high) and CD-ROM disks. These products are being developed under a joint project of the NOAA National Geophysical Data Center (Boulder, Colorado), the NOAA Great Lakes Environmental Research Laboratory (Ann Arbor, Michigan), and their associated Cooperative Institutes at the University of Colorado and the University of Michigan. The maps of Lake Michigan, Lake Erie, and Lake St. Clair are currently available.

Address: http://www.glerl.noaa.gov/gldr/

Nautical Charts on the Web

National Ocean Service, NOAA. Listed under Products and Services: nautical charts, tide tables, and the Great Lakes Hydrograph (a multidecade graph of mean monthly lake levels).

Address: http://www.nos.noaa.gov/

Canadian Hydrographic Service, Department of Fisheries and Oceans, Canada.

Address: http://www.chshq.dfo.ca/chs_hq/prodserv.html

Tides on the Web

Tidal information for the next four days. The National Oceanic and Atmospheric Administration (NOAA) has information on tides at the following web site:

Address: http://www.noaa.gov

Precipitation Data on the Web

Detroit District, U.S. Army Corps of Engineers. Verified and preliminary precipitation data by month, lake basin, and Great Lakes Basin plus outflows from Lakes Superior and Ontario.

Address: http://www.lre.usace.army.mil/hmpghh.html

Storm Surges on the Web

Detroit District, U.S. Army Corps of Engineers . Storm probability tables, by lake and by month (only recent months) and storm water level rise at key locations for these probabilities: 20%, 10%, 3%, 2%, 1%.

Address: http://www.lre.usace.army.mil/storm/strmini.html

Waves and Wind on the Web

NOAA National Data Buoy Center, Building 1100, Stennis Space Center, MS 39529. Station information, real time data, archived data, and an index for midlake buoys and Coastal-Marine Automated Network (C-MAN) stations on the Great Lakes.

Address: http://seaboard.ndbc.noaa.gov/ **or** http://www.nws.fsu.edu/buoy/

Great Lakes Environmental Research Lab (GLERL) - NOAA, Ann Arbor, Michigan. C-MAN station and NDBC data buoy conditions at midlake locations (buoy data only for May to November) for past 36 hours, including winds, waves. Also available: table of months and years that NDBC buoy data is available plus current marine weather forecasts.

Address: http://www.glerl.noaa.gov/data/data.html

Great Lakes Coastal Forecast System. Great Lakes Environmental Research Lab (GLERL) - NOAA, Ann Arbor, Michigan. Maps of major winds and waves over the Great Lakes can be obtained by going to the web site given below. Select: 1) Data in left hand column, 2) Great Lakes Forecast System, 3) Nowcast Maps, and 4) Superior or Huron to get maps of the entire basin.

Address: http://www.glerl.noaa.gov

U.S. Army Corps of Engineers' Coastal Hydraulics Laboratory at the Waterways Experiment Station (WES) in Vicksburg, Mississippi. The availability of Wave Information Studies (WIS) reports can be found by going to the web site below. Select: 1) Library, 2) Publications, 3) Coastal Engineering Publications, 4) Wave Information Studies (WIS) Related Publications, and 5) Reports. At the top of the Reports page, select Obtaining WIS Reports to get addresses and information for ordering copies.

Address: http://www.wes.army.mil/Welcome.html

National Climatic Data Center (NCDC), NOAA. Asheville, North Carolina. Wind data for the continental U.S.

Address: http://www.ncdc.noaa.gov/

Datums on the Web

Great Lakes Datums. Detroit District, U.S. Army Corps of Engineers (USACE). Available: information on changes in Great Lakes datum from International Great Lakes Datum 1955 (IGLD55) to IGLD85. Text with table for each lake. For further information, see the companion Engineering Notes #6. Great Lakes Vertical Datums.

Address: http://sparky.nce.usace.army.mil/IGLD.1985/igldhmpg.html

Latitude/Longitude Position Finder. It is sometimes helpful in doing datum conversions to know the latitude and longitude of shoreline positions of interest. The following site allows identification of any site, using up to nine "zoom levels" for zooming in on the precise location of interest. Patience is required: the fourth zoom level brings some detail to the map and all levels may be needed for a particular site.

Address: http://www.juggling.org/bin/un.cgi/map-find

Coastal Engineering on the Web

Wisconsin Sea Grant's Coastal Engineering. Explanations of coastal processes described in this manual are found at the following web page. A number of these explanations are animated.

Address: http://www.seagrant.wisc.edu/advisory/coastal_engr/index.html

USACE Coastal & Hydraulics Laboratory (formerly the Coastal Engineering Research Center), Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS, 39180. Information is provided about the organization, areas of research, publications (some online) and library.

Address: http://chl.wes.army.mil/

New Coastal Engineering Manual (CEM) on the Web. The Coastal and Hydraulics Laboratory is in the process of replacing the 1984 Shore Protection Manual (SPM) with a new Coastal Engineering Manual (CEM). Information about the CEM are available on the Internet. The CEM will be made available to the public in 2000. Check the Coastal and Hydraulics Laboratory's web site under Publications.

Experience with Coastal Structures. The Coastal and Hydraulics Laboratory's Repair, Evaluation, Maintenance and Rehabilitation (REMR) Research Program. At the Coastal and Hydraulics Laboratory's web site, select: 1) Publications. Under REMR, select 2) Structures Laboratory Publications, and 3) Technical Reports.

Coastal Engineering Software. The Coastal Hydraulics Laboratory has a collection of software for coastal engineering design and analysis called the Automated Coastal Engineering System (ACES). ACES is written in Fortran 77 and operates in a DOS environment.

Address: http://chl.wes.army.mil/software/aces/

Coastal Engineering Technical Notes. The Coastal and Hydraulics Laboratory publishes short technical notes on coastal engineering subjects as timely supplements to their other documents. At the Coastal and Hydraulics Laboratory's web site, select: Publications.

Coastal Research on the Web

National Oceanic and Atmospheric Administration (NOAA). The agency's home page provides information about the organization, NOAA news, weather, and a variety of issues including a wide variety of research including research on storms, waves, currents, circulation and climate.

Address: http://www.noaa.gov/

Datums

Benchmark elevations around the Great Lakes. Go to the NOAA National Ocean Service (NOAA-NOS) Web site: **http://mapindex.nos.noaa.gov/default.htm** or go to this National Geodetic Survey site: **http://www.ngs.noaa.gov/**. For the first site, click on *Product Descriptions*. Choose *Geodetic Control Points* and select that *NOS-National Geodetic Service* Web site. Click on *Data Sheets* or click on Map Finder. The instructions show the different ways in which the data sheets with their benchmark elevations can be accessed in a search process. Benchmark elevations are given in meters above the North American Vertical Datum 1988 (NAVD 88). Primary coastal benchmarks also have *dynamic height* elevations in meters above International Great Lakes Datum. For the second site, select *Data Sheets* and then *NGS map*. In up to nine zoom views, it will search for control elevations. Latitude and longitude of positions are helpful in locating nearest survey control points with known elevations. Web site: **http://www.juggling.org/bin/un.cgi/map-find**.

Datum Conversions. A Windows-based software program, *WISCON*, is available to convert survey coordinates and elevations in Wisconsin from one Wisconsin datum/coordinate system to another. The software supports five horizontal coordinate systems and three North American horizontal datums as well as the National Geodetic Vertical Datum of 1929 (NGVD 1929) and the North American Vertical Datum of 1988 (NAVD 88). The software is available for $165 (U.S.) per copy plus $5.00 shipping plus the applicable sales tax for Wisconsin residents (5 or 5 1/2%).

Order WISCON from: State Cartographer's Office, 550 North Park Street, 160 Science Hall, Madison, WI 53706-1491. Phone: 608-262-3065. Fax: 608-262-5205.

Recession Rate Information

The longest recession rates can be obtained by updating surveyed measurements from the shoreline to the closest section corners. Some of these earliest measurements can be found in old land survey records that date to the time of European settlement. Ask your state or provincial government staff about the availability of these old land records.

Well-documented recession rates on similar and nearby property are a good source to use. Consult a local or regional planning agency regarding the availability of information on long-term local recession rates that may have been measured by the agency.

U.S. Shorelines of Lakes Erie and Ontario

The Buffalo District of the USACE plans to add shoreline recession rate data for these shorelines to their web site listed on page 83. In June 1998, this part of their web site was under construction.

Illinois Shoreline of Lake Michigan

Dr. Michael J. Chrzastowski, Illinois State Geological Survey, Natural Resources Building, 615 E. Peabody Drive, Champaign, Illinois 61820.

Michigan Shorelines of Lakes Huron, Michigan and Superior

Martin Jannereth, Michigan Department of Environmental Quality, Box 30458, Lansing, MI 48909-7958.

Ohio Shoreline of Lake Erie

Donald Guy, Ohio Geological Survey. Division of Geological Survey. Great Lakes Center, 1634 Sycamore Line, Sandusky, Ohio 44870-4132. Fax: 419-626-8767.

Wisconsin Shorelines of Lakes Michigan and Superior

For recent recession rate information contact the following agencies:

Bay-Lake Regional Planning Commission, Suite 211, Old Fort Square, 211 N. Broadway, Green Bay, WI 54303-2757. Phone: 920-448-2820. Fax: 920-448-2823. This commission serves the following coastal counties: Marinette, Oconto, Brown, Door, Kewaunee, Manitowoc, and Sheboygan.

Southeastern Wisconsin Regional Planning Commission, P.O. Box 1607, Old Courthouse, 916 N. East Avenue, Waukesha, Wisconsin 53187-1607. This commission serves the following coastal counties: Ozaukee, Milwaukee, Racine, and Kenosha.

Historic Recession Rates for Wisconsin Shores

Long-term recession rates were estimated and published in a series of reports for most Wisconsin coastal counties in the late 1970s. There is a Technical Report which describes and summarizes the project plus separate appendices for Kenosha, Racine, Milwaukee, Ozaukee, Sheboygan, Manitowoc, Kewaunee, and parts of Door County on Lake Michigan. These reports do not contain error estimates for the estimated recession rates. An additional appendix covered Douglas County and western Bayfield County on Lake Superior. The reports are available from: Map Sales Office, Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705. Phone: 608-263-7389.

Recent Wisconsin Studies

Some recent shoreline recession rates (1978-1992) were measured and compared with the 1977, 1980 published rates for Sheboygan, Manitowoc, Kewaunee, and Door Counties. This information is in a draft report: Lake Michigan Shoreline Recession and Bluff Stability in Northeastern Wisconsin: 1996, written by the Bay-Lake Regional Planning Commission. A similar report compared recession rates of 1963-1995 and 1963-1975 (published in the 1977 reports) for Kenosha, Racine, Milwaukee, and Ozaukee Counties. This information is in a draft report: Lake Michigan Shoreline Recession and Bluff Stability in Southeastern Wisconsin: 1995, written by the Southeastern Wisconsin Regional Planning Commission. For information from these two draft reports, contact: Mr. Oscar Herrera, Chief, Wisconsin Coastal Management Program, Division of Energy and Intergovernmental Relations, 101 East Wilson Street, 6th floor, P.O. Box 7868, Madison, WI 53707-7868.

Tides

Long-term tide predictions for particular locations. The National Ocean Service of NOAa will provide predictions either by phone or by email, for a fee. Call the NOS office between 7 am and 3 pm EST at: 301-713-2815. Or, email: ipss@ceob.nos.noaa.gov. Email submissions should include your full name, postal mailing address, phone number (with area code), the locations for which predictions are desired, the format and options desired. See the NOAA web site (http://www.noaa.gov) for available formats and options. The fee for these services in August 1998 was $31 per year for predictions at one location and an additional $10 for a year of predictions at each additional location.

