INFLUENCE OF WATER LEVEL, WAVE CLIMATE AND WEATHER ON COASTAL RECESSION ALONG A GREAT LAKES SHORELINE

By

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ABSTRACT

The purpose of this study is to investigate the influence that lake level, wind-generated waves, precipitation and extreme storm events have on the rate of erosion of glacially-formed bluffs at two Lake Michigan shoreline sites in Wisconsin. Recession rates are determined from digital orthophotos constructed using historical aerial photographs taken at least once every decade from the 1940s to present.

The temporal variation in recession rates over intervals ranging between 6 and 17 years were determined for the toe and crest of the site with high (30–45 m) bluffs and for the crest but not the toe at the site with low (9–11 m) bluffs. Both the toe of the high bluffs and the crest of the low bluffs show temporal recession-rate patterns that closely match the changes in the average lake-water level. The crest of the high bluffs recedes at a rate that is relatively insensitive to lake level changes.

The annual average of the peak monthly wave-impact heights that the waves reach shows a dramatic rise during 1964-75, a period during which the maximum toe recession rate is measured for the high-bluff site. A similar sharp rise in wave-impact height occurs near the beginning of the 1967-75 period, during which the maximum crest-recession rate is measured for the low-bluff site.

Once the limitations of the wind-wave-hindcasted data are accounted for, the epoch-averaged deepwater wave power shows very little perceptible change over each erosion interval for the high-bluff site. The annual mean deepwater wave power

reaches elevated levels between 1970 and 1980. This interval coincides with a period of elevated toe-recession rate at the high-bluff site and a period of elevated crest-recession rate at the low-bluff site. The epoch-averaged deepwater wave power reaches a local maximum during a period where elevated recession rates are measured at both the toe of the high bluffs and the crest of the low bluffs.

The variation in the average number of storm occurrences per year over each erosion epoch does not follow the trends of recession rate magnitude observed at the crest or toe of either of the study sites.

The average annual precipitation considered over each erosion epoch shows a weak correlation to the recession rate at the crest of the slopes at both sites.

The recession measurements represent spatial averages of rates measured at increments of 10-20 m along the shoreline over a distance of about 500–700 m. Five spatial averages are reported for each site. A bathymetric profile at the middle point of each of the five spatially averaged areas is known to 6 m depth.

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INTRODUCTION

The population in Wisconsin's Lake Michigan coastal counties is increasing at a rate about double that of the statewide growth rate (GLIN). This trend suggests a current and future pressure to develop lands adjacent to the Lake Michigan shoreline. Unfortunately, this shoreline is receding, creating major land use-conflicts and a need to incorporate a better understanding of bluff recession into land-use decision-making.

Erosion of the bluffs on the Great Lakes affects people today on a multitude of levels. Homeowners whose house and property are on the shores of these lakes stand to lose some of their land and, even worse, their houses. Visitors to the shores of the lakes may be threatened by a flow of sediment rapidly sliding down the slope. Bluff erosion is also a key part of a larger process known as littoral transport. This process refers to the transport of sand, gravel and some limited amounts of silt by currents and waves on or near the shoreline. Littoral transport includes the transport of the material along the shoreline, onto the shore, or into the lake. Nearly all of the sand and gravel in the transport system is derived from the bluffs. A given stretch of shoreline has either a balanced sand sediment supply, has a deficit in its sand supply budget, or has a surplus. Sand supply influences erosion by supplying the material that builds and maintains beaches and offshore bars. These features serve to dissipate wave energy and their absence usually results in increased erosion (ACEf).

In Wisconsin, local regulatory agencies hold the responsibility of establishing recommended setbacks of buildings from the bluff crest, although there are model ordinances from the state. In most cases these ordinances require knowledge of the historical bluff recession rate and prediction of future recession rates. This thesis contributes one component of a study that aims to develop a model that will predict shoreline recession in the future. Ultimately, I hope this research will contribute to land use decision making along the shore of Lake Michigan as well as the other Great Lakes.

Due to their erodible nature and their close proximity to Lake Michigan, the oversteepened, glacially-formed bluffs have been retreating since the lake's formation some 10,000 years ago and will likely continue to do so for some time to come. Shore protection structures may serve to temporarily slow the retreat rate, but may not affect the long-term pace of shoreline recession. The Lake Michigan shoreline in Wisconsin extends from the Illinois border to the tip of Door County. Along this stretch of shoreline, the bluffs vary in height from 10 to 45 m (30 to 140 ft) and vary in composition from unconsolidated deposits of gravel, sand, silt and clay to bedrock. While the bluffs retreat at indiscernible rates where bedrock rims the shore, significant erosion rates are measured where the bluffs are composed of till or sandy outwash deposits.

Waves are a primary erosion force along Great Lakes coasts. Wave forces are greatest during storms. Many of the dramatic episodes of bluff erosion have been observed during storms (Powers 1958). During periods of elevated lake level, the wave attack extends higher along the shoreline profile and bluff recession accelerates. During periods of lower than average water levels, wave attack is less noticeable, but is occurring offshore in the form of lakebed downcutting. Figure 0.1 illustrates a number of natural agents of bluff erosion.

This study investigates the link between lake level, wave effects, precipitation and the rate of shore recession over a 2-mile stretch of high bluffs in Ozaukee County, Wisconsin and a 4-mile stretch of low bluffs in Manitowoc County, Wisconsin.

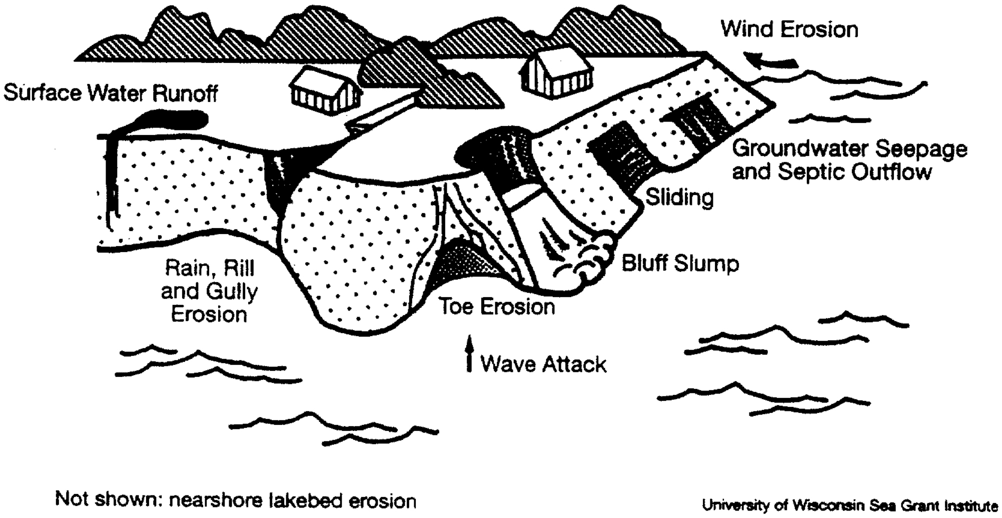


Figure 0.1 Coastal Erosion – Causes and Effects (Keillor 1998).

1 STATEMENT OF THE PROBLEM

1.1 Significance of the Study

Shoreline erosion is an ongoing process along most unprotected parts of the coast, whether it is noticeable or not. High lake level in combination with high waves results in greater erosive forces reaching to and above the toe of the Lake Michigan till bluffs. High waves approaching the shore during periods of low lake level erode the lakebed offshore and prepare the conditions for the bluffs to be exposed to higher waves when the level eventually rises. While these statements are generally well-accepted, there is currently a lack of quantitative verification of the relationship between lake level coupled with nearshore geometry and wave effects, and the erosion observed at the bluffs. While the erosive effects of storm events and heavy precipitation are widely reported in the literature, there is currently an insufficient *quantitative* database to substantiate this claim.

One of this study's unique aspects is its focus on the temporal changes that have occurred to two shoreline reaches of relatively limited extent. Recession rates have been determined for 5-6 time intervals. A number of studies that compared the influence of wave action, lake levels and climate on erosion rates have, with few exceptions, been carried out over long shoreline distances but few temporal erosion intervals (Kamphuis 1987, Wilcock *et al.* 1998, Jibson and Odum 1994, Sunamura 1969). Sites with long shoreline distances are often more variable in geology and geometry than are short reaches. Gelinas and Quigley (1973) reported that the local geology along the shoreline is ultimately responsible for the magnitude of erosion rates. Gelinas and Quigley (1973) considered the wave energy distribution at the wave-breaking points for six locations along a shoreline on the north side of Lake Erie. The rate of erosion increased in direct correlation with wave energy up to 2 m/yr across the eroding clayey till along the shore. Wind direction, fetch distance and shoreline orientation were considered for the calculation of wave energy to which the shore was exposed. Two areas of excessive erosion (greater than 2.5 m/yr) correlated with an absence of glacial till and the presence of easily eroded sand and silt extending to lake level (Gelinas and Quigley 1973).

To carry out a study that compares historical recession rates with lake level and wave action over several time periods, a number of erosion epochs must first occur during which recession rates, lake levels and wave action have varied *and are measurable*. Except at single field sites, bluff recession is extremely difficult to measure accurately over short (less than 5-10 years) time periods. Stereo-coverage aerial photography of the Lake Michigan coastline started in the late 1930's. Since that time there have been shoreline aerial photographs taken at least every decade and more frequently in recent years. Wind and climate data are available electronically beginning in the late 1940's (MWRCC). Thus, there are potentially five to six erosion epochs that can be studied with aerial photographs. The technology to transform historical photographs into digital orthophotos has significantly improved in quality and availability over the past few years. The techniques and the available data have developed to a point where a shoreline erosion study can provide valuable, quantifiable insights into the interactions between wave action, water level, storms, precipitation and recession rate of bluffs along Lake Michigan. Moreover, our density of temporal measurements is much greater than in most previous studies and thus provides an extensive database for analysis.

1.2 Research Questions

This study addresses the following research questions:

- Do the long term average lake level, wave-impact height, and precipitation vary significantly among the epochs studied?
- Is there a clear similarity between historical lake level trends over time and 5-to-10-year averages of recession rates?
- Is there a relationship between deepwater wave power and bluff-recession rate?
- Can precipitation be tied to the recession rates observed at the bluff crest for high bluffs?
- Does the spatial variation in recession rates for the study sites form any meaningful patterns?

1.3 Limitations of the Study

As mentioned in the introduction and more fully detailed in Section 2.2, there are numerous and diverse driving mechanisms that contribute to the long-term recession rate of unconsolidated bluffs adjacent to Lake Michigan. The limited extent of the site and the fairly homogeneous stratigraphy across the site reduce the impact of highly varying geology and bluff geometry on any temporal changes in recession rates across the site. Thus, the dominant factors producing changing shoreline recession rates over time at the two study sites are expected to be the lake level, wave action, storms and precipitation events. Very few man-made coastal structures are present, few slope modifications have occurred, and only minor spatially varying natural conduits for groundwater exist across both sites. Apart from variations in the nearshore beach slope along the site, there is no other factor incorporated in this study that will change the nearshore wave parameters considered across the shoreline reaches. Unaccounted-for factors such as changes in geology, hydrogeology, vegetative cover, slope geometry and bluff engineering properties across the site may influence our measured rates of recession. However, their influence is anticipated to be relatively small and not mask the influence of the wave and climate factors considered in this study.

Elevated groundwater level contributes to a reduction of the static factor of safety of a slope and the resulting recession observed from slope failure (Edil and Vallejo, 1980). As groundwater elevation monitoring data are not available for the study site over the time period of interest, it could not be considered directly in the analysis. However, a side effect of heavy, sustained precipitation is the raising of the groundwater level. Hence, this factor is indirectly considered.

Recession rates, if measured at least every decade over hundreds of years, would provide a superior means to distinguish the short-term rates from the long term rates and their respective agents. Such data, along with coincident wave data, would provide better grounds for establishing a statistical relationship between wave climate and recession rate. However, due to the temporal extent over which we have wave and recession rate data, we are practically limited to the erosion epochs adopted for this study.

1.4 Definitions of Terms

A number of terms are defined here in the context in which they will be used in this report. The term **bluff** refers to a high, steep bank composed of unconsolidated, erodible materials such as glacial till or dune sand. **Erosion** is the volumetric loss of bluff material from the slope due to the wearing away of land by the action of natural forces. **Recession** is the retreat of the bluff toe or crest. Recession measurement provides physical evidence that erosion is occurring. **Recession rate** refers to the time rate of change in position of a slope feature (e.g. the bluff slope or crest) measured perpendicular to the shoreline. For the purposes of this study, the **shore** is a narrow strip of land in immediate contact with the water, including the zone between high and low water lines. The **nearshore** zone extends from the water's edge to the outer limit of the breaking wave zone. The intact, fine-grained glacial sediments at the lake bottom in the nearshore zone are often lined with sand and gravel derived from the bluffs nearby or from sediments being carried parallel to the shore by littoral transport. The **offshore** zone extends lakeward of the zone of the nearshore currents and is often considered "deep water". The fine-grained sediments derived from till bluff sediments are deposited into the lake in the offshore zone. Offshore also refers to the direction away from the shore, toward a lake or other large body of water.

Wave height is the vertical distance between a wave crest and the preceding trough. **Wavelength** is the horizontal distance between similar points on two successive waves (for example, crest to crest or trough to trough), measured in the direction of wave travel. The **foreshore** (lower beach) is the part of the shore lying between the upper limit of wave wash, or lowest berm, and the water's edge at low water. The runup and return of the waves ordinarily traverse the foreshore. The **backshore** (upper beach) is a zone of the shore or beach lying between the foreshore and the bluffs or dunes above the beach and is acted upon by waves only during severe storms, especially when combined with exceptionally high water. A **beach** is a zone of sediment that extends landward from the low water line to the place where there is marked change in material or form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach—unless otherwise specified—is the mean low water line. A beach includes foreshore and backshore. A **berm** is a nearly horizontal low ridge on the beach or backshore formed at the high water line by waves depositing material. Some beaches have no berms, while others have one or several. An **offshore bar** is a submerged embankment of sand or other natural material built on the lake bottom in shallow water by the action of currents and waves. Figure 1.1 illustrates the terms described above.

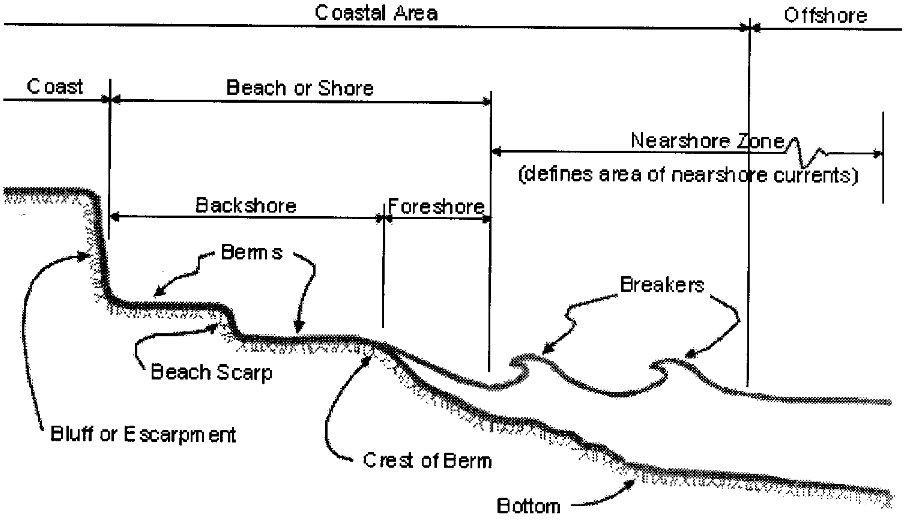


Figure 1.1 Regions of the Coastal Zone
(picture courtesy of the USACE)

An **orthophoto** is a photograph that has the geometric characteristics of a map. It no longer has the scale, tilt, or relief distortions that normal aerial photographs contain (J. Kruepke, 2000). **Orthorectification** is the transformation that occurs when a scanned aerial photograph in raster form, the camera parameters, a digital elevation model, visual orientation information and an existing orthophoto are combined to produce a spatially and geometrically correct digital orthophoto.

1.5 Organization of the Thesis

This thesis is presented in seven chapters. Chapter 2 provides a broad overview of the existing literature on this topic and reviews the scope and results of a number of similar and pertinent investigations. The natural processes currently affecting the Lake Michigan coastline are outlined. A description of the geologic setting and glacial history of the site is provided in Chapter 3. Chapter 4 consists of a review of the methods used to measure recession rates, to present wind and precipitation data, and to assess lake level and wave climate changes. The results are presented in Chapter 5 and are discussed in Chapter 6. A brief discussion of the implication of this study's results and recommendations for further work comprise Chapter 7.

2 LITERATURE SURVEY AND BACKGROUND

2.1 Literature Overview

A prime objective of this study is to determine the influence that wave climate, coupled with lake level, has had on the historical recession rates observed at the toe and crest of high bluffs and the crest of low bluffs along two Wisconsin coastal reaches. The effect of precipitation and storm events on the recession rate at the crest is also considered. A number of closely related studies have been reported in the literature and are summarized here.

Jibson and Odum(1994) examined bluffs along 30 km of the Lake Michigan shoreline from Wilmette to Waukegan, Illinois. Bluff retreat was measured at 100-m intervals along a 30-km shoreline for two time periods, 1837 –1937 and 1937 –1987. Temporal changes in lake levels and precipitation magnitudes were compared to the rates of bluff retreat. Spatial differences in bluff retreat rate were compared to variations in bluff height, bluff lithology and construction of shore-protective works to determine the influence that these factors have on bluff retreat rates. Local rates of retreat varied from 10 to 75 cm/yr spatially among segments of the bluffs (defined by lithology) and between time periods for a given bluff segment. For the entire area, the average retreat rate was not found to vary significantly between the two time periods and was found to be 20-25 cm/yr. The average lake levels and precipitation did not vary significantly for the two time periods, nor did their standard deviations. Hence, the available data did not allow the effect of lake level and precipitation on bluff retreat to be assessed. Shore protection appears to have altered the spatial distribution in retreat rate, but has had little effect on the average regional retreat rates. Wave activity was not considered.

Wilcock *et al.* (1998) examined the effects of direct wave activity on the toe of the fossiliferous Cavert Cliffs in Maryland. The study aimed to answer the following:

- Are there threshold wave and water level conditions that initiate direct undercutting of the toe,
- Are there any features of storm, or combination of wave and storm surge, that are most contributory to slope erosion, and
- Can the erosive ability of the wave be coupled with the material resistance of the slope to allow a more appropriate comparison with erosion rates?

A long-term, 140-year historical erosion record (one erosion epoch) was incorporated. Long-term wind records were used to develop wave and water level records for 11 sites along a 45 km length of shoreline. The relative wave strength, an index representing the influence of both cumulative wave activity and material resistance, is compared to erosion rates. This index is defined as the ratio of wave pressure to the cohesive strength of the material (Wilcock *et al.* 1998). The frequency distribution of relative wave strength is estimated based on a 37-year wind record, estimates of storm surge, offshore wave geometry and nearshore wave transformation. Wilcock *et al.* found that the locations experiencing the largest erosion are those with the largest relative wave strength. A minimum relative wave strength for initiating erosion was also defined for the sites studied. The cumulative duration of about 50 hours during which the relative wave strength exceeds a value of 0.1 was found to distinguish undercut from non-undercut slopes across a site whose geology varies little. Slope processes such as freeze/thaw disintegration and gravitational slumping produced all the erosion where the computed relative wave strength and duration was considered insufficient to cause undercutting.

Dewberry and Davis (1994) investigated wave hazards accompanying extreme floods and storm events in the Great Lakes. Extreme floods are likely to occur only when the overall lake elevation is much higher than the long-term average. The U.S. Army Corps of Engineers' Great Lakes hindcast wave data was used to obtain the offshore wave history for the years between 1956 and 1987 near the shore. Wave parameters measured at the NOAA buoys located in the south and north ends of the lake were found to be strongly correlated with the hindcast wave information.

The Dewberry and Davis (1994) study attempts to assign erosion hazards associated with wave action during flood events based on a comparison of historical erosion rates and base floods in the past. Extreme coastal floods are associated with strong onshore winds and sizable incident waves. While such storm conditions can cause significant removal of erodible materials, Dewberry and Davis (1994) point out a number of complications with analyzing storm-related erosion:

- Great Lakes sites have extreme variations in wave climates. The water level coupled with wave magnitude is a dominant factor for erosion.

- Storm-water level represents the local surge added to the overall lake elevation. Lake levels show large fluctuations on a seasonal basis and over decades, while the surge magnitude varies widely between shoreline sites.
- Winter winds, surges and waves are the most extreme during the winter months, but ice cover and its effects on shore processes are in effect for shorter or longer time periods over the winter depending on site location.
- Previous mean-water levels can affect erosion susceptibility for a site due to the time lag that occurs between lake-level change and complete profile response.
- Basic erodibility of a given site can vary dramatically as different soil units are exposed at the bluff face.

Given the above complications, Dewberry and Davis (1994) state that a large database is required to establish an adequate empirical basis on likely storm erosion for the base flood on the Great Lakes. Moreover, erosion data for very intense storms during high lake level periods is relatively sparse. Dewberry and Davis state that the frequency of expected wave action is in contrast with the relative rarity of extremely high lake level, but these two factors combined typically regulate shore erosion. Wave characteristics define the capacity for removal of unconsolidated shore material, and lake level defines the elevation at which wave-induced erosion is focused. Duration of extreme storm events over a given time period may be related to erosion magnitude through the time available for progressive wave effects (Dewberry and Davis 1994). Dewberry and Davis (1994) cite a number of studies carried out on sandy shores of Lake Michigan, with dunes or bluffs located behind the shore.

A study by Birkemeier (1981) was cited in the Dewberry and Davis (1994) report. Birkemeier (1981) reviewed shore changes over a 52-month period, and found that the amount of bluff recession increased steadily from the beginning of the study in August 1970 through 1973. Thereafter, recession decreased as mean levels repeated those of 1973. The erosion rate pattern was found to be seasonally dependent, peaking during early spring and late fall and in phase with the annual storm cycle but not with the lake level cycle. The greatest erosion amount was observed during a major storm event that occurred over two days in March, 1973. Birkemeier (1981) also noted that bluff erosion is a two-step process – erosion of the base of the bluff by wave action, followed by gravity failure of the bluff slope. This process results in new material being deposited at the base of the bluff, thus continuing the cycle.

Dewberry and Davis (1994) point out that the complex variability seen in shoreline erosion suggests that a single storm at one site or even the total storm duration up to a few years in one place may not allow accurate erosion prediction. Any erosion projection must rely on appropriate application of averaged results recorded over long intervals (decades at least) (Dewberry and Davis 1994).

2.2 Natural Processes Affecting the Lake Michigan Shoreline

2.2.1 Bluff Processes

Because much of the Wisconsin shoreline has bluffs of till or lake sediment above the beach, one component of shore erosion is bluff stability. Material properties (including angle of internal friction, cohesion and unit weight), slope geometry, and groundwater level determine the static stability of a slope (Edil and Vallejo 1980). Edil and Vallejo (1980) and Peters (1982) describe the influence of each of these slope parameters on the overall stability of Lake Michigan bluff slopes. Factors that influence the friction angle and cohesion are the grain size of the soils and vegetation existing on the slope. Changing lake level, precipitation, and runoff directly affect the groundwater level. As the water level rises, the factor of safety (stability) of the slope decreases according to effective stress slope stability analyses. Edil and Vallejo (1980) report a distinct reduction in the inclination of a stable slope when the groundwater level rises from ¼ to ¾ of the slope height. Natural processes causing change to the bluff geometry on the Great Lakes include frost action, seepage effects, sheet wash, weathering and wave action (Edil and Vallejo 1980).

Frost action, seepage, sheet wash and weathering are referred to as “face degradation” effects (Edil and Vallejo 1980). Face degradation effects remove slope materials more or less continuously in relatively small quantities from the surface of the slope. Sheetwash is the unconfined flow of water over the slope surface after a rainfall (Sterrett 1980). Sheetwash and rill erosion have been found to account for up to 34% of the material removed from a profile in Bender Park in Milwaukee County, Wisconsin (Sterrett 1980). Saturated soil that is frozen can, upon melting, be so weak that it flows down the slope. Freeze/thaw has been found to be a dominant cause of weaking of the soil and its subsequent removal on some coastal slopes (Wilcock et al. 1998, Sterrett 1980). No known past research isolating the effects of seepage and weathering processes on bluff recession rates exists. Wave action at the toe of the slope serves to weaken and remove exposed bluff material, thereby undercutting the toe of the overall slope and reducing the stability, discussed in detail in Section 2.2.2 and (Jibson and Odum, 1994).

The stability of coastal slopes is uniquely complicated by the dynamic slope geometry. Over time, the slopes evolve in response to the effects listed above. The pattern and rate of slope change depends upon bluff height, stratigraphy, soil types, and vegetative cover (Edil and Vallejo 1980). In general, high (30–45 m or 100–150 ft) bluffs change slowly because of the large mass of material that must be eroded at the base to influence the overall stability. The long “cycle” time of high soft sediment bluffs arises due to the episodic failure mode of these high bluffs (Mickelson and Edil 1998). Single failure events occur locally and at a rapid rate. A significant amount of material above the failure plane is deposited at the base of the slope and functions as a buttress for the slope for a number of years until the waves erode all of the failed material. Once the slump block material is removed, the waves resume their direct attack on the intact bluff face. The Ozaukee County reach studied in this thesis mostly fails by large slumps (Mickelson and Edil 1998). Some high bluff faces show an en echelon pattern or a constant slope angle during retreat.

Low (10 m or less) bluffs respond rapidly and more predictably to lake level, wave climate and precipitation patterns than high bluffs. The predominant slope processes of the lower bluffs, such as those in the Manitowoc County site are shallow slumps, translational slides and face degradation. Generally such bluffs that experience erosion at the base have no trees and very little vegetation. Due to a much shorter "cycle" time of the slope failures that occur on these slopes, there is not enough time for a tree to take root and grow.

2.2.2 Coastal Processes

Lake Level Change

Change in lake level is commonly considered to be a major factor controlling changes in bluff retreat rate (Bray and Hooke 1997, Kirk et. al. 2000, Carter 1976). As the lake level rises, the beach narrows and more waves arriving at the shore impact the bluff toe. Davis, Seibel and Fox (1973) consider differences in the local rates of erosion along the eastern Lake Michigan shore to be more attributable to the presence or absence of nearshore sand bars, man-made coastal structures, and the frequency of intense storms than to the relatively long-term fluctuations of lake level. Lake level, they contend, plays only a passive role in coastal erosion, not a causative one. By this they mean that a high lake level "sets the stage" for erosion to occur, but doesn't cause the erosion. Powers (1958), meanwhile, declares that "protective structures built by man, storms of unusual severity, and fluctuations in mean lake level" are the three chief factors responsible for variation in erosion rates over time.

Ever since the last glaciers retreated about 10,000 years ago, the system's lake levels and outflows have been fluctuating, affecting the lakeshore environment and human activities. Unlike oceans, where ebbs and tides are constant and predictable, Great Lakes water level fluctuations are almost never regular, nor can their levels be predicted accurately in the long term. This is because the many factors affecting Great Lakes water levels and flows are never constant and likely cannot be predicted accurately in the long term. Short-term lake and river level forecasts are available for all of the Great Lakes and the connecting channels throughout the year. Forecasts are produced weekly, monthly and bi-monthly and are available via the internet (GLIN).

The major influences on Great Lakes hydrology are weather and climate, both of which affect the balance of water in the Great Lakes and their connecting channels. Water enters the system as precipitation, runoff (including snowmelt) from the surrounding land, and groundwater inflow. Water leaves the system by evaporation from the water's surface, the St. Lawrence River, groundwater outflow, consumptive uses, and diversions.

Natural lake level variations can be subdivided into three categories: short term (changes within a few days or less), medium term (changes within a year), and long term (changes over a few years or more). Short-term changes are due to wind-stress buildup, barometric pressure changes and seiche (resonant oscillations) activity. These effects are more pronounced at the confined north and south ends of Lake Michigan. Medium-term (seasonal) changes affect the entire lake and are caused primarily by differences in rates of runoff, evaporation, and evapotranspiration. A typical seasonal cycle for Lake Michigan shows a high in June-July and a low in January-February. Long-term changes are caused by major variations in the climate within the Great Lakes basin and glacio-isostatic rebound (Carter 1976, USACE/GLC 1999). Climate changes include precipitation magnitude as well as the evaporation and runoff rates. Glacio-isostatic rebound refers to the rebounding of the earth's crust from the removed weight of the glaciers. The glacial ice was the thickest (and therefore the heaviest) and retreated most recently in the northern part of the Great Lakes basin. As a result, the apparent water levels across the basin are shifting as this crustal rebound takes place. The two Wisconsin sites for the present study are in the southern part of the Great Lakes basin, where the rebound effect is either neutral or causing a gradual rise in water levels. The shore at Port Colborne, Ontario has been raised by 0.37 ft/century (U.S. Army Engineer Division 1965) and reportedly more than 0.53 m per century in the northern part of the basin (USACE/GLC,1999).

Wave Erosion

Surface waves generated by wind blowing across lakes coupled with sufficiently high water levels are considered a principal cause of recession along shorelines (Jibson and Odum 1994, Dewberry & Davis 1994, Davidson-Arnott and Pollard 1980, Sunamura 1976). The average wave height and period increase as the wind velocity or fetch increases. There is, however, a limit to which the wave height and period can grow for a given wind speed with unlimited fetch and duration (Sorensen 1997). The fetch associated with waves approaching the two sites of this study is so large that the bulk of the wind waves are duration-limited.

Wind waves generated on the Great Lakes are capable of eroding till bluffs both directly and indirectly (Kamphuis 1987, Carter 1976). Waves deform and break when the water depth is 1 to 1½ times the wave height. This means that the more gentle the nearshore slope is, the farther offshore the waves will break and the less the energy the waves will have upon reaching the shoreline. Wave energy is directly related to wave height.

Upon reaching the shoreline, the beach absorbs some of the remaining wave energy before the base of the bluff is reached. Assuming a constant beach slope, if the beach is sufficiently wide, or the lake level sufficiently low, no wave energy will be transmitted to the bluffs. However, in cases where the beach is narrow (high lake level) a much greater proportion of wave energy will reach the bluff (Carter 1976).

The continuous onslaught of waves serves to erode and wash away the intact, exposed bluff face and to remove slumped material at the base of the bluff. Thus, the erosion of the bluffs is a continuing but not a continuous process.

For cohesive shorelines, nearshore downcutting impacts bluff stability indirectly. The nearshore zone is compositionally and geotechnically closely related to the lower layers of the bluff, but can be extremely weathered (Keillor, 2000) and covered discontinuously with deposits of sand of varying thickness (Kamphuis, 1987). Nearshore downcutting is the general planing down of the lakebed surface due to the abrasive action of erosive waves in the presence of sand (Nairn-a). Kamphuis (1987) showed that the wave-related processes taking place on the foreshore could actually control the long-term rate of bluff erosion. This can occur where significant downcutting produces deeper water. This creates a condition where more wave energy impacts the bluffs than previously would take place. The real threat of nearshore downcutting exists for all till shorelines where there is an insufficient sand supply to provide adequate protection of the till lake bed from wave action.

2.2.3 Weather

The weather directly influences bluff erosion rates (Dewberry and Davis 1994, Carter 1976, Jibson and Odum 1994, Davidson-Arnott and Polard 1980, Powers 1958). As discussed in Section 2.2.2, wind-generated waves exert powerful erosive forces at the base of the bluff. Continual wave action undercuts the toe of the slope and steepens the nearshore zone, both of which ultimately lead to slope failure. Extreme storm events are associated with increased wave attack due in part to the higher wave energy associated with higher winds and associated higher waves. The local, ephemeral rise in water level (storm surge) associated with prolonged unidirectional winds also causes the bluffs to experience more wave action during storms (Powers 1958).