NOAA's National Ocean Service stopped publishing tide and tidal current volumes with the 1995 editions. However, the data is made available to commercial publishers who continue to print hard copy volumes of tides and tidal currents for coastal waters. Here are the three publishers that NOAA recognizes as publishing complete tidal references, using NOAA data:

- ProStar Publications. East Coast: 3 Church Circle, Suite 109, Annapolis, MD 21401. West Coast: 13486 Beach Avenue, Marina Del Rey, CA 90292. Phone: 800-481-6277 reaches both locations.

- Reed's Nautical Almanacs. Thomas Reed Publications, Inc., 13A Lewis Street, Boston, MA 02113. Phone: 800-995-4995.
- International Marine, P.O. Box 182607, Columbus, OH 43218-2607. Phone: 800-262-4729.

Source of information on tides: Woods Hole Sea Grant Program, August 1998.

Waves

Wave height information for 317 deep water locations along the Great Lakes coasts can be found in the reports of the Wave Information Studies of US Coastlines (WIS reports), published in 1991 and 1992 by the Coastal Engineering Research Center, Waterways Experiment Station, USACE. There is a separate volume for each of the Great Lakes with Canadian shorelines included.

The WIS reports contain the following information:

- Percent occurrence of wave height (0.25 m increment) and period (1 second increment) for each of 16 directions of approach and a summary table for all directions combined.
- Mean and maximum significant wave heights for each direction of wave approach.
- Mean peak wave period for each direction of wave approach.
- Mean significant and largest significant wave heights by month and year.
- Thirty-two-year statistics for each station: mean significant wave height and mean peak period, standard deviation of wave height and period data, largest significant wave height and the peak period associated with it, the average direction and date of the largest wave, and most frequent direction of wave approach.
- Return period (2,5,10,20,50 year) wave heights for each of three directions of approach and for all directions of approach, combined, with standard deviations. Not given: wave periods associated with these waves.
- Monthly mean and maximum wave heights and peak wave periods at midlake NOAA data buoys (Great Lakes reports).
- Selected comparisons between measured and calculated wave heights and wave periods at midlake buoys and at shoreline sites (Great Lakes reports).

These WIS reports are available from the National Technical Information Service 5285 Port Royal Road, Springfield, VA 22161.

Waves and Wind in Ocean Coastal Waters and mid-Great Lakes

The National Oceanographic Data Center has released a seven disc CD-ROM set containing 16.5 gigabytes of historical coastal buoy data through December 1997. On-line Internet links are provided to updated data, time series plots, and other information. To order, contact: NOAA/NESDIS, 1315 East-West Highway, Silver Springs, MD 20910. Email: aallegra@nodc.noaa.gov.

The National Data Buoy Center (NDBC) has current wind, wave and water temperature conditions for 21 deep water buoys in midlake portions of the Great Lakes. This information can be found at the web site listed in a previous section of this Appendix. NDBC also has Climatic Summary Tables for these buoys. These tables are available from: The National Data Buoy Center, Building 1100, Stennis Space Center, MS 39529.

Wind

- U.S. Department of Commerce. National Weather Service. Dicennial Census of United States Climate, Climatography of the United States. Summary of hourly observations of wind records over a 10-year period at major airports around the United States.

- Design Storm Winds. For flood insurance purposes on the Great Lakes, the Federal Emergency Management Agency (FEMA) uses a steady 40 miles/hour wind, blowing over the longest overwater distance (FEMA 1991). For flood insurance purposes on ocean coasts, FEMA guidelines indicate that a sustained wind speed of 60 miles/hour with extratropical storms occurring on a spring high tide usually produces 100-year flood elevations (FEMA 1995). The 100-year flood elevation associated with hurricanes is likely with sustained winds in excess of 120 miles/hour.

- National Climatic Data Center, NOAA. 151 Patton Avenue, Asheville, North Carolina 28801. Phone: 704-271-4800. Fax: 704-271-4876. Email: nndcorders@nndc.noaa.gov

- Extreme Wind Speeds at 129 Stations in the Contiguous United States. National Bureau of Standards Building Science Series 118. U.S. Department of Commerce.

Appendix 2

Appendix 2
High Lake Levels and Storm Surges

Storm Surges along U.S. Coastlines of the Great Lakes

Tables 11-15 are summarized from tables of monthly rise values having different possibilities of occurrence, made by the Detroit District, U.S. Army Corps of Engineers. Only the maximum rise over the 12 months is given for each location and each degree of possibility.

Caution: The values in Tables 11-15 may change. Recheck and confirm the values on the originating web site: http://sparky.nce.usace.army.mil/storm/strmprob.html
These values do not represent maximum possible storm surges on islands or points and in bays where surge values may be larger or smaller.

Table 11. Possibilities of Storm-Induced Rises (in Feet) on Lake Superior

Location	20%	10%	3%	2%	1%
Duluth, Minnesota	1.1	1.2	1.4	1.6	1.7
Grand Marais, Minnesota	0.6	0.8	1.0	1.3	1.5
Marquette, Michigan	1.2	1.5	1.9	2.1	2.4
Ontonagon, Michigan	0.9	1.3	2.1	2.8	3.5
Point Iroquois, Michigan	1.4	1.6	1.8	2.0	2.2

Table 12. Possibilities of Storm-Induced Rises (in Feet) on Lake Michigan

Location	20%	10%	3%	2%	1%
Calumet Harbor, Illinois	1.6	1.9	2.3	2.5	2.8
Green Bay, Wisconsin	2.2	2.6	3.3	4.1	4.9
Holland, Michigan	1.1	1.3	1.7	1.9	2.2
Kewaunee, Wisconsin	0.9	1.1	1.5	2.0	2.6
Ludington, Michigan	1.0	1.1	1.3	1.4	1.5
Milwaukee, Wisconsin	1.2	1.4	1.7	1.9	2.1
Port Inland, Michigan	1.7	1.9	2.3	2.9	3.5
Sturgeon Bay, Wisconsin	1.0	1.3	1.5	2.5	3.2

Table 13. Possibilities of Storm-Induced Rises (in Feet) on Lake Huron and Lake St. Clair

Location	20%	10%	3%	2%	1%
DeTour Village, Michigan	0.7	0.8	0.8	0.9	0.9
Essexville, Michigan	2.2	2.6	3.1	3.6	4.1
Harbor Beach, Michigan	0.8	0.9	1.2	1.4	1.8
Harrisville, Michigan	0.7	0.8	1.0	1.2	1.5
Lakeport, Michigan	1.4	1.7	2.1	2.5	3.0
Mackinaw City, Michigan	1.1	1.3	1.7	1.9	2.1
St. Clair Shores (Lake St. Clair)	0.8	0.9	1.1	1.3	1.4

Table 14. Possibilities of Storm-Induced Rises (in Feet) on Lake Erie

Location	20%	10%	3%	2%	1%
Buffalo, New York	5.0	5.8	6.8	7.4	8.1
Cleveland, Ohio	1.2	1.5	1.8	2.0	2.4
Erie, Pennsylvania	2.4	2.8	3.3	3.7	4.1
Fairport Harbor, Ohio	1.0	1.1	1.6	2.0	2.4
Fermi Power Plant, Michigan	2.4	2.8	3.4	3.8	4.2
Marblehead, Ohio	1.9	2.3	2.9	3.4	3.9
Sturgeon Point, New York	4.4	4.9	5.5	6.0	6.7
Toledo, Ohio	3.1	3.5	4.1	4.6	5.1

Table 15. Possibilities of Storm-Induced Rises (in feet) on Lake Ontario

Location	20%	10%	3%	2%	1%
Cape Vincent, New York	1.1	1.2	1.5	1.8	2.0
Olcott, New York	0.6	0.7	0.9	1.0	1.1
Oswego, New York	0.9	1.1	1.4	1.6	1.8
Rochester, New York	0.7	0.8	1.0	1.1	1.4

100-Year Flood Elevations for the Great Lakes Prepared for the Federal Emergency Management Agency (FEMA)

In 1988, the U.S. Army Corps of Engineers revised upwards the 1977 flood elevations of 10-, 50-, 100- and 500-year *return period* open-coast flood events for FEMA partly because a prolonged period of high water levels had changed the data base. Tables 16 through 21 summarize only the 100-year flood event elevations that are used for federal flood insurance purposes.

> Caution: FEMA is in the process of adding a wave runup elevation to flood elevations at certain locations. Check with FEMA or with appropriate county planning and zoning offices to confirm elevations or obtain updated values.
>
> All N-year flood elevations have some uncertainty. In the Great Lakes a decade ago, this uncertainty for 100-year flood elevations ranged from 0.2 to 0.7 feet above the stated flood elevation to 0.3 to 1.0 feet below the stated elevation, depending on the length of the water level gauge record used for estimating the flood elevation (USACE 1988c). These ranges in flood elevation are for a 95% level of confidence.
>
> Only the IGLD 1955 and NGVD 1929 elevations were taken from the USACE 1988 report. The IGLD 1985 conversions are based on the datum differences at low water datum for each lake (Coordinating Committee 1992). Flood elevations in Table 21 are only given at the gauging stations in the connecting rivers because each river has a unique flood profile that can be found in the reference for Table 21.

Table 16. 100-Year Flood Elevations (in Feet) Prepared for FEMA Use on Lake Superior in 1988.

Reach (approximate limits)	IGLD 1955	IGLD 1985	NGVD 1929
Whitefish Point to Au Sable Point, Michigan	603.5	604.6	604.4
Au Sable Point to Copper Harbor, Michigan	603.4	604.5	604.4
Copper Harbor to Point Detour, Wisconsin	603.5	604.6	604.6
Point Detour, Duluth-Baptism River, Minnesota	603.4	604.5	604.6
Baptism River to Pigeon River, Minnesota	603.3	604.4	604.5

Source: USACE 1988a. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

> Caution: Open-coast flood elevations are not applicable to the following locations on Lake Superior: Whitefish Bay, Huron Bay, Keweenaw Bay, Chequamegon Bay, Grand Island, Apostle Islands, other islands, points of land and bays.

Table 17. 100-Year Flood Elevations Prepared for FEMA Use on Lake Michigan in 1988

Reach	IGLD 1955	IGLD 1985	NGVD 1929
Cross Village to Point Betsie, Michigan	583.2	583.9	584.4
Point Betsie to Little Sauble Point, Michigan	583.3	584.0	584.6
Little Sauble Point to Benton Harbor, Michigan	583.4	584.1	584.8
Benton Harbor, Chicago, to Wilmette, Illinois	583.5	584.2	585.0
Wilmette to Zion, Illinois or Illinois /Wisconsin border	583.4	584.1	584.8
IL/WI border to Wind Point, Racine, Wisconsin	583.2	583.9	584.6
Wind Point to Latitude 43 deg. 30 min. N	583.0	583.7	584.3
Latitude 43 deg. 30 min. N to Cana Island, Wisconsin	583.1	583.8	584.3
Cana Island to Point aux Barques	583.3	584.0	584.4
Point aux Barques to St. of Mackinac	583.5	584.2	584.5

Source: USACE 1988a. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

Caution: Open-coast flood elevations are not applicable to the following locations on Lake Michigan: Green Bay, Little Traverse Bay, Grand Traverse Bay, other bays, points of land, islands, and the Straits of Mackinac.