Precipitation affects lake level, local groundwater conditions and surface runoff. The effect of groundwater table changes and lake level has been discussed above. During periods of intense precipitation, rainwater running down the slopes as surface runoff carries sediments from the bluff face to the lakeshore. For high bluffs that are buttressed by former slides, the falling rain is a contributor to the loss of bluff material at the crest of the overall slope.

During the winter months, wave action at the shore is limited by the presence of shorefast ice. Since the largest wave heights at stations around Lake Michigan generally occur between November and February, it is important to know the freeze-up and break-up dates when considering wave action at the shore. While Barns and Kempema (1994) reveal that coastal ice plays a significant role in removing and transporting sediment from the coast in southern Lake Michigan, this effect is not considered in this study due to a lack of quantitative studies of ice effects in our local study area. Clearly, however, sediment is removed by ice during winter and spring, probably contributing to nearshore downcutting.

While no site-specific data are available, the U.S. Army Corps of Engineers (1994) analysed half-month data sets between December and March to provide the ice concentration at each 5-km cell throughout the lake. The median value, representing an estimate of the 50th-percentile point of the ice concentration probability distribution, is referred to as the “normal” winter ice concentration. According to this 31-year study, a significant amount of ice exists out into the lake adjacent to the Ozaukee County for a fairly limited time period, from February 15 to 28. However, shorefast ice exists for a much longer period of time than the time period during which the median ice concentration was 50%. For this study, ice is assumed to line the shore between December 1 and March 15 (Keillor, 2000).

3 DESCRIPTION OF STUDY AREA

3.1 Site Description

Ozaukee County

A 3.2 km (2 mile) long shoreline site is located approximately 20 km south of Port Washington, Wisconsin on the western shore of Lake Michigan (Figure 3.1). The site lies within Township 9N, Range 22E, and Sections 5 and 8 (Figure 3.2).

This study area is along the lake shoreline where till bluffs rise between 30 and 45 m (100 to 140 ft) above lake level. The shoreline is oriented at a constant 012° – 192° from magnetic north. The area's land use is rapidly changing from agricultural to rural residential. There are an increasing number of new residential developments near the shoreline, increasing the demand for more accurate knowledge of shore processes and rates of shore retreat.

Manitowoc County

A 6.4 km (4 mile) reach site is located approximately 7 km north of Two Creeks in Manitowoc County, Wisconsin (Figure 3.1). The site lies within Townships T21N, R24E, Sections 2, 11 and 13 and T22N, R24E, Section 36 (Figure 3.3). The Kewaunee nuclear powerplant is at the north end of the site and the Point Beach nuclear powerplant is at the site's south end. The shoreline is a slightly concave shape, with the orientation varying from 343°-163° from magnetic north at the south end (WTR-1) to 4°-184° from magnetic north at the north end (WTR-5). Table 3.1 summarizes the shoreline orientations for each profile at the site.

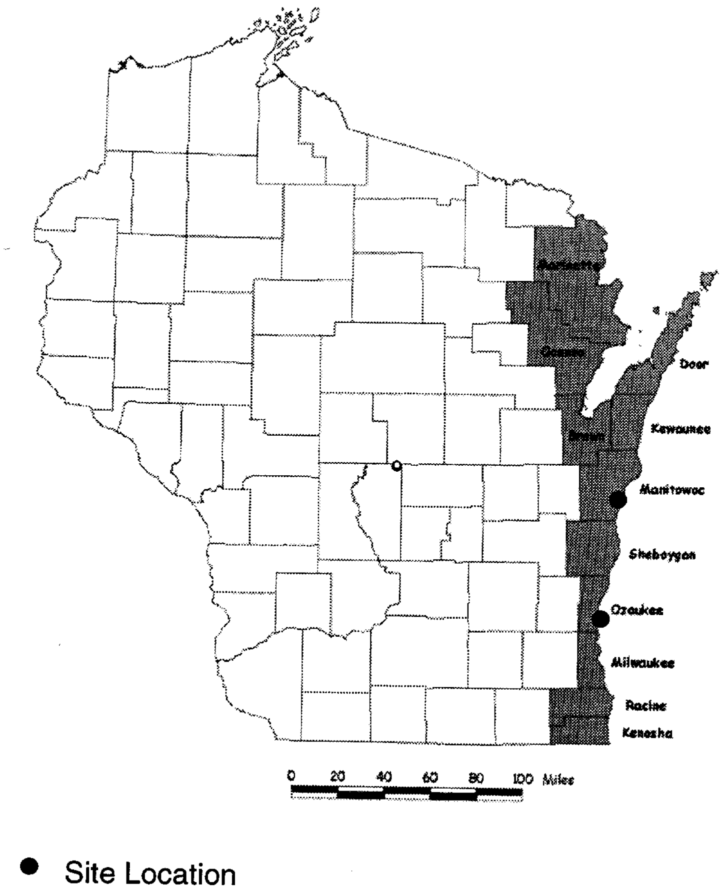


Figure 3.1. Site Location Map. Wisconsin Coastal Counties are shaded regions. Manitowoc and Ozaukee study sites are indicated with black circles. (LICGF, 2000)

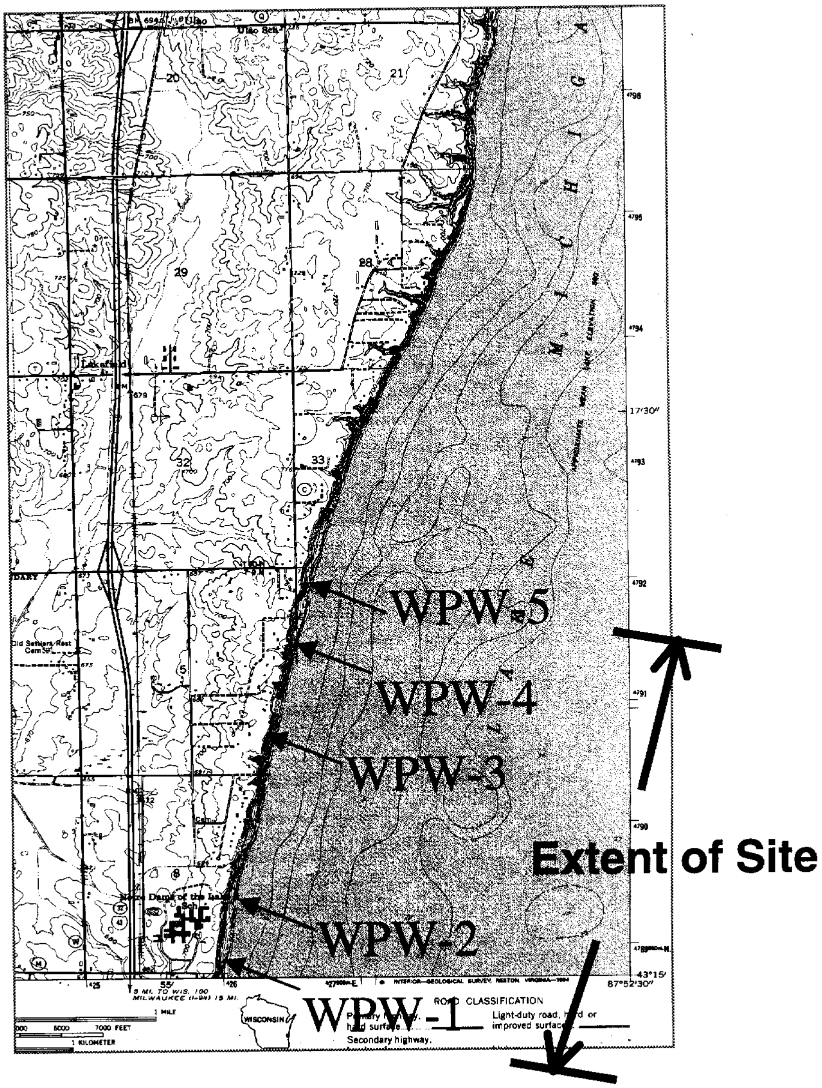


Figure 3.2 Map showing extent of Ozaukee County site. Profile locations WPW-1 to WPW-5 indicated. GPS positions of shore profiles are in Appendix V.

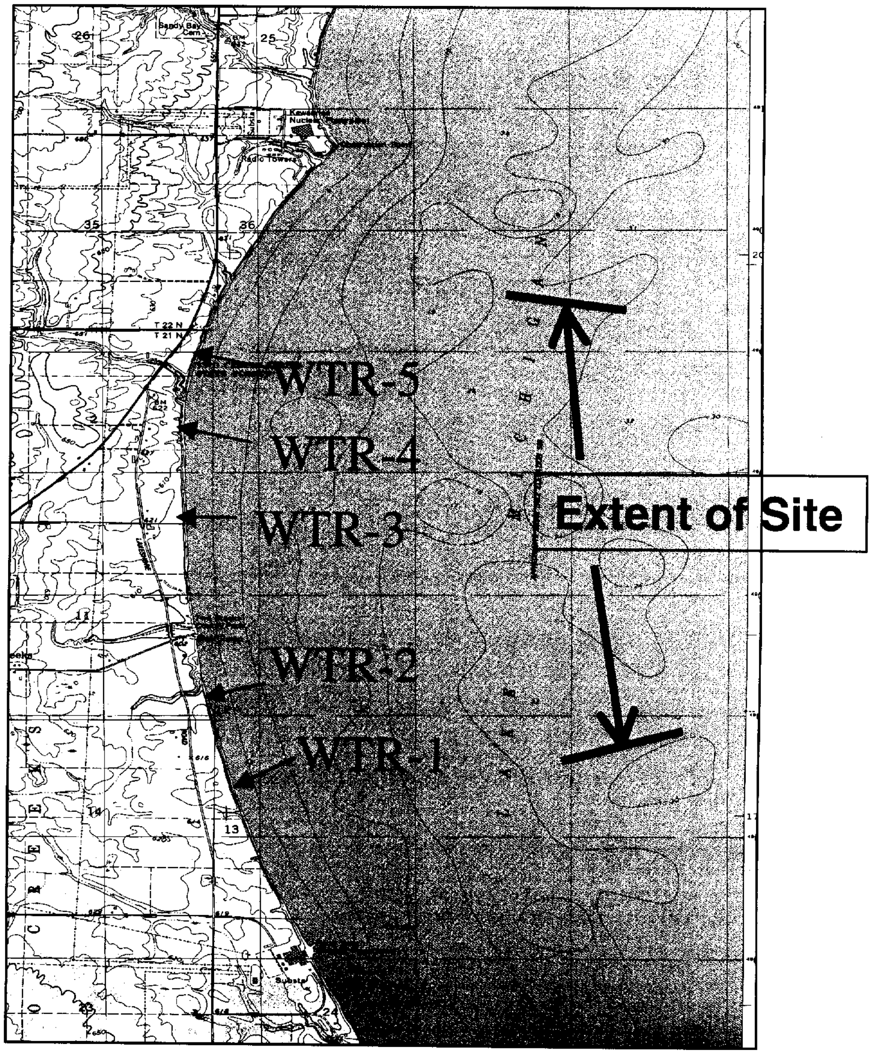


Figure 3.3 Map showing extent of Manitowoc County site. Profile locations WTR-1 to WTR-5 indicated. GPS positions of profiles at the shore are in Appendix V.

Table 3.1 Shoreline Orientations for Manitowoc Site Profiles.

	WTR-1	WTR-2	WTR-3	WTR-4	WTR-5
Shore Orientation [degrees from North]	343°–163°	347°–167°	358°–178°	358°–178°	4°–184°

The land parcels along this shoreline reach is also going through a development stage, but at a slightly lower rate than the Ozaukee County site.

3.2 Geology and Glacial History

3.2.1 Wisconsin

During the Paleozoic Era (between 250 and 570 million years ago), the global sea advanced onto Wisconsin's eroded and weathered Precambrian rock surface and entirely covered the state (Mickelson and Syverson 1997). Sedimentary rocks were deposited as the ocean depth fluctuated. Sandstone was formed where rivers transported sand-sized sediment to the shallow parts of the sea. During the later part of the Paleozoic, thick shale and limestone layers were formed. The subsiding basin in Michigan produced a tilting of the rock layers to the east along the west shore of present-day Lake Michigan. The Devonian shale is the youngest marine rock in the state and is 370 million years old.

The Laurentide Ice Sheet covered much of Wisconsin several times during the last 1.6 million years during what is known as the Quaternary Period. The glacial features present today are products of the last major phase of glaciation, called the

Late Wisconsin Glaciation. This glacier advanced into Wisconsin about 24,000 years ago. Following several stages of advance and retreat, ice disappeared from the Lake Michigan basin about 11,000 years ago.

3.2.2 Ozaukee County, Wisconsin

Mickelson and Syverson (1997) report on the Quaternary geology of the Ozaukee and Washington Counties in Wisconsin. Figure 3.4 shows a diagrammatic cross section of glacial deposits and underlying bedrock in Ozaukee and Washington Counties.

The Devonian shale, where it exists, overlies the Silurian dolomite formation. The shale, a comparatively soft unit, was largely scoured out by Pleistocene glaciers. Glacial features dominate the landscape of these counties. The unconsolidated bluff sediments exposed at this site are either glacial in origin or are lake sediments. Figure 3.5 is a North-South cross section showing Quaternary deposits exposed in the Lake Michigan shore bluffs of Ozaukee County. The upper half of the bluff consists of the Ozaukee Till, underlain by lake sediment and outwash deposits.

3.2.3 Manitowoc County, Wisconsin

This site is also underlain by Silurian dolomite and the bedrock setting is almost identical to the Ozaukee County site.

Acomb *et al.* (1982) describe the till stratigraphy present along the Lake Michigan

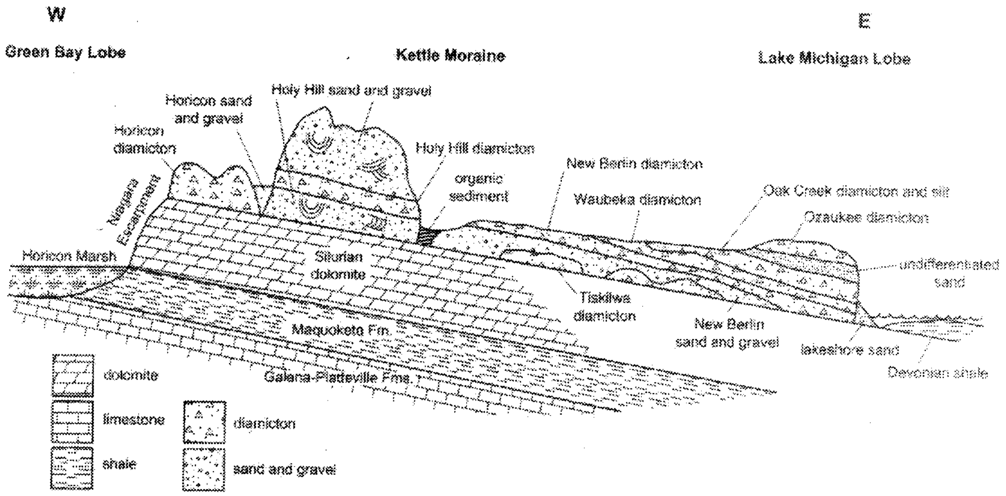
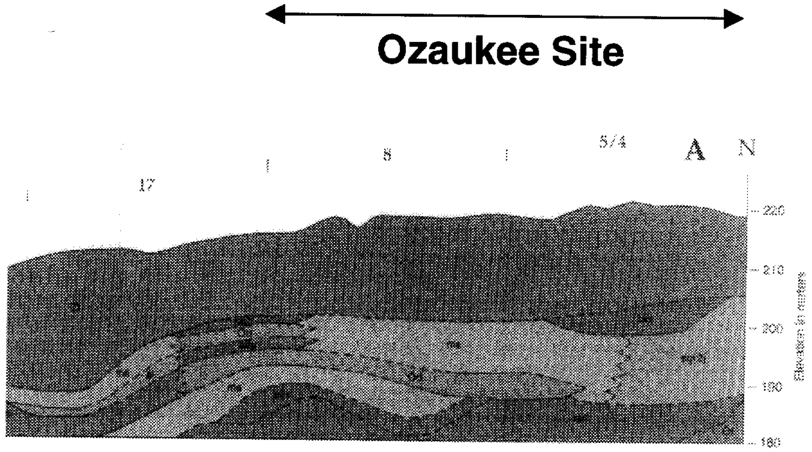


Figure 3.4 Diagrammatic Cross Section Showing Glacial Deposits and Bedrock in Ozaukee and Washington Counties.

North–south cross sections showing Quaternary deposits exposed in the Lake Michigan shore bluffs of Ozaukee County, Wisconsin

▨	Till of the Ozaukee Member
▨	Till of the Oak Creek Formation
▨	Till of the Waubeka Member
▨	Till of the New Berlin Member
▨	Interbedded silt and waterlaid diamicton of the Oak Creek Formation
▨	Nearshore lake sediment composed of medium- and coarse-grained sand
▨	Sand or sand and gravel deposited in outwash stream or delta; may include some beach sediment. Number in parentheses is estimate of diameter in inches of the coarsest 90th percentile of clasts in the gravel fraction.
▨	Lake sediment composed primarily of silt
▨	Lake sediment composed of interbedded silt and fine sand
▨	Lake sediment composed of interbedded silt and clay



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James M. Robertson, Director and State Geologist

Figure 3.5. North-South cross section showing Quaternary deposits exposed in the Lake Michigan shore bluffs of Ozaukee County (Mickelson and Syverson 1997).

shoreline in eastern Wisconsin. Figure 3.6 shows a diagrammatic cross section along the Lake Michigan shore bluff section containing the Manitowoc County site.

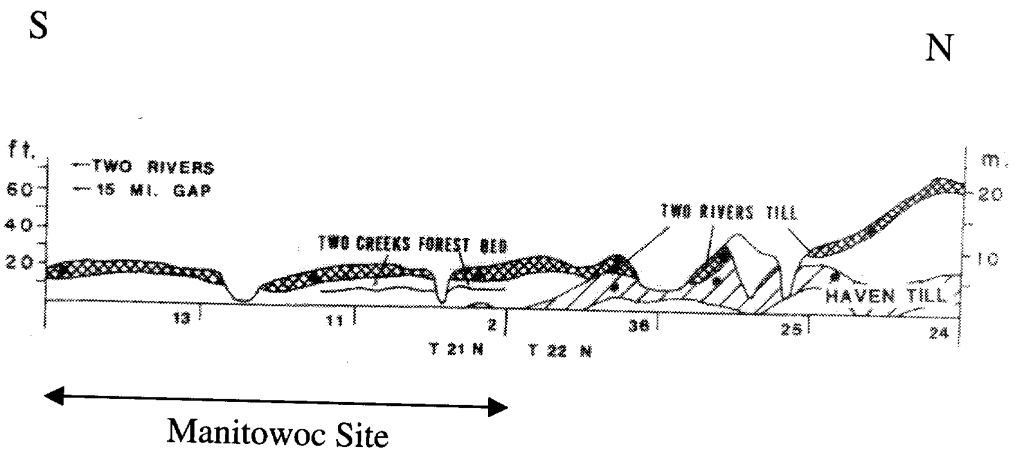


Figure 3.6 North-South cross section showing Quaternary Deposits exposed in the Lake Michigan shore bluffs of Manitowoc County (Acomb *et al.* 1982).

4 RESEARCH PROCEDURES

4.1 Recession Rate Measurement

4.1.1 Choice of Method

Three different methods of measuring bluff erosion have been documented in the literature. The following paragraphs summarize these methods. Subsequently, the method chosen for this study is described and justified.

Berg and Collinson (1976) measured distances to the bluff crest from known cultural features behind the bluff using historical topographic maps. The cultural features, consisting of railroad lines, road intersections, and driveways were chosen based on their fixed presence over the 103-year period of interest. This method has been used where positions of the bluff crest and these cultural features were mapped over time and where surveyed historical bluff lines are not accurate enough or not available. An accuracy of 3 m (10 ft) was reportedly attained for six profiles along a 4-km (2.5-mile) long section of Lake Michigan shoreline in Illinois.

Gelinas and Quigley (1973) determined a long-term, 159-year rate of erosion using a combination of early map surveys and recent aerial photography. Estimates of erosion over 3-km intervals were determined for north shore of the central part of Lake Erie. Their “maximum probable error” was estimated at 38 m or 0.25 m per year.

The use of horizontal peglines installed into cohesive till bluff slopes has been widely used to measure erosion where a high frequency of measurements are needed over relatively short time periods (Highman and Shakoor 1998, Amin 1991, Carter and Guy 1988, Sterrett 1980). This method entails driving stiff metal pegs horizontally into the slope at locations where the waves reach the bluff. The distance between the end of the driven peg and the bluff face is measured at intervals of between approximately one to two weeks (Highman and Shakoor 1998). The erosion magnitude is the difference between the exposed peg length at the beginning and the peg length at the end of each interval. This method is considered to be accurate within centimeters, but it is generally only carried out over time periods of two years or less. The unattended pegs are susceptible to being tampered with or destroyed by members of the public or irretrievably covered with eroding bluff soils (Amin 1991, Sterrett 1980).

The use of historical and recent aerial photography is the most popular method to measure changes in bluff position over long time periods or shorter periods for rapidly-receding areas (Kruepke 2000, S.E.H. Baker 1997, Berg and Collinson 1976, Sunamura and Horikawa 1969, Bird and Armstrong 1970, Carter 1976). This method has evolved over time as the computer technology to handle spatial data has improved (Burrough and McDonnell 1998). Prior to the 1990's, historical bluff lines were mapped directly onto the photos and the retreat distance measured. The technology to create digital orthophoto images (photos that have been orthorectified and are geometrically correct, see Section 4.1.3) accurate to within 1 – 3 m is now available.

The choice adopted for this study is to use historical aerial photographs to create digital orthophotos. These raster images are used to map bluff lines directly on the computer screen. A script program created by Joon Heo, a Ph.D. student in Civil Engineering at the University of Wisconsin-Madison, with Arcview™ is used to measure the average recession rates along each section of interest. This choice is determined based on the quality of the method, the availability of historical data, and the objectives of the study. The digital orthophotos provide an unequalled tool for creating a visual image of the bluff slopes as well as a tool to map and analyze historical bluff lines. While peglines would provide valuable, short-term measurements, they would not capture the recession-rate sequence characterized by long term bluff cycles. The high bluff slopes at the Manitowoc study area demonstrate a bluff slope evolution cycle of considerable length. Pegline data is not available for this long a period. Wave and wind data are available only for the 1956 –1997 period. Water-level data are available dating back to the late 1800s. Historical photos are available for at least each decade beginning from the early 1940's to present. Hence, the natural choice is to use available historical aerial photography to capture bluff-recession rates over periods of decades and to compare these to lake level and wave climate. The methodology for orthophoto creation is outlined in Sections 4.1.2 and 4.1.3.

4.1.2 Historical Airphoto Availability

Air photographs used to determine recession rates were collected from a number of sources and came in a variety of forms. The source and details of the air photographs used to measure the recession rates at the Ozaukee site are summarized in Table 4.1.

Table 4.1 Air Photography Database for Ozaukee Study Site.

YEAR	DATE	SCALE	TYPE AND DATA FORM	SOURCE
1941	September 7	1:20,000	Black and White Photo Prints	Robinson Map Library, UW-Madison
1950	October 3	1:20,000	Black and White Photo Prints	Robinson Map Library, UW-Madison
1956	May 16	1:20,000	Black and White Photo Prints and Digital Orthophoto	Robinson Map Library UW-Madison and SEH Baker (1997)
1964	June 4	1:20,000	Black and White Photo Prints	Robinson Map Library, UW-Madison
1975	May 27	1:12,125	Black and White Infrared Photo Prints	Wisconsin Department of Natural Resources
1988	August 16	1:20,000	Red Infrared Scanned Photo	US Army Corps of Engineers
1995	April	1:20,000	Black and White Digital Orthophoto	SEH Baker (1997)
1999	September 22	1:6,000	Color Photo Prints	US Army Corps of Engineers

As can be seen from Table 4.1, there is at least one air photograph representative for each decade from the 1940s to the present. Where more than one photo set was available in a given decade, only one set was adopted for this study. The choice of products from the two flights carried out in the 1950s was clear. The 1950 photos were developed on thin, poor-quality paper and are now warped. While the photogrammetric software effectively removes most distortions inherent to aerial photography, it cannot handle warped paper. Excessive errors in the resulting digital orthophoto would result from using the deteriorated photos, so the 1956 photos were chosen instead.

Photos taken from the years 1941, 1964, 1975 and 1988 were initially in analogue form. They were scanned in order to produce digital orthophotos using a process described in Section 4.1.3.

Two sets of photos were in the form of digital orthophotos at the outset of the study. The Wisconsin Coastal Management Program funded a Lake Michigan Recession Rate study carried out by Short Elliot Hendrickson Inc. and Michael Baker Jr. Inc. (S.E.H. Baker 1997). Digital orthophotos and mapped bluff lines for 1956 and 1995 were products of this report. The author considers these orthophotos and mapped bluff features at least as accurate as the digital orthophotos created for this study. Hence, these digital products are adopted for this study.

The historical airphotos used to create orthophotos for the Manitowoc Site are listed in Table 4.2. J. Kruepke (2000) has already created digital orthophotos from aerial photographs for years 1938, 1961 and 1967. The S.E.H. Baker product (S.E.H. Baker 1997) included digital orthophotos and mapped bluff lines for years 1952 and 1992. The digital orthophotos for the remaining years of record, 1975 and 1999, were constructed for this study using Orthomapper™ (see Section 4.1.3).

Table 4.2 Air Photography Database for Manitowoc Study Site.

YEAR	DATE	SCALE	TYPE AND DATA FORM	SOURCE
1938	July 4	1:20,000	Black and White Digital Orthophoto	J. Kruepke (2000)
1952	September	1:20,000	Black and White Digital Orthophoto	SEH Baker (1997)
1961	October 6	1:20,000	Black and White Digital Orthophoto	J. Kruepke (2000)
1967	August 28	1:20,000	Black and White Digital Orthophoto	J. Kruepke (2000)
1975	June 2	1:12,125	Black and White Photo Prints	Wisconsin Department of Natural Resources
1992	May	1:20,000	Black and White Digital Orthophoto	SEH Baker (1997)
1999	September 22	1:6,000	Color Photo Prints	US Army Corps of Engineers

4.1.3 Construction of Digital Orthophoto Mosaics

An orthophoto is basically a mapped photograph that is geometrically correct in the same way that a topographical map is correct with respect to map scale and projection (Burrough and McDonnell 1998). To create an orthophoto accurate enough to assess bluff changes on the scale of decades, the following distortions must be removed:

- Tilt – the camera may be unintentionally tilted up to 3°,
- Elevation Differences – relief displacement occurs when features on the photo are above or below a given datum elevation of the terrain,
- Variable Scale – due to adjustments to plane's flying altitude, and
- Radial Lens Distortion – due to imperfections in the camera lens.

A new softcopy method for orthorectification of photographs has been developed which requires no ground control and can be used on a desktop computer (Kruepke 2000). The Orthomapper™ software utilizes photogrammetric techniques that remove most of the above errors and enables quantification of any errors that remain. A recent MS thesis by Kruepke (2000) documents the Orthomapper™ methodology and recommended error analysis. The Orthomapper™ Manual outlines the steps required to produce a digital orthophoto from one or more aerial photographs.

If no ground-survey data are available, a Digital Elevation Model (DEM) and a previously-rectified photo that covers the area of the image are required. The essential process of creating an orthophoto consists of three primary steps. A basic outline is provided below, with more detail provided where the procedure adopted deviates from the standard method.

1. Scanning

The aerial photographs are scanned on a UMAX™ Mirage IIse large format (A3 size) high-resolution flatbed scanner. The prints are scanned at a resolution of 700 dots per inch (dpi). This resolution level produces a raw pixel size of approximately 0.72 m (2.4 feet) for photographs at a scale of 1:20,000.

2. Digital Orthophoto Production

Interior Orientation of Visual Images The camera focal length, scanning resolution, and number of fudicial marks are entered for a single image. The user locates the positions of the fiducial marks on the screen, thus allowing the program to locate the principal point of the digital image.

Visual Exterior Orientation Matching "control" points are entered on the existing orthophoto and the image. Geographical coordinates from the existing orthophoto are used, together with the elevation data from the DEM, to conduct a single-space resection, which removes the image's tilt and scale distortions. The standard deviation of the least squares fit of each of the matched points and the overall RMS error for the rows and columns are provided in an on-screen user interface. "Tie" or "Pass" points are entered in regions that are shared with adjacent, overlapping images. Tie points are used to create an orthophoto mosaic. These points are used to "tie" the individual images together and provide a consistent coordinate system for the mosaic.

Create a Digital Orthophoto or Orthophoto Mosaic

The user runs the "Create Orthophoto" command in the Orthomapper™ program. The appropriate airphoto images, digital elevation models and digital orthophoto quadrants are inputs to this command.

3. Quality Control

The orthophoto created with Orthomapper™ is viewed together with a previously existing orthophoto image in a split screen. This allows the user to check the quality of the new orthophoto. Because pixels from the two images with the same coordinate are displayed at exactly the same screen location, the positions of land features that have remained fixed over the time period between the photos should coincide.

The DEMs and existing orthophotos used for this project originate from the USGS Global Land Information site (USGS). Four 30–m resolution DEMs and six USGS Digital Orthophoto Quadrangles (DOQQ) are used to create orthophotos for the 2-mile site in Ozaukee county. A DEM consists of an array of elevations for ground positions at regularly spaced intervals (USGSa). The elevation data are stored as profiles where the spacing along and between each profile is 30 m.

While the ready access to elevation data from the USGS is eminently useful, there are some drawbacks to their fixed temporal aspect and the coarse spacial resolution. Kruepke (2000) and Rodman (2000) outline recommended modifications to the standard procedure with regards to the use of DEMs representative of recent or current elevations for the purpose of constructing historical orthophotos. To map bluff lines accurately, the DEM model must show very accurate elevations at the bluff feature (e.g. crest or toe) on the day the photo was taken. The DEM portrays elevations tied to positions of the bluff edge that were accurate in 1992. While the elevations of the bluff crest and toe have likely not changed greatly over the years, their positions have shifted landward. The crest location as represented on the 1992 DEM is located some distance shoreward of the 1941 bluff crest. Because of this inaccuracy in the DEM, the digital orthophotos created from historical photographs would show incorrect positions of the bluff crest and toe.

As described above, the 30-m resolution of the DEMs results in inherent inaccuracies of the orthophoto product. A 30-m resolution effectively means that every 30 m-by-30 m area is associated with an overall "representative" elevation. The representative elevation is often assumed to be located at the center of the area. To project pixels from a place on the scanned aerial photo into a real-world location, the Orthomapper™ program uses a three-dimensional rubber sheeting process. This requires knowledge of the ground elevation at each pixel location. To obtain pixel elevations the program calculates interpolated values of elevation between the centers of every DEM cell. For the photographs used in this study, pixels are sized between 0.44 and 0.72 m. While a 30-m DEM resolution is reasonable for large-scale, regional studies involving fairly flat land, the interpolated elevations will not work for the bluffs. As the bluffs at the Ozaukee site, for example, are as little as 30–60 m wide and up to 30–45 m high, the interpolation process will assign an elevation near the crest that is too low, and the elevation near the toe will be assigned an elevation that is too high. Depending upon how far the bluff feature is from the center of the aerial photograph, this can create significant error.