Table 18. 100-Year Flood Elevations Prepared for FEMA Use on Lake Huron in 1988

Reach	IGLD 1955	IGLD 1985	NGVD 1929
Fort Gratiot to Lakeport, Michigan	583.2	583.9	584.5
Lakeport to stream 3 mi. S of Lexington	583.1	583.8	584.4
Stream to 4 miles N of Lexington, Michigan	583.0	583.7	584.3
4 mi. N of Lexington to Port Sanilac, Michigan	582.9	583.6	584.2
Port Sanilac to stream 3.5 mi. S of Forestville, Michigan	582.8	583.5	584.1
Stream to Harbor Beach, Michigan	582.7	583.4	584.0
Harbor Beach to Presque Isle, Michigan	582.6	583.3	583.8
Presque Isle to False Detour Channel	582.5	583.2	583.6

Source: USACE 1988a. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

Caution: Open-coast flood elevations are not applicable to the following locations on Lake Huron: Saginaw Bay, Thunder Bay, Straits of Mackinac, Les Cheneaux Islands, Drummond Island, St. Joseph Island, other bays, points of land, and islands.

Table 19. 100-Year Flood Elevations for FEMA Use on Lake Erie and Lake St. Clair in 1988

Reach	IGLD 1955	IGLD 1985	NGVD 1929
Buffalo to SW end, Lackawanna, New York	580.3	580.9	581.6
SW end of Lackawanna to Stream A about 4. 5 mi. NE of Sturgeon Point	579.6	580.2	580.9
Stream A to Sturgeon Point	578.9	579.5	580.2
Sturgeon Point to coast E of Angola, New York	578.3	578.9	579.6
Coast E of Angola to Silver Creek, New York	577.8	578.4	579.1
Silver Creek to Dunkirk, New York	577.3	577.9	578.7
Dunkirk to Barcelona, New York	576.9	577.5	578.3
Barcelona to Stream B 9 mi. NE of Erie Harbor Light	576.5	577.1	578.0
Stream B to E end of Erie, Pennsylvania	576.2	576.8	577.7
E end of Erie to beacon 18 mi. NE of Conneaut Harbor, Ohio	575.9	576.5	577.4
Beacon to Stream C 9. 5 mi. NE of Conneaut Harbor, Ohio	575.6	576.2	577.1
Stream C to 6 mi. NE of Ashtabula Harbor	575.4	576.0	576.9
6 mi. NE to 4. 5 mi. SW of Ashtabula Harbor, Ohio	575.2	575.8	576.7
4. 5 mi. SW of Ashtabula Harbor to Stream D 7 mi. NE of Fairport, Harbor, Ohio	575.1	575.7	576.6
Stream D to Rocky River, Cleveland, Ohio	575.0	575.6	576.6
Rocky River to Avon Point, Ohio	575.1	575.7	576.7
Avon Point to Lorain, Ohio	575.3	575.9	576.9
Lorain to Vermillion, Ohio	575.5	576.1	577.1
Vermillion to Huron, Ohio	575.8	576.4	577.4
Huron to Sandusky, Ohio	576.1	576.7	577.7
Sandusky to Lakeside, Ohio	576.4	577.0	577.9
Lakeside to Turtle Creek, Ohio	576.7	577.3	578.2
Turtle Creek to Cedar Point (near Toledo, Ohio)	577.0	577.6	578.5
Cedar Point, Toledo to Huron River, Michigan	577.3	577.9	578.8
Lake St. Clair, U.S. shore	578.2	578.8	579.6

Source: USACE 1988a. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

Caution: Open-coast flood elevations are not applicable to the following locations on Lake Erie: Erie Harbor, Sandusky Bay, Maumee Bay, other bays, points of land, and islands.

Table 20. 100-year flood elevations prepared for FEMA use on Lake Ontario in 1988

Reach	IGLD 1955	IGLD 1985	NGVD 1929
Stony Point to Nine Mile Point	248.5	249.0	249.7
Nine Mile Point to Sodus Bay, New York	248.4	248.9	249.6
Sodus Bay to Braddock Point Light	248.3	248.8	249.5
Braddock Point Light to Thirty Mile Point Light	248.2	248.7	249.4
Thirty Mile Point Light to Niagara River Mouth	248.1	248.6	249.2

Source: USACE 1988a. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

Caution: Open-coast flood elevations are not applicable to the following locations on Lake Ontario: Little Sodus Bay, Sodus Bay, Irondequoit Bay, other bays, islands, and points of land.

Table 21. 100-Year Flood Elevations for FEMA Use on Great Lakes Connecting Rivers in 1988

River and Gauge	IGLD 1955	IGLD 1985	NGVD 1929
St. Marys River, SW Pier above locks	604.18	605.3	604.88
St. Marys River, US Slip below locks	584.30	585.4	585.01
St. Marys River, Detour gauge	582.97	584.1	583.80
St. Clair River, Fort Gratiot, Michigan	583.59	584.2	584.84
St. Clair River, Dunn Paper gauge	583.32	583.9	584.58
St. Clair River, mouth of Black River	582.60	583.2	583.83
St. Clair River, Dry Dock gauge	581.39	582.0	582.67
St. Clair River, Marysville gauge	581.78	582.4	583.05
St. Clair River, St. Clair gauge	581.18	581.8	582.44
St. Clair River, Algonac gauge	579.00	579.6	580.30
Detroit River, Windmill Point gauge	578.24	578.8	579.53
Detroit River, Fort Wayne, Michigan	576.77	577.4	577.83
Detroit River, Wyandotte gauge	577.93	578.5	579.34
Detroit River, Gibraltar gauge	576.63	577.2	578.07
Upper Niagara River, Niagara Intake	565.46	566.1	566.60
Lower Niagara River, Ashland Ave. gauge	346.51	347.0	347.65
St. Lawrence River, Cape Vincent gauge	248.25	248.8	249.36
St. Lawrence River, Ogdensburg gauge	247.75	248.3	248.55

Source: USACE 1988b. IGLD 1985 values are approximate values only. Contact FEMA or county planning and zoning office to confirm or obtain updated flood elevations.

Coastal Sectors for Storm Surge and 100-Year Flood Level Information along Canadian Coastlines of the Great Lakes

Tables 22 through 25 help locate the sectors used by the Ontario Ministry of Natural Resources (OMNR) to estimate the storm surge values and the 100-year flood elevations for the Canadian Great Lakes coasts that are given in Tables 26 through 33.

Caution: The stated boundaries of the sectors given in Tables 22 through 25 are provided as a helpful guide and are only approximations. Some of these sector boundaries are uncertain within several kilometers due to the large scale of the available maps and may be in error. For verification of boundaries, check with the appropriate OMNR office or with a source listed in Appendix 1. Such verification is particularly important for properties within a few kilometers of the boundaries stated in Tables 22 through 25 if the difference in storm surge values or flood elevations between adjacent sectors seems significant.

Table 22. Storm Surge Sector Locations on the Canadian Open Coast of Lake Superior

Sector No.	Sector Name	Approximate Sector Boundaries
S-1	Pine Point	Pigeon River to Mink Point
S-2	Thunder Bay	Mink Point to Shesheeb Point
S-3	Rossport	Shesheeb Point to Otter Head
S-4	Michipicoten	Otter Head to Coppermine Point
S-5	Gros Cap	Coppermine Point to point opposite Birch Point in Michigan
S-6	Pointe Louise	Pointe aux Chenes to Pointe aux Pins, Whitefish Bay

Table 23. Storm Surge Sector Locations on the Canadian Coast of Lake Huron and Georgian Bay

Sector No.	Sector Name	Approximate Sector Boundaries
H-1	Neebish	Neebish to Richards Landing
H-2	Richards	Richards Landing to Campment D'ours Island
H-3	Hilton	St. Joseph Island: Campment D'ours Island to Hay Point
H-4	St. Joseph	St. Joseph Island, W Shore: Lake Munuscong to Hay Point
H-5	Thessalon	About 8 km W of Bruce Mines to Thessalon
H-6	Mississagi Bay	Thessalon to Blind River
H-7	Little Current	North Channel coast: Blind River to Barie Island
H-8	Cape Robert	Manitoulin Island coast: Barie Island to Mississagi Strait light
H-9	N. Cockburn Island	N shore, Cockburn Island
H-10	N.A.	S shore, Cockburn Island
H-11	South Shore	S shore, Manitoulin Island
H-12	N. Georgian Bay	E shore of Manitoulin Island and N and E shore of Georgian Bay to Pointe au Baril
H-13	Parry Sound	E shore of Georgian Bay: Pointe au Baril to 45 deg. 11 min. N Lat.
H-14	Collingwood	E and S shore of Georgian Bay: 45 deg. 11 min. N Lat. to about 5 km. NW of Collingwood Harbor
H-15	Meaford	About 5 km NW of Collingwood Harbor to Cape Crocker
H-16	Dyer's Bay	Cape Crocker to about 7 km W of Cabot Head
H-17	Tobermory	About 7 km W of Cabot Head to Cape Hurd
H-18	Southampton	W coast of Bruce Peninsula: Cape Hurd to Pine River
H-19	Point Clark	Pine River to 4-5 km S of Point Clark Light
H-20	Goderich	4-5 km S of Point Clark Light to Drysdale/St. Joseph
H-21	Kettle Point	Drysdale/St. Joseph to Blue Point
H-22	Brights Grove	Blue Point to Point Edward

Table 24. Storm Surge Sector Locations on the Canadian Coast of Lake St. Clair

Sector No.	Sector Name	Approximate Sector Boundaries
SC-1	Walpole	N shore
SC-2	Mitchell	Mitchell Bay
SC-3	Dover	Mitchell Bay to 8 km NNE of Thames River mouth
SC-4	Thames	8 km NNE of the Thames River mouth to Thames River mouth
SC-5	Tremblay	Thames River mouth to 8 km W of Thames River mouth
SC-6	Stoney Point	8 km W of Thames River mouth to Ruscom River
SC-7	Belle River	Ruscom River to stream mouth 7-8 km E of Windsor
SC-8	Tecumseh	Stream mouth 7-8 km E of Windsor to Windsor

Table 25. Storm Surge Sector Locations on the Canadian Coasts of Lake Erie

Sector No.	Sector Name	Approximate Sector Boundaries
E-1	Bar Point	Bar Point to Colchester
E-2	Kingsville	Colchester to Leamington
E-3	Pelee West	Leamington to tip of Point Pelee
E-4	Wheatley	Tip of Point Pelee to Port Crewe
E-5	Port Crewe	Port Crewe to about 7 km. W of Erieau
E-6	Erieau	About 7 km W of Erieau to tip of Pointe aux Pins
E-7	Port Glasgow	Tip of Pointe aux Pins to Plum Point
E-8	Port Stanley	Plum Point about 5 km E of Port Stanley
E-9	Port Bruce	About 5 km E of Port Stanley to Port Bruce
E-10	Port Burwell	Port Bruce to Port Burwell
E-11	Hemlock	Port Burwell to Clear Creek
E-12	Clear Creek	Clear Creek to 80 deg. 30 min. W Long. (Point A)
E-13	Erie View	Point A. to base of Long Point, 33 km from tip of Long Point
E-14	Long Point Park	21-23 km W, to 30-33 km W of the tip of Long Point
E-15	Long Point Central	8-9 km W, to 21-23 km W of the tip of Long Point
E-16	Long Point East	Tip of Long Point to 8-9 km W of the tip of Long Point
E-17	Long Point Bay	Tip of Long Point to about 4 km E of Port Dover
E-18	Nanticoke	About 4 km E of Port Dover to Peacock Point
E-19	Selkirk	Peacock Point to Grant Point
E-20	Port Maitland	Grant Point to a point about 7 km SE of the Grand R. mouth
E-21	Mohawk Point	Point about 7 km SE of the Grand River mouth to Mohawk Point
E-22	Port Colborne	Mohawk Point to about 7 km NW of Point Abino
E-23	Point Abino	About 7 km NW of Point Albino to Point Abino
E-24	Crystal Beach	Point Abino to Windmill Point
E-25	Fort Erie	Windmill Point to Fort Erie

Table 26. Storm Surge Sector Locations on the Canadian Coasts of Lake Ontario

Sector	Sector Name	Approximate Sector Boundaries
O-1	Port Weller	Niagara River mouth to about 4 km WNW of Jordon Harbor
O-2	Burlington	About 4 km WNW of Jordon Harbor to Bronte
O-3	Oakville	Bronte to Clarkson
O-4	Mississauga	Clarkson to Gibraltar Point
O-5	Toronto	Gibraltar Point to point 2 km E of Frenchman's Bay
O-6	Oshawa	2 km E of Frenchman's Bay to 4 km WSW of Darlington
O-7	Cobourg	4 km WSW of Port Darlington to Brighton
O-8	Wellington	Brighton to West Point, including Wellington Bay
O-9	Point Petre	West Point to Prince Edward Point
O-10	Prince Edward	Prince Edward Point to Amherst Island
O-11	Kingston	Amherst Island to Wolfe Island (Canadian/U.S. border)

Storm Surges along Canadian Coastlines of the Great Lakes

Tables 27 through 31 were reprinted from *Great Lakes System Flood Levels and Water Related Hazards,* Conservation Authorities and Water Management Branch, Ontario Ministry of Natural Resources (dated February 1989) (OMNR 1989). These tables can be used with the method described in the manual to help in estimating whether or not a property is *obviously at risk* of flooding or has an *apparently low risk* of flooding.