In light of the above, the author chooses to modify the existing DEMs to optimize the accuracy of the bluff crest and toe position. To modify the DEMs to take care of the time-varying bluff elevation and the coarse spatial resolution, a more detailed set of elevation data is required. Dr. David Hart of the LICGF provided a two-foot contour interval topographic map in the form of an Arcview™ shape file. Ozaukee County employees effected the creation of the shape file. This map provides sufficient detail to assign an elevation of the bluff crest and toe that is accurate to within 0.6 -1.2 m (2-4 ft). To deal with the changing position of the bluffline, two DEMs are created from the existing 30-m resolution product. The crest is extended lakeward by approximately 500 m to create the DEM to be used to produce orthophotos for bluff crest mapping. The toe is extended shoreward by 90 m to produce a DEM that would create digital orthophotos suitable for bluff toe mapping. If the toe had been extended shoreward by more than 90 m the elevation at control points would have been altered. This would have introduced additional error into the final orthophoto product.

4.1.4 Coastal Recession Rate Calculations Using Historical Airphotos

Arcview™ and ArcInfo™, two software packages created by ESRI (Environmental Systems Research Institute) are used to map and analyze the bluff recession rates using digital orthophotos. Digital polylines are created representing bluff crest and bluff toe lines for each of the dates for which aerial photography was taken. The original airphotos are viewed in stereo beside the computer to confirm the toe and crest locations using a three-dimensional view.

Five areas are chosen at each site for comparison of recession rates. Each of the five areas is centered at the location of the measured offshore profile locations (see Figures 3.2 and 3.3). The offshore profile work is discussed more in Section 4.3.2. The orthophotos generated from historic photography are used to estimate the rate of coastal bluff recession over a number of epochs. A script tool within ArcView™ developed recently by Joon Heo, a Ph.D. student in the Department of Civil and Environmental Engineering, UW-Madison, enables the average rate over a length of shoreline to be computed. Heo developed three methods to compute recession rates. The baseline approach, considered by the author and Heo to be the superior method, is adopted for this study. This approach requires the creation of an additional polyline that is approximately parallel but offset to the historic shorelines for which the recession rate is measured. The script program calculates the distance from the baseline to two digitized historic blufflines. The user specifies the number of equally spaced intervals to use for recession rate calculation. The script tool calculates the average recession rate by taking an average of the difference in the distances determined from the baseline to the two offset blufflines (Kruepke 2000).

4.2 Available Climate Data

4.2.1 Wind Data

A continuous record of wind speed and wind direction can be used to calculate wave parameters or determine the number of storm events in a given time interval. Wave height and period can be used to compute the deepwater wave power and the wave runup at the shore. The relationship between deepwater wave power, runup heights and the observed recession rates are investigated. The calculations of wave power and runup are discussed in Sections 4.3.4 and 4.3.6 respectively.

Wind data is obtained from two sources. The Army Corps of Engineers created a comprehensive long-term wave climate database for the Great Lakes (ACE, Hubertz *et al.* 1991). The numerical wave hindcast results of the ACE study are heavily dependent upon high-quality wind data. The ACE study used the historical continuous wind observations made at seven land stations and two anemometer-equipped buoys to estimate wind fields over Lake Michigan throughout the 42-year span. Due to the lack of hourly data at all stations, the wind data were sampled every 3 hours (Hubertz et al, 1991).

The ACE study results contain wind parameters for every 3-hour increment between January 1, 1956 and December 31, 1997. Hence, wind data are available at 3-hour increments for the period 1956 -1997 at 60 virtual stations near the shoreline. This is equivalent to 122,728 readings taken over a 42-year period. These data are free and available for download from their FTP site (ACE).

The second source of wind data is a set of direct readings from an anemometer in Milwaukee. Hourly wind data have been recorded at the Milwaukee Airport since the early 1900's (MWRCC, Owen). Digital hourly data collected from 1949 to present at the Milwaukee Airport were purchased from the Midwestern Regional Climatic Data

Center (MRCDC). Gaps in the data are interpolated to provide a near-continuous time series. All land-based wind data are corrected to the standard 10 m height above ground surface using the standard 1/7th power law for the wind speed profile (Davenport 1960). The approximation

$$U_{10} = U_z \left(\frac{10\text{m}}{z} \right)^{\frac{1}{7}} \qquad \text{Equation 4.1}$$

estimates wind speed, U_{10}, at an elevation of 10 m above ground surface from the observed speed U_z recorded at elevation z. Before the hourly land wind data could be applied to the shoreline study site, a correction that accounts for the difference between overland air temperature and water temperature needs to be applied (Schwab and Morton 1984). Schwab and Morton (1984) tested three different empirical methods for determining overlake wind speed as a function of overland wind speed and the difference between the overland air temperature and water temperature. They concluded that the empirical methods for determining overlake from overland wind speed have not improved over the years and a better method is needed.

For the purpose of the present study, a rough comparison is made between the 3-hourly wind station data and the elevation-corrected Milwaukee airport wind data. The average of wind speeds derived from wind field models (Dewberry and Davis 1994) over the water at locations near the two study sites is determined for the entire period of record (between 1956 and 1997). The average of the wind speed measured on land at the Milwaukee airport is determined for the same time period (between 1956 and 1997). The expected range of values for the ratio between the land-measured wind speeds and the lake wind speeds is approximately 0.7–0.9 (ACEc 1973).

Since the Milwaukee wind data are available on an hourly basis, they are used to determine the number of storm events that occurred during each erosion epoch. A further discussion on how storm events are determined is given in Section 4.2.3. The 3-hour interval during which wind data is reported from the ACE data is not considered to be a small enough time step to examine storm activity.

4.2.2 Precipitation Data

Over periods of years, precipitation affects the lake level (ACEe 1999). Over periods of hours, days and weeks precipitation can increase groundwater levels and alter surface runoff. It is likely that periods of intense rainfall affect bluff retreat rates (Jibson and Odum 1994). For this study, the average rate of annual precipitation over each erosion epoch is compared to the average rate of bluff retreat. The analysis of average annual data enables the detection of gradual, long-term changes in precipitation amounts (Jibson and Odum 1994).

Hourly precipitation data are recorded at the Milwaukee Airport. Precipitation data for the interval from 1950 to present were purchased from the Midwestern Regional Climate Center.

4.2.3 Extreme Storm Events

Amin (1991) states that the generation of waves sufficiently large to cause erosion requires that wind from a constant direction exceeds some minimum value. These conditions may be termed *storm events*. The frequency of storm activity is likely to influence the rate of bluff erosion. Powers (1958) and Carter (1976) identify storms as a key erosion agent.

Amin (1991) and Davidson-Arnott and Pollard (1980) both use the following criteria to define a storm event:

1. Winds occur within the range of directions affecting the study area
2. Winds must blow for a minimum of six hours consecutively with velocities in excess of 4.5 m/s (10 mph).
3. Wind direction for a single event can vary through two octants (eg. west and northwest). If a third direction occurs for 3 hours or less and then returns to the two octants considered, then these values are included and the event continued. Otherwise the event is terminated.
4. A single direction is assigned to the storms based first on duration; if winds blow for approximately the same length of time from two octants then the direction associated with the highest wind speed is chosen.
5. A storm event is terminated either when direction switches for more than 3 hours or when the value of the six-hour running mean of wind speed falls below 4.9 m/s (11 mph).

Criteria similar to the rules given above are used to distinguish storm from non-storm events based on the available hourly wind data (see Section 4.1.5.). The wind data used for this study are reported in degrees from north rather than octants. The algorithm used to define storm events for this study is defined below:

(i) Wind has to blow for at least 6 hours consecutively with velocities in excess of 4.5 m/s (10 mph). Any events that are shorter or with lower speeds are eliminated.

(ii) A storm terminates when the 6-hour running average drops below 4.5 m/s (10 mph), or wind directions for a single storm event vary through more than two octants. That means minimum and maximum wind direction of one event is less than 90 degrees apart.

(iii) Directions are assigned to all storm events by determining the average wind direction.

(iv) Eliminate any storm event with assigned directions other than between 12 and 192 degrees from magnetic north.

4.3 Coastal Processes

4.3.1 Water Level Changes

Changes in bluff retreat rates commonly have been expected to correlate with fluctuations in lake level (Jibson and Odum 1994). The average, minimum, maximum and range of lake levels within each erosion epoch are compared to the recession magnitude of each erosion epoch. Historical lake level information from

1860 to present is found on the NOAA website in graphical form (NOAA). Digital monthly lake levels dating from 1860 to present were obtained from Dr. Frank Quinn of NOAA.

4.3.2 Wave Data

The wave data analyzed to determine deepwater wave power and runup are products of the Michigan wind wave hindcasting project conducted by the Army Corps of Engineers (Hubertz *et al.* 1991). A numerical wind wave hindcasting model called DWAVE (Resio and Perrie 1989) was used to simulate wave growth, dissipation, and propagation in deep water. Wave parameters including wave height, mean wave direction and wave period were computed at a number of virtual "stations" located at a selected number of points within twenty miles of the Lake Michigan shore and at a few sites in the middle of the lake. Station locations are shown in Figure 4.1. Station 11 is closest to the Ozaukee County study site. Station 18 is closest to the Manitowoc County study site. The ACE study results contain wave parameters for every 3-hour increment between January 1, 1956 and December 31, 1997. The data are free and available for download from their FTP site (ACE).

4.3.3 Bathymetry Data

Nearshore bathymetric profiles at the study site are used for the determination of the elevation at the toe of the bluff and the calculation of runup magnitude. The runup calculation requires information about the slope of the beach in the swash zone.

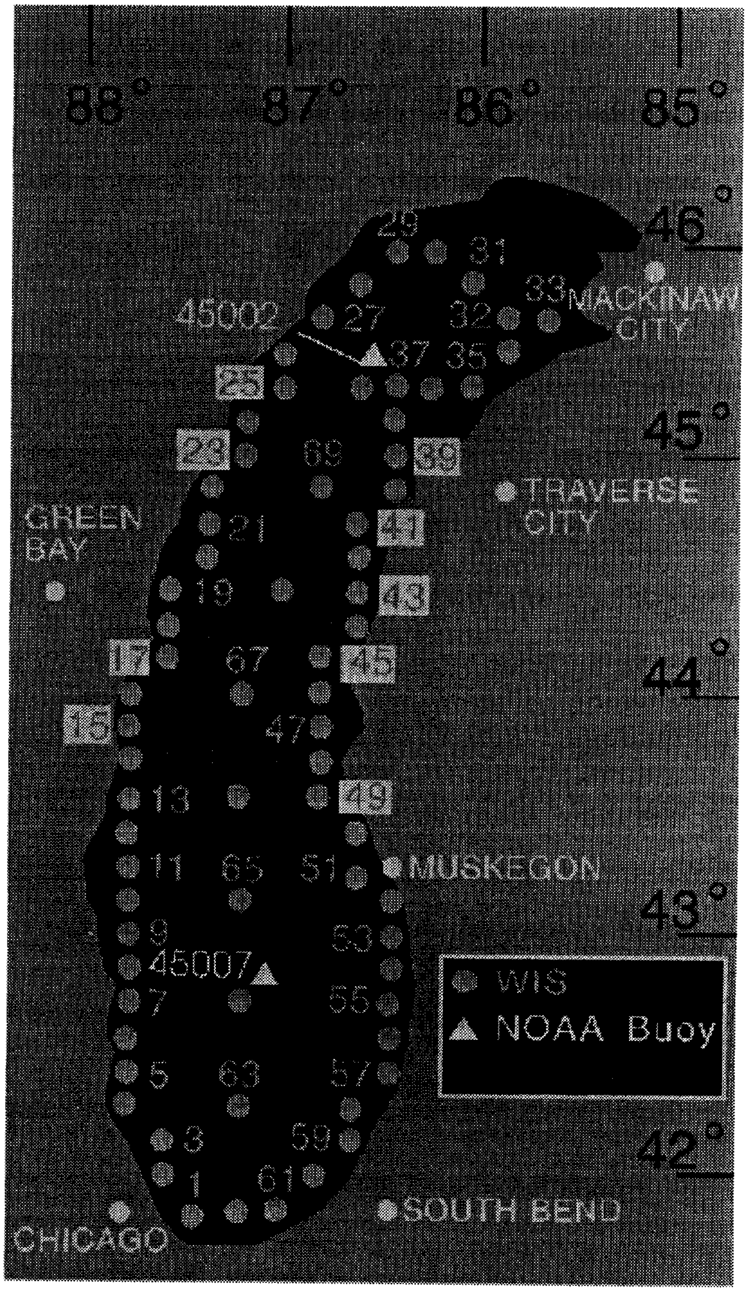


Figure 4.1 U.S. Army Corps of Engineers WI Hindcast wave data station locations (Hubertz et. al. 1991). From website http://bigfoot.wes.army.mil/c434.html

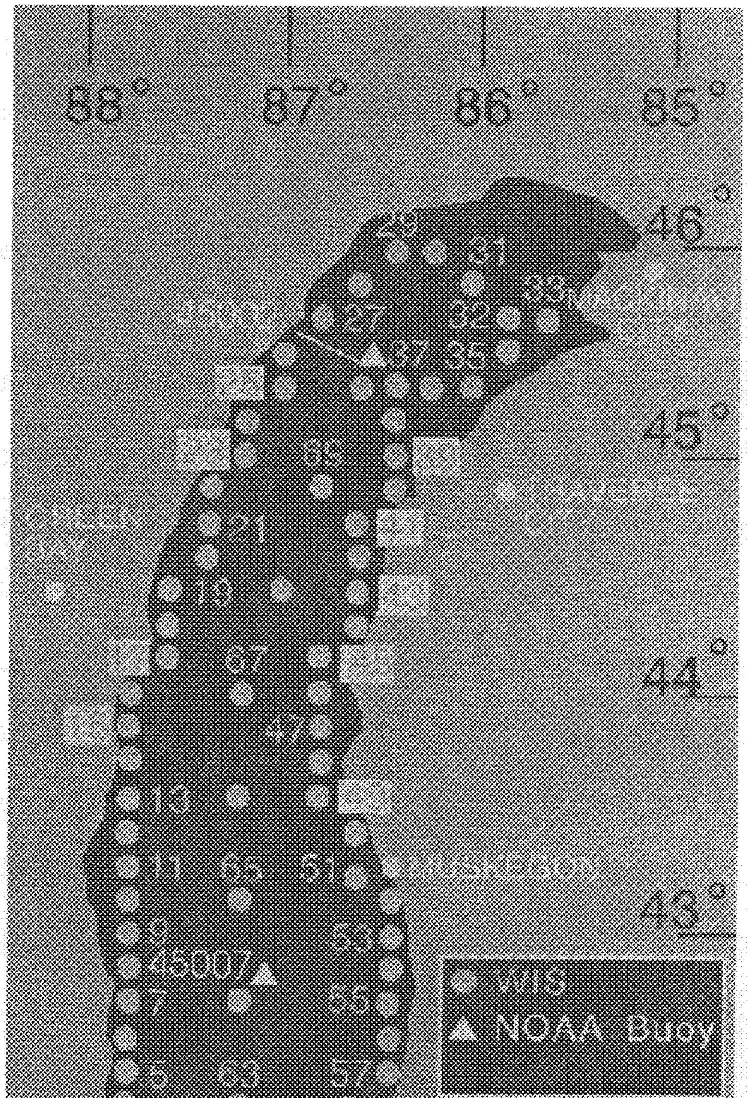


Figure 4.1 U.S. Army Corps of Engineers WI Hindcast wave data station locations (Hubertz et. al. 1991). From website http://bigfoot.wes.army.mil/c434.html

A number of combined bluff-profile survey / bathymetric soundings were carried out at the sites as part of the Great Lakes Protection Fund project. A survey station was set up on the beach near the base of the bluff. The offshore soundings were carried out with the boat always in the sight line of the survey station. Sounding depths were collected digitally, with the still water level being the reference elevation, out to a point 450 m (1500 ft) or more offshore. The sounding profiles were terminated when a depth of 5.5 –6 m (18 –20 ft) was reached. The sounding data was collected using a fathometer mounted on the boat. The accuracy of the depth measurements are considered to be within +/-10 cm (0.3 ft) (G. Meadows, personal communication). Brian Caufield of the University of Michigan carried out the nearshore surveys. Using a survey rod, survey positions were established at major slope breaks starting from the top of the beach to a distance offshore where the lake depth reaches 1.5 m (5 ft). The nearshore surveys overlapped with the offshore soundings to enable the University of Michigan project team to construct continuous offshore profiles from the beach to 6 m (20 ft) depth. Five offshore profiles surveyed in each site area are shown in Figures 3.2 and 3.3.

4.3.4 Deepwater Wave Power

Wave power is the wave energy per unit time transmitted in the direction of wave propagation (Sorensen, 1997). The wave energy that the waves have upon reaching the shore enables them to erode the beach and bluff toe materials. By applying linear wave theory for small amplitude waves, the wave energy flux at the shore can be expressed as

$$P = \frac{En}{T} = \overline{E} \cdot C_g \ , \qquad \text{Equation 4.2}$$

where P denotes the wave energy flux (power) per unit width of wave crest, E is the wave energy per unit width of wave crest, and T is the wave period. The index n can be interpreted as the fraction of the mechanical energy in a wave that is transmitted forward during each wave period (Sorensen 1997). As the wave propagates towards the shore n increases from 0.5 in deep water to 1.0 in shallow water. The wave power can also be viewed as the product of the energy density, $\overline{E}$, and the wave group velocity (celerity), C_g. The energy density is

$$\overline{E} = \frac{\rho g H^2}{8}, \qquad \text{Equation 4.3}$$

where ρ is the density of water, g is a gravitational constant, and H is the wave height.

In this study, the two shoreline reaches under consideration are relatively short, so variations in wave energy among the profile locations due to wave refraction are expected to be negligible. The deepwater wave height is taken as an available alternative for the wave energy equivalent at the shore. Amin (1991) found a significant positive correlation between toe recession and deepwater wave power based on weekly recession measurements at peglines along a Lake Erie bluff shoreline site. To check that the waves provided at the ACE station locations are deepwater waves, the following test was performed. The wavelength was determined using the dispersion relationship

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{L}, \qquad \text{Equation 4.4}$$

where L is the wave length, T is the period and d is the depth of water (Sorensen 1997). Since the period is known for each 3-hour interval and the water depth is known for each station, the wavelength is the only unknown and can be determined by successive approximation, i.e. iteratively solving Equation 4.4 for L. However, we are interested only in determining whether or not the wave is a deepwater one. The criterion for deepwater is

$$\frac{d}{L} > \frac{1}{2}, \qquad \text{Equation 4.5}$$

where d is the water depth and L is the wavelength. For the deepwater criterion to be satisfied at a station of known depth the following must be true

$$L < L_{\max} = 2d , \qquad \text{Equation 4.6}$$

where L_{max} is the largest wavelength that meets the deepwater criterion. The dispersion relationship given in equation 4.4 can be rearranged into the following expression that defines the wave period:

$$T = \sqrt{\frac{2\pi L}{g} \cdot \frac{1}{\tanh\left(\frac{2\pi d}{L}\right)}} \qquad \text{Equation 4.7}$$

Since the expression given on the right in Equation 4.7 increases monotonously as L increases, it is sufficient to determine all periods T in the record greater than the period T_{max} associated with $L_{max}=2d$. For each station the percentage of occurrences of waves with periods greater than the maximum allowable will be reported. This will be the proportion of waves that do not meet the deepwater criterion.

The deepwater wave power for all waves directed toward the shoreline at the study sites are determined for each 3-hour time step using wave parameters from the WIS hindcast data set. An average, minimum and maximum deepwater wave power is calculated for each of the erosion epochs for which hindcast wave data is available.

4.3.5 Wind-Setup Effect

Sustained high winds from one direction can push the water level up at one end of the lake and make the water level drop by a corresponding amount at the opposite end (ACEe). This is referred to as *wind setup*. Changes in barometric pressure can add to this effect. Lake Erie is most susceptible to storm surges due to its east-west orientation in an area of prevailing westerly winds and its shallow western end. As Lake Michigan is deeper than 200 m in some parts and over half the lake is deeper than 100 m, the storm surge effect is expected to be less pronounced at Lake Michigan than at Lake Erie. The wind-induced setup is estimated using the following nonlinear solution to a two-dimensional control volume approach:

$$S_w = d\left\{\left(1+\frac{2\tau_x \Delta x}{\rho_w g d_1^{\,2}}\right)^{\frac{1}{2}} - 1\right\}, \qquad \text{Equation 4.8}$$

where S_w is the wind-induced setup, d_1 is the water depth, τ_x is the wind stress, Δx is the fetch distance, ρ_w is the density of water and g is the gravitational constant. The wind stress is determined using the following relation:

$$\tau_x = \rho_w K U_{10}^2 , \qquad \text{Equation 4.9}$$

where the wind drag coefficient, K, equals:

1.21×10^{-6} if $U_{10} < 5.6$ m/s or

$1.21 \times 10^{-6} + 2.25 \times 10^{-6}(1-(5.6/U_{10})^2)$ if $U_{10} \geq 5.6$ m/s.

U_{10} is the wind speed at 10 m height above the water surface. To estimate this effect at the study site, the fetch lengths associated with all wind directions impacting the sites are determined. Depths of 50 m and 100 m are considered in our analysis to estimate the influence that wind wave setup has on the wave-impact heights.

4.3.6 Wave Runup and Wave-Impact Height Calculations

Once a wave breaks, a part of its contained energy dissipates. The remainder of the energy it has will be expressed in its ability to run up the face of the beach and possibly partially up the bluff slope. The runup is defined as the maximum vertical elevation above the still water level to which the water from the breaking waves rises on the beach. The runup magnitude is dependent on the wave height and period of incident deepwater waves, the surface slope and profile of the shore and the nearshore, the toe depth, and the roughness and the permeability of the slope face.

A number of methods for calculating runup are provided in the literature. Much research has been conducted for the purposes of better estimating wave runup on steeply sloping, impermeable coastal structures. The Army Corps of Engineers (1984) and Mase (1989) have established empirical relationships for determining the runups on smooth, impermeable slopes. Ahrens and Seelig (1996) propose a method for estimating the runup on a sand or gravel beach. They developed a relationship that determines the elevation above the still water level exceeded by two percent of all runups. Their method uses deepwater wave parameters, the slope of the beach in the surf zone and median sediment sizes in the swash and surf zones to compute the runup magnitudes. The beach and nearshore sediment size likely influence the rate at which wave energy dissipates as it runs up a slope. Consequently, the Ahrens and Seelig equations may be more suitable for determining runup on natural beaches than the Army Corps of Engineers Method (ACE 1987).

As the available nearshore slope information is much more detailed where soundings have been carried out, the bathymetric profiles will be used for the runup calculations. Historical nearshore slope profiles are not available for the profile locations. The recently measured slopes of interest are assumed to stay constant over the time period considered for this study. The validity of this assumption can be revisited once there are new profiles carried out at the same locations. We do not have grain size data on material in the beach and swash zone so the equations by Ahrens and Seelig (1996) cannot be applied. Instead, the empirical results by Mase (1989) are used to calculate the runup. The Army Corps of Engineers software for calculating runup, ACES™, determines beach runups based on the work by Mase (1989). Mase(1989) proposed the following formula for determining representative runup heights of random waves on gentle, smooth and impermeable slopes

$$\frac{R}{H_0} = a\xi^b, \quad for \quad \frac{1}{30} \le \tan\theta \le \frac{1}{5} \quad and \quad 0.007 \le \frac{H_0}{L_0}, \qquad \text{Equation 4.10}$$

where R is the distance that the water runs up to from the still water level and H_0 is the deepwater wave height. The deepwater significant wavelength is represented by L_0 and θ is the off-horizontal angle of the beach slope in the swash zone. The surf similarity parameter, ξ, is given by

$$\xi = \frac{\tan\theta}{\sqrt{\frac{H_0}{L_0}}} \qquad \text{Equation 4.11}$$

The coefficients a and b in equation 4.10 above were determined from laboratory experimental wave data (Mase 1989). The coefficients are:

$a =$ 2.32, $b = 0.77$ for R_{max}, the highest expected runup

$a =$ 1.86, $b = 0.71$ for R_2, the 2% excess runup height

$a =$ 1.70, $b = 0.71$ for $R_{1/10}$, the average of highest one-tenth of all runups

$a =$ 1.38, b=0.70 for $R_{1/3}$, the average of highest one-third of all runups

$a = 0.88$, $b=0.69$ for R_{avg}, the mean runup height.

It is important to know whether the wave energy has sufficient velocity and mass to reach the toe of the bluff. Runup magnitude increases as the slope of the beach that intersects the still water line increases provided that the slope remains within the bounds given in equation 4.10. However, the steeper the beach is, the less lateral impact this body of water mass has. Since there has been insufficient research to determine the erodibility of the bluffs and the method of normalizing wave energy arriving at the beach into a primarily destabilizing force is not well known, the relationship between runup and bluff erosion is not well known. Nonetheless, the runup vertical distance can be added to the still water lake levels at any given time to establish the level to which the waves reach. This level can then be compared with the level of the base of the bluff to determine whether or not waves are reaching the bluff at a given time.

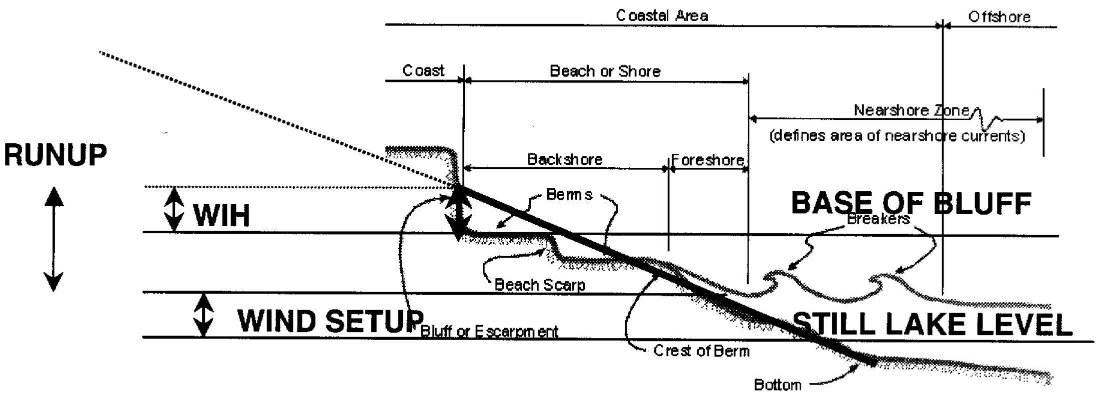
The wave-impact height is the height above the elevation of the bluff to which the wave runup reaches. Wave-impact height is calculated using the following relation

$$\text{Wave-Impact Height} = \{\text{Runup}\} + \{\text{Still Lake Level}\} - \{\text{Base of Bluff Elevation}\},$$

and if the wind setup is included the following is used

Wave-Impact Height = {Runup} + {Still Lake Level} + {Wind Setup} – {Base of Bluff Elevation}.

Figure 4.2 illustrates the physical meaning of the wave impact height.



Wave Impact Height = {Runup} +
{Still Lake Level} +
{Wind Setup} –
{Base of Bluff Elevation}

Figure 4.2 Illustration of the Wave-Impact Height calculation. Photo courtesy of USACE.

4.4 Analysis of Bluff-Toe Recession Rate

A prime objective of this study is to assess the dependence of recession rates at the bluff toe (for the high-bluff site) and the bluff crest (for the low-bluff site) on hydrodynamic factors, precipitation and storm occurrence on a temporal basis. The lake level, wave power, precipitation and storm activity all vary over the time lengths considered. While naturally varying factors may tend to be relatively constant when averaged out over extended periods of time, the 6-15–year epochs are considered short enough to show temporally changing values. Representative wave-impact height, lake level, deepwater wave power, precipitation and storm occurrence are each considered independent, time-varying factors that can influence the recession rate of the bluff toe. This study will determine if the sites' recession rates, wave and lake level data suggests that any or all of these factors control the rate at which the toe or crest recedes.

Even though the bluffs at both study sites have fairly uniform geology, geometry and shoreline orientation, some spatial variation in recession rates is expected. Precipitation, lake level and storm occurrence will be experienced nearly equally throughout the site, so no spatial variation in recession rates is expected due to these factors. The spatial variation of toe recession rate may be due any or all of the following:

➢ <u>Spatial variation in bathymetry</u>. The position at which the onshore waves break is determined by both wave parameters and the lake bottom profile. While this effect is not quantified, a qualified judgement is made regarding the potential influence of any variation in bathymetry on the spatial variation of recession rates at the toe.

- Variable beach slopes at the swash zone. The beach slope has a major influence on the degree to which waves run up the slope. Both the runup and the wave-impact height calculations will be different for each of the five profiles at each site since the beach slopes are all slightly different. The degree to which this variation influences spatial differences in toe-recession rates is taken into account.
- Spatial variations in the resistance to erosion of the bluff material itself. As the high bluffs erode, mass wasting material is fed to the upper part of the beach. As the recession rates reflect the change in the position of the top of the beach, the state of the soil at the top of the beach may influence the recession rate. If the soil at the top of the beach is the edge of the intact bluff face, the recession rate will likely be lower than if the soil is a mass wasting product that has been shed from the upper part of the slope.
- Spatial variations of the elevation of the base of the bluff. If the base of the bluff is high, fewer waves will reach the bluff and less erosion is expected. A low elevation of the base of the bluff would lead to a greater number of waves impacting the bluff and a higher recession rate is expected.

4.5 Analysis of Bluff-Crest Recession Rate

Ozaukee Site

The rate of retreat of the crest of the high bluffs at the Ozaukee County site is not expected to correlate strongly with the hydrodynamic components considered for the toe recession rate. Since the lake is so far below the crest, the waves cannot have any direct erosive impact on the bluff face. The indirect influences of the lake on the overall stability of the bluff may, however, show a somewhat weaker dependence of the crest recession rate on the lake factors. When the lake level is higher, the groundwater table in the slope is higher. The elevated water table may contribute to the reduction of the stability of the slope to the point of failing. If the failure scarp extends to the crest of the bluff, the high water level can then be said to have contributed to the recession at the crest. During high-water-level periods, more waves reach the toe of the bluffs. Since the direct wave action at the toe removes slope material and reduces the overall stability of the slope, a large-scale slump failure may result from both high lake levels and powerful waves eroding the toe. Thus, a higher lake level combined with the wave action could be related to crest recession at the high-bluff site, but on a much larger temporal scale than is considered for this study.

The high bluffs at the Ozaukee site are, along much of the reach, buttressed by a large mass of slumped material. This slumped material has been eroding for at least the past 60 years, a time period during which few large-scale slump events have been observed. This is a further reason justification that there is likely to be no relation between lake level and crest-recession rate over the time period of this study over the area fronted with a large mass of failed material.

If we find that the crest has been retreating over the past 60 years at the Ozaukee site despite the natural buttress that is currently protecting it, the factors contributing to the ongoing retreat could then be attributed to precipitation and intense storm activity. Significant precipitation increases the moisture content in the clay-rich till making up the bluff crests. The bluff face below the crest is near-vertical due to the overconsolidated, dry state of the glacial till. When the till is moistened the cohesive material weakens significantly and can lose the strength required to maintain a steep slope angle and fail locally.

During periods of intense precipitation, excess water runs down the bluff slope, picks up soil particles from the face of the slope and transports them downslope towards the lake. Over time, this removal of soil particles by rain drops results in a net cumulative loss of slope material. Intense storms are associated with high winds and often rain activity. The combination of winds and rain during storms accelerates the removal of slope material on a particle scale. The wind loosens the soil particles on the slope face and carries them away.

The relationship between precipitation rate and storm occurrence and crest-recession rate is assessed for each erosion epoch at the Ozaukee site.

Manitowoc Site

The recession rate of the crest of the low bluffs at the Manitowoc site is expected to strongly reflect the influence of lake level and wave climate. While the storm occurrence and precipitation rates influence the recession rate at the low-bluff crest in the same way as described above for the high bluffs, a stronger influence is expected from lake level and wave impact height variations. There is no large mass of material buttressing the slope at the Manitowoc site. The crest of the bluff is only about 10 m above the lake level. The bluff slope is void of trees and any other major vegetation and has a relatively constant slope. This indicates that the slope is being constantly worn away by wind and wave action so that large vegetation does not have an opportunity to develop.

The relationship between lake level, wave impact height, precipitation rates, storm frequency and crest erosion rates will be assessed for each erosion epoch at the Manitowoc site.

5 RESULTS

5.1 Airphoto Recession-Rate Analyses

5.1.1 Digital Orthophotos

Digital historic orthophotos were constructed according to the procedures outlined in Section 4.1.3. The nature of the spatial and temporal extent of the resulting orthophoto coverage is summarized for the Ozaukee site in Table 5.1.

Table 5.1 Summary of Years for which Digital Orthophotos are Produced for Ozaukee Site.

	Bluff Crest Mapping		**Bluff Toe Mapping**	
Year	DEM modification to map Bluff Crest	Profile Coverage	DEM modification to map Bluff Toe	Profile Coverage
1941	Bluff crest elevation modified and extended lakeward 200-300 m	1-3	Bluff toe elevation assigned as 176.8 m (580 ft) and extended shoreward by 90 m	1-3
1956	Not done – S.E.H. Baker data used	1-5		1-5
1964	Bluff crest elevation modified and extended lakeward 200-300 m	1-4		1-5
1975		1-4		1-5
1988		1-4		1-5
1995	Not done – S.E.H. Baker (1998) data used	1-5	Not done – S.E.H. Baker (1998) data used	1-5

Profiles for which recession-rate measurements for the Ozaukee County site are possible are indicated in Table 5.1 (see Figures 3.2 and 3.3 for profile locations). The 1941 orthophoto only includes profiles 1-3 because the 1941 aerial photographs did not extend far enough north to two of the profiles (4 and 5). Profile 5 was not included in any of crest line mapping with the new orthophotos because the crest was discernible neither on the airphotos when viewed in stereo nor on the digital image viewed on the computer screen. Dense tree cover in the vicinity of the bluff crest line of profile 5 precluded crest mapping with an adequate level of accuracy. Prints of the digital orthophotos used for the recession-rate analyses are provided in Appendix I.

The temporal and spatial extent of orthophoto coverage for the Manitowoc site is given in Table 5.2. As there are few trees along the crest of the bluffs at this site the crest could be mapped across most of the reach. Recession rates for all profiles are determined.

Table 5.2 Summary of Years for which Digital Orthophotos are Produced for Manitowoc Site.

	Bluff Crest Mapping	
Year	DEM modification to map Bluff Crest	Profile Coverage
1938	Bluff crest elevation modified and extended lakeward 200-300 m	1-5
1952	Not done – S.E.H. Baker data used	1-5
1961	Bluff crest elevation modified and extended lakeward 200-300 m	1-5
1967		1-5
1975		1-5
1992	Not done – S.E.H. Baker data used	1-5
1999	Bluff crest elevation modified and extended lakeward 200-300 m	1-5

5.1.2 Recession-Rate Error Estimate

The bluff-recession rates calculated based on historical orthophotos have an error associated with:

- inaccuracies of the digital orthophoto due to the limited resolution of the digital elevation model and potential inaccuracies in the reference digital orthophoto quadrangle, and
- difficulties in discerning the bluff or toe feature on the aerial photographs which results in inaccurate delineation of the bluff toe and crest, and
- the scale of the aerial photos (most are 1:20,000) limits the pixel size of the raster digital orthophoto image. The pixel size is 0.72 m for the 1:20,000 photos. The digitized features cannot be more accurate than the size of the pixels that comprise the historic orthophoto.

Kruepke (2000) carried out a detailed error analysis of bluff-recession rate determination using digital orthophotos. Kruepke (2000) considered the above error sources. Orthophotos were produced using aerial photographs taken at a scale of 1:20,000 using the Orthomapper Software. The difference in locations of road centers in the constructed orthophotos and in the reference orthophoto were determined at a number of locations by Kruepke (2000). As Kruepke's sites were located in the Manitowoc County reach and her methods were adopted for this study, the error analysis she reports is highly applicable to this study. Kruepke reports a maximum measurement error of 3 m.

Since the erosion epochs are of varied duration, the rate errors associated with the reported recession rates are different for each erosion epoch (Kruepke, 2000). In light of Kruepke's results a total error of 3 m is adopted for each recession measurement. The rate errors associated with the recession rate measurements are summarized in Table 5.3.

Table 5.3 Recession Rate Measurement Error.

Site	Epoch	Duration [years]	Rate Error [m/yr]
Ozaukee	1941-56	14.70	0.20
	1956-64	8.06	0.37
	1964-75	10.98	0.27
	1975-88	13.23	0.23
	1988-95	6.63	0.45
Manitowoc	1938-52	14.17	0.21
	1952-61	9.10	0.33
	1961-67	5.90	0.51
	1967-75	7.77	0.39
	1975-92	16.93	0.18
	1992-99	7.40	0.41

The recession rate errors vary between a minimum of 0.20 m/yr (1941-56 epoch considered for the Ozaukee site) and a maximum 0.51 m/yr (1961-67 epoch considered for the Manitowoc site).

5.1.3 Recession Rates over Time

The rates at which the toe and crest of the bluff have retreated in the past are calculated based on the distance between digitized historical bluff lines measured perpendicular to the shore. The bluff features are mapped on-screen as polyline features in ArcView™. To reduce the error associated with the misinterpretation of a few points along the bluff feature, the recession distance is calculated at increments of 10-20 m along a distance of a few hundred meters. Only the spatially averaged recession distance is reported.

There are six orthophotos available to study the recession rates of the bluffs at the Ozaukee Site. The five erosion periods, or epochs are described in Table 5.4 below.

Table 5.4 Erosion Epochs Considered for Ozaukee Site.

Epoch #	Start of Epoch [dd-mmm-yy]	End of Epoch [dd-mmm-yy]	Duration of Epoch [years]
1	07-Sep-41	16-May-56	14.70
2	16-May-56	04-Jun-64	8.06
3	04-Jun-64	27-May-75	10.98
4	27-May-75	16-Aug-88	13.23
5	16-Aug-88	01-Apr-95	6.63

Recession measurements are made for time periods ranging in length from 6.6 to 14.7 years for the Ozaukee site. Seven orthophotos (six erosion epochs) are considered for the Manitowoc site, as shown in Table 5.5.

Table 5.5 Erosion Epochs Considered for Manitowoc Site.

Epoch #	Start of Epoch [dd-mmm-yy]	End of Epoch [dd-mmm-yy]	Duration of Epoch [years]
1	04-Jul-38	01-Sep-52	14.17
2	01-Sep-52	06-Oct-61	9.10
3	06-Oct-61	28-Aug-67	5.90
4	28-Aug-67	02-Jun-75	7.77
5	02-Jun-75	01-May-92	16.93
6	01-May-92	22-Sep-99	7.40

Recession measurements are made for time periods ranging in duration from 5.9 to 16.9 years for the Manitowoc site.

Bluff Toe

The spatially and temporally averaged rates of bluff-toe recession measured at the Ozaukee site are summarized in Table 5.6.

Table 5.6 Ozaukee Site Bluff-Toe Recession Rates.

Profile →	WPW-1 [m/yr]	WPW-2 [m/yr]	WPW-3 [m/yr]	WPW-4 [m/yr]	PW-5 [m/yr]
Epoch #1	0.36	0.54	0.44	*	*
Epoch #2	-0.01	0.06	0.30	0.07	0.11
Epoch #3	2.19	1.78	0.97	1.31	1.11
Epoch #4	1.50	0.75	0.19	0.44	0.36
Epoch #5	-0.35	-0.14	0.34	-0.13	-0.94

*recession rates not measured due to lack of aerial photography coverage

The positive rates in Table 5.6 indicate bluff toe retreat. The negative recession rates indicate a near-zero toe retreat or a net deposition at the toe over the course of the erosion epoch.

Recession rates are measured at the crest but not at the toe of the bluff at the Manitowoc site. The Manitowoc bluffs are much lower and steeper than the Ozaukee County site, so the toe was extremely difficult to discern on orthorectified aerial images.

Bluff Crest

The recession-rate analysis of the bluff crest makes use of orthophotos created over the same epochs as used for the toe-recession analysis for the Ozaukee site. The Ozaukee site crest-recession rates are presented in Table 5.7. The rate of bluff–

crest and bluff–toe recession measured over time for the Ozaukee site is shown in Figure 5.1.

Table 5.7 Ozaukee Site Crest Recession Rates.

Profile →	WPW-1 [m/yr]	WPW-2 [m/yr]	WPW-3 [m/yr]	WPW-4 [m/yr]	WPW-5 [m/yr]
Epoch #1	0.32	0.22	0.47	*	*
Epoch #2	0.02	0.24	-0.03	-0.21	*
Epoch #3	-0.05	0.08	-0.05	0.51	*
Epoch #4	0.71	0.46	0.44	0.32	*
Epoch #5	0.66	0.48	0.69	0.45	*

*recession rates not measured due to lack of aerial photography coverage(Epoch #1) and due to the inability to discern the bluff top on the digital orthophoto (WTR-5, epochs 2-5)

In Table 5.7 the negative recession rates are within the estimated error (see Table 5.3) and are considered to be approximately zero. This makes sense since the crest, unlike the toe, should experience no loss or a net loss (not a gain) of material over time.

As the bluffs at the Manitowoc site are considered to retreat in a more or less parallel manner, the crest recession should reflect the recession at the toe. There may be some time lag between the waves eroding the base of the bluff and the response at the crest, but this lag is expected to be shorter than the duration of the epochs considered. The results of crest-recession-rate measurements at the Manitowoc County are summarized in Table 5.8. The crest-recession rates at the Manitowoc site are shown over time in Figure 5.2.

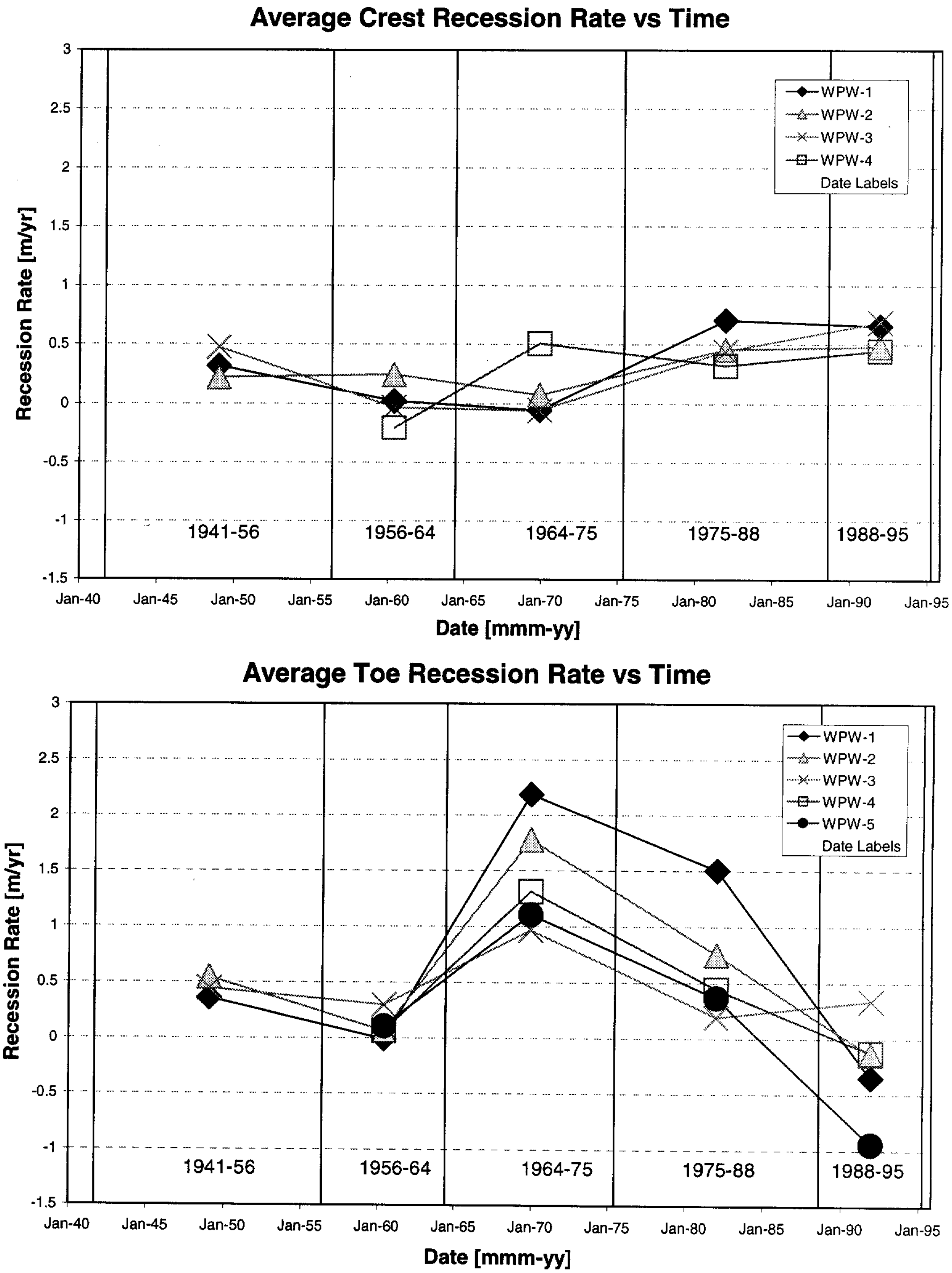


Figure 5.1 Bluff-Crest and Bluff-Toe-Recession Rate over Time at the Ozaukee Site.

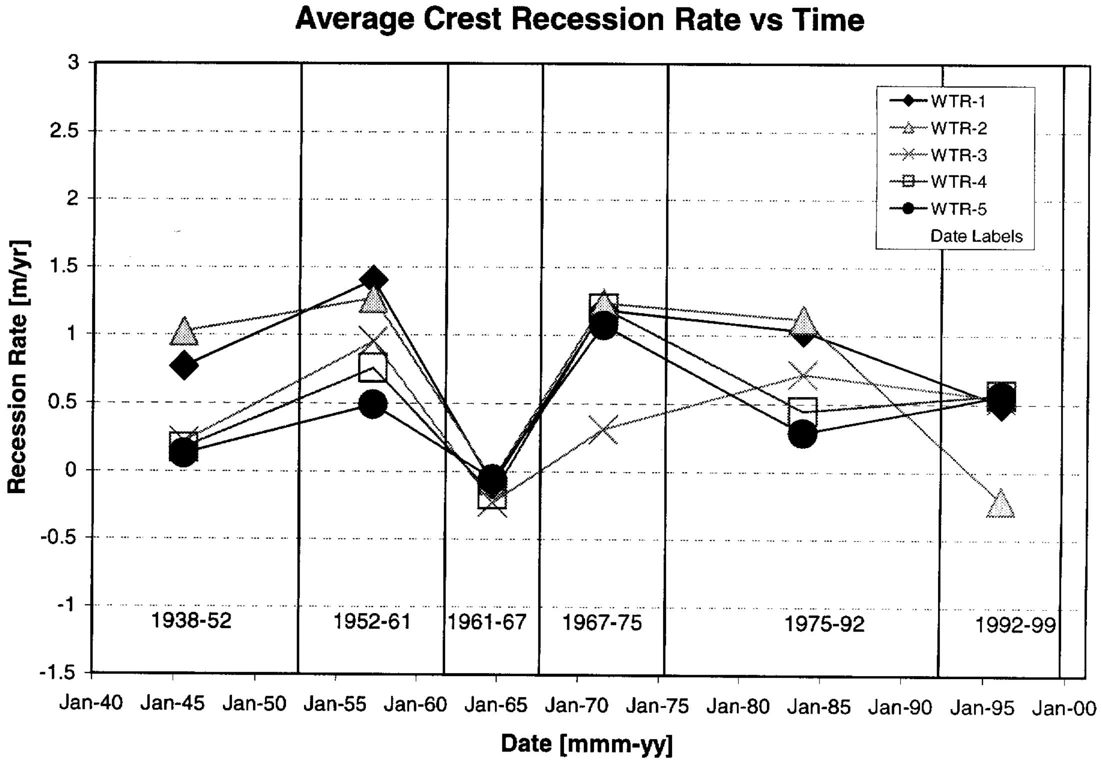


Figure 5.2 Bluff-Crest Recession Rate over Time at the Manitowoc Site.

Table 5.8 Manitowoc County Site Crest-Recession Rates.

Profile →	WTR-1 [m/yr]	WTR-1-2 [m/yr]	WTR-1-3 [m/yr]	WTR-1-4 [m/yr]	WTR-1-5 [m/yr]
Epoch #1	0.77	1.02	0.22	0.17	0.13
Epoch #2	1.40	1.27	0.95	0.76	0.49
Epoch #3	-0.09	-0.06	-0.23	-0.17	-0.05
Epoch #4	1.19	1.23	0.31	1.20	1.07
Epoch #5	1.03	1.12	0.72	0.45	0.29
Epoch #6	0.50	-0.21	0.54	0.57	0.56

Positive recession rates shown in Table 5.8 indicate a net removal of crest material. All the negative numbers shown are within the estimated error (see Table 5.2) and are considered to be approximately zero.

5.1.4 Recession Rates over Distance

As discussed in Chapter 2, changes in geologic and hydrologic conditions can affect the rate of bluff erosion on a spatial scale. The spatial variability of recession rates at the two study sites is considered. While the geology is not considered significantly variable at either the Ozaukee or the Manitowoc site, the geometry of bluffs at the Ozaukee site changes from a near-straight slope at the south end (profiles WPW-1 an WPW-2) to a stepped profile to the north (profiles WPW-3 to WPW-5). A treed slump block buttresses the overall slope across approximately the northern two-thirds of the Ozaukee Site. The bluffs at the Manitowoc site, however, consist of short, consistently bare and straight slopes. The spatial variation in recession rates for each epoch considered at the toe and crest of the Ozaukee County site is shown in Figure 5.3. Figure 5.4 portrays the spatial variability in recession rates of the bluff crest at the Manitowoc site.

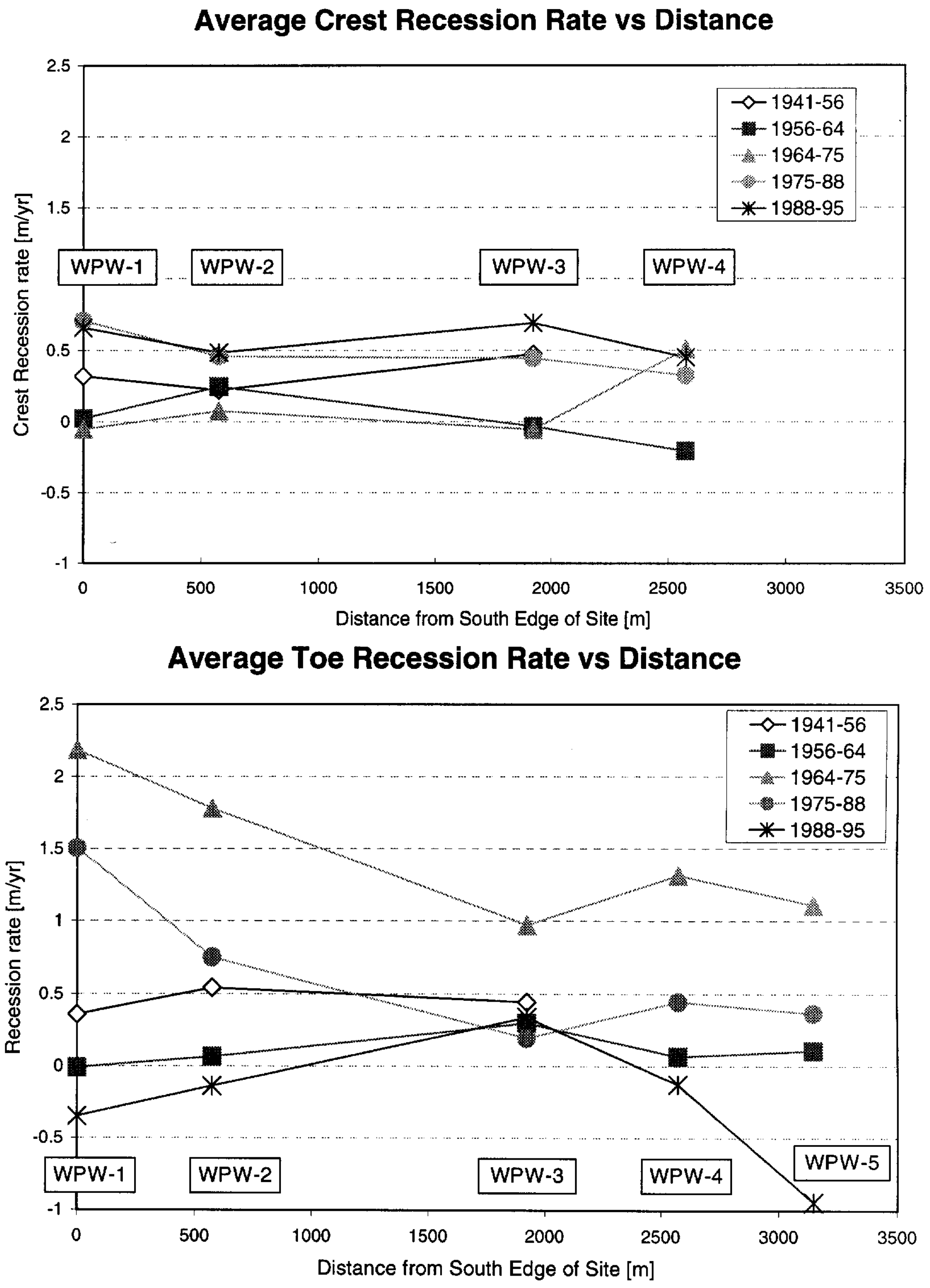


Figure 5.3 Spatial Variation in Recession Rate at the Ozaukee Site.

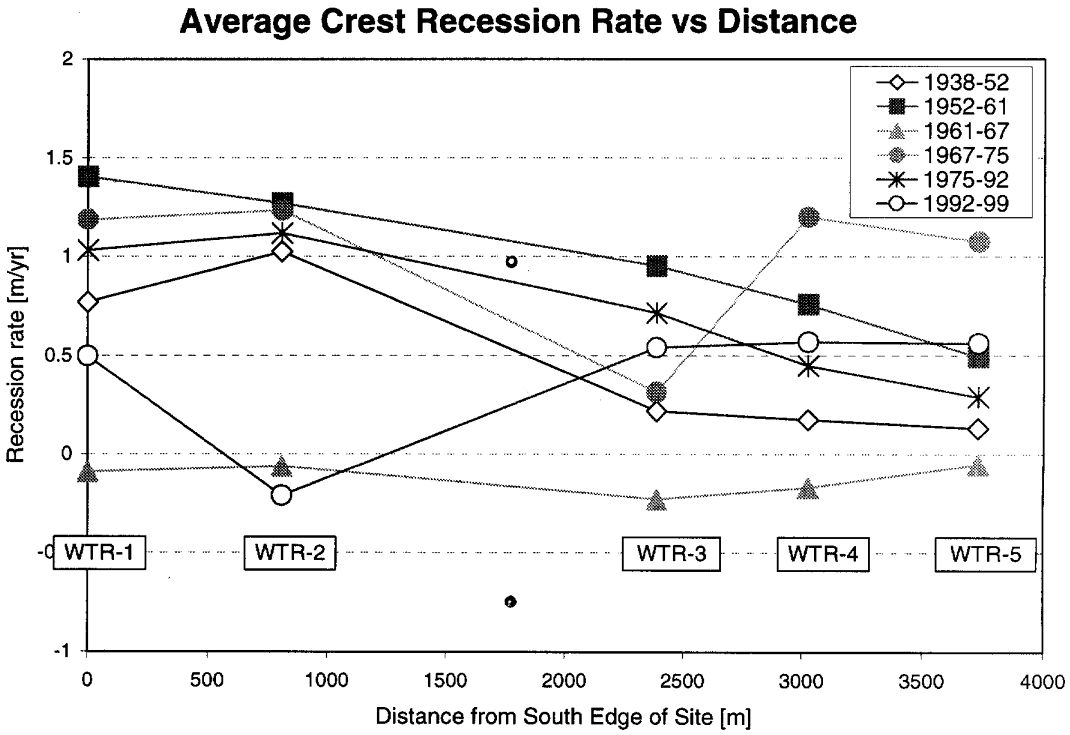


Figure 5.4 Spatial Variation in Recession Rate at the Manitowoc site.

5.2 Coastal Processes

5.2.1 Lake Levels

The lake level data have been provided on a monthly basis. The monthly lake levels are provided in chart form in Appendix II. The average, maximum and minimum lake level over each erosion epoch for the Ozaukee and Manitowoc County sites are given in Tables 5.9 and 5.10 respectively.

Table 5.9 Lake Level Statistics for Ozaukee County Erosion Epochs.

Epoch Start Year	Epoch End Year	Average Lake Level [IGLD85, m]	Maximum Lake Level [IGLD85, m]	Minimum Lake Level [IGLD85, m]
1941	1956	176.53	177.23	175.83
1956	1964	176.14	176.73	175.54
1964	1975	176.55	177.27	175.56
1975	1988	176.83	177.52	176.36
1988	1995	176.52	176.92	176.13

Table 5.10 Lake Level Statistics for Manitowoc County Erosion Epochs

Epoch Start Year	Epoch End Year	Average Lake Level [IGLD85, m]	Maximum Lake Level [IGLD85, m]	Minimum Lake Level [IGLD85, m]
1938	1952	176.38	177.23	175.83
1952	1961	176.43	177.13	175.70
1961	1967	176.00	176.00	175.54
1967	1975	176.79	177.27	176.21
1975	1992	176.74	177.52	176.13
1992	1999	176.68	176.68	176.26

The Ozaukee site epoch-averaged lake levels vary from 176.14 m to 176.83 m [IGLD85] and the Manitowoc site epoch-averaged lake levels range from 176.00 m to 176.79 m [IGLD85].

5.2.2 Wave Data

As discussed in Section 4.3.2, the wave data used for this study is obtained from a pre-existing wind wave hindcast dataset produced by the U.S. Army Corps of Engineers. These wave data represent two separate wind wave hindcasting efforts (ACE). The first wind wave hindcasting project was carried out for the period 1956-87 and the second makes up the remaining years, 1988-95. The wind field constructed for the earlier hindcast project was derived from land-based wind measurements and is considered of poorer quality than the wind field used for the 1988-95 study, which incorporated open water buoy wind data (Lin 2000). In addition, the earlier hindcast used a 15–km bathymetric grid cell size while the recent hindcast used a finer 5–km bathymetric grid (Lin 2000). While the same software was used for both hindcasting efforts, the products are not considered directly comparable (Lin 2000).

Since this hindcast data set is the most complete historical record of available wave information near the shores of the two study sites, simple corrections were made to the earlier wave data to create a more consistent and complete time series of wave data. The wave periods and heights were adjusted by a factor of 1.15 so the average period across the 1956 to 1987 data set is the same as the average from 1988-97. Similarly, the wave heights were adjusted so that a consistent temporal average was attained. In the raw data, wave heights from 1956-87 were scaled by a factor of 1.21 and 1.32 for station M0011 (near the Ozaukee site) and M0018 (near the Manitowoc site) respectively. Table 5.11 provides the time periods during which wave data are available and the maximum hindcast wave heights for each erosion epoch.

Table 5.11 Wave Data Availability and Maximum Wave Heights.

Site	Start	End	Duration [years]	Fraction of Epoch for which wave data is Available	Maximum Wave Height [m]
Ozaukee	1-Jan-56	16-May-56	0.373	0.03	3.8
	16-May-56	04-Jun-64	8.058	1.00	5.1
	04-Jun-64	27-May-75	10.984	1.00	5.1
	27-May-75	16-Aug-88	13.233	1.00	4.6
	16-Aug-88	01-Apr-95	6.627	1.00	5.2
Manitowoc	1-Jan-56	06-Oct-61	5.767	0.63	3.0
	06-Oct-61	28-Aug-67	5.896	1.00	5.7
	28-Aug-67	02-Jun-75	5.896	1.00	4.5
	02-Jun-75	01-May-92	7.767	1.00	5.1
	01-May-92	25-Aug-99	16.926	0.77	5.4

As indicated in Tables 5.9 and 5.11, the erosion epochs that spanned the years before 1956 or past 1999 do not have a complete time series of wave data associated with them. The first erosion epoch for the Ozaukee site, 1941–56 only overlaps with wave data for 3 percent of the duration of the epoch. For this reason the wave data summaries calculated for this early period at the Ozaukee site are not considered in the wave parameter – recession rate comparison. The latest erosion epoch, 1988-95 overlaps completely with wave data. The earliest erosion period for the Manitowoc site, 1938–52, has no overlap with wave data so this period is not considered for a comparison between recession rate and wave climate. The 1952–61 and 1988–92 erosion epochs for the Manitowoc site have 63% and 77% overlap so the wave information for both these epochs is included in the analysis.

5.2.3 Deepwater Wave Power

The hindcast wave data obtained for stations near the Ozaukee and Manitowoc sites are assessed for their deepwater character using the techniques outlined in Section 4.3.4. The number and percentage of 3-hour wave intervals whose period is less than T_{max} (Equation 4.7) provides an indication of the frequency of occurrence of waves that do not satisfy the deepwater criterion. The station depths and percentage of waves satisfying the deepwater criterion for the stations near the two sites are summarized in Table 5.12.

Table 5.12 Results of Deepwater Check.

Site	WIS Station #	Depth [m]	T_{max} [s]	Number of Occurences where $T>T_{max}$ (percentage)
Ozaukee	M0011	100	11.34	0 (0%)
Manitowoc	M0018	46	7.69	869 (0.71%)

Table 5.12 indicates that virtually all of the waves in the hindcast data set satisfy the deepwater criterion. Hence, the wave power calculated based on these data can be considered deepwater wave power. Values of deepwater wave power are calculated at the 3-hour intervals that wave data are available. The shoreline orientations for all profiles at both study sites are provided in Section 3.1. Only waves that were directed towards the shoreline were considered. Waves oriented more than 90° from the perpendicular to the shoreline are not considered to have significant impact on the recession of the bluffs at the sites. A statistical summary of the deepwater wave power calculated for the two study sites is shown in Tables 5.13 and 5.14.

Table 5.13 Ozaukee Site - Statistics on Deepwater Wave Power.

Epoch →	1941-56	1956-64	1964-75	1975-88	1988-95
Maximum [kW]	NO DATA	236	189	179	259
Date of Maximum	NO DATA	11/21/1962	03/25/1969	11/20/1977	04/01/1993
Mean [kW]	NO DATA	5.56	5.65	5.33	5.76
Standard Deviation	NO DATA	12.4	12.4	11.7	11.0

Table 5.14 Manitowoc Site – Statistics on Deepwater Wave Power.

Epoch →	1938-52	1952-61	1961-67	1967-75	1975-92	1992-99
Maximum [kW]	NO DATA	137	356	183	236	279
Date of Maximum	NO DATA	11/08/1960	04/14/1964	11/17/1969	08/28/1977	04/01/1993
Mean [kW]	NO DATA	3.30	3.85	4.94	4.35	4.76
Standard Deviation	NO DATA	7.02	10.7	10.7	8.94	9.82

The minimum wave power is not provided because there are a number of entries during each epoch where the wave power is zero, so the minimum values would not provide meaningful information.