Caution: While the values in the tables have been checked against the source document, there may be undetected errors in either set of tables. The values in these tables are also subject to revision as new data on water levels become available. Confirm values with and consult the Ontario Ministry of Natural Resources, which produced the original data and would prepare any future revisions.

Table 27. Storm Surge (Wind Setup) Frequencies on the Canadian Coast of Lake Superior

Sector	Return Period (Years)					
	2	5	10	25	50	100
Pine Point	0.24	0.33	0.40	0.52	0.62	0.75
Thunder Bay*	0.26	0.31	0.35	0.38	0.41	0.43
Rossport*	0.28	0.37	0.45	0.56	0.66	0.76
Michipicoten*	0.42	0.56	0.64	0.74	0.80	0.86
Gros Cap*	0.43	0.53	0.60	0.67	0.71	0.76
Pointe Louise	NA	NA	NA	NA	NA	0.96

Surge values in meters.
*Sites where surge values with reoccurrence intervals were generated from recorded surge records. At other sites, surges were calculated using the Atmospheric Environment Service's computer model SURGE.
Source: OMNR 1989.

Table 28. Storm Surge (Wind Setup) Frequencies on the Canadian Coast of Lake Huron

Sector	Return Period (Years)					
	2	5	10	25	50	100
Neebish, Richards, Hilton, and St. Joseph	NA	NA	NA	NA	NA	0.48
Thessalon*	0.28	0.33	0.37	0.41	0.45	0.48
Mississagi Bay	0.35	0.42	0.47	0.53	0.58	0.63
Little Current*	0.40	0.51	0.59	0.69	0.78	0.87
Cape Robert	0.34	0.40	0.44	0.49	0.54	0.58
N. Cockburn Island	0.29	0.35	0.39	0.44	0.48	0.53
South Shore, Cockburn Island	0.15	0.18	0.20	0.22	0.24	0.25
South Shore, Manitoulin Island	0.15	0.18	0.20	0.22	0.24	0.25
N. Georgian Bay	0.34	0.41	0.46	0.50	0.53	0.56
Parry Sound*	0.42	0.53	0.61	0.72	0.82	0.92
Collingwood*	0.50	0.61	0.68	0.78	0.85	0.93
Meaford	0.39	0.49	0.55	0.62	0.68	0.73
Dyer's Bay	0.32	0.39	0.45	0.51	0.56	0.61
Tobermory*	0.25	0.32	0.36	0.43	0.48	0.54
Southampton	0.19	0.23	0.25	0.27	0.28	0.30
Point Clark	NA	NA	NA	NA	NA	0.49
Goderich*	0.36	0.43	0.48	0.55	0.61	0.67
Kettle Point	0.44	0.53	0.59	0.66	0.72	0.78
Brights Grove	0.52	0.64	0.72	0.83	0.91	1.00

Surge values in meters.
*Sites where surge values with reoccurrence intervals were generated from recorded surge records. At other sites, surges were calculated using the Atmospheric Environment Service's computer model SURGE.

Source: OMNR 1989.

Table 29. Storm Surge (Wind Setup) Frequencies on the Canadian Coast of Lake St. Clair

Sector	Return Period (Years)					
	2	5	10	25	50	100
Walpole	0.55	0.70	0.79	0.91	0.99	1.07
Mitchell	0.68	0.86	0.97	1.10	1.18	1.27
Dover	0.59	0.76	0.86	0.97	1.04	1.11
Thames	0.65	0.83	0.94	1.07	1.16	1.24
Tremblay	0.34	0.45	0.53	0.64	0.74	0.85
Stoney Point	0.32	0.41	0.47	0.56	0.63	0.71
Belle River*	0.31	0.44	0.53	0.64	0.72	0.81
Tecumseh*	0.28	0.33	0.36	0.40	0.42	0.45

Surge values in meters.
*Sites where surge values with reoccurrence intervals were generated from recorded surge records. At other sites, surges were calculated using the Atmospheric Environment Service's computer model SURGE.
Source: OMNR 1989.

Table 30. Storm Surge (Wind Setup) Frequencies on the Canadian Coast of Lake Erie

Sector	Return Period (Years)					
	2	5	10	25	50	100
Bar Point*	0.61	0.80	0.89	0.98	1.03	1.07
Kingsville*	0.60	0.72	0.79	0.85	0.90	0.94
Pelee West	0.43	0.56	0.66	0.78	0.88	0.99
Wheatley	0.51	0.65	0.73	0.84	0.91	0.98
Port Crewe	0.31	0.39	0.44	0.51	0.55	0.60
Erieau*	0.28	0.34	0.37	0.42	0.46	0.49
Port Glasgow	0.30	0.40	0.47	0.58	0.67	0.77
Port Stanley*	0.40	0.53	0.63	0.75	0.85	0.96
Port Bruce	0.56	0.67	0.72	0.77	0.79	0.81
Port Burwell	0.63	0.74	0.78	0.81	0.81	0.82
Hemlock	0.72	0.88	0.94	0.98	1.00	1.01
Clear Creek	0.81	0.99	1.07	1.15	1.19	1.23
Erie View	0.92	1.13	1.23	1.32	1.38	1.43
Long Point Park	0.96	1.23	1.37	1.54	1.64	1.74
Long Point Central	1.05	1.34	1.51	1.70	1.82	1.94
Long Point East	1.11	1.42	1.60	1.81	1.94	2.07
Long Point Bay	1.15	1.32	1.42	1.52	1.59	1.66
Nanticoke	1.24	1.42	1.52	1.63	1.71	1.77
Selkirk	1.28	1.47	1.58	1.69	1.77	1.84
Port Maitland	1.40	1.60	1.71	1.82	1.90	1.96
Mohawk Point	1.45	1.66	1.77	1.89	1.97	2.04
Port Colborne*	1.32	1.61	1.80	2.01	2.17	2.32
Point Abino	1.60	1.85	1.99	2.14	2.25	2.34
Crystal Beach	1.70	1.95	2.08	2.22	2.31	2.39
Fort Erie	1.80	2.07	2.21	2.36	2.46	2.55

Surge values in meters.
*Sites where surge values with reoccurrence intervals were generated from recorded surge records. At other sites, surges were calculated using the Atmospheric Environment Service's computer model SURGE.
Source: OMNR 1989.

Table 31. Storm Surge (Wind Setup) Frequencies on the Canadian Coast of Lake Ontario

Sector	Return Period (Years)					
	2	5	10	25	50	100
Port Weller*	0.16	0.27	0.39	0.59	0.79	1.06
Burlington*	0.33	0.44	0.53	0.67	0.79	0.94
Oakville	NA	NA	NA	NA	NA	0.81
Mississauga	NA	NA	NA	NA	NA	0.72
Toronto*	0.16	0.21	0.24	0.28	0.31	0.34
Oshawa	0.12	0.15	0.17	0.20	0.21	0.23
Cobourg*	0.21	0.27	0.31	0.36	0.40	0.44
Wellington	0.13	0.17	0.21	0.27	0.32	0.39
Point Petre	0.10	0.13	0.16	0.20	0.23	0.27
Prince Edward	0.14	0.21	0.26	0.34	0.40	0.47
Kingston*	0.31	0.40	0.46	0.54	0.60	0.66

Surge values in meters.
*Sites where surge values with reoccurrence intervals were generated from recorded surge records. At other sites, surges were calculated using the Atmospheric Environment Service's computer model SURGE.
Source: OMNR 1989.

100-Year Flood Elevations along Canadian Coastlines of the Great Lakes

Tables 32 through 37 are adapted from *Great Lakes System Flood Levels and Water Related Hazards,* Conservation Authorities and Water Management Branch, Ontario Ministry of Natural Resources, February 1989 (OMNR 1989). The frequencies of peak instantaneous 100-year lake level elevations were calculated by combining individual frequency distributions of monthly mean lake levels and surge values using the OMNR HYDSTAT computer program.

> Caution: All 100-year frequency elevations have some range of uncertainty.

The 100-year elevations in OMNR (1989) were given in meters above IGLD 1955. Conversions to IGLD 1985 and CGD (Canadian Geodetic Datum) are given for the more limited set of gauging sites in shoreline sectors marked with an asterisk in Tables 32-37. These conversion values were obtained from the Canadian Hydrographic Service and are used with permission (Sandilands, 9/25/97, personal communication). The conversion values include a hydraulic correction factor to adjust water elevation at each site to lake elevation at the master gauge site on each lake. For the other sectors, the conversions to IGLD 1985 and CGD were estimated by the author and are indicated to tenths of meters rather than hundredths of meters to reflect uncertainty about their values. If more accurate conversions are needed for particular sites, contact a local government office or one of the sources in Appendix 1. Downstream of Lake Huron, CGD elevations approximate IGLD 1985 elevations.

Table 32. 100-Year Flood Elevations on the Canadian Shores of Lake Superior

Sector	IGLD 1955	IGLD 1985	CGD
Pine Point	183.91	184.3	184.0
Thunder Bay*	183.77	184.15	183.84
Rossport*	183.94	184.40	184.00
Michipicoten*	184.10	184.54	184.14
Gros Cap*	184.03	184.41	184.13

Pointe Louise	184.20	184.5	184.3

Elevations in meters. *Water gauge locations. Source: OMNR 1989.

Table 33. 100-Year Flood Elevations on the Canadian Shores of Lake Huron

Sector	IGLD 1955	IGLD 1985	CGD
Neebish	177.7	178.0	177.9
Richards	177.6	177.9	177.8
Hilton	177.5	177.8	177.7
St. Joseph	177.6	177.9	177.8
Thessalon*	177.52	177.78	177.71
Mississagi Bay	177.62	177.9	177.8
Little Current*	177.73	178.07	177.94
Cape Robert	177.59	177.9	177.8
N. Cockburn Island	177.54	177.8	177.8
South Shore, Cockburn Island	177.38	177.7	177.6
South Shore, Manitoulin Island	177.38	177.7	177.6
N. Georgian Bay	177.60	177.9	177.8
Parry Sound*	177.74	178.07	177.96
Collingwood*	177.80	178.04	178.00
Meaford	177.67	177.9	177.9
Dyer's Bay	177.58	177.9	177.7
Tobermory*	177.52	177.80	177.66
Southampton	177.43	177.7	177.6
Point Clark	177.50	177.7	177.7
Goderich*	177.61	177.80	177.80
Kettle Point	177.72	177.9	177.9
Brights Grove	177.84	178.0	178.0

Elevations in meters. *Water level gauge locations. Source: OMNR 1989.

Table 34. 100-Year Flood Elevations on the Canadian Shores of Lake St. Clair

Sector	IGLD 1955	IGLD 1985	CGD
Walpole	176.40	176.6	176.6
Mitchell	176.58	176.8	176.8
Dover	176.46	176.7	176.6
Thames	176.55	176.8	176.8
Tremblay	176.16	176.4	176.4
Stoney Point	176.10	176.3	176.3
Belle River*	176.14	176.36	176.35
Tecumseh*	176.01	176.19	176.20

Elevations in meters. *Water level gauge locations. Source: OMNR 1989.

Table 35. 100-Year Flood Elevations on the Canadian Shores of Lake Erie

Sector	IGLD 1955	IGLD 1985	CGD
Bar Point*	175.59	175.77	175.80
Kingsville*	175.49	175.67	175.69
Pelee West	175.38	175.6	175.6
Wheatley	175.29	175.5	175.5
Port Crewe	175.17	175.4	175.4
Erieau*	175.12	175.30	175.30
Port Glasgow	175.20	175.4	175.4
Port Stanley*	175.35	175.54	175.52
Port Bruce	175.43	175.6	175.6
Port Burwell	175.49	175.7	175.7
Hemlock	175.64	175.8	175.8
Clear Creek	175.77	176.0	175.9
Erie View	175.93	176.1	176.1
Long Point Park	176.12	176.3	176.3
Long Point Central	176.29	176.5	176.4
Long Point East	176.40	176.6	176.5
Long Point Bay	176.13	176.3	176.3
Nanticoke	176.23	176.4	176.4
Selkirk	176.29	176.5	176.4
Port Maitland	176.42	176.6	176.6
Mohawk Point	176.49	176.7	176.6
Port Colborne*	176.61	176.80	176.76
Point Abino	176.73	176.9	176.9
Crystal Beach	176.81	177.0	177.0
Fort Erie	176.95	177.1	177.1

Elevations in meters. *Water level gauge locations. Source: OMNR 1989.

Table 36. 100-Year Flood Elevations on the Canadian Shores of Lake Ontario

Sector	IGLD 1955	IGLD 1985	CGD
Port Weller*	76.04	76.17	76.14
Burlington*	75.93	76.01	76.01
Oakville	75.83	75.9	75.9
Mississauga	75.73	75.8	75.8
Toronto*	75.61	75.74	75.69
Oshawa	75.55	75.7	75.6
Cobourg*	75.67	75.80	75.74
Wellington	75.58	75.7	75.7
Point Petre	75.54	75.7	75.7
Prince Edward	75.62	75.8	75.8
Kingston*	75.81	75.99	75.95

Elevations in meters. *Water level gauge locations. Source: OMNR 1989.

Table 37. 100-Year High Water Elevations along Canadian Shores of Great Lakes Connecting Rivers

Sector	Approximate Location	IGLD 1955	IGLD 1985	CGD
St. Marys, SR-1. *	Pointe aux Pins Bay and Leigh Bay	184.30	184.68	184.40
St. Marys, SR-2. *	Sault Ste. Marie below the locks	178.12	178.39	178.23
St. Marys, SR-3.	E end, Sault Ste. Marie to shore opposite Point Lewis on Sugar Island	178.0	178.3	178.1
St. Marys, SR-4.	Shore opposite Point Lewis on Sugar Island to Point Charles	177.9	178.2	178.0
St. Marys, SR-5.	Point Charles to S end of Lake George (Birch Point)	177.8	178.1	177.9
St. Clair. SCR-1.	Point Edward, N shoreline	177.7	177.9	177.8
St. Clair. SCR-2.	Point Edward, central shoreline	177.6	177.8	177.7
St. Clair. SCR-3.	Point Edward, S shoreline	177.5	177.7	177.6
St. Clair. SCR-4.	Sarnia, N half of shoreline	177.4	177.6	177.5
St. Clair. SCR-5.	Sarnia, S half of shoreline	177.3	177.5	177.5
St. Clair. SCR-6.	Dow Chemical to 42 deg. 55 min. N	177.2	177.4	177.4
St. Clair. SCR-7.	42 deg. 55 min. N Lat. to N end, Stag Island	177.1	177.3	177.3
St. Clair. SCR-8.	N end, Stag Island to Stag Island Shoal Light	177.0	177.2	177.2
St. Clair. SCR-9.	Stag Island Shoal Light to Mooretown	176.9	177.1	177.1
St. Clair. SCR-10.	Mooretown to Ontario Hydro	176.8	177.0	177.0
St. Clair. SCR-11.	Ontario Hydro to Kessel Point Light	176.7	176.9	176.9
St. Clair. SCR-12.	Kessel Point Light to Fawn Island	176.6	176.8	176.8
St. Clair. SCR-13.	Fawn Island to Port Lambton	176.5	176.7	176.7
St. Clair. SCR-14.	Port Lambton*	176.37	176.57	176.54
Detroit, DR-1.	Peach Island to 82 deg. 59 min. W Long.	176.0	176.2	176.2
Detroit, DR-2.	82 deg. 59 min. W Long. to Ambassador Bridge	175.9	176.1	176.1
Detroit, DR-3.	Ambassador Bridge to Riviere Aux Canards	175.8	176.0	176.0
Detroit, DR-4.	Riviere Aux Canards to S end, Bois Blanc Island	175.7	175.9	175.9
Detroit, DR-5.	S end, Bois Blanc Island to Bar Point	175.6	175.8	175.8

*Water level gauge locations. Source: OMNR 1989.

Worksheets

Worksheets

Worksheet for Estimating Storm Surge and Wave Runup

Step 1: Estimate the highest still water lake level by (1) selecting the maximum twentieth-century water level from Table 1 on the next page (repeated from page 13), or (2) use the highest recorded or projected monthly mean level for the lake from the most recent U.S. Army Corps of Engineers or Canadian monthly bulletins of lake levels. Keep in mind that new record high levels may be possible in the future.

Step 2: Find the typical storm surge for the area on Figure 5 (page 108). Remember that storm surges at some locations can be twice the values shown in Figure 5. If the property is on a shallow bay and subject to extreme storm surges, contact the local city engineer's office or a professional coastal engineer for more precise storm surge information.

Step 3: Select the appropriate minimum wave runup value from Table 2 on the next page. Keep in mind that the actual runup on a property is likely to exceed these values.

Step 4: Select the equivalent land elevation for Great Lakes chart datum from Table 3 (page 107). If the property is within city limits, check with the local city engineer's office for the proper number for converting city datum to NGVD or MSL.

Step 5: Add the highest still water level, typical storm surge value, and minimum wave runup value to the equivalent NGVD elevation to estimate the storm wave runup elevation. Remember that the uncertainties involved are likely to total more than a foot.

Step 6: Compare the storm wave runup elevation to the property or building's elevation as determined from a topographic map or site survey. If the property has shore protection, also compare the storm wave runup elevation to the elevation of the crest of the shore protection structure.

Step 1:	Highest still water level	______	feet above IGLD chart datum
Step 2:	Typical storm surge	+______	feet
Step 3:	Minimum wave runup	+______	feet
Step 4:	Equivalent NGVD elevation	+______	feet above NGVD
Total:	Storm wave runup elevation	=______	feet above NGVD
Step 5:	Elevation of property and/or crest of shore protection	-______	feet above NGVD (or MSL)
Difference:		=______	feet

If the storm wave runup elevation is nearly equal to or greater than the property's elevation (a positive number), the property is likely to be flooded. A negative difference of a foot or more indicates the property is likely to be safe from flooding unless the lake rises to a new record high levels or the property is subject to extreme storm surges or wave runup that is significantly greater than the minimum value used.

Site:______________________________	Date:______________________
Evaluation by:______________________	Time:______________________

Table 1. Record Great Lakes Water Levels 1918-1996 (Relative to IGLD 1985)

Lake	Record High Levels, Monthly Mean (above Chart Datum)			Record Low Levels, Monthly Mean (below Chart Datum)		
	Feet	Meters	Year	Feet	Meters	Year
Superior	+2.3	+0.7	1985	–1.6	–0.5	1926
Huron	+4.9	+1.5	1986	–1.4	–0.4	1964
Michigan	+4.9	+1.5	1986	–1.4	–0.4	1964
St. Clair	+5.0	+1.6	1986	–1.8	–0.5	1936
Erie	+5.1	+1.5	1986	–1.0	–0.3	1936
Ontario	+5.3	+1.6	1952	–1.4	–0.5	1934

Source: U.S. Army Corps of Engineers 1998.

Table 2. Approximate Land Elevation Equivalents for Great Lakes Chart Datums

Lake	Chart Datum[1] Feet[2]	Chart Datum[1] Meters[2]	Equivalent Land Elevation NGVD 1929[3] Feet	Equivalent Land Elevation NAVD 1988[4] Feet	Equivalent Land Elevation CGD[5] Meters
Superior	601.1	183.2	601.0	601.0	182.9
Michigan	577.5	176.0	578.1	577.6	N/A
Huron	577.5	176.0	578.1	577.6	176.0
St. Clair	572.3	174.4	573.1	572.5	174.4
Erie	569.2	173.5	570.1	569.4	173.5
Ontario	243.3	74.2	244.0	243.4	74.2

1). IGLD 1985. Sources: 2) Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1992, 3) U.S. National Ocean Service 1987, 4) National Geologic Survey 1998, and 5) Canadian Geodetic Datum (CGD or GSC) Canadian Hydrographic Service 1987.

Table 3. Minimum Wave Runup Values for Open Coasts of the Great Lakes

Minimum Wave Runup Values in Feet above a Storm Surge Elevation	
Beaches	2.0 feet (0.6 meters)
Riprap Revetments	2.0 foot (0.6 meters)
Vertical Seawalls*	3.0 feet (0.9 meters)

*Runup on seawalls is treated differently than runup on beaches or revetments. The values given in the table are for the seawall crest elevation above the storm water elevation.

Table 4. Maximum Wave Runup and Freeboard for a Set of Great Lakes Conditions[1]

Site Conditions	Beach Runup[2, 5]	Riprap Runup[2, 3]	Seawall Freeboard[2, 4]
Beach slope: 1:10	4–8 (1.2–2.4)		
Beach slope: 1:20	2–5 (0.6–1.5)		
Max. water depth at base of riprap: 1–2 ft. (0.3–0.6 m)		2–4 (0.6–1.2)	
Max. water depth at base of riprap: 2–4 ft. (0.6–1.2 m)		3–8 (0.9–2.4)	
Max. water depth at base of riprap: 4–5 ft. (1.2–1.5 m)		6–10 (1.8–3.0)	
Max. water depth at base of seawall: 1–2 ft. (0.3–0.6 m)			2–4 (0.6–1.2)
Max. water depth at base of seawall: 2–4 ft. (0.6–1.2 m)			4–6 (1.2–1.8)
Max. water depth at base of seawall: 4–5 ft. (1.2–1.5 m)			6–8 (1.8–2.4)

1. "10-year" storm wave conditions, Wisconsin coasts, Lakes Michigan and Superior. Wave periods of 7-10 seconds, deepwater wave heights of 12–18 feet (3.7–5.5 meters).
2. Measurements are given in feet (meters).
3. Riprap slopes of 1:2 (vertical:horizontal distance).
4. Acceptable overtopping rates: 4.5 gallons/minute/shoreline foot. Nearshore slope: 1:30.
5. Minimum runup values for nearshore lakebed slopes of 1:50 inshore of 10-foot (3-meter) water depths. Maximum runup values for nearshore lakebed slopes of 1:10 inshore of 5-foot (1.5-meter) water depths.