The maximum deepwater wave power at the Ozaukee site, 259 kW, is associated with the same epoch (1988–95) as the maximum mean wave power. The lowest mean deepwater wave power, 5.33 kW was calculated for the 1975–88 period. The 1975–88 period is also associated with the lowest maximum wave power, 179 kW.

The Manitowoc site shows the greatest deepwater wave power, 356 kW, during the 1961–67 period, which does not correspond to the period with the highest mean wave power. The maximum mean wave power, 4.94 kW was calculated for the 1967–75 period.

All mean values of deepwater wave power calculated at the Manitowoc site are lower than the mean values calculated at the Ozaukee site. However, the maximum peak wave power is higher for the Manitowoc site (356 kW) than for the Ozaukee site (259 kW).

5.2.4 Wind Setup

The effects of wind setup are analysed using the methods outlined in Section 4.3.5. The wind setup is calculated based on wind speed, wind direction and fetch (distance across the lake from the site in the direction from which the wind blows). Wind setup is considered for two effective depths of the lake, 50 m and 100 m. The setup computed with an assigned average lake depth of 50 m is greater than a setup calculated with an assigned depth of 100 m. The values computed for wind setup were added to the impact wave height, discussed in Section 5.2.4. The effects of augmenting the static lake level with the wind setup on the wave-impact height values are shown in Appendix IV. The wind setup effect on the wave-impact height is not nearly as dramatic as the variations due to lake level and offshore wave parameters (i.e. wave height and period).

5.2.5 Wave-Impact Heights

The wave-impact height (WIH) is the vertical distance above the base of the bluff to which the waves reach. It is computed from the following relation:

Wave-Impact Height = {Runup} + {Still Lake Level} + {wind setup} – {Base of Bluff Elevation}.

The wave–impact height is determined for each 3-hour increment for which wave data are available, from 1956 to 1997. The elevations of the base of the bluffs and beach slope that are inputs to the runup equation are provided in Table 5.15.

Table 5.15 Base of Bluff Elevations and Beach Slopes.

Site	Profile	Base of Bluff Elevation [IGLD85, m]	Beach Slope (tan θ)
Ozaukee	WPW-1	176.65	0.127
	WPW-2	176.88	0.130
	WPW-3	176.88	0.130
	WPW-4	176.77	0.108
	WPW-5	176.91	0.154
Manitowoc	WTR-1	176.55	0.112
	WTR-2	176.94	0.147
	WTR-3	177.43	0.137
	WTR-4	176.85	0.134
	WTR-5	176.84	0.129

Equation 4.10 is applied to determine the runup height, R, for each wave directed towards the site. The range of allowable beach slopes specified by Mase(1989) is between 0.033 and 0.20. The beach slopes used to compute wave-impact heights for all 10 profiles fall within this range.

The wave–impact heights reported here are calculated based on the R_2 runup height. The R_2 is the runup height exceeded by 2% of all runups associated with a given wave condition and beach slope. The minimum, maximum, mean and standard deviation of all wave-impact heights (WIH) over each of the epochs for the Ozaukee and Manitowoc sites are given in Tables 5.16 and 5.17 respectively.

Table 5.16 Ozaukee Site - Statistics of Wave-Impact Heights (WIH).

Profile	Epoch	Minimum WIH [m]	Maximum WIH [m]	Mean WIH [m]	SD(WIH) [m]
WPW-1	56-64	-1	6.5	0.8	0.9
	64-75	-0.9	6.4	1.2	1.0
	75-88	-0.2	6.4	1.5	0.9
	88-95	-0.5	7.5	1.3	0.8
WPW-2	56-64	-1.3	8.0	0.8	1.1
	64-75	-1.2	6.3	1.0	1.0
	75-88	-0.4	6.2	1.2	0.9
	88-95	-0.7	7.4	1.0	0.8
WPW-3	56-64	-1.3	6.4	0.6	0.9
	64-75	-1.2	6.3	1.0	1.0
	75-88	-0.4	6.2	1.2	0.9
	88-95	-0.7	7.4	1.0	0.8
WPW-4	56-64	-1.1	5.6	0.5	0.8
	64-75	-1.1	5.7	0.9	0.9
	75-88	-0.3	5.6	1.2	0.8
	88-95	-0.6	6.5	1.0	0.7
WPW-5	56-64	-1.3	7.3	0.7	1.0
	64-75	-1.2	7.1	1.1	1.1
	75-88	-0.5	7.0	1.4	1.0
	88-95	-0.7	8.3	1.2	0.9

Table 5.17 Manitowoc Site - Statistics of Wave-Impact Heights (WIH).

Profile	Epoch	Minimum WIH [m]	Maximum WIH [m]	Mean WIH [m]	SD(WIH) [m]
WTR-1	1952-61	-0.8	5.5	0.7	0.7
	1961-67	-1.0	7.1	0.5	0.7
	1967-75	-0.3	6.1	1.4	0.8
	1975-92	-0.3	6.5	1.3	0.7
	1992-99	-0.1	7.1	1.3	0.7
WTR-2	1952-61	-1.2	6.3	0.5	0.8
	1961-67	-1.4	8.4	0.3	0.9
	1967-75	-0.7	7.0	1.3	0.9

Profile	Epoch	Minimum WIH [m]	Maximum WIH [m]	Mean WIH [m]	SD(WIH) [m]
	1975-92	-0.7	7.5	1.1	0.9
	1992-99	-0.5	8.2	1.2	0.8
WTR-3	1952-61	-1.6	5.5	-0.1	0.8
	1961-67	-1.9	7.4	-0.2	0.8
	1967-75	-1.2	6.2	0.7	0.9
	1975-92	-1.2	6.6	0.6	0.8
	1992-99	-1.0	7.3	0.6	0.8
WTR-4	1952-61	-1.1	6.0	0.5	0.8
	1961-67	-1.3	7.9	0.3	0.8
	1967-75	-0.6	6.6	1.3	0.9
	1975-92	-0.7	7.0	1.2	0.8
	1992-99	-0.4	7.8	1.2	0.8
WTR-5	1952-61	-1.1	5.8	0.5	0.7
	1961-67	-1.3	7.6	0.3	0.8
	1967-75	-0.6	6.5	1.2	0.9
	1975-92	-0.6	6.8	1.1	0.8
	1992-99	-0.4	7.6	1.2	0.8

The extreme statistics shown as maximum wave-impact heights shown in Tables 5.15 and 5.16 likely represent infrequent events that do not last long enough to have a major erosive effect on the toe of the bluff. The minimum wave-impact height also represents an infrequent occurrence, but one when there is likely to be no influence on the bluff. The duration coupled with the magnitudes of the extreme values are likely more meaningful factors to consider when correlating the wave-impact height with recession rate. The mean values of wave-impact height appear to be a positive number for each of the erosion intervals considered. This could indicate that either there have been more times that the waves have hit the bluffs than not or that there have been low wave-impact heights over much of the time, interspersed with periods of extremely high wave-impact heights. The temporal distribution of wave-impact heights is not sufficiently characterized by the first (mean) and second (standard deviation) moments for each epoch to determine which of the above cases have actually occurred. The statistics provided in Tables 5.16 and 5.17, while meaningful, represent entire erosion epochs with durations of 6 years or more and provide limited information on the pattern of wave-impact heights that occurred over smaller time increments *during* each epoch. However, below a method is described to circumvent this problem.

As discussed in Chapter 2, extreme events consisting of high waves with their associated high wave-impact heights are likely to cause the greatest amount of recession at the base of the bluff. The greater the number of high wave-impact heights that are experienced, the more the recession magnitude is likely to be. To better quantify the amount of extreme wave activity on a temporal scale finer than the duration of each epoch, the maximum wave-impact height for each month of the entire hindcast period is computed. Annual averages based on these monthly peaks are then determined. These annual averages of monthly peaks may provide a better indication of the wave-impact heights on the bluff during each erosion period. The results are presented in Section 5.5.4.

5.3 Climate

5.3.1 Precipitation

The precipitation magnitude was recorded at the Milwaukee airport from January 1950 to present. Monthly precipitation collected during this period is analyzed. The monthly precipitation magnitudes for the duration of record are provided in Appendix

III. In addition, the total magnitude of precipitation during each epoch divided by the number of years in the given epoch is determined. This “annualized average” is calculated for each erosion epoch whose time interval overlaps with the period during which precipitation data are available. The time intervals during which precipitation data are available during the erosion epochs and the “annualized averages” are shown in Table 5.18.

Table 5.18 Annualized Averages of Precipitation over Erosion Epochs.

Site	Start	End	Duration [years]	Fraction of Epoch for which precipitation data is available	Annualized Average Precipitation [mm per year]
Ozaukee	1-Jan-50	16-May-56	6.38	0.43	800
	16-May-56	04-Jun-64	8.06	1.00	708
	04-Jun-64	27-May-75	10.98	1.00	803
	27-May-75	16-Aug-88	13.23	1.00	901
	16-Aug-88	01-Apr-95	6.63	1.00	876
Manitowoc	1-Jan-50	01-Sep-52	2.67	0.19	912
	01-Sep-52	06-Oct-61	9.10	1.00	757
	06-Oct-61	28-Aug-67	5.90	1.00	684
	28-Aug-67	02-Jun-75	7.77	1.00	808
	02-Jun-75	01-May-92	16.93	1.00	905
	01-May-92	25-Aug-99	7.32	0.99	793

The annualized average precipitation values ranged from 708 mm per year (1956–64 epoch) to 901 mm per year (1978–88 epoch) for the Ozaukee Site. This range represents a maximum variation of about 28% from the low value of 708 mm per year.

The precipitation values range from 684 mm per year (1961–67 epoch) to 912 mm per year (1950–52). This range represents a maximum variation of 33% from the minimum value of 684 mm per year. However, the maximum precipitation rate of 912 mm per year is an annual amount based on precipitation recorded between 1950 and 1952, a period representing less than 20% of the total duration of the 1938–52 erosion epoch.

5.3.2 Wind Data and Storm Events

As outlined in Section 5.2.2, the 3-hourly over-water wind and wave data from stations along the coast are products of two different wind-wave hindcasting projects. The first project spanned the years between 1956 and 1987. The second project extended from 1988 to 1997. The wind-field model generated for the earlier project is based solely on wind gauge data collected on land. The wind field for the more recent project included over-water (buoy) data as well as land data. The averages of wind speeds for both of these time periods are summarized in Table 5.19 for both the station (over-water) wind data and the Milwaukee (over-land) wind data. The Milwaukee wind data used for these averages have been corrected to the standard 10 m elevation above ground.

Table 5.19 Over-Land and Over-Water Average Wind Windspeeds

	Milwaukee wind gauge (hourly, land) [m/s]	M0011 stn. (PW site, every 3 hours) [m/s]	M0011 stn. Ratio of Land/water wind averages [m/s]	M0018 stn. (TR site, every 3 hours) [m/s]	M0018 stn. Ratio of Land/water wind averages [m/s]
1956-87	10.2	11.9	0.9	10.4	1.0
1988-97	9.3	6.4	1.4	6.1	1.5

The over-land to over-water ratios for the 1956-1987 period are 0.9 and 1.0 for the two stations nearest the study sites. Since the wind field for this early epoch was based solely on land-collected wind data and the Milwaukee airport anemometer was the closest gauge to both study sites, the ratio of over-land to over-water wind speeds should be consistent with the expected values. The values of 0.9 and 1.0 are in or near the expected range of 0.7-0.9 (see Section 4.2.1.). A sudden drop in the station (over-water) wind speed occurs in January 1988 for both M0011 and M0018. This is due to a changed input for the calculation of the wind field: The more recently generated wind-field models include buoy (see Figure 4.1) data as well as land-recorded data. Unfortunately, no further detailed information concerning the models used could be obtained from the USACE who provided the station wind data. Obviously, comparison of the over-water and over-land wind speeds does not apply for the more recent hindcast study results. Because of the uncertain long-term consistency of the station wind data, the present study does not rely on it. Instead the consistent over-land (Milwaukee) data were used for counting storm events.

After 1987, the average wind speeds dropped but, interestingly enough, average wave heights increased. The same software (DWAVE) was used for both the early and the recent wind wave hindcast projects. Since buoy data are available for the entire 1988-97 period, the wave data recorded at buoy locations were used to scale all the modeled virtual station data for the recent hindcast results. Such complete scaling was not possible for the earlier hindcast due to the limited buoy data available for the 1956-87 period.

For the purpose of computing storm events, the hourly elevation-corrected Milwaukee wind data is used. No additional factor due to the over-land to over-water ratio is applied. The frequency of storm events on an annual basis and on a per-epoch basis were determined to allow a comparison of the temporal variation in recession rates with the storm activity. The presence and number of storms was determined based on the algorithm outlined in Section 4.2.3. The hourly wind data's temporal coverage begins in January 1, 1950 and continues to August 5, 2000. There are a number of "gaps" in the wind data. Wind speed and direction during no-data periods of duration 4 hours or less are interpolated based on the speeds and directions measured at either end of the no-data periods. Longer no-wind periods are considered to be times void of data. If blanked data occurs during a storm event, the blank period would initiate the termination of a storm event. Table 5.20 summarizes the storm statistics for the Ozaukee site. The annual number of storms and the epoch-averaged number of storms per year are provided in Figures 5.7 and 5.8 for the Ozaukee and Manitowoc sites respectively.

Table 5.20 Storm Statistics for Erosion Epochs of the Ozaukee site.

Epoch →	1950-56	1956-64	1964-75	1975-88	1988-95
Total Number of Storms	664	946	1306	1604	830
Number of Storms per year	104	117	119	121	125
Total Duration of Storm Activity [hrs]	11762	17710	22707	26799	13004
Weighted Average of Speed During Storms [m/s]	10.1	10.7	10.4	10.4	9.6

Epoch →	1950-56	1956-64	1964-75	1975-88	1988-95
Weighted Average of Wind Directions During Storms [degrees from north]	96.9	103.1	103.1	99	95.3
Average Speed of Most Intense Storm [m/s]	27	22.4	20.8	21.4	19.1
Maximum Wind Speed [m/s]	44.3	37.6	32.2	53.7	31

Because the duration of each epoch is different, the number of storms per year represents a degree of storm activity relative to duration over which storms are counted. The number of storms per year appears to be generally rising over time, with the peak annual storm frequency associated with the most recent epoch, 1988–95. The weighted average for both the direction and wind speed during storms is weighted based on storm duration. The longer the storm lasted, the more its wind speed or direction influences the weighted average.

Since the shoreline orientation varies among the profiles at the Manitowoc site, the storm statistics were computed separately for each profile. The annual number of storms and the epoch-averaged storm counts were not found to vary significantly among the profiles. The storm count statistics are shown for the two profiles whose orientations are the same (WTR-3 and WTR-4) in Table 5.21. The storm statistics for the remaining profiles are provided in Appendix VI. Figure 5.8 provides the annual and epoch-averaged deepwater wave power, storm counts and recession rates relevant for the WTR-3 and WTR-4 profiles. Similar plots for the remaining profiles are provided in Appendix VI.

Table 5.21 Storm Statistics for Erosion Epochs of the Manitowoc site. Shoreline Orientation for WTR-3 or WTR-4 (358°-178°) assumed.

Epoch →	1952-61	1961-67	1967-75	1975-92	1992-99
Total Number of Storms	266	990	714	865	1994
Number of Storms per year	100	109	121	111	118
Total Duration of Storm Activity [hrs]	4845	17821	12832	15603	35157
Weighted Average of Speed During Storms [m/s]	9.8	10.5	10.2	10.8	10.5
Weighted Average of Wind Directions During Storms [degrees from north]	74.5	84.8	87.5	83.1	78.6
Average Speed of Most Intense Storm [m/s]	18.8	20.9	22.1	20.8	22.4
Maximum Wind Speed [m/s]	33.5	38.9	35.4	32.2	53.7

It is important to keep in mind that the same hourly wind data set was used to create the statistical summaries in both Table 5.19 and Table 5.20. Because the erosion epochs differ and the shoreline orientations are different for the two sites, the summaries are presented separately. The maximum number of storms per year at the Manitowoc site was observed during the 1967–75 epoch, whereas the least number of storms were observed during the 1952–61 period.

5.4 Recession-Rate Analysis at Crest

5.4.1 Precipitation Magnitude and Crest-Recession Rate

The annual precipitation rates and the average precipitation rates per epoch are shown with the crest-recession rates for the Ozaukee site in Figure 5.5. There is a

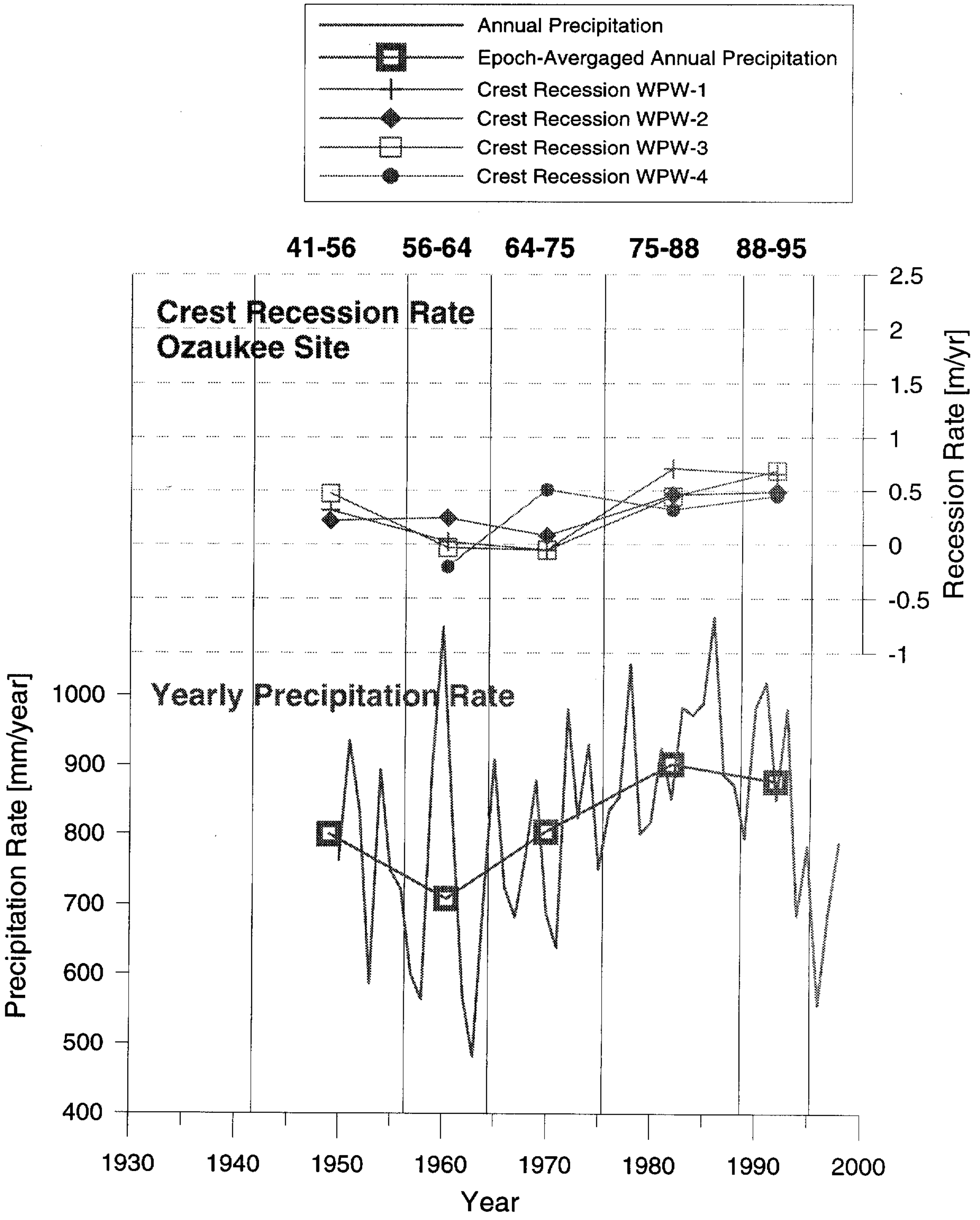


Figure 5.5 Crest-Recession Rate and Precipitation Rate at the Ozaukee Site.

steady increase in the average lake levels starting after the 1956–64 period. With the exception of WPW-4, this appears to match the trend of increasing crest-recession rates after the 1964–75 period. However, the crest-recession rate values are relatively low (between 0 and 0.5 m/yr) and the change in precipitation rates over the span of decades does not vary appreciably. The precipitation magnitudes on the scale of years do, however, show some notable changes, particularly the maximum yearly value of over 1000 mm in 1959.

The precipitation rate and crest-recession rate over time for the Manitowoc site are shown in Figure 5.6. The overall minimum of annualized precipitation averaged over the erosion epochs occurs during the 1961–67 epoch. This is the same period during which we see virtually no crest recession. The increased recession rates are measured on either side of this low-erosion epoch. Slightly increased precipitation rates have also occurred on either side of the low-precipitation epoch. However, the average precipitation and recession rate trends over time do not entirely agree. The epoch-averaged precipitation rates show a local maximum in the earliest epoch (1938-52), whereas recession rates for the earliest epoch are lower than the following (1952-61) rate. The 1938-52 erosion epoch only overlaps with precipitation data by 19%, so the average precipitation rate may not be representative of the entire epoch.

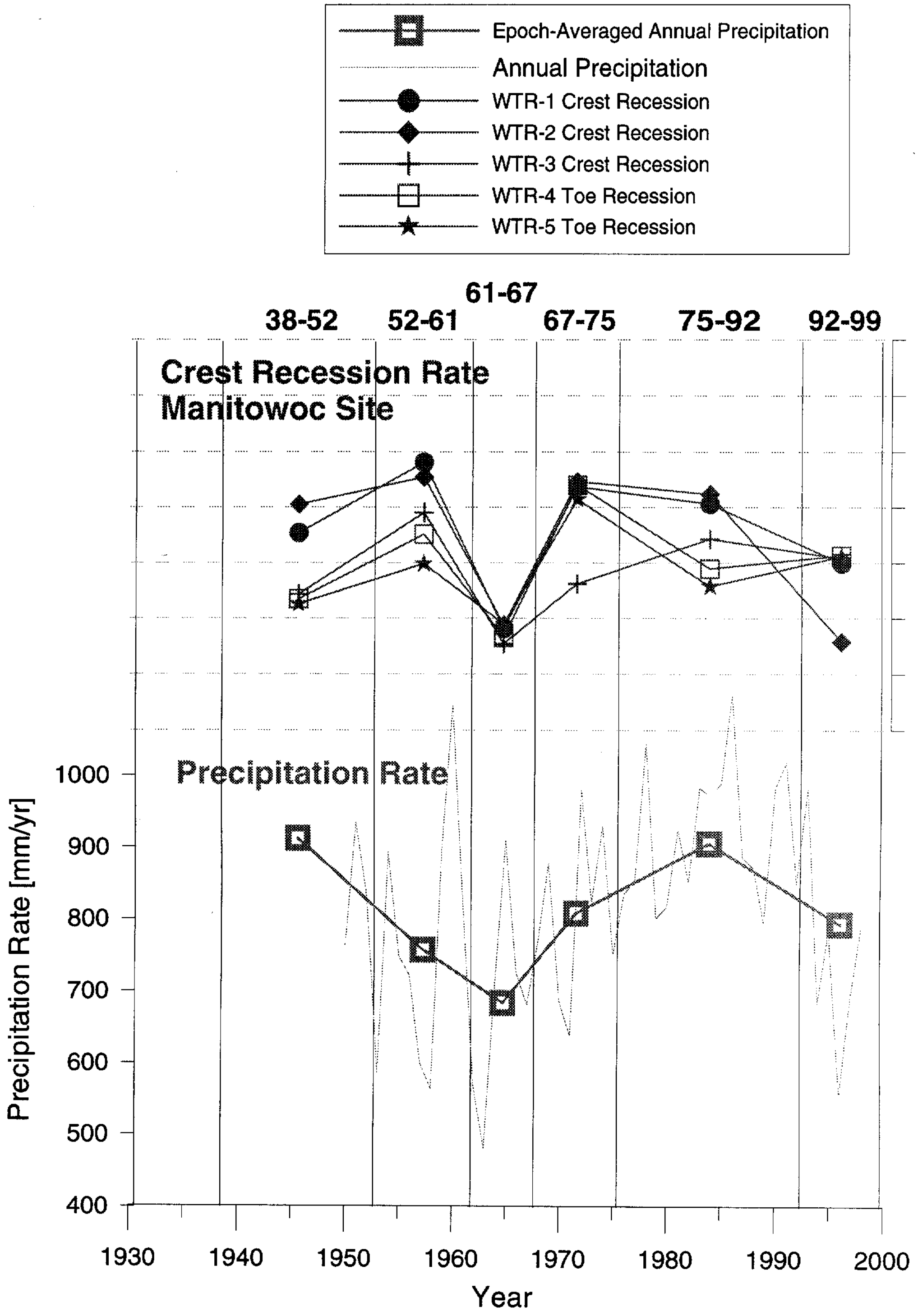


Figure 5.6 Crest-Recession Rate and Precipitation Rate at the Manitowoc Site.

5.4.2 Storm Events and Crest-Recession Rate

The number of storms per year is shown on an annual basis and on an epoch-averaged basis for the Ozaukee site in Figure 5.7 and for the Manitowoc site in Figure 5.8. The crest and toe-recession rates (where measured) are shown on these figures for one representative crest profile at each site. For the Ozaukee site, the highest average rate of storms occurs during the most recent erosion epoch (1988-95), a time where the crest-recession rate is at or near its highest level. A number of consecutive years of elevated storm activity occur in the mid-1960's and the early 1970's. Both of these periods are associated with a high crest-recession rate at the Ozaukee site.

At the Manitowoc site a relatively large average number of storms per year, on the time scale of epochs, occurred during the period (1961-67) when the lowest rate of recession took place. The maximum average number of storms per year is observed during the most recent epoch, 1992-99. At the time scales being considered, the crest-recession rate does not appear to be strongly influenced by storm frequency. The annual storm frequency calculated are greater than 100 storms per year. This is equivalent to more than 1 storm every four days. This seems to be a higher frequency than would be expected for extreme storm activity at the two study sites. Consequently, a more extreme storm definition may be appropriate to determine the number of storms that significantly contribute to bluff recession.

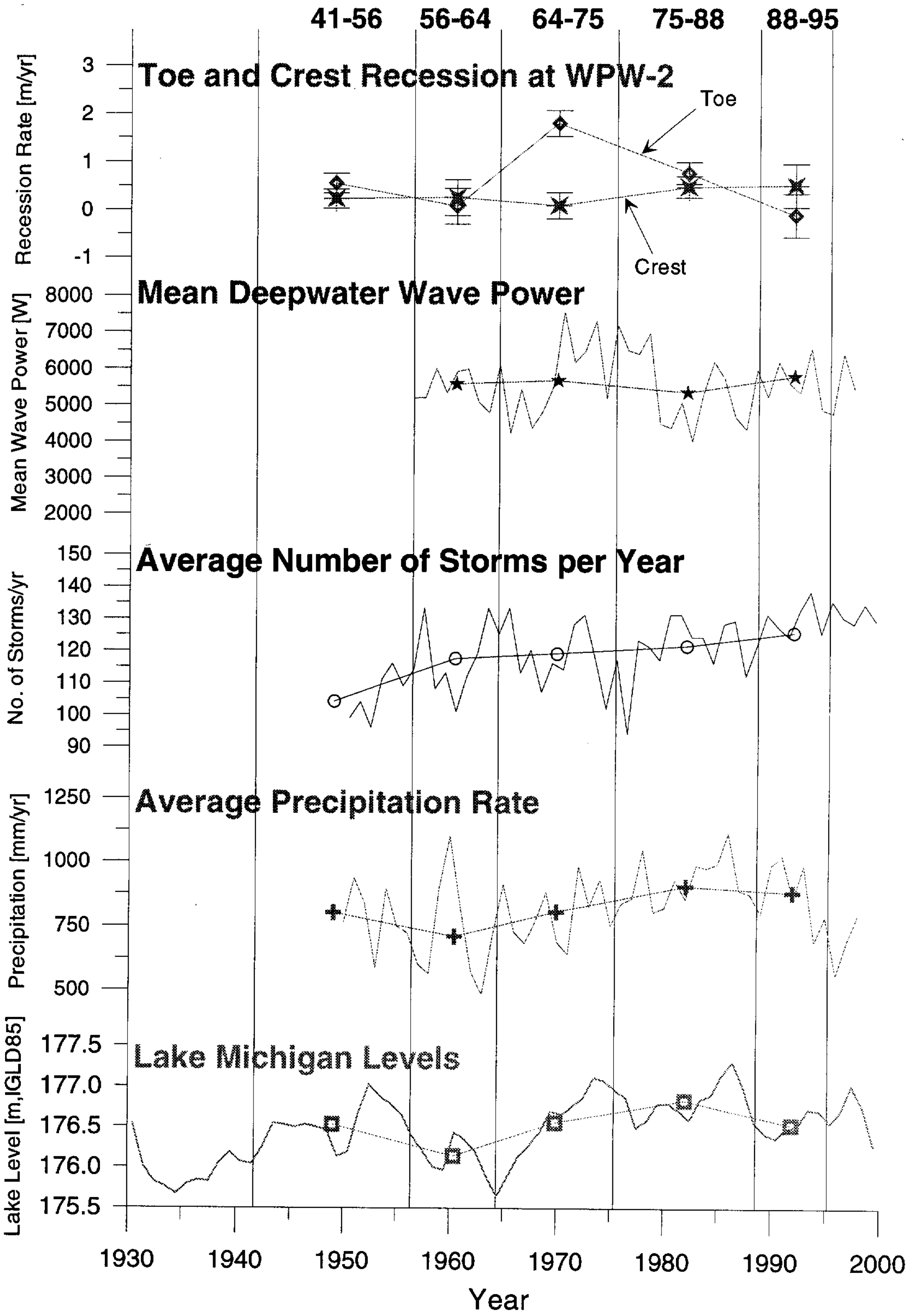


Figure 5.7 Lake Level, Storm Count, Precipitation, Wave Power and Recession Rate at the Ozaukee Site.