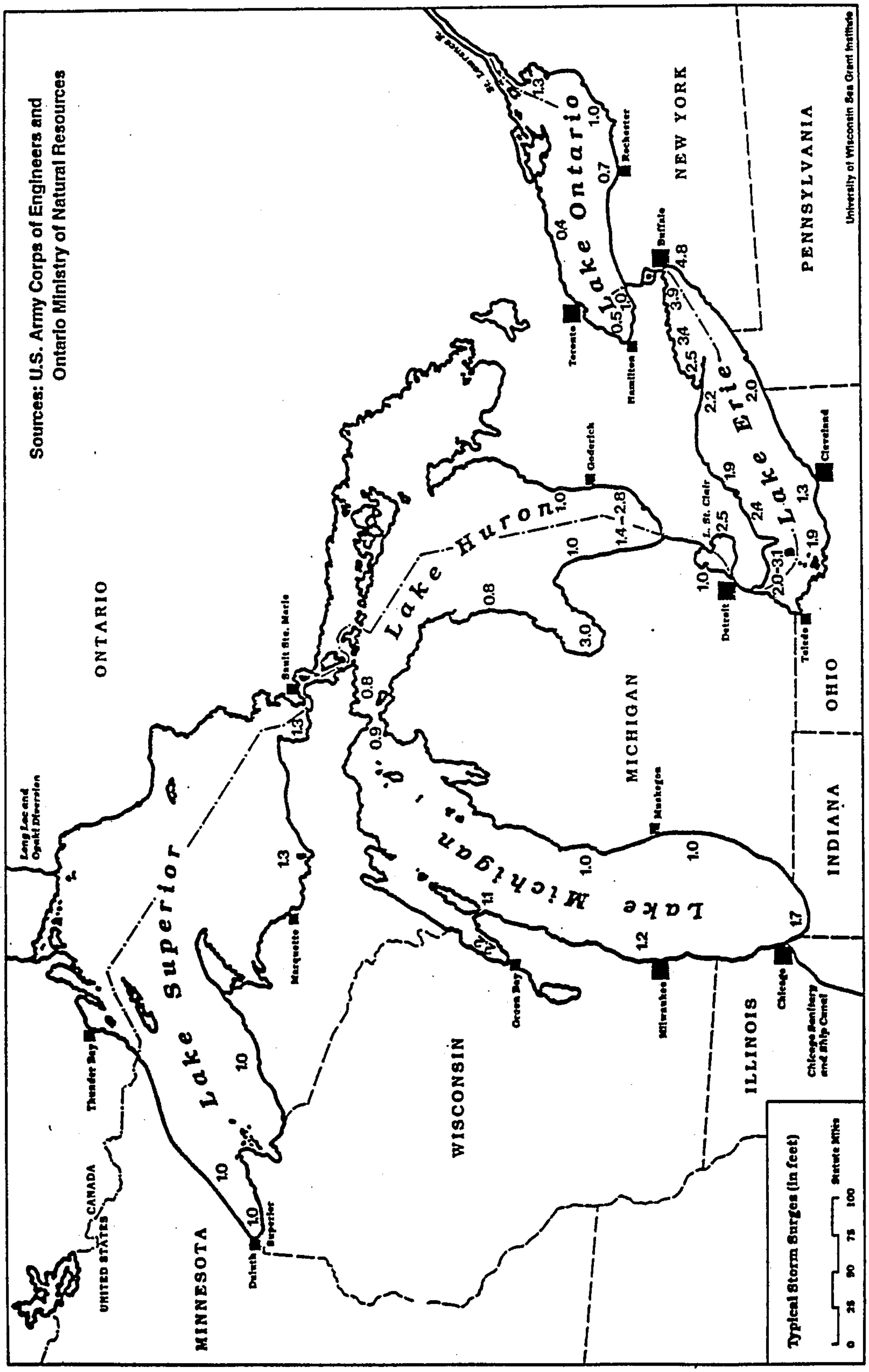

Figure 5. (Repeated from page 15) Generalized storm surges in the Great Lakes (Sources: U.S. Army Corps of Engineers and Ontario Ministry of Natural Resources)

Worksheet for Estimating Construction Setback Distance for Property without Shore Protection

Step 1: Select a recession rate for the property from local or regional planning agencies. Well-documented recession on similar property nearby is another good source to use. If long-term recession rate data are unavailable, an engineering analysis is necessary for this estimate.

Step 2: Determine the number of years of protection needed to cover the life of the mortgage and/or the useful life of the house. In some areas, a minimum number of years or a minimum setback distance is mandated by ordinance: Check with the city or county planning and zoning administrator.

Step 3: Determine the recession setback by multiplying the recession rate (Step 1) by the required number of years of protection (Step 2).

Step 4: Determine the construction setback by adding a minimum facility setback to the recession setback (Step 3) to preserve the option of relocating the house. (See figure 10 on the next page.) Check with a house mover for the minimum distance needed to safely bring in house moving equipment. In many locations, a minimum facility setback distance of 25 feet is adequate.

Step 1:	Recession rate	______	feet per year
Step 2:	Time period	×______	years
Step 3:	Recession setback	=______	feet from bluff edge
Step 4:	Minimum facility setback setback	+______	feet
Step 5:	Construction setback	=______	feet from bluff edge

If the selected recession rate is an accurate indicator of future recession, the construction setback distance will provide adequate protection of the property for the desired period of time. If possible, also calculate the construction setback using other documented recession rates for the area. To be safe, always use the largest calculated construction setback distance.

Site:______________________ Date:______________________

Evaluation by:______________________

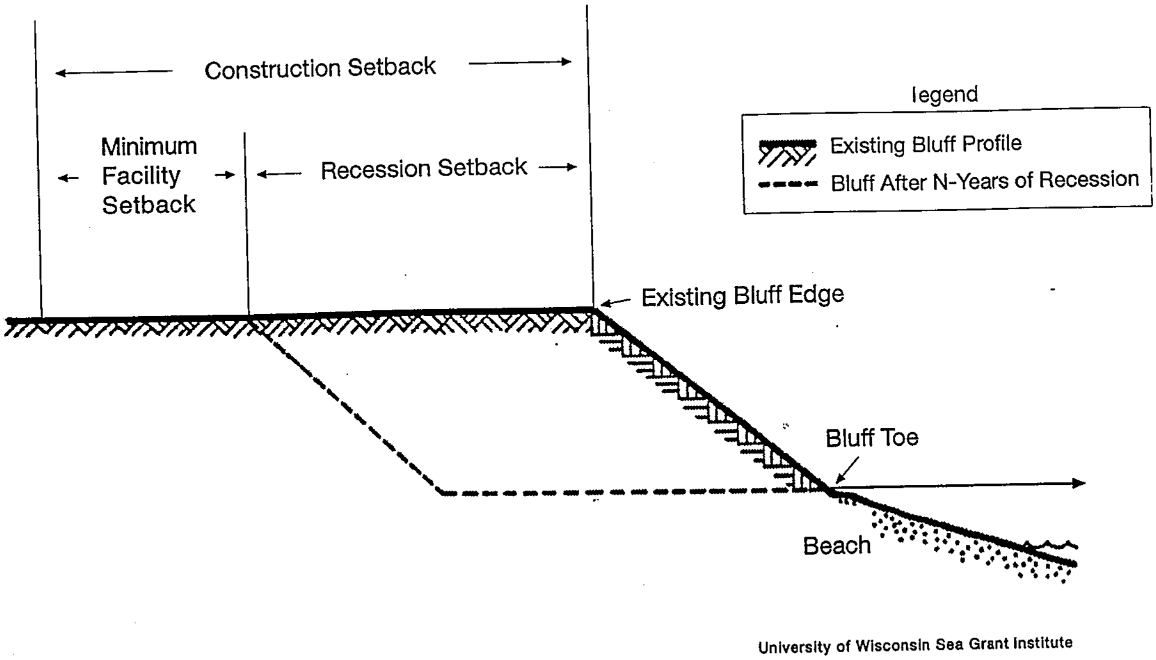

Figure 10. (Repeated from page 41) Construction setback distance for property without shore protection.

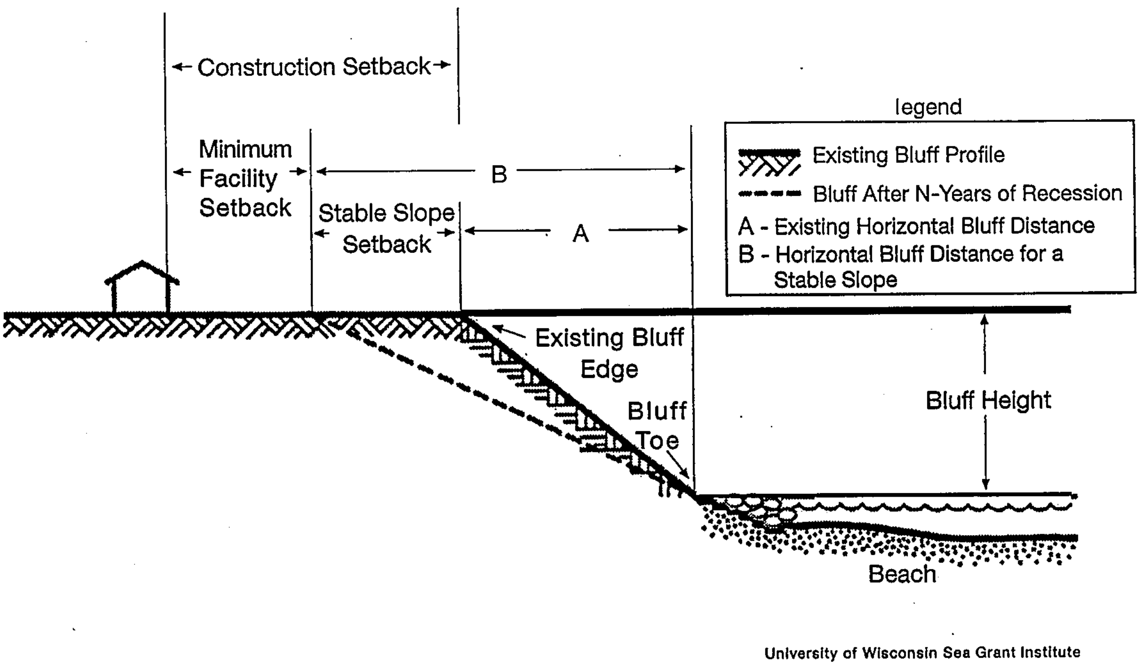

Figure 11. (Repeated from page 42) Construction setback distance for property with shore protection.

Site:______________________________ Date:____________________

Evaluation by:______________________________

Worksheet for Estimating Construction Setback Distance for Property with Shore Protection

Step 1: First, evaluate the effectiveness of the shore protection structure. One way to do this is to compare it to the designs shown in the Corps of Engineers *Help Yourself* brochure or the Ontario Ministry of Natural Resources *How to Protect Your Shore Property* booklet. If you are uncertain of its effectiveness, assume it is inadequate or have the structure professionally evaluated by an engineer.

If the shore protection structure has not been well maintained or it shows any of the signs of failure depicted in the *Help Yourself* brochure, assume the structure will soon fail. In either case, since the property essentially has no shore protection, its construction setback should be calculated as if it were a property without shore protection.

Step 2: Measure or estimate the height of the property's lakeside bluff or bank and also the horizontal distance ("A" in figure 11, opposite) between the top edge of the bluff or bank and its toe. Note the relative (fractional) height of any evidence of groundwater in the bluff.

Step 3: Select the appropriate stable slope ratio for Wisconsin coasts from Table 8 on page 113 (outside Wisconsin, consult the state or provincial department of natural resources or the local planning agency). Calculate the stable slope distance inland from the toe of the bluff ("B" in figure 11) by multiplying the stable slope ratio by the height of the coastal bluff or bank as measured in Step 2.

Step 4: Estimate the stable slope setback from the top edge of the bluff by subtracting the horizontal bluff distance ("A") from the stable slope distance ("B") calculated in Step 3.