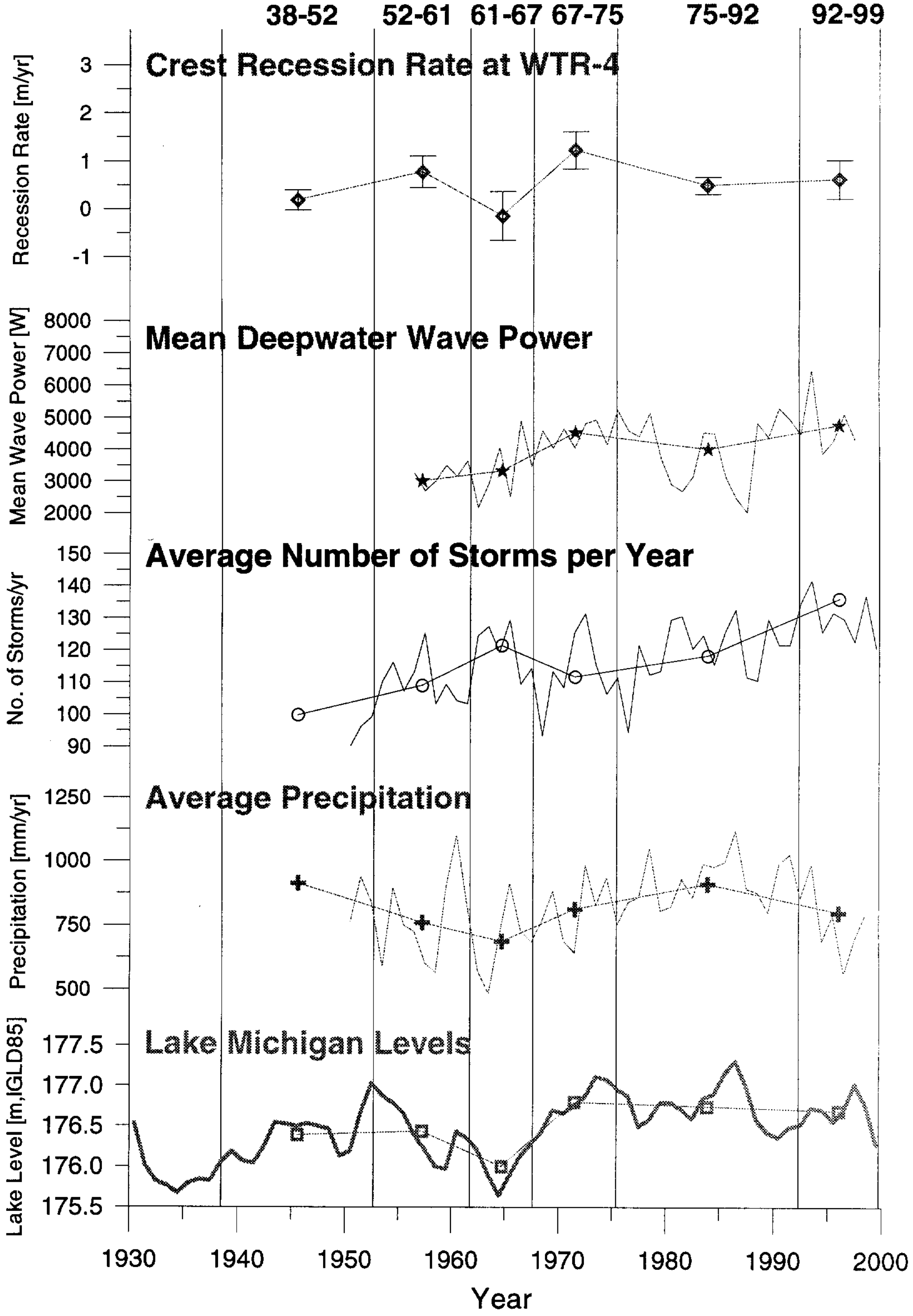


Figure 5.8 Lake Level, Storm Count, Precipitation, Wave Power and Recession Rate at the Manitowoc Site.

5.4.3 Crest-Recession Rate and Lake Level

The crest-recession rate is likely to be influenced by lake level for sites where the lag time between undercutting at the base and the response in the form of failure at the crest is on the order of years or months. For the Ozaukee site, the response of the crest to the undercutting at the toe is expected to be on the order of 50 to 100 years. In contrast, at the lower bluffs at Manitowoc County there is likely to be a crest response time on the order of years between the removal of toe material and the retreat at the crest.

Figure 5.9 shows the crest-recession rates at the Ozaukee site and the Lake Michigan Lake levels over time. While there is little recession during the low water level period during the 1960's, the recession rate does not rise definitively rise thereafter as does the level of the lake. A rise in crest recession rate is discernible between the 1964–75 epoch and the 1975–88 epoch. This is coincident with a further rise in lake level. However, the crest recession maintains its rate of 0.5 m per year through the final erosion epoch while the lake level drops significantly.

The recession rate of the bluff crest at the Manitowoc site is shown together with historic lake level in Figure 5.10. The crest shows equivalently high (1-1.5 m/yr) recession rates before and after the 1961–67 epoch for profiles WTR-1 and WTR-2. The lake level shows a local low during the low-erosion period of 1961-67. The lake–level rise after the 1961-67 period is of greater magnitude than the lake–level

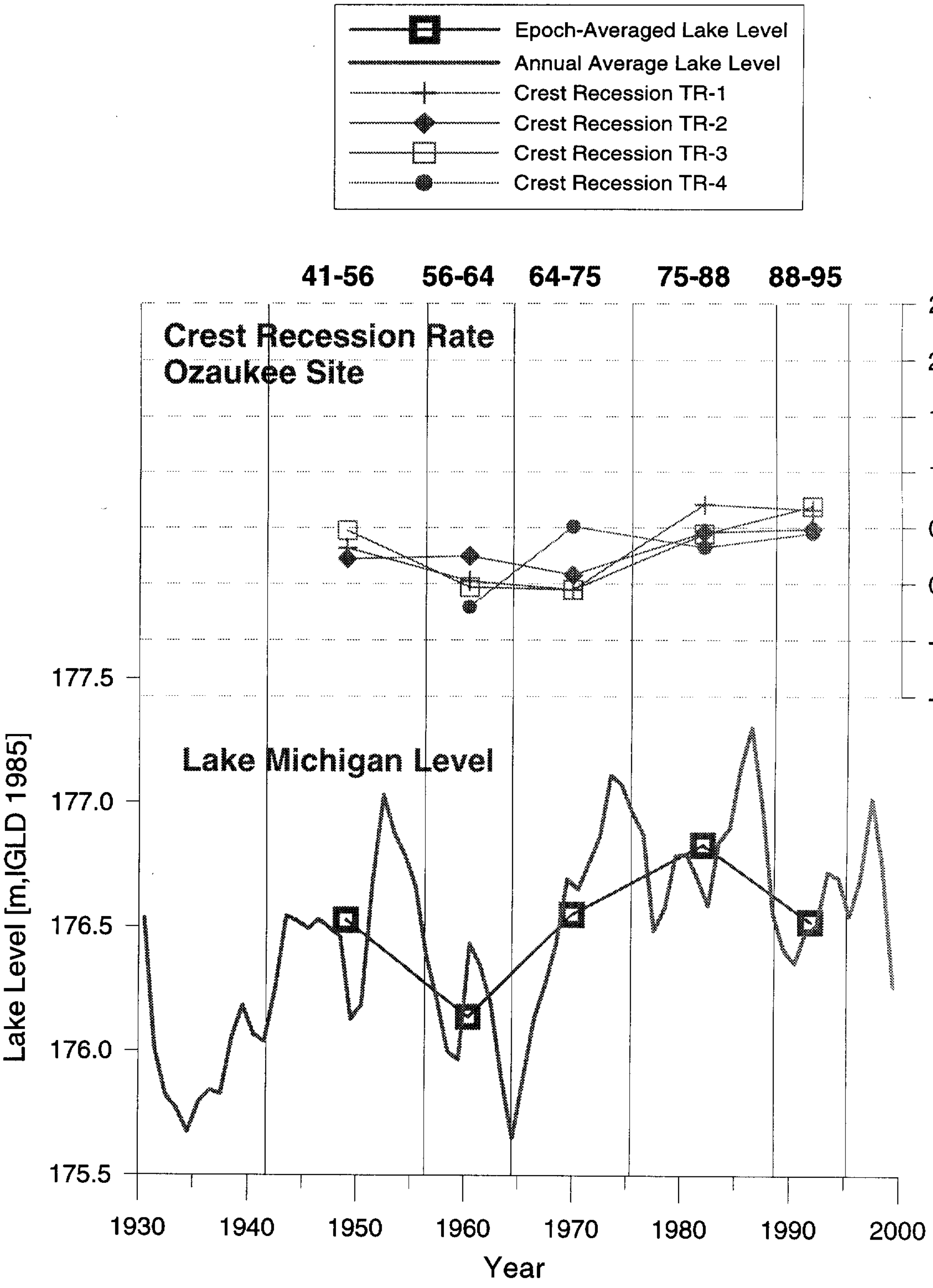


Figure 5.9 Crest-Recession Rate and Lake Level at the Ozaukee Site.

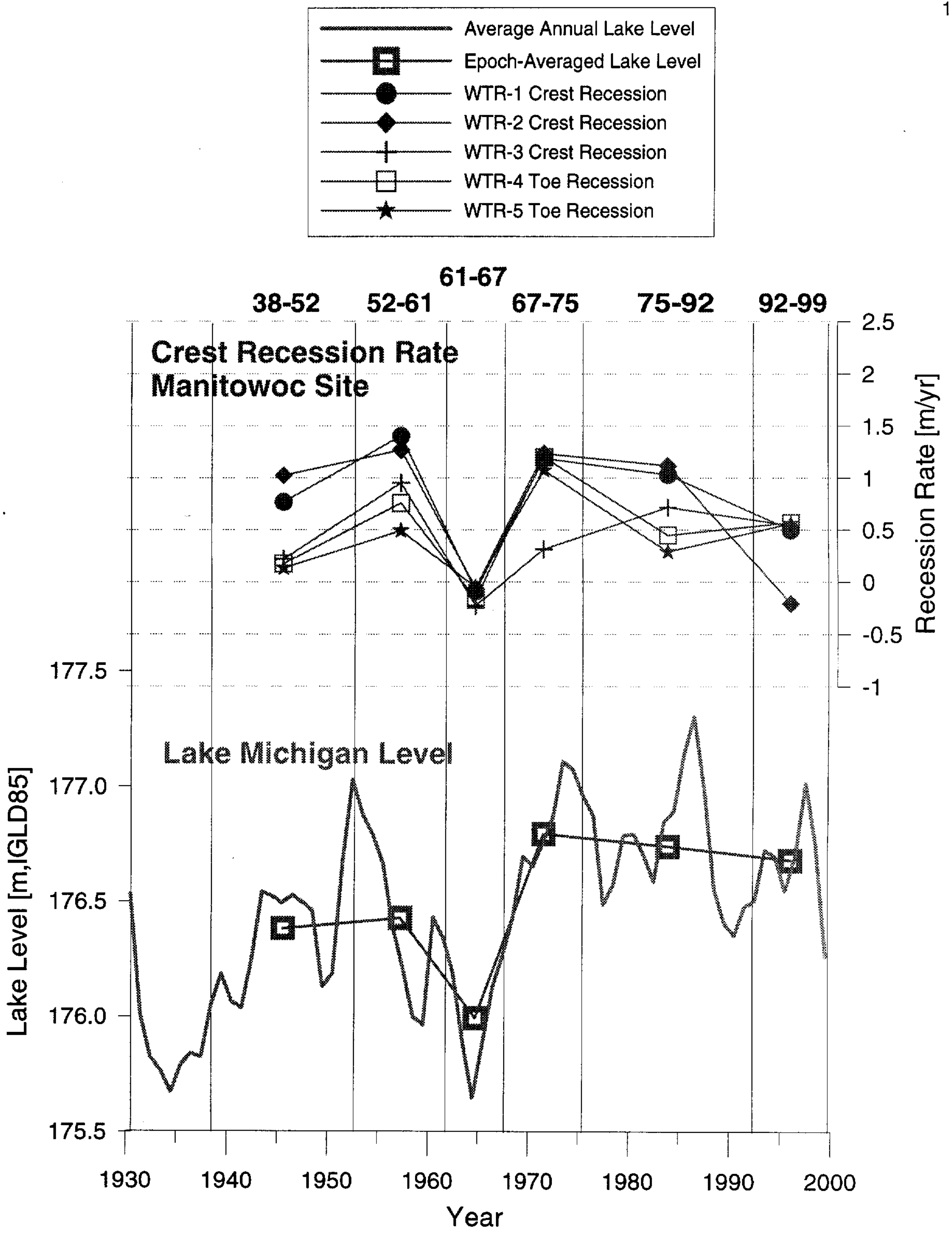


Figure 5.10 Crest-Recession Rate and Lake Level at the Manitowoc Site.

fall before this low lake level period. Profiles WTR-4 and WTR-5 show less recession per year before the low lake level period than after. The bluffs at WTR-3 show a recession rate pattern over time that corresponds the least with lake level changes.

The variations in lake level, therefore, are matched extremely well by changes in crest-recession rates of 2 of the 5 profiles (WTR-4 and WTR-5), moderately well by crest-recession changes in 2 profiles (WTR-1 and WTR-2) and poorly in profile WTR-3.

5.5 Recession-Rate Analysis at the Toe

5.5.1 Storm Events and Toe-Recession Rate

Toe-recession data are available only for the Ozaukee Site. The number of storm events over each year and averaged over each erosion epoch and toe-recession rate at WPW-2 is shown in Figure 5.7. The peak annual storm count occurs, as mentioned in Section 5.4.2, during the most recent erosion epoch (1988–95). For four of the five profiles, the lowest recession rate occurred during this recent epoch. Indeed, the recession rates for these four profiles are negative numbers due to the presence of mass wasting material building up at the toe of the bluff that has not yet been removed by wave action.

5.5.2 Lake Level and Toe-Recession Rate

The toe-recession rate and Lake Michigan level over time is shown for the Ozaukee site in Figure 5.11. A reduced recession rate coincides with a drop in average lake level from the first epoch (1941–56) to the second epoch (1956–64). The maximum recession rates recorded for this study occurred during the 1964–75 epoch. While this does not represent the maximum epoch-based average lake level, it represents a time period that experiences the most dramatic rise in lake level. Lake Michigan rose by more than a meter during this epoch. Following the 1964–1975 period, the recession rates for nearly all the profiles continue to fall through to the most recent epoch considered (1988-95). During the 1975-88 epoch, time at which the recession rates had already begun to fall, the average lake level over the scale of epochs reached a maximum.

5.5.3 Deepwater Wave Power, Wave-Impact Heights and Toe-Recession Rates

The trend of deepwater wave power over time is shown in Figures 5.7 and 5.8 for the Ozaukee and Manitowoc sites respectively. The deepwater wave power reaches its annual peak during the 1964-75 epoch, a time when the highest recession rate is observed at the toe at Ozaukee County. The annual mean deepwater wave power stays at an elevated level until 1980. Outside of this trend of high values between 1970 and 1980, the deepwater wave power seems to vary about a relatively constant mean value.

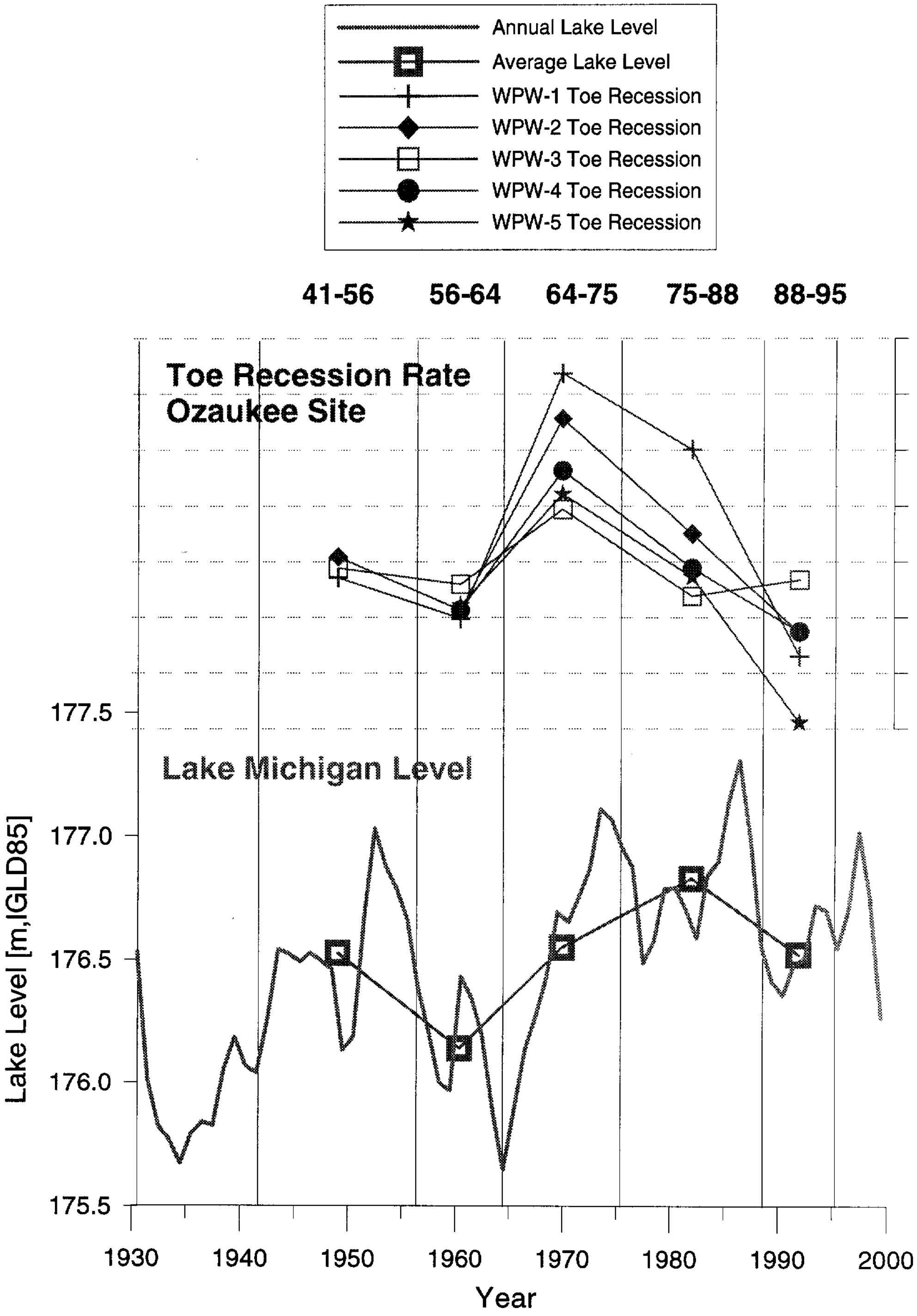


Figure 5.11 Toe- Recession Rate and Lake Level at the Ozaukee Site.

The consistently high annual mean deepwater wave power between 1970 and 1980 is also observed at the Manitowoc site. The wave power rises and stays high starting during the 1967–75 erosion epoch, a time at which the highest recession rate was observed for 3 of the 5 profiles (WTR-3 to WTR-5). For the remaining two profiles (WTR-1 and WTR-2), the maximum recession rates were not attained between 1967 and 1975, but the measured rates still show a dramatic increase from the 1961–67 period to the 1967–75 period.

The annual average of maximum monthly wave-impact heights is shown together with the toe-recession rate for the Ozaukee site in Figure 5.12. The annual average of peak monthly wave impact varies from 2.5 m to 5.0 m. A large jump in peak wave-impact heights occurs during the epoch associated with a dramatic rise in toe-recession rates (1964–75) at the Ozaukee site. The small differences in beach slope and bluff toe elevations for the different profiles account for the vertical differences, but do not appear to alter the trends in wave-impact height over time.

The annual average of peak monthly wave-impact heights and crest-recession rate at the Manitowoc site is shown in Figure 5.13. The annual average of peak monthly wave impact varies from 1.75 m to 4.5 m. At the Manitowoc site, the wave-impact heights rise dramatically early in the 1967–75 epoch, the time period during which the highest recession rate occurs.

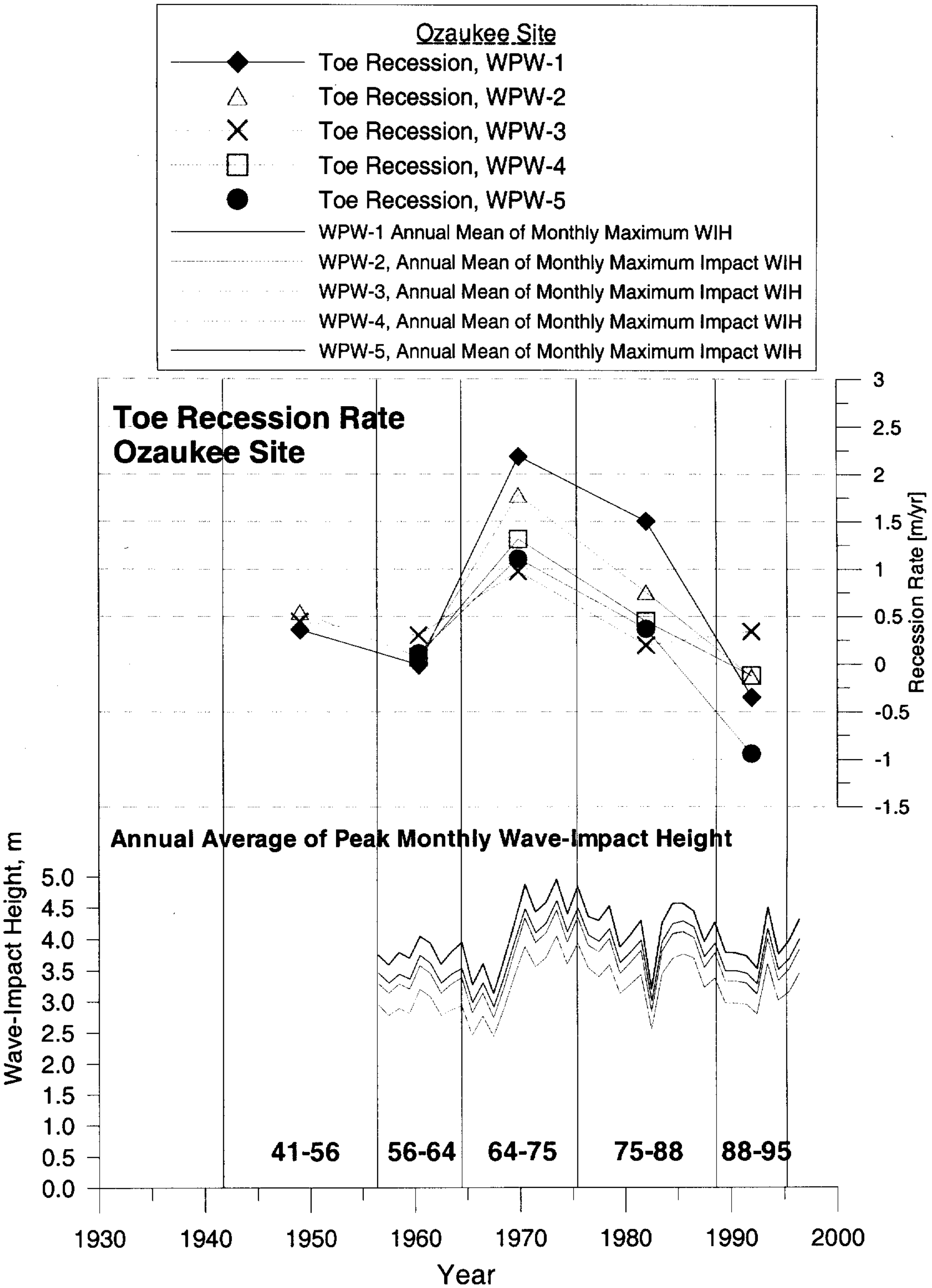


Figure 5.12 Wave-Impact Height and Toe-Recession Rate at the Ozaukee Site.

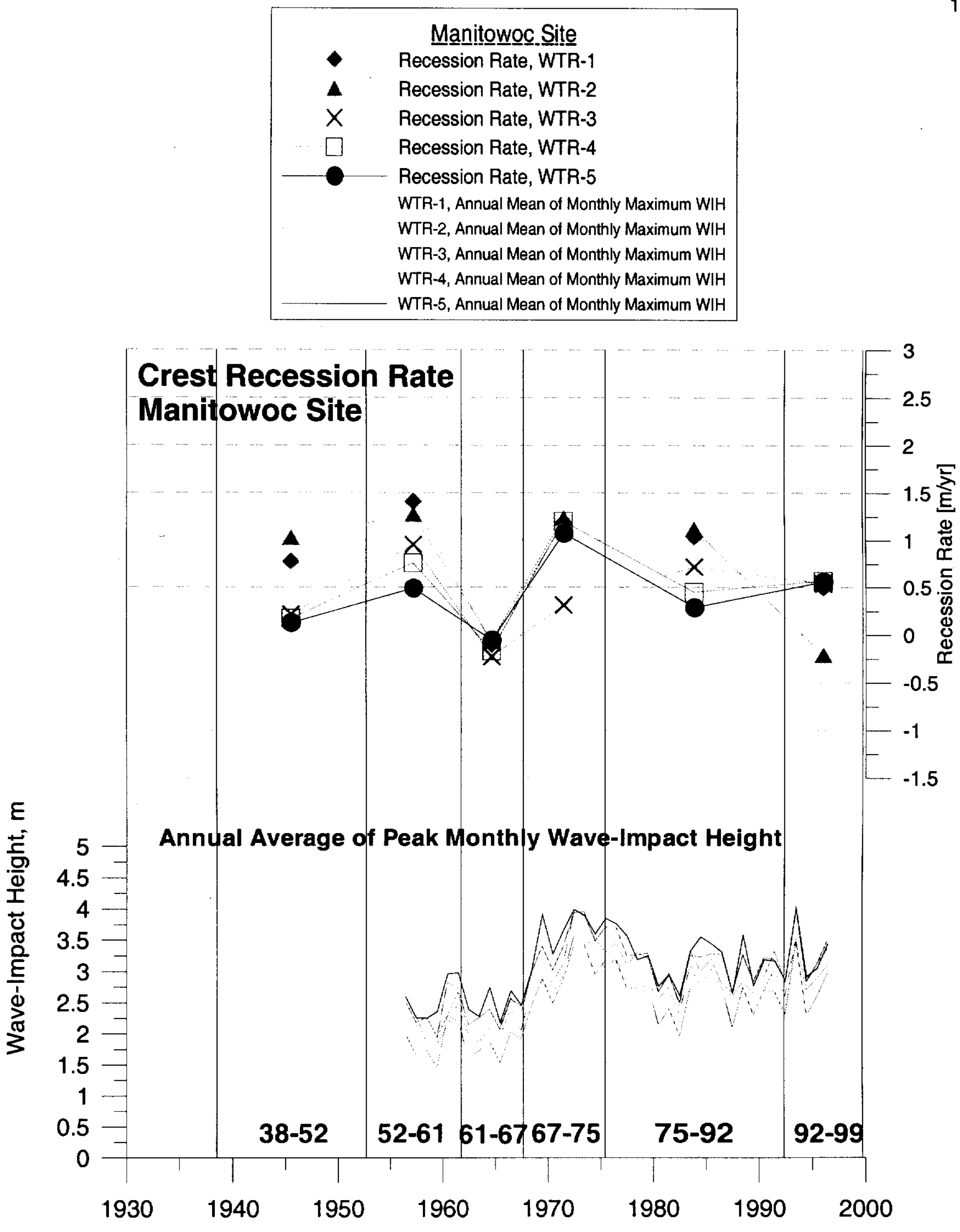


Figure 5.13 Wave-Impact Height and Toe-Recession Rate at the Manitowoc Site.

6 DISCUSSION AND CONCLUSIONS

The factors that influence the recession rates of coastal slopes can be categorized as land-based, water-based or shore-based. Table 6.1 summarizes a number of influences reported for each of these three categories and indicated ones considered for this study.

Table 6.1 Summary of Reported Factors Influencing Bluff Erosion.

Zone	Influencing Factor	Author(s)	Considered In This Study [YES/NO]
Water	Water level	Jibson and Odum (1994) Gelinas and Quigley (1973) Bray and Hooke (1997) Kirk et al. (2000) Bray et al. (1997)	YES
	Storm activity	Dewberry & Davis (1994) Jibson and Odum (1994)	YES
	Wind and wave climate	Wilcock et al. (1998) Gelinas and Quigley (1973) Davidson-Arnott et al. (1980) Sunamura (1977) Carter (1976)	YES
	Storm surge	Gelinas and Quigley (1973)	YES
Land	Geology/Lithology	(Kamphuis 1987)	NO (but varies little)
	Bluff Height/Geometry	Edil and Mickelson (1998)	NO (but varies little)
	Groundwater Elevation	Edil and Vallejo (1980)	NO
	Erosion Resistance of Bluff Soil	Wilcock et al. (1998)	NO
Shore	Beach width and Volume	Carter (1976) Berg and Collinson (1976)	NO
	Beach Sediment Grain Size	Kamphuis (1987)	NO
	Presence of Coastal Structures	Carter (1976)	NO

Zone	Influencing Factor	Author(s)	Considered In This Study [YES/NO]
	Beach and nearshore Profile	Carter (1976)	YES
	Nearshore Downcutting	Kamphuis (1987) Nairn (1995)	NO
	Shore Orientation	Kamphuis (1987) Gelinas and Quigley (1973)	YES

A number of previous coastal erosion studies have considered large spatial extents but most have examined few temporal ranges. The present study assesses the spatial variation of recession rates across two shoreline reaches of limited spatial extent. The two study sites are located along the Lake Michigan shoreline in Ozaukee and Manitowoc counties in Wisconsin. The temporal variation of recession rates over 5 and 6 erosion epochs that span a total of 54 and 61 years are considered for the Ozaukee and Manitowoc sites respectively.

All water-based factors listed in Table 6.1 are included in this study. The land-based factors are not directly considered. However, the lithology of both study sites is fairly well known and does not change appreciably within each site. The bluff height and geometry have been measured from time to time over the past 20 years. The influence of bluff lithology and geometry on the spatial variation in recession rates is not analyzed quantitatively. Groundwater level has not been measured continuously at the study sites over time or over distance so this factor is not considered.

Changes in beach width, beach volume, and sediment type, all of which are known to vary somewhat across the sites, is not considered in this study. The beach slope in the swash zone is an input to the runup calculation. The runup is used, together with the lake level and base-of-bluff elevation, to calculate the wave-impact height. The shoreline orientation is considered for the computation of storm activity, deepwater wave power and wave-impact height. Only waves and winds directed towards the shoreline are included in the storm frequency, wave power and runup calculations.

One of the main objectives of this study was to single out the influence of the long-term average lake level, wave-impact height and precipitation on recession rate during each erosion epoch. The epoch-averaged and annual average lake level show a significant variation over time for both the Ozaukee site and the Manitowoc site. The trend of annual average monthly maximum wave-impact height varies greatly over time and compares more favorably to the trends of recession rate than does the epoch minimum, maximum or mean wave-impact height. The slight differences in beach height and elevations of the base of the bluff from profile to profile affect the absolute value of wave-impact height but do not affect its general trend over time. The variation in precipitation magnitudes on an annual basis is large; the annual precipitation varies from a low of 500 mm per year to a high of 1120 mm per year. The epoch-averaged precipitation rates vary much less and show trends over time similar to the epoch-averaged lake level.

Lake level has an unquestionable influence on the recession rate of two of the three features measured on the bluffs at both sites. The toe-recession rate of the high bluffs at Ozaukee County and the crest-recession rate of the low bluffs at Manitowoc County show remarkably similar patterns over time to the epoch-averaged lake levels. Figure 5.11 shows that bluff-toe recession rate and lake level share common trends over time at the Ozaukee County site. Figure 5.10 shows good agreement between the crest recession rate and lake level trends at the Manitowoc County site. Since consistently low recession rates are observed throughout the time period of record at the crest of the Ozaukee bluffs there is a relatively poor match between recession trends and lake level trends.

The crest-recession rate trends observed at the high bluffs of the Ozaukee site do not correspond well with lake level changes, but the toe–recession rate shows trends similar to that of lake level over time. This is because the 60-year period of this study is shorter than the cycle time for waves to erode the base of the high bluffs sufficiently to cause a failure that extends to the crest. While recession rates at the toe of the Manitowoc bluffs were not quantified for this study, visual observations made of these low bluffs over the past 25 years suggest that the retreat at the crest follows closely behind the retreat at the toe. These data suggest that the bluff failure cycle time at the Manitowoc site is considerably shorter than the 5-15 year intervals considered for this study. The difference in recession rate between the toe and the crest at the high-bluff site and the parallel retreat at the low-bluff site has been suggested for a number of years. The findings of this research have finally confirmed these judgments quantitatively.

Berg and Collinson (1976) state that high lake levels are a primary cause of bluff erosion. Bluff top recession of bluffs varying in height between 6 m and 27 m was considered for their study. They suggest that bluff erosion rate rises a few years after lake level rises, but the elevated rate can be maintained or even accelerated as the lake level decreases from a high level. According to Berg and Collinson, as lake level rises, well-developed beaches delay the onset of maximum erosion rates because it takes time to deplete the beach. They attribute the observed time lag between a fall in lake level and a decreased erosion rate to the time required to vegetate the scarified bluffs.

The present study finds that peak recession rates, measured over the scale of decades, actually *precede* the maximum epoch-averaged lake level for the bluff toe at the Ozaukee site. The maximum toe-recession rate occurs during an epoch (1964–75) that experiences the most dramatic *rise* in lake level. The Manitowoc site bluff-crest recession rates generally follow the pattern of average lake level with no temporal shift in either direction. The recession intervals considered for the Berg and Collinson (1976) study were short enough (1 year intervals) to observe a time delay before erosion rates increased after a rise in lake level, and a sustained high erosion rate while lake level fell. These time lags observed by Berg and Collinson are on the order of 3-4 years long. The erosion epochs considered for this study (5–

15 year intervals) are too long to see a delay in the onset of high recession rate due to high water level or a delay in the fall of recession following a drop in lake level.

Amin (1991) observed a strong correlation between deepwater wave power and bluff-toe recession rates. Amin collected recession data by measuring exposed horizontal peg lengths every one or two weeks over a period of two years. Data from the present study do not show nearly as strong a relationship between deepwater wave power and recession rate as Amin's study. The time resolution used by Amin was much finer and the amount of recession data generated was much greater than the present study. Accurate recession-rate measurements recorded on the scale of weeks may be the key requirement to establish a strong statistical correlation between recession rate and wave power. However, a study such as Amin's that only spans a total of two years' time cannot consider the influence of lake level, since the cycle time of lake level variation is on the scale of 10-15 years for the Great Lakes.

Another important factor may be the beach width. Since the bluffs at Amin's site had very little protective beach, shoreward waves were regularly reaching the base and the face of the bluffs. The two Wisconsin bluff sites adopted for this study have relatively wide beaches. During low lake level periods, the waves rarely reach the bluffs and when the lake level rises the bluff is reached more frequently. The reduced frequency with which the waves impact the bluffs at the Wisconsin study sites may be part of the reason for the relatively poor agreement with deepwater wave power and bluff recession. An area of further research would be to assign a "trigger" lake level, below which the waves do not impact the bluffs and no deepwater wave power is included and above which the waves play a role and the deepwater wave power is considered in the computation of an effective wave power value over an erosion epoch.

Davis *et al.* (1973) state that the lake level merely plays a passive role by providing the appropriate conditions for bluff recession to occur. The actual removal of material, they contend, is due in part to high waves associated with intense storms. The present study introduces consideration of the annual average of maximum monthly wave impact heights. This factor shows considerable promise for explaining trends in bluff-recession rates over time. Because the wave-impact height combines the lake level with the wave effects, it should show a better agreement with bluff-recession rate over time than lake level alone. Indeed, Figure 5.12 shows a clear, sharp rise in wave-impact height during the 1964-75 epoch, a time where the epoch-averaged lake level does not reach a maximum but the lake level peaks.

The influence of storm counts and precipitation magnitude on recession rate pales in comparison to the effect that lake level and wave-impact height have on the recession rate of the bluffs. By applying the storm definition given in Section 4.2.3 to the Milwaukee wind data we have determined that there is approximately 1 storm every 3 days based on annual rates. Since we know storms do not occur this frequently, our storm definition is clearly not isolating the extreme events that are capable of eroding bluff material. A more severe storm definition would yield a storm count over each epoch that can be better compared to observed recession rates. Since the epoch-averaged precipitation trend is so similar to that of the lake level, it is difficult to decouple the effect of precipitation from the effect that lake level has on the recession rate.

7 IMPLICATIONS AND FUTURE WORK

7.1 Implications of the Study

The findings of this study emphasize the influence of the lake level and wave climate on the erosion rates of the soft-sediment bluffs along the coast of Lake Michigan. The resolution in time at which recession data are available clearly limits the ability to establish a clear relationship between recession rate and hydrodynamic factors. Lake level and wave height are generally measured on an hourly basis, whereas recession is measured either on a very fine time scale (1–2 weeks) using peg lengths over a total of 1–2 years, or it is measured every 5–15 years over 60 years or more using orthorectified historical aerial photographs. With peg length data available at a temporal resolution close to that of the lake level and wave data, an observation period of 2 years is not sufficient to observe the extreme highs and lows that Lake Michigan sees over a cycle of, say, 15 years. The 5-year-or-greater interval of recession rate (as used for this study) also has its limitations: The recession that occurs during a rising lake level in a lake level cycle that ranges from a high to a low lake level over a time period of less than 5 years would not be resolvable. To correlate lake level with recession rate, a representative lake level over the recession epoch must be established. The mean lake levels of a number of lake level cycles that have similar extreme highs and lows may have very similar average values. However, the duration of each high and low lake level cycle, not accounted for in such a comparison, is expected to have a significant influence on the recession rate. Thus, the optimal data set would be a combination of frequent recession measurements and frequent lake level and wave information taken over a long (at least 50 years) time period. This type of data set would allow the determination of the optimal time interval to use for establishing a clear relationship between recession rate and hydrodynamic factors.

7.2 Recommended Further Work

More finely temporally spaced recession data would allow an improved correlation between lake level and wave factors to be established. The technology to begin collecting such a data set would have to be developed in a way that collects recession data consistently, accurately and frequently. The lake level clearly has an influence on recession rate. The wave-impact height, or the annual average of peak monthly wave-impact heights, appears to show a very promising correlation with average recession rates. It would be worthwhile to experiment with a number of different parameters that incorporate both the water level and the wave climate with a temporally more resolved recession data set.

This study was carried out for two sites of limited spatial extent whose bluffs did not vary significantly in geology and geometry. Recession rate, lake level and wave data from other sites of limited spatial extent, but with geology and geometries differing from those studied here, should be analyzed. This would help establish a more universal understanding of the interactions between the lake level, the wave climate, and other factors influencing the ongoing erosion on the Great Lakes shores.

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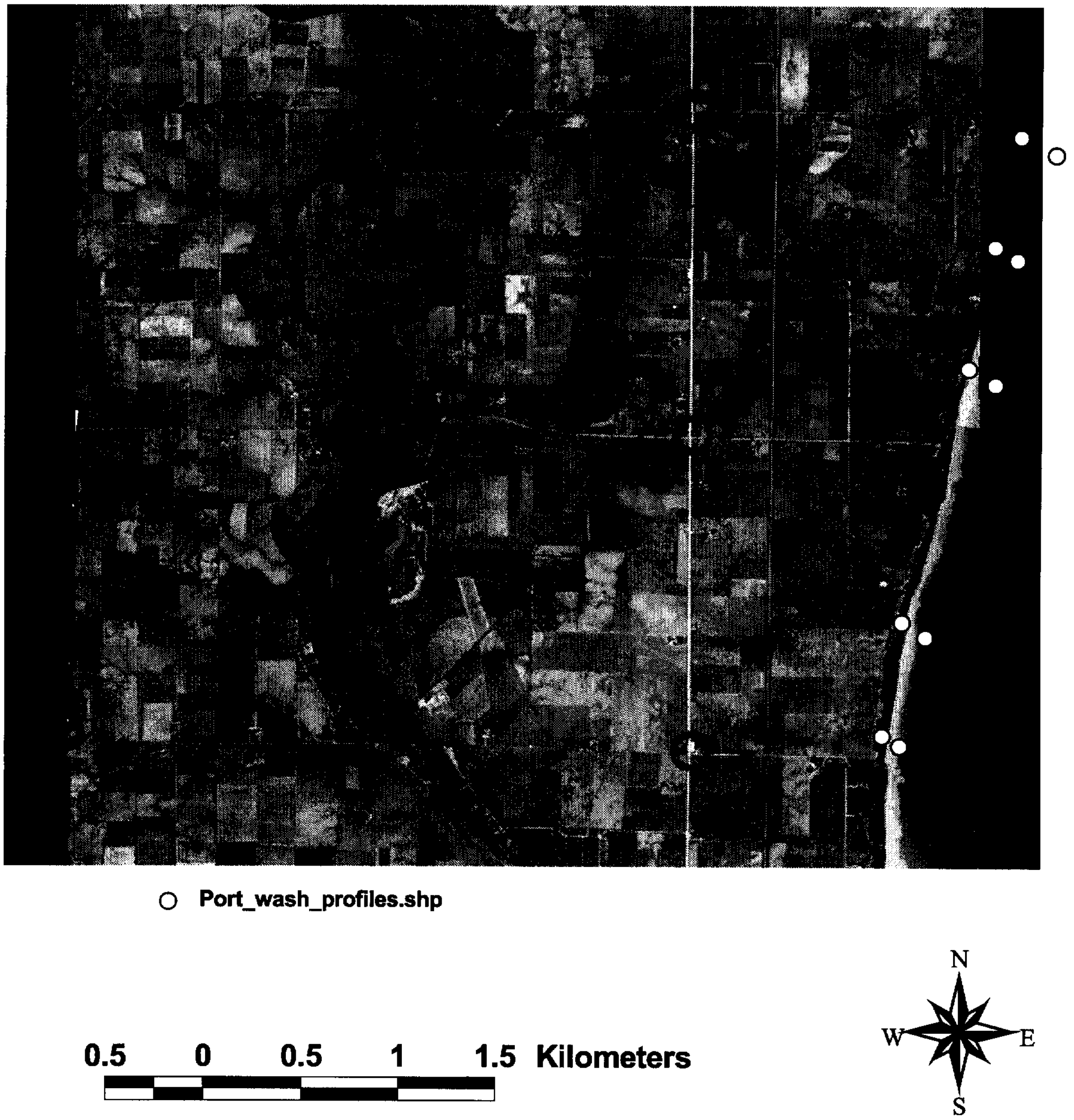
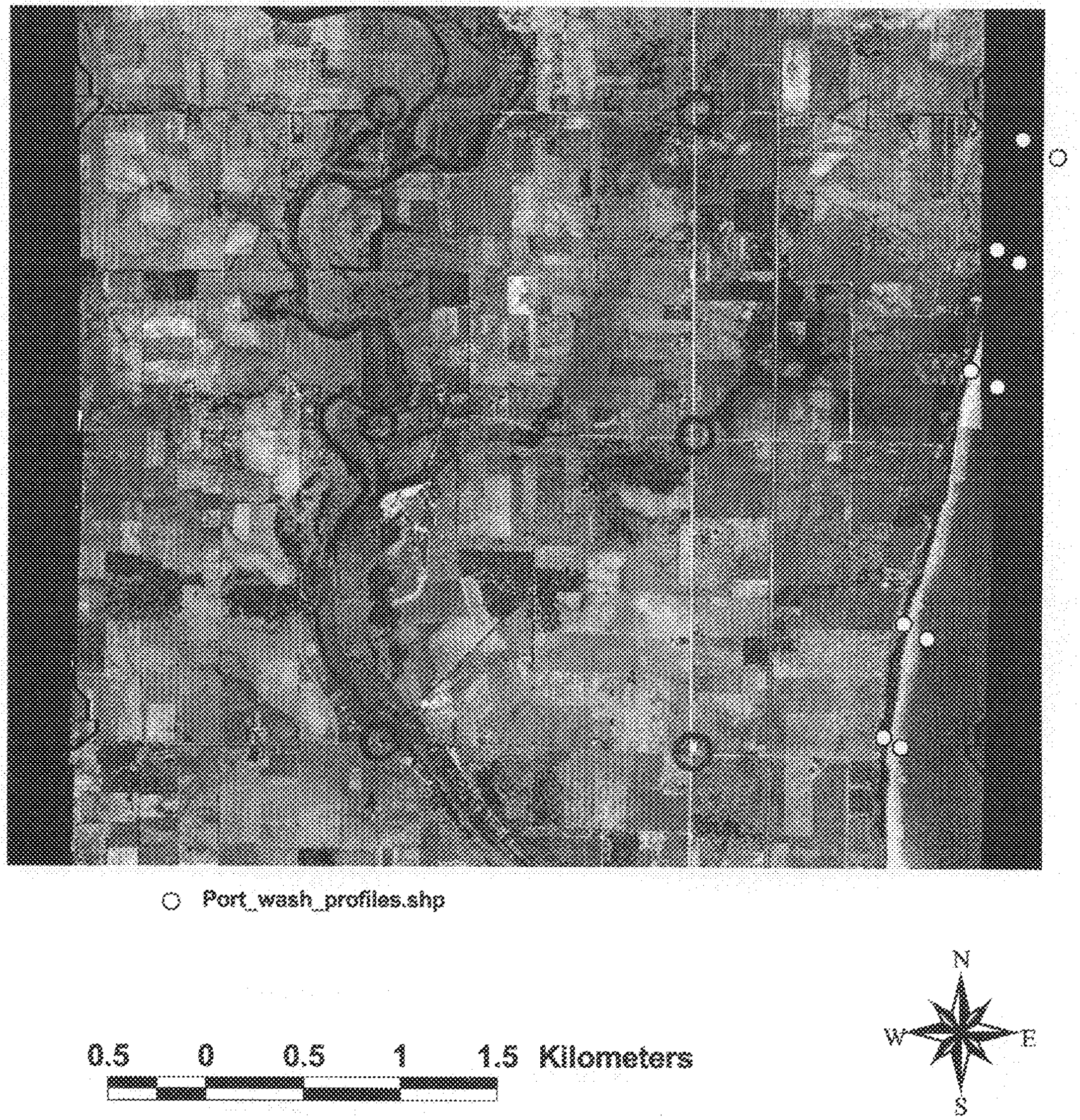
APPENDIX I Digital Orthophotos Used for Recession Rate Analysis

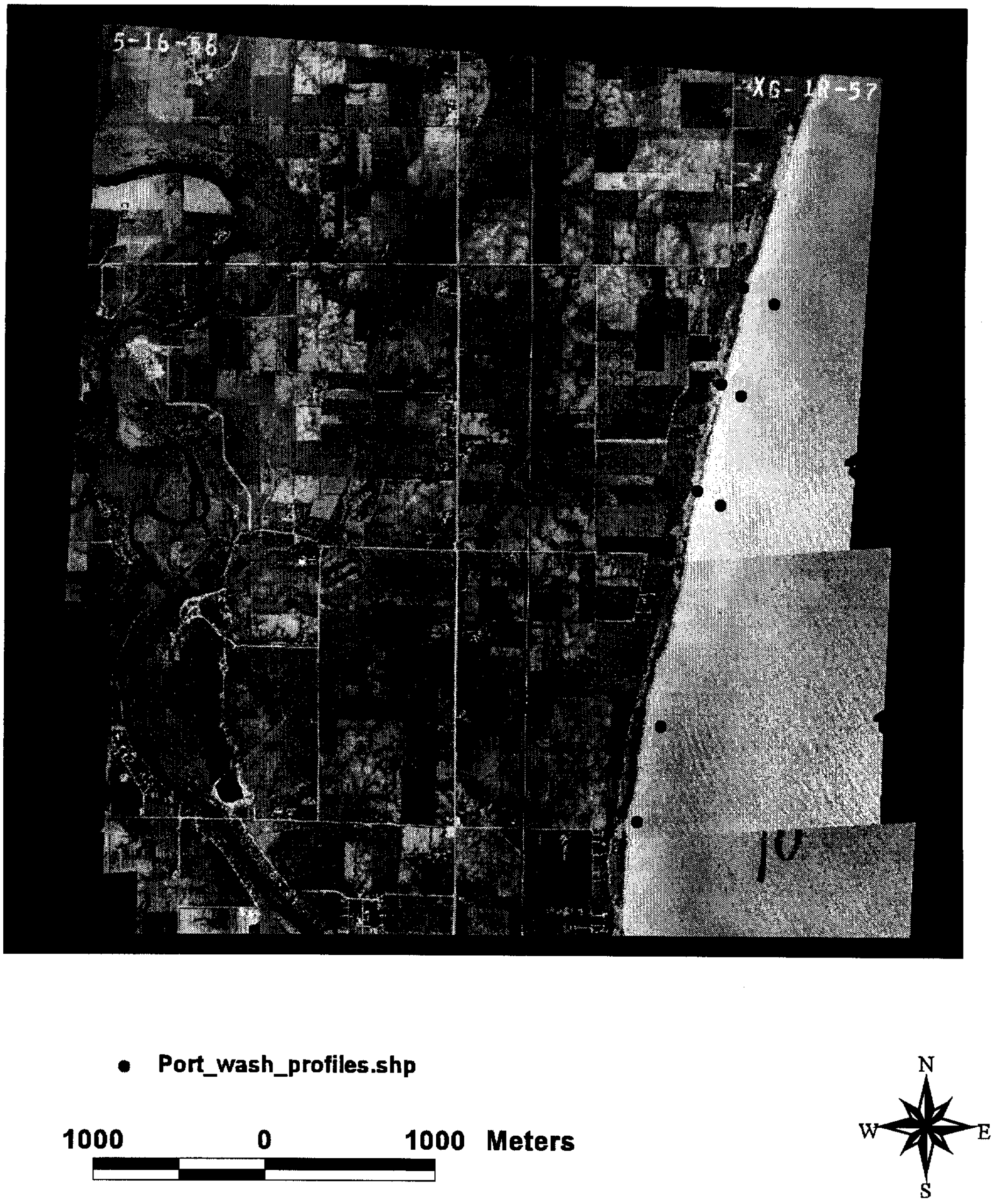
Digital Orthophoto Mosaic Ozaukee County Site 1941



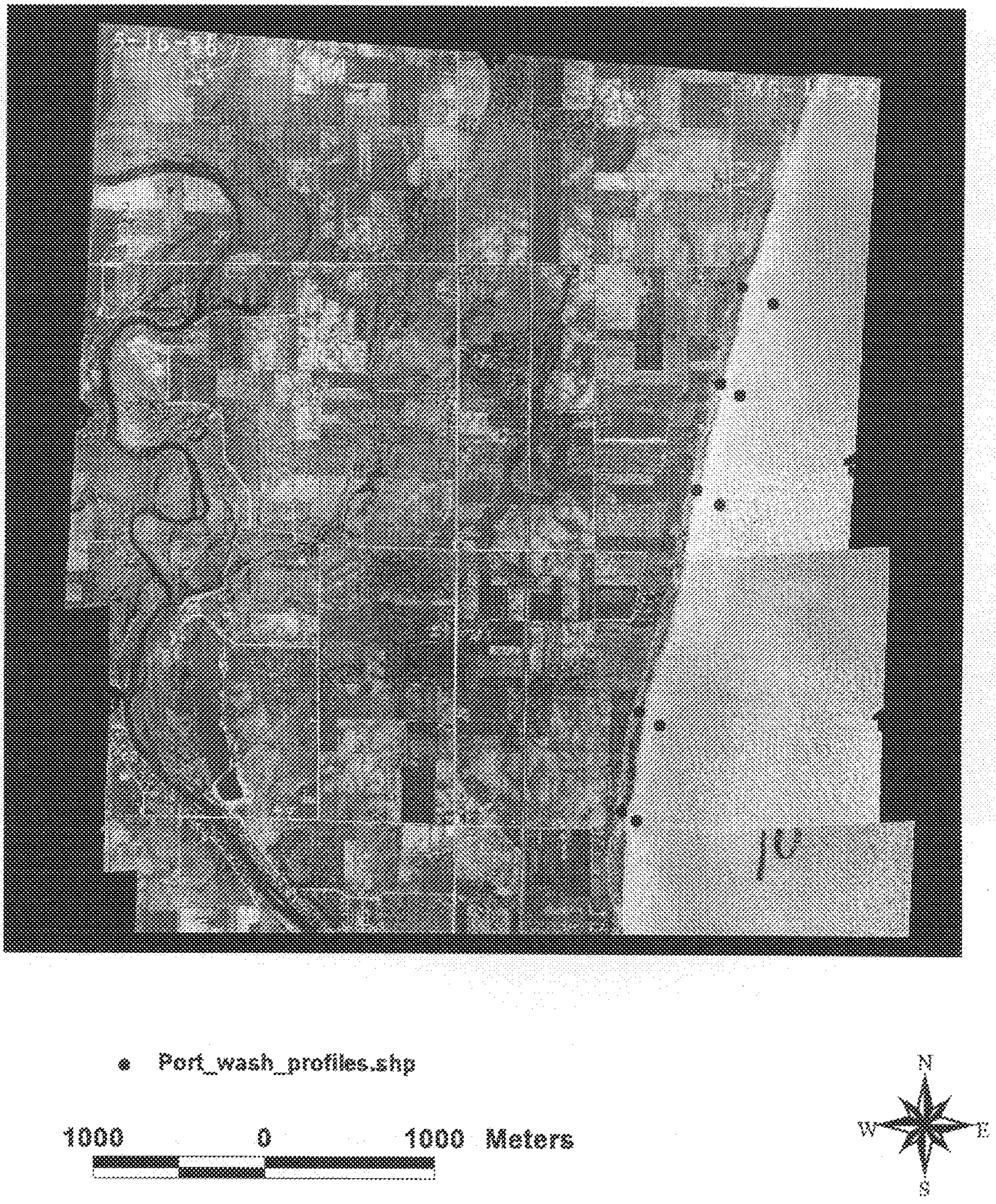
Digital Orthophoto Mosaic
Ozaukee County Site
1941



1956 Historical Orthophoto Mosaic Ozaukee Co.,WI

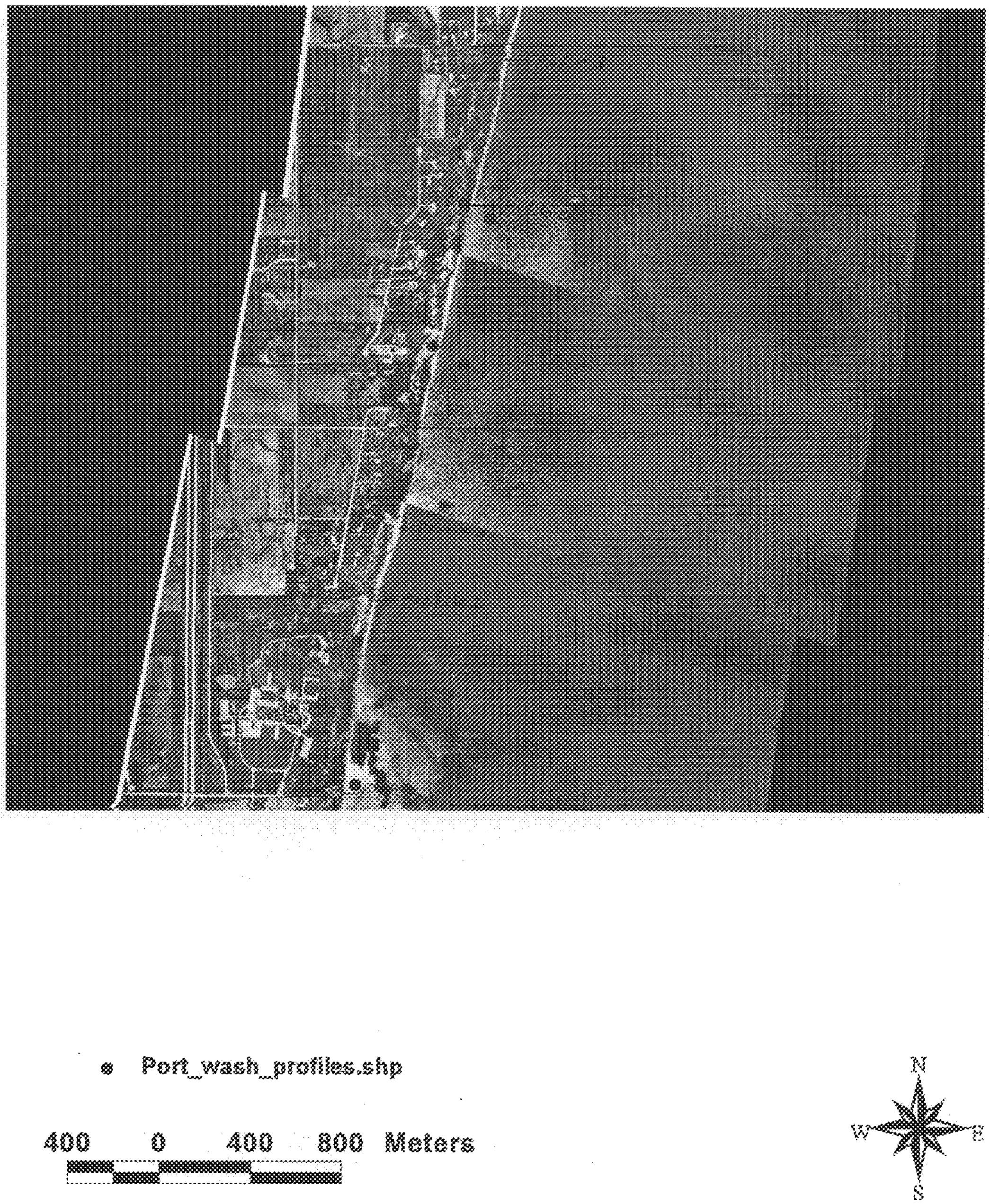


1956 Historical Orthophoto Mosaic Ozaukee Co.,WI

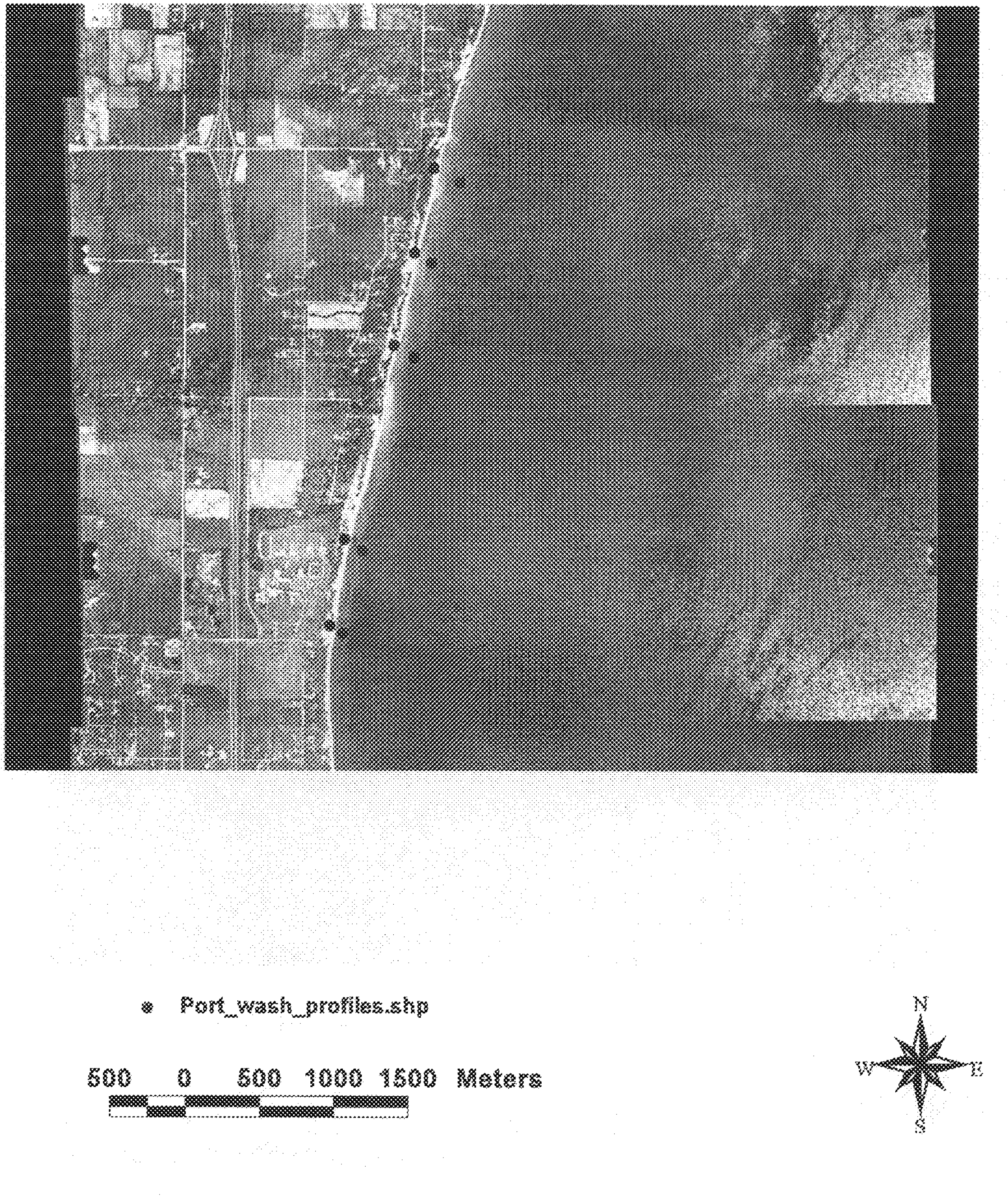


1964 Historical Orthophoto Mosaic Ozaukee Co.,WI

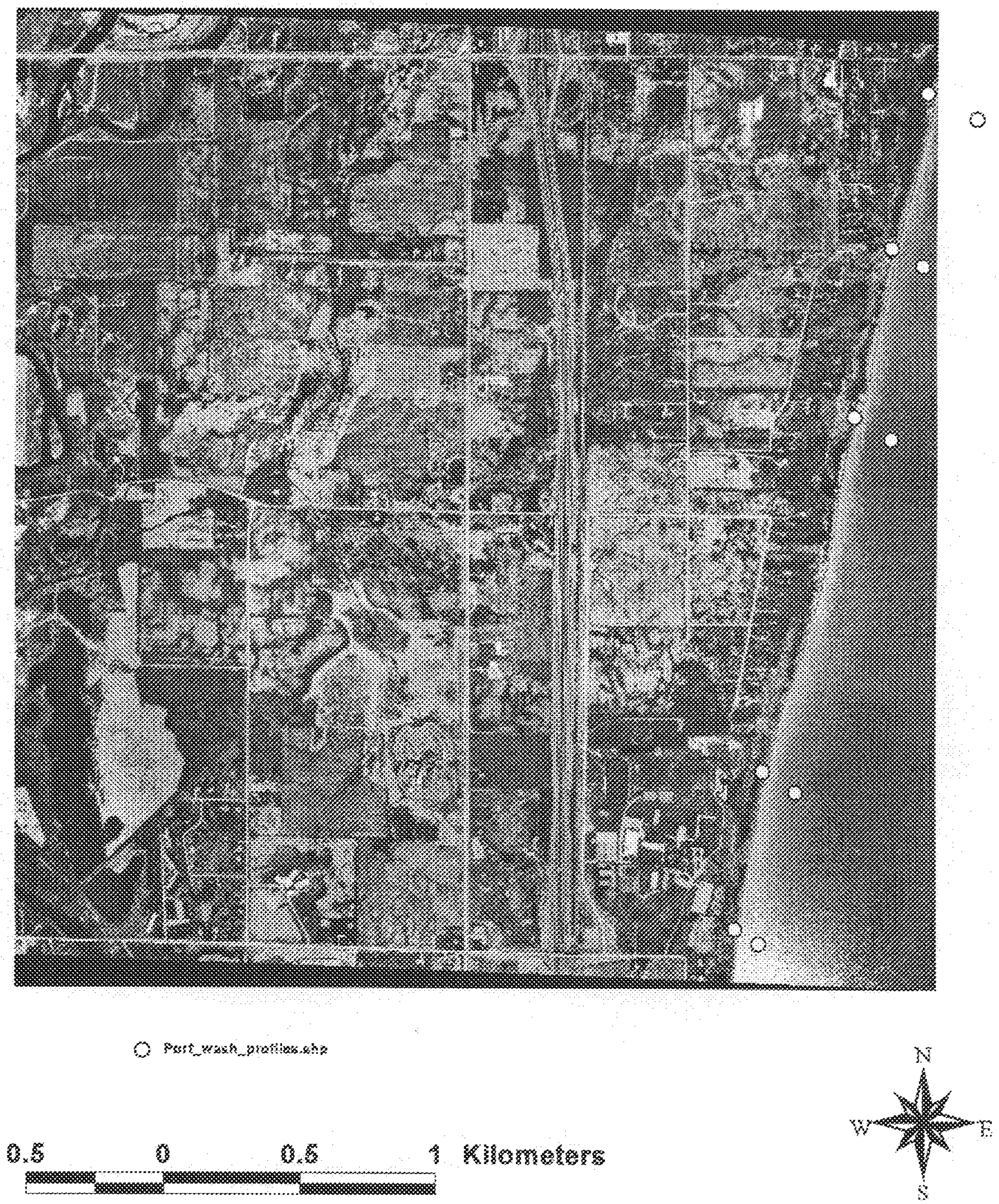
1975 Historical Orthophoto Mosaic
Ozaukee Co.,WI