Step 5: Estimate the construction setback by adding the stable slope setback calculated in Step 4 and a minimum facility setback (25 feet is usually adequate) for the option of moving the house later.

Step 2:	Height of bluff	________	feet
Step 3:	Stable slope ratio	×_______	feet/foot
Product:	Stable slope distance (B)	=_______	feet from toe of bluff
Step 4:	Horizontal distance (A)	-_______	feet from toe to top edge
Difference:	Stable slope setback	=_______	feet from bluff top edge
Step 5:	Minimum facility setback	+_______	feet
Sum:	Construction setback	=_______	feet from bluff top edge

Given the uncertainties involved in making this estimate, always consider the construction setback to be the minimum distance a building should be located from the top edge of a coastal bluff or bank.

Site:______________________________ Date:____________________

Evaluation by:______________________________

Site:____________________________ Date:__________________

Evaluation by:________________________

Table 8. Ultimate Stable Slope Ratios for Wisconsin Great Lakes Coastal Bluffs with Stabilized Bases

Location on Wisconsin Great Lakes Coastlines	Max. Height of Groundwater in Bluff (measured from base) H = bluff height	Stable Slope Ratio[1] Horizontal Feet: Vertical Foot efa[2] = 30°	Range[3]
Lake Michigan	base of bluff	1.7:1	2.1:1 to 1.4:1
	1/4H	1.8:1	2.5:1 to 1.5:1
	1/2H	3.0:1	3.4:1 to 2.2:1
	3/4H	3.5:1	4.3:1 to 2.6:1
	H	3.5:1	5.4:1 to 2.9:1
Lake Superior			min. ratio
Douglas County	1/2H	3.4:1	3.4:1 to 2.2:1
W. Bayfield County	1/2H	3.6:1	3.6:1 to 1.8:1
E. Bayfield County	base of bluff	2.2:1	2.2:1 to 1.3:1
Madeline Island	base of bluff	2.6:1	2.6:1 to 1.5:1
Ashland/Iron counties	1/2H	3.7:1	3.7:1 to 2.0:1
Ontario, Canada bluffs (Terraprobe, 1994)	unstated conditions	2.75:1	
	unknown soil conditions	3:1 or flatter[4]	
	heavy groundwater seepage	4:1 to 5:1	

Sources: Vallejo and Edil 1979, Edil and Vallejo 1980, Schultz et al. 1984, and Terraprobe, 1994.

1. The stable slope ratios are derived from ultimate stable slope angles below which rapid soil movements on slopes are not expected to occur, but slow creep may occur. The angles were developed for weathered natural slopes having a bulk unit weight of 21 kN/cu.m. The stable slope ratios were derived for safety factors of 1.0 and are therefore *not conservatively safe.*
2. The slope ratios for an effective angle of internal friction (efa) of 30°.
3. The range of slope ratios for the Lake Michigan coast represents efas of 25° (lower limit) and 35° (higher and steeper limit). The ranges of slope ratios for the Lake Superior coast are for measured ranges of efas in the respective locations between 19° and 40°.
4. The Terraprobe report passes along the recommendation of many Regional Conservation Authorities for slopes where there is little or no information on subsurface conditions. No citation is given.

Caution about Table 8: Use of the stable slope ratios is no guarantee of future bluff stability at any particular coastal site. Table 8 illustrates stable slope ratios for bluffs with particular uniform cohesive soil properties. Bluff soils are typically nonuniform.

The stable slope ratios are appropriate for cohesive bluffs 60 feet (18 meters) or more in height but were not developed for lower bluffs and banks. These values were intended to be used with natural slopes having the same properties as measured in Wisconsin coastal bluffs. The stable slope ratios were derived for safety factors of 1.0 and are therefore not conservatively safe.

At some coastal bluff sites, slow creep and shallow slides may take place at the stable slope ratios given in Table 8. External alterations to a bluff can invalidate the ratios given in the table: alterations such as adding a building to the top of the bluff or wave erosion of the base of a previously-stable bluff. Conservatism can be practiced by choosing greater stable slope ratios and by adding additional setback distances in working with the stable slope ratios. Such choices are best made by trained professional geologists or engineers.

Engineering Notes

Engineering Notes

#6 Great Lakes Vertical Datums—Draft 5/20/98

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Why Datums Are Important

Property owners, contractors, and engineers try to account for highest and lowest water levels when siting coastal buildings and other structures on the Great Lakes. They build shore protection structures, intending no significant overtopping from high water levels and waves. Unfortunately, they sometimes fail because of inadequate or inaccurate information about site and water elevations.

A common problem with contractors' sketches and engineers' or architects' drawings of coastal sites and shore protection structures is the lack of dimensioned land and water elevations relative to some stated and dated reference elevation. These omissions make it difficult to determine whether or not landside elevations of buildings, docks, roads, or shore protection structures are adequate for anticipated water levels. Another problem occurs when the calculation of a landside elevation in reference to a water elevation is done incorrectly. Both types of error can lead to unanticipated flooding and property damage.

Ignoring vertical datums can lead to errors of nearly two feet (nearly a meter). Land and water elevations need to be determined for coastal development purposes and stated in terms of a dated reference elevation, or *vertical datum.*

People who maintain or use marinas and harbors in the Great Lakes and connecting waterways also need information on water elevations and water depths in harbors and waterways for safe navigation of commercial, recreational, and other vessels. Water depths on navigation charts are shown in feet or meters below a reference elevation, called a *chart datum* (or *low water datum,* LWD), which is a vertical datum.

What Is a Vertical Datum?

A *vertical datum* (or *plane of reference* or *datum plane*) is:

> A... base elevation used as a reference from which to reckon heights or depths. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks... Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1995

A vertical datum is referenced to a certain bench mark (a *controlling bench mark)* at a particular location on land. The bench mark (*BM*) has a known, published elevation. The datum is used as a reference elevation from which land elevations or water depths are measured at other locations.

The Benefits of Using These Notes

These notes are intended to explain Great Lakes vertical datums and provide information about the current and recently used regional, national, and continental datums used in the Great Lakes Basin. The notes will help you make correct conversions between vertical land and water datums and provide information on where to get elevations on coastal land sites.

Disclaimer: These notes are not intended as a design guide to provide a standard for professional practice. Elevations given in these notes should be checked against elevation data from primary sources. Some of the sources of information needed for such surveys are listed at the end of these notes. The notes and data in the notes have been checked. However, errors may have been overlooked. If errors are detected, please bring them promptly to the attention of the author. The information provided in these notes is not an adequate substitute for an on-site survey by a trained professional surveyor, geologist, or engineer.

Some Uses of Datums

The land-based elevations of coastal sites can be compared with extreme storm water elevations on the Great Lakes and St. Lawrence River to describe the vulnerability of particular coastal property to flood damage. Wisconsin Sea Grant Advisory Service's new *Coastal Processes Manual* shows how to make such evaluations with step-by-step examples.

The best method for establishing the elevation of a coastal site is to hire a surveyor to do a leveling survey from the nearest bench mark with a documented elevation. The surveyor will typically run a loop of survey positions from the bench mark to the coastal site and back to the bench mark to determine and document the elevation and the survey error.

A quicker (but only approximate) method is possible if the site can be located with confidence on a topographic map with detailed elevation contours. For example, the U.S. shores have been mapped by the U.S. Geological Survey with contour lines measured in feet above MSL 1929 or NGVD 1929 (older maps) or NAVD 1988 (for newer maps). Canadian shores have been mapped using the Canadian Geodetic Datum. (MSL stands for mean sea level, NGVD stands for National Geodetic Vertical Datum, IGLD refers to International Great Lakes Datum, and NAVD means North American Vertical Datum.)

If the site is on one or more contours, the approximate elevation of the site can be estimated. With either method, the difference between the bench mark or map datum and IGLD 1985 datum needs to be determined in order to compare site elevations to the relevant water elevations.

Tables 1 and 2 show *approximate* lake elevations at master water level gauge sites on the Great Lakes referenced to different datums. Water levels at the master gauge sites are used to define *lake levels* and are referred to in lake level forecasts and in historic lake level records.

Table 1. Approximate Land Elevation Equivalents for Great Lakes Chart Datums in Feet

Lake	Chart Datum (Feet)		Equivalent Land Elevation (Feet)	
(Master Gauge Location)	IGLD1955 (1)	IGLD1985 (1)	NGVD 1929 (2)	NAVD 1988 (3)
Superior (Marquette)	600.0	601.1	601.0	601.0
Michigan (Harbor Beach)	576.8	577.5	578.1	577.6
Huron (Harbor Beach)	576.8	577.5	578.1	577.6
St. Clair (St. Clair Shores)	571.7	572.3	573.1	572.5
Erie (Fairport)	568.6	569.2	570.2	569.4
Ontario (Oswego)	242.8	243.3	244.0	243.4

SOURCES:
1. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1992)
2. U.S. National Ocean Service, NOAA
3. NOAA National Geodetic Survey

Table 2. Approximate Land Elevation Equivalents for Great Lakes Chart Datums in Meters

Lake	Chart Datum (Meters)		Equivalent Land Elevation (Meters)		
(Master Gauge Site)	IGLD1955 (1)	IGLD1985 (1)	NGVD 1929 (2)	NAVD 1988 (4)	Canadian Geodetic Datum-(3)
Superior (Marquette)	182.9	183.2	183.2	183.2	182.9
Michigan (Harbor Beach)	175.8	176.0	176.2	176.0	N/A
Huron (Harbor Beach)	175.8	176.0	176.2	176.0	176.0
St. Clair (St. Clair Shores)	174.2	174.4	174.6	174.4	174.4
Erie (Fairport)	173.3	173.5	173.8	173.6	173.5
Ontario (Oswego)	74.0	74.2	74.4	74.2	74.2

SOURCES:
1. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1992)
2. U.S. National Ocean Service, NOAA
3. Canadian Hydrographic Service.

> The exact elevations listed in Tables 1 and 2 are accurate only for the year of the datum and at the master gauge sites on each lake. If the elevations are used at any other locations or times, they will be approximations. This is why the elevations are given only to the nearest tenth of a foot or meter and are not adequate for survey purposes.

The Land We Live on Is Moving: Vertical Datums Don't Last Forever

Few people are aware that the land they build on in the Great Lakes Basin is not stationary but slowly rising, still recovering from the great weight of the glaciers that departed about 20,000 years ago. This rising of the land is called *isostatic rebound*. Some parts of the basin are rising faster than other parts. Thunder Bay, Ontario, is rising nearly 1.5 feet (0.46 meters) per century, relative to Toledo, Ohio (Coordinating Committee 1995). The eastern end of Lake Superior and the northern ends of Lakes Huron and Michigan are rising faster than the opposite ends of these lakes. The outlets of Lakes Superior and Michigan are rising faster relative to the rest of these two lake basins, making water levels rise at the western and southern ends of Superior and Michigan, respectively. Locally, some coastal land may undergo lowering (*subsidence*) as groundwater is withdrawn if the groundwater table is lowered substantially.

Along every lake and river in the Great Lakes Basin, information on land elevations is current and accurate only in the relatively brief period of time that the latest datum represents. Over decades following the establishment of the latest datum, the elevations of coastal sites change in relation to the elevations of other sites because of the differential, local movement of the earth's crust, or because of instability of the sites (such as local subsidence). Across the Great Lakes Basin, land elevations change with respect to reference sea levels because the land is rising across the basin with isostatic rebound or because sea level is changing. Vertical datums are changed when

- the vertical elevation differences between sites change enough to cause serious surveying inaccuracies
- there is deterioration of the reference gauge and site upon which the datum is based
- new and improved surveying methods with better surveying accuracies become available
- there is a desire to integrate different datum systems

The first two reasons in this list were the primary reasons for replacing the IGLD 1955 (IGLD55) datum with the IGLD 1985 (IGLD85) datum. The second two reason were secondary.

International Great Lakes Datum of 1985

The IGLD 1985 Datum is based on water levels that existed in 1985, the central year in the period 1982-1988 during which water level information was collected for the datum revision. The new datum was officially implemented January 1992. A primary vertical control network consisting of 78 leveling loops containing 1,119 bench marks was set up in Canada and the United States. Independent leveling data across this network indicated a difference in adjusted heights of about seven centimeters (2 ¾ inches) from Pointe-au-Pere (the site of the IGLD 1955 Datum's controlling bench mark on the Gulf of St. Lawrence) to the west end of Lake Superior. This error of seven centimeters occurred over a direct water route distance of approximately 1,695 miles or 2,729 kilometers (Coordinating Committee 1992).

North American Vertical Datum of 1988

Coincident with the development of IGLD 1985 was the development of a new *North American Vertical Datum, 1988* (NAVD 1988). NAVD 1988 is a new vertical datum for Canada, Mexico, and the United States. In the United States, NAVD 1988 replaces the old *National Geodetic Vertical Datum 1929* referred to as NGVD 1929 and also known as *Sea Level Datum of 1929*, *USGS Datum, C&GS Datum*, and MSL 1929.

Local City Datums

In addition to the regional and continental datums, numerous local city datums are in use. Information on converting elevations from the datums mentioned above to local city datums should be available from city engineering or planning offices.

A Comparison of Datums

Tables 1 and 2 provide a comparison of the elevations used for defining Great Lakes chart datums (also called Low Water Datum, or LWD). The tables show that elevations can be off by as much as 1.5 feet or more than half a meter if attention is not paid to which datum is used in giving a land or water elevation. A typical use of these tables is comparing an old design water elevation with a forecast high or low water level (referenced to the new IGLD 1985 datum).

Variations in Datum Difference by Location

From site to site around the Great Lakes, there are variations in the differences between datums. The difference in elevation values between the old IGLD 1955 datum and the new IGLD 1985 datum varies from as little as 0.27 feet (0.083 meters) at one primary bench mark on Lake Ontario to as much as 1.52 feet (0.464 meters) at one primary bench mark on Lake Superior (Coordinating Committee 1995).

For the general user, Tables 1 and 2 should provide an adequate basis for comparing land and water elevations. The errors in using the tables are on the order of half a foot, or a few tenths of a meter; less than the uncertainties about 100-year flood elevations, storm surges, and wave runup.

For Engineers and Surveyors Only

Tables 1 and 2 are not sufficiently adequate for survey design and construction; further investigation is warranted. The Coordinating Committee's 1995 booklet gives elevations in IGLD 1985 and the difference between IGLD 1985 and IGLD 1955 elevations for 66 primary bench marks along the shores of the Great Lakes and connecting rivers, plus 41 primary bench marks along the St. Lawrence River. The Coordinating Committee's 1992 pamphlet gives elevations in the two datums for 13 key bench marks in the Great Lakes and along the St. Lawrence River as well as elevations in feet and meters for both the Low Water Datum (or Chart Datum) and the Ordinary High Water Mark (OHWM), below which the U.S. Army Corps of Engineers and other authorities have jurisdiction.

Tables 1 and 2 use an approximation of the difference in elevation value between the old IGLD 1955 datum and the new IGLD 1985 datum at the primary bench mark where the master water level gauge for a particular lake is located (Table 3). It is the water elevations at these master gauges that are recorded and forecast in the U.S. and Canadian monthly water level bulletins.

Table 4 shows the approximate errors to be expected using the information in Tables 1 and 2 at sites other than the master gauge sites around the Great Lakes and along the connecting rivers. The "errors" are actually the variations in datum differences at other primary bench marks from the datum difference at the bench mark for each master water level gauge. The range of datum differences at the primary bench marks on a particular Great Lake or connecting river is assumed to represent the range of datum differences at all locations along the shores of that waterbody.

If the variations in Table 4 appear too large, the user will either need to obtain a copy of the Coordinating Committee's 1995 booklet, obtain information about particular bench marks from the web sites or other sources provided at the end of these notes.

Table 3. Datum Differences at Primary Bench Marks for Master Water Level Gauges in the Great Lakes (IGLD 1985 Elevation – IGLD1955 Elevation)

Lake	Master Gauge	IGLD85-IGLD55(ft)	IGLD85-IGLD55(m)
Superior	Marquette	1.132	0.345
Michigan	Harbor Beach	0.702	0.214
Huron	Harbor Beach	0.702	0.214
St. Clair	St. Clair Shores	0.627	0.191
Erie	Fairport	0.574	0.175
Ontario	Oswego	0.518	0.158

Source: differences computed from elevations in the Coordinating Committee (1995) reference.

Table 4. Variations in the Difference between IGLD 1955 and IGLD 1985 Datums at Primary Bench Marks (BM) Compared with Datum Difference at Master Gauge Bench Marks

Lake or River	Master Gauge BM	Variation (feet)	Variation (meters)
Superior	Marquette	- 0.197 to + 0.390	- 0.060 to + 0.119
St. Marys River	Ref. to Marquette	- 0.233 to – 0.240	- 0.071 to – 0.073
St. Marys River	Ref. to Harbor Beach	+ 0.190 to + 0.197	+ 0.058 to + 0.060
Lake Huron	Harbor Beach	- 0.062 to + 0.413	- 0.019 to +0.126
St. Clair River	Ref. to Harbor Beach	- 0.059 to - 0.119	- 0.018 to – 0.038
St. Clair River	Ref. to St. Clair Shores	- 0.016 to – 0.049	- 0.005 to – 0.015
Lake St. Clair	St. Clair Shores	+ 0.079	+ 0.024
Detroit River	Ref. to St. Clair Shores	- 0.026 to + 0.0.049	- 0.008 to + 0.015
Detroit River	Ref. to Fairport	+ 0.026 to + 0.102	+ 0.008 to + 0.031
Lake Erie	Fairport	+ 0.003 to + 0.148	+ 0.001 to + 0.045
Niagara River	Ref. to Fairport	- 0.043 to – 0.056	- 0.013 to – 0.017
Niagara River	Ref. to Oswego	0.000 to + 0.013	0.000 to + 0.004
Lake Ontario	Oswego	- 0.2 46 to + 0.059	- 0.075 to + 0.018
Lake Michigan	Harbor Beach	- 0.210 to – 0.007	-0.064 to – 0.002

Source: Variations computed from primary gauge datum differences given in the Coordinating Committee (1995) reference.

There are also some differences between the new IGLD 1985 and the new NAVD 1988 datums. The elevations of primary bench marks for master gauge stations on each of the Great Lakes and Lake St. Clair are given in Table 5 along with the differences between the two datums. For the user working with elevations to the nearest tenth of a meter, the two datums can be assumed to be equal. For the user working with elevations to the nearest tenth of a foot, the datum differences on the shores of Lake Erie and Lake St. Clair are sufficient to warrant looking up the elevations of the nearest bench mark on the National Geodetic Survey web site identified at the end of these Notes.

The IGLD 1985 datum is a *water datum* based on dynamic heights (dynamic head) of water. The NAVD 1988 datum is a *land datum* based on orthometric heights on land. A particular bench mark will have a NAVD 88 orthometric elevation and a different dynamic height. The Coordinating Committee's 1995 booklet provides an explanation with examples of how to make conversions between these datums. The committee's booklet also contains hydraulic correction factors for each of the primary bench marks to adjust lake levels published for master water level gauge locations to lake levels at the other primary bench mark sites. The largest of these published hydraulic correction factors is 0.374 feet (0.114 meters). At the time a new vertical datum is established, the mean water level (MWL) values at all of the water level gauging stations should be the same. During the IGLD85/NAVD88 surveys, the MWL values were slightly different because of cumulative differences in leveling adjustments (Coordinating Committee 1995). Hydraulic correction factors were determined to give each gauge the same MWL value as the master gauge for each lake. Many of the benchmarks on the NGS web site do not have elevations in terms of the old NGVD (or MSL) 1929 datum because the datum was not used in surveys at these sites.

Table 5. Elevations of Primary Bench Marks at Master Water Level Gauge Locations on the Great Lakes Referenced to the NAVD 1988 and IGLD 1985 Datums

Lake	Master Gauge BM location and BM name	BM Elevation NAVD 1988 (meters)	BM Elevation IGLD 1985 (meters)	NAVD88-IGLD85 (meters)	NAVD88-IGLD85 (feet)
Superior	Marquette: U329	189.916	189.933	- 0.017	- 0.057
Michigan	Harbor Beach: E237	179.762	179.732	+ 0.030	+ 0.098
Huron	Harbor Beach: E237	179.762	179.732	+ 0.030	+ 0.098
St. Clair	St. Clair Shores: FOOD	177.020	176.970	+ 0.050	+0.164
Erie	Fairport: 321	175.981	175.918	+ 0.063	+0.207
Ontario	Oswego: LAKE	77.503	77.487	+ 0.016	+ 0.052

Source: National Geodetic Survey Web site.

For Information about United States Bench Marks on Great Lakes Shores

Go to the NOAA National Ocean Service (NOAA-NOS) Web site:

http://mapindex.nos.noaa.gov/default.htm

Click on *Product Descriptions*. Choose *Geodetic Control Points* and select the *NOS-National Geodetic Service* Web site. Click on *Data Sheets*. The instructions show the different ways in which the data sheets with their benchmark elevations can be accessed in a search process. Benchmark elevations are given in meters above the North American Vertical Datum 1988 (NAVD 88). Primary coastal benchmarks also have *dynamic height* elevations in meters above International Great Lakes Datum.

Or, contact: National Ocean Service, Office of Ocean and Earth Sciences, Measurement Branch, Great Lakes Section. SSMC4, N/OES211, Sta. 7523, 1305 East-West Highway, Silver Spring, Maryland 20910.

For Information about Canadian Bench Marks on Great Lakes Shores

Contact: Canadian Hydrographic Service's Web site—http://chswww.bur.dfo.ca/danp/appendixa.html
Or, contact: Regional Tidal Officer, Canadian Hydrographic Service, Fisheries and Oceans Canada, Canada Centre for Inland Waters. 867 Lakeshore Road, Burlington, Ontario L7R 4A6

For ordering information about primary vertical control (bench marks) contact: Canadian Geodetic Survey, Natural Resources Canada, 615 Booth Street, Ottawa, Ontario K1A OE9

To Obtain More Information about IGLD 1985

Contact: U.S. Army Corps of Engineers' Web site—
http://sparky.nce.usace.army.mil/IGLD.1985/igldhmpg.html
Or, contact: U. S. Army Corps of Engineers Detroit District, P.O. Box 1027, Detroit, Michigan 48231-1027

Contact: Canadian Hydrographic Service's Web site—
http://chswww.bur.dfo.ca/danp/igld1985.html (Contains the Coordinating Committee 1995 report information on primary bench mark elevations on both Canadian and U.S. shores.)
Or, contact: Great Lakes Water Level Communications Centre, Environment Canada, Canada Centre for Inland Waters, 867 Lakeshore Road, Burlington, Ontario L7R 4A6

References

Coordinating Committee. 1992. IGLD 1985, Brochure on the International Great Lakes Datum 1985. Coordinating Committee on Great Lakes Basin Hydraulic and Hydrologic Data. January 1992.

Coordinating Committee. 1995. Establishment of International Great Lakes Datum (1985). The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. December 1995. 17 pages plus appendices.

These materials can be obtained at the same addresses as given for IGLD 1985 information.

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See the coastal hazards information on this Web site:

http://www.seagrant.wisc.edu

Click on *Outreach*, then *Coastal Engineering*, and then *Coastal Hazards*.