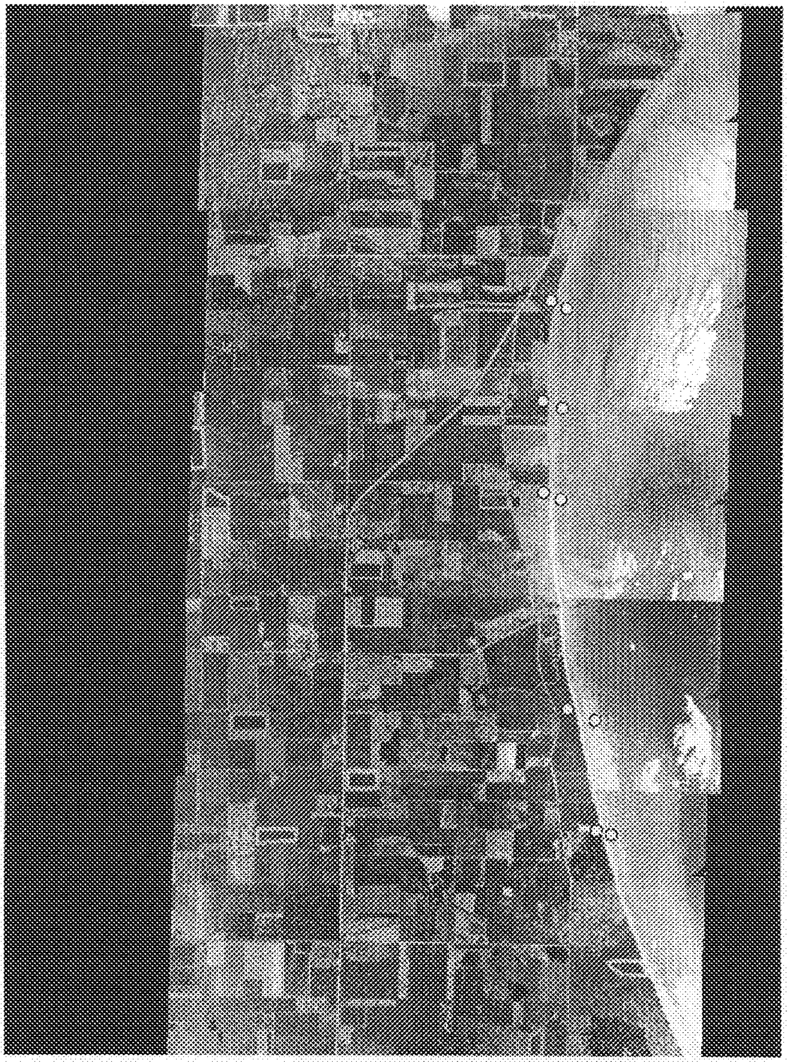
1988 Historical Orthophoto Mosaic Ozaukee Co.,WI



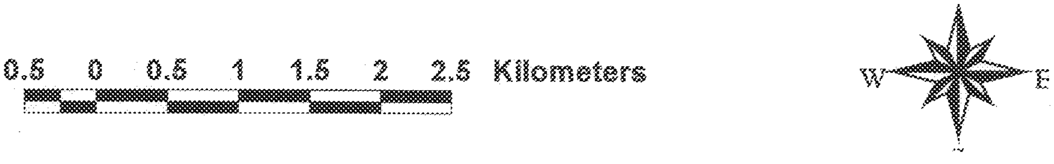
Digital Orthophoto Mosaic
Ozaukee County Site
1995



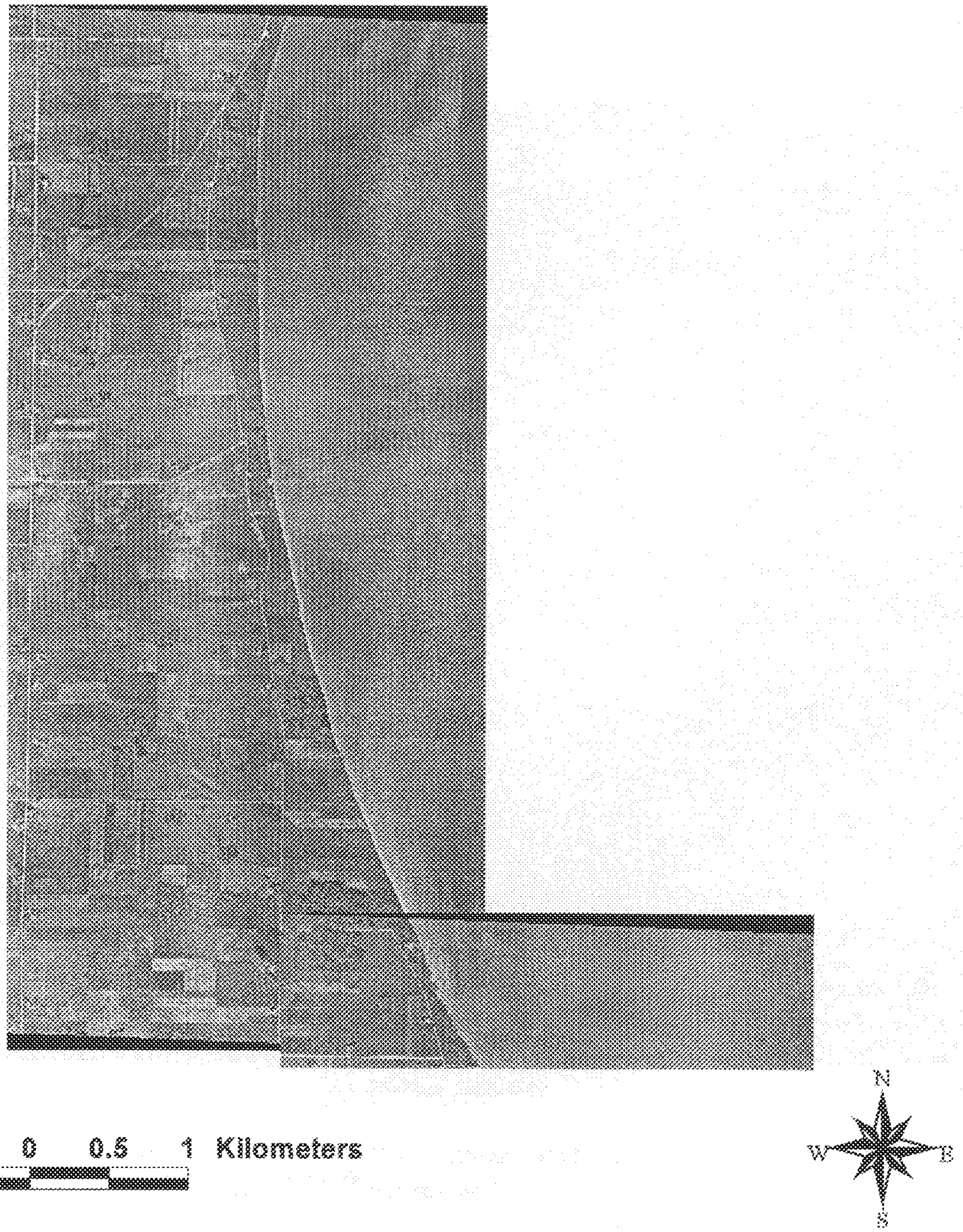
Digital Orthophoto Mosaic Manitowoc County Site 1938



○ **Profiles_man.shp**

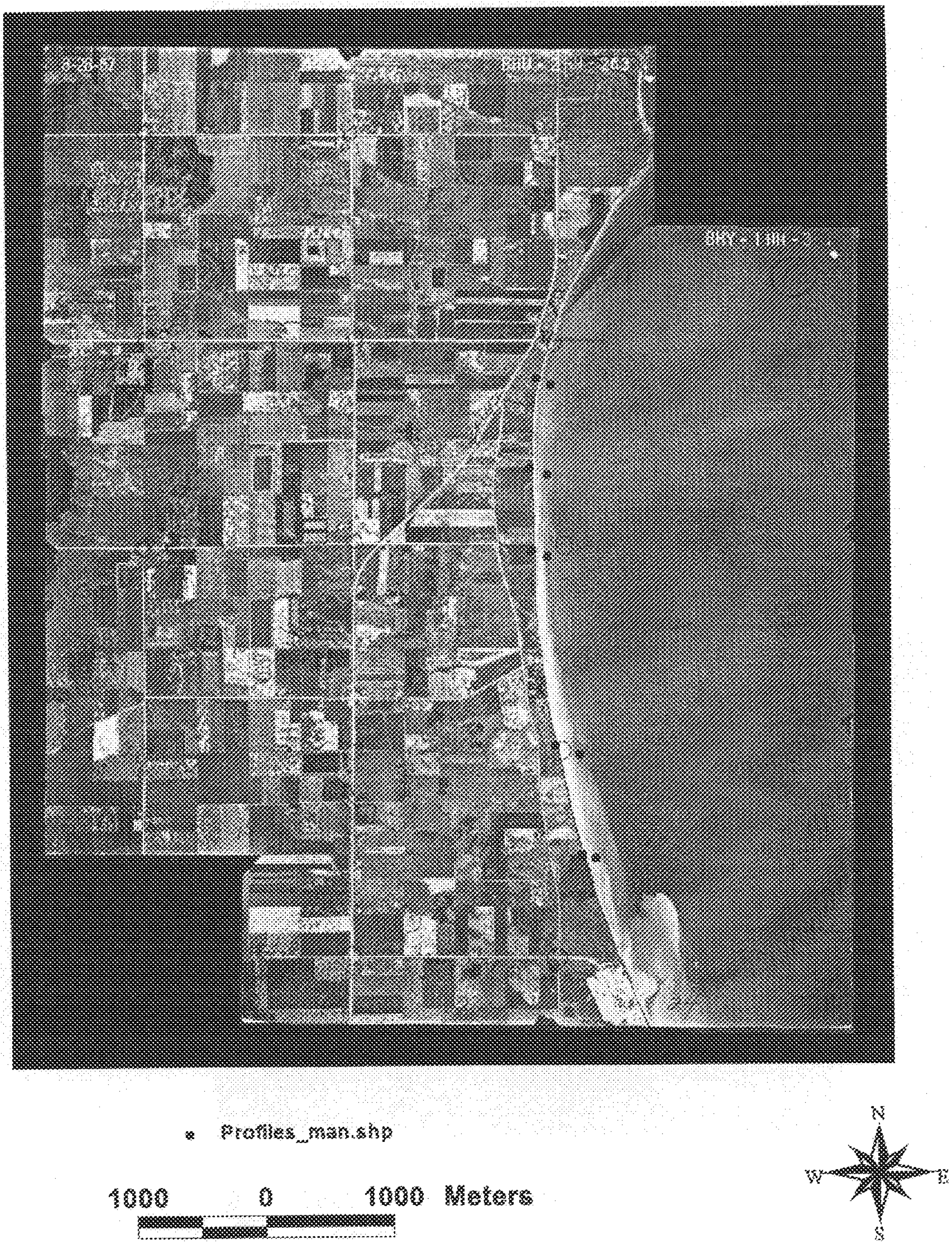


Digital Orthophoto Mosaic
Manitowoc County Site
1952

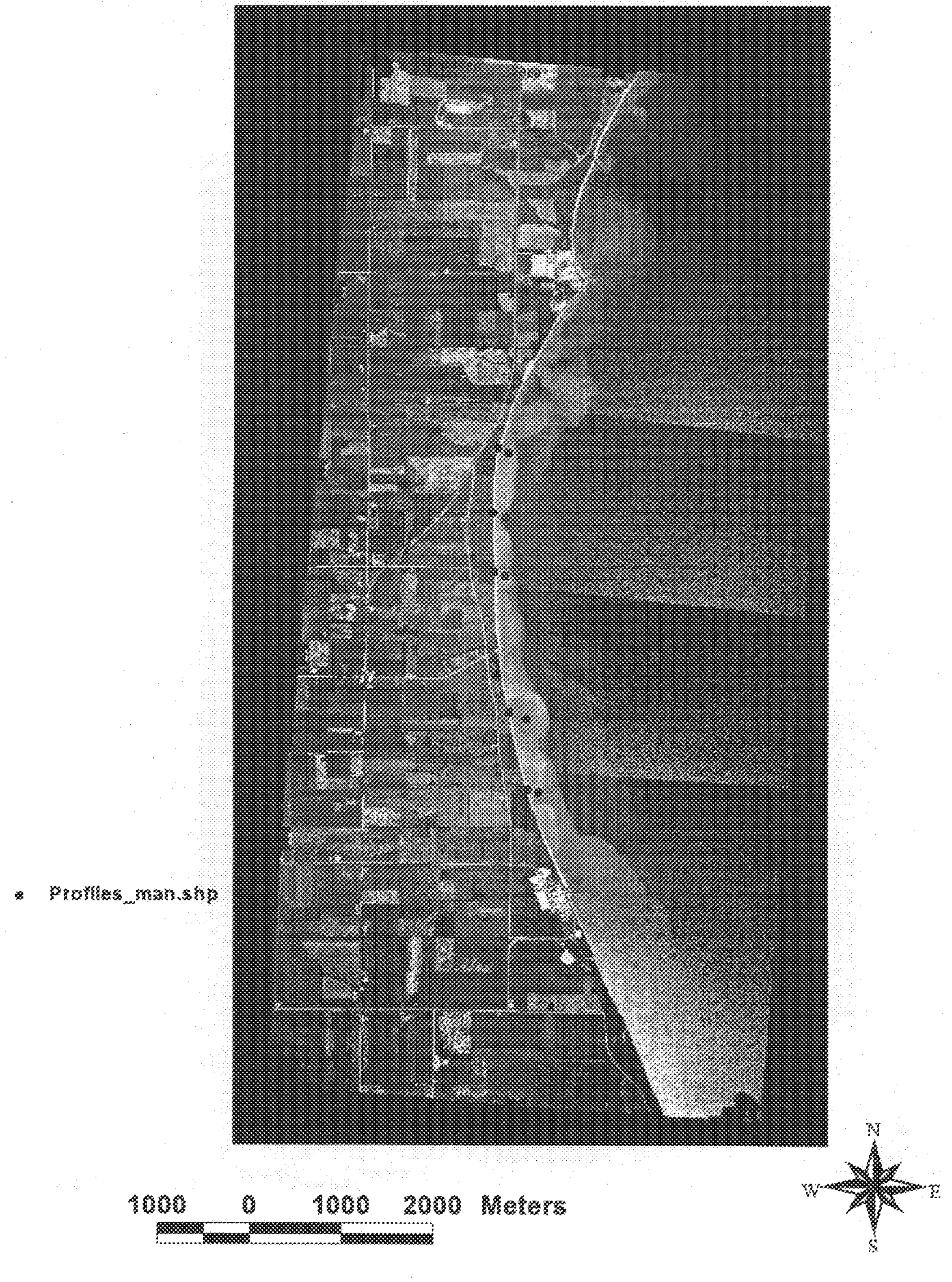


1961 Historic Orthophoto□Mosaic
Two Creeks, Manitowoc Co., WI

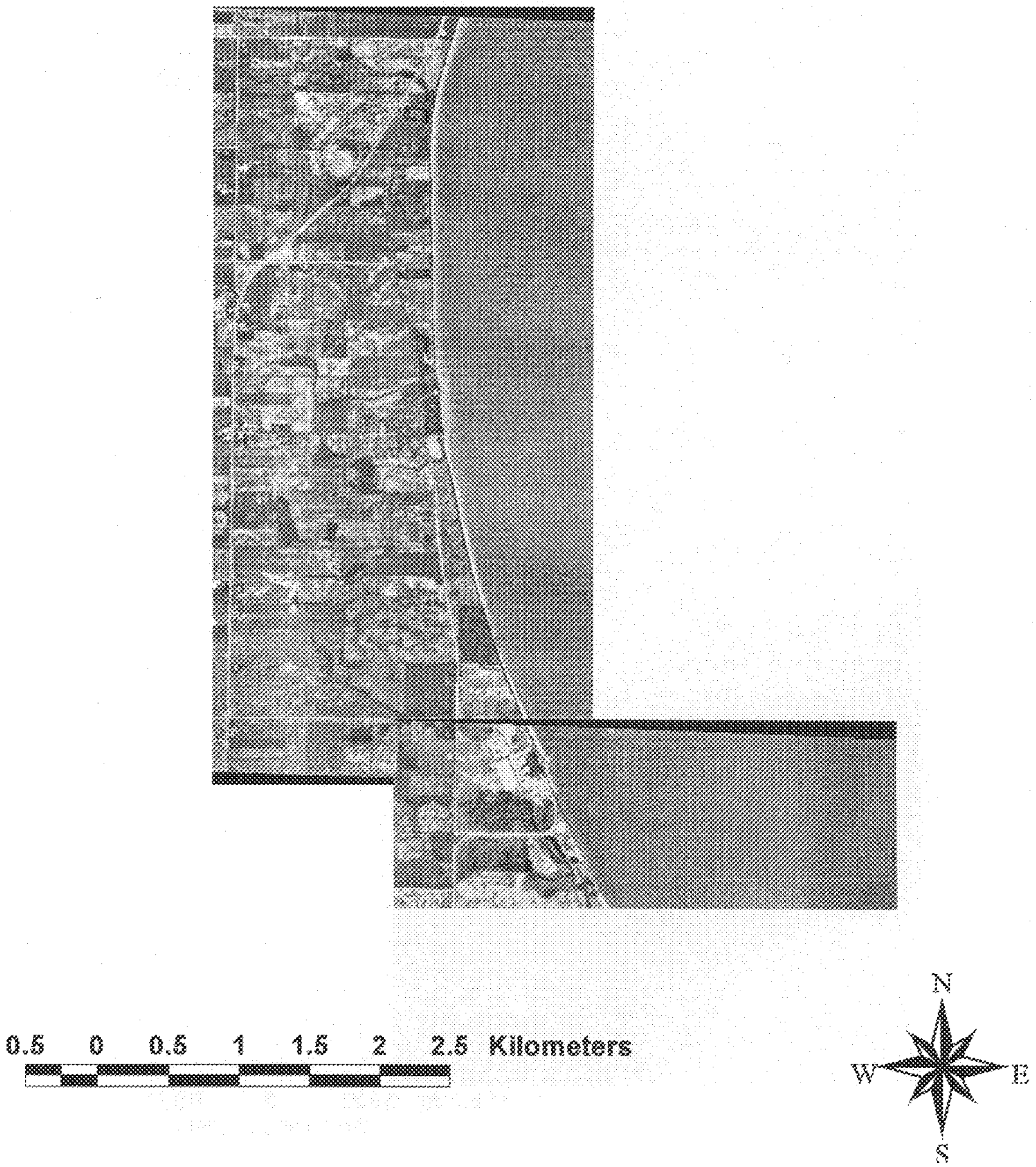
1967 Historic Orthophoto□Mosaic
Two Creeks, Manitowoc Co., WI



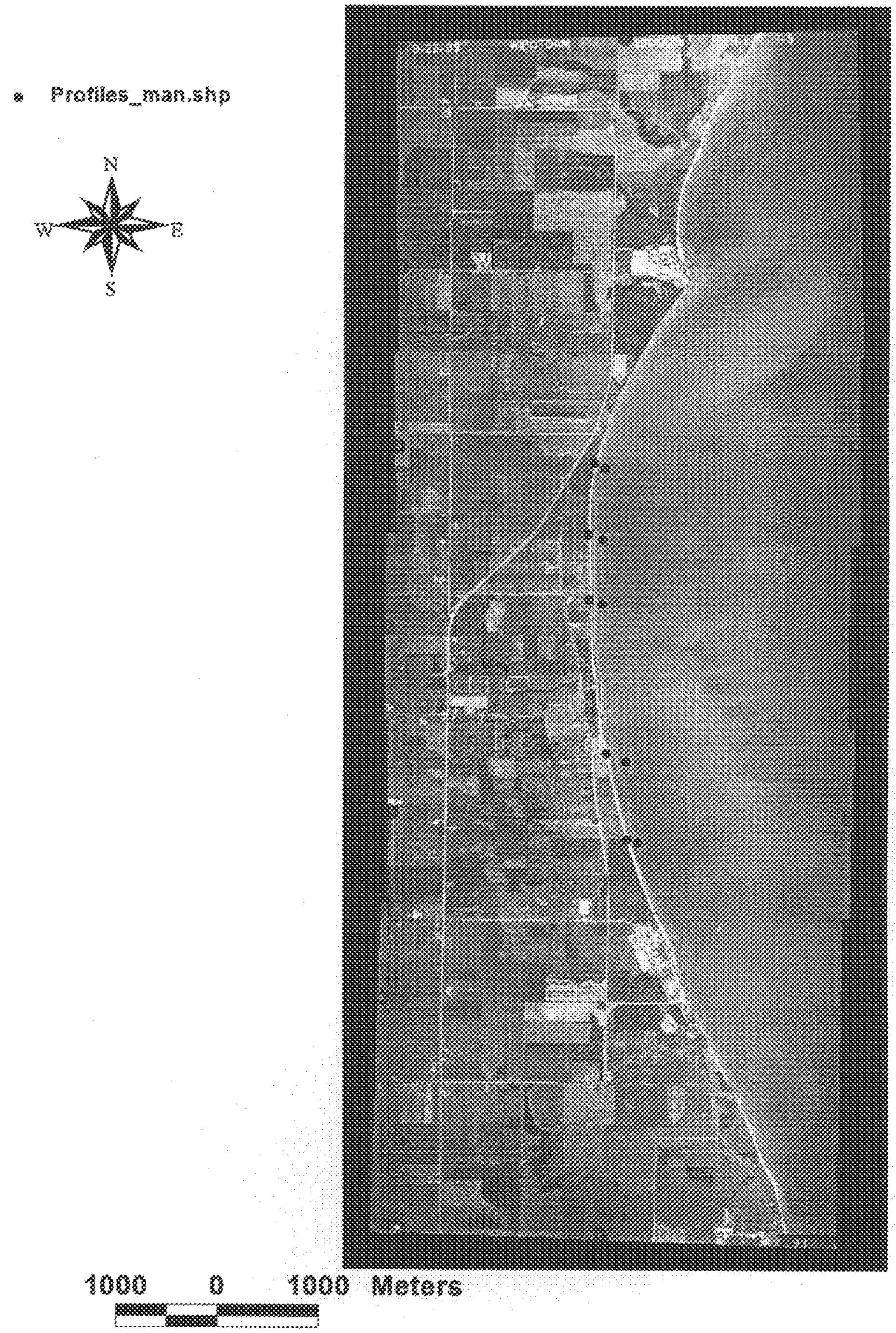
1988 Historic Orthophoto□Mosaic
Two Creeks, Manitowoc Co., WI



Digital Orthophoto Mosaic
Manitowoc County Site
1992



1999 Historic Orthophoto Mosaic
Two Creeks, Manitowoc Co., WI



APPENDIX II Monthly Lake Levels Measured at Milwaukee, WI

U. S. Department of Commerce
NOAA - NOS Rockville, Maryland
Great Lakes Water Levels

Station: 908-7058 and 908-7057
Milwaukee,Wisconsin on Lake Michigan
Monthly and Annual Average Elevations
Water Levels in Meters, IGLD (1985)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
1860	177.11	177.16	177.17	177.21	177.25	177.29	177.30	177.24	177.18	177.08	176.98	176.94	177.16
1861	176.90	176.93	177.05	177.08	177.21	177.26	177.30	177.37	177.27	177.24	177.17	177.12	177.16
1862	177.06	177.01	177.10	177.15	177.23	177.26	177.24	177.23	177.21	177.18	177.06	177.02	177.15
1863	176.99	177.01	177.01	177.01	177.07	177.10	177.08	177.04	176.99	176.96	176.91	176.93	177.01
1864	176.86	176.82	176.89	176.94	176.96	176.96	176.93	176.87	176.79	176.67	176.62	176.58	176.82
1865	176.52	176.54	176.60	176.74	176.79	176.80	176.94	176.94	176.90	176.83	176.66	176.57	176.74
1866	176.49	176.42	176.43	176.57	176.62	176.71	176.79	176.81	176.76	176.73	176.70	176.62	176.64
1867	176.62	176.63	176.69	176.77	176.84	176.94	176.98	176.96	176.88	176.78	176.64	176.53	176.77
1868	176.48	176.47	176.68	176.65	176.73	176.80	176.80	176.70	176.63	176.56	176.54	176.45	176.62
1869	176.42	176.44	176.36	176.48	176.58	176.74	176.85	176.93	176.90	176.79	176.75	176.67	176.66
1870	176.69	176.71	176.80	176.93	177.04	177.08	177.11	177.08	177.13	177.01	176.88	176.78	176.94
1871	176.82	176.80	176.98	177.04	177.15	177.16	177.17	177.10	176.90	176.69	176.67	176.49	176.91
1872	176.45	176.45	176.38	176.46	176.54	176.65	176.75	176.74	176.72	176.69	176.60	176.40	176.57
1873	176.40	176.41	176.50	176.68	176.85	176.95	176.94	176.97	176.91	176.89	176.82	176.81	176.76
1874	176.80	176.88	176.93	176.90	176.89	177.01	176.98	176.99	176.91	176.79	176.73	176.62	176.87
1875	176.58	176.54	176.56	176.67	176.84	176.91	176.92	176.97	176.95	176.90	176.84	176.78	176.79
1876	176.77	176.83	176.93	176.99	177.18	177.30	177.41	177.39	177.37	177.20	177.23	177.08	177.14
1877	177.04	177.04	177.04	177.16	177.12	177.15	177.14	177.10	177.04	177.04	177.00	176.98	177.07
1878	176.95	176.93	176.98	176.98	177.07	177.12	177.12	177.02	176.96	176.93	176.89	176.79	176.98
1879	176.70	176.70	176.71	176.71	176.75	176.77	176.80	176.74	176.70	176.63	176.57	176.58	176.70
1880	176.59	176.56	176.57	176.62	176.73	176.88	176.95	176.96	176.87	176.76	176.67	176.62	176.73
1881	176.62	176.68	176.77	177.05	176.90	176.97	176.96	176.96	176.89	176.99	176.94	176.91	176.89
1882	176.84	176.84	176.95	176.99	177.02	177.10	177.12	177.18	177.14	177.02	176.95	176.85	177.00
1883	176.77	176.79	176.81	176.88	177.02	177.13	177.32	177.31	177.25	177.18	176.96	177.02	177.04
1884	176.95	176.99	177.07	177.12	177.19	177.24	177.19	177.14	177.07	177.07	176.96	176.95	177.08
1885	176.95	177.02	177.01	177.07	177.18	177.24	177.27	177.33	177.29	177.25	177.16	177.07	177.15
1886	177.14	177.14	177.23	177.31	177.39	177.41	177.35	177.28	177.21	177.18	177.08	176.98	177.23
1887	176.95	177.06	177.11	177.10	177.16	177.20	177.18	177.14	177.03	176.89	176.80	176.76	177.03
1888	176.70	176.69	176.74	176.81	176.92	177.01	177.01	176.97	176.93	176.85	176.84	176.66	176.84
1889	176.65	176.64	176.64	176.64	176.66	176.80	176.86	176.79	176.74	176.66	176.55	176.50	176.68
1890	176.52	176.51	176.50	176.60	176.67	176.80	176.82	176.79	176.73	176.70	176.60	176.49	176.64
1891	176.48	176.41	176.47	176.56	176.59	176.64	176.58	176.56	176.49	176.38	176.26	176.25	176.47
1892	176.28	176.34	176.31	176.33	176.45	176.59	176.62	176.64	176.58	176.51	176.42	176.34	176.45
1893	176.34	176.38	176.42	176.56	176.65	176.75	176.75	176.70	176.60	176.56	176.44	176.42	176.55
1894	176.42	176.43	176.51	176.56	176.72	176.77	176.78	176.76	176.62	176.56	176.48	176.37	176.58
1895	176.32	176.28	176.28	176.33	176.38	176.40	176.37	176.33	176.25	176.13	176.07	176.03	176.26
1896	176.06	176.07	176.07	176.13	176.21	176.31	176.29	176.27	176.24	176.23	176.16	176.14	176.18
1897	176.14	176.16	176.26	176.31	176.46	176.54	176.60	176.58	176.51	176.42	176.34	176.27	176.38
1898	176.26	176.30	176.40	176.49	176.58	176.62	176.61	176.55	176.44	176.44	176.32	176.21	176.44
1899	176.20	176.22	176.28	176.37	176.50	176.60	176.66	176.64	176.60	176.50	176.44	176.29	176.44
1900	176.24	176.28	176.33	176.37	176.44	176.48	176.51	176.56	176.54	176.55	176.50	176.40	176.43
1901	176.33	176.32	176.45	176.50	176.63	176.64	176.67	176.69	176.63	176.52	176.42	176.33	176.51
1902	176.27	176.23	176.30	176.32	176.43	176.49	176.60	176.60	176.48	176.43	176.40	176.31	176.41
1903	176.25	176.30	176.36	176.44	176.47	176.53	176.58	176.56	176.58	176.52	176.41	176.30	176.44
1904	176.32	176.32	176.41	176.55	176.66	176.78	176.78	176.75	176.73	176.69	176.60	176.49	176.59
1905	176.45	176.41	176.47	176.58	176.66	176.78	176.82	176.81	176.78	176.65	176.57	176.52	176.63
1906	176.52	176.56	176.61	176.66	176.74	176.78	176.78	176.77	176.66	176.61	176.56	176.54	176.65
1907	176.52	176.54	176.56	176.63	176.68	176.79	176.79	176.77	176.76	176.69	176.56	176.53	176.65
1908	176.48	176.50	176.52	176.61	176.79	176.83	176.89	176.85	176.72	176.61	176.41	176.37	176.63
1909	176.29	176.34	176.36	176.44	176.60	176.66	176.65	176.66	176.57	176.43	176.38	176.38	176.48
1910	176.31	176.31	176.33	176.44	176.48	176.50	176.48	176.43	176.42	176.36	176.26	176.16	176.37
1911	176.09	176.15	176.10	176.17	176.26	176.34	176.29	176.28	176.26	176.22	176.13	176.16	176.20
1912	176.11	176.12	176.13	176.19	176.34	176.47	176.50	176.52	176.55	176.46	176.46	176.39	176.35
1913	176.34	176.28	176.37	176.58	176.68	176.72	176.72	176.72	176.63	176.57	176.47	176.42	176.54
1914	176.35	176.35	176.34	176.38	176.45	176.53	176.58	176.55	176.49	176.45	176.28	176.20	176.41
1915	176.17	176.24	176.22	176.20	176.25	176.30	176.33	176.39	176.33	176.27	176.17	176.16	176.25
1916	176.07	176.12	176.16	176.31	176.49	176.68	176.74	176.66	176.54	176.52	176.53	176.51	176.44
1917	176.47	176.44	176.48	176.60	176.70	176.83	176.94	176.92	176.86	176.76	176.70	176.57	176.69
1918	176.58	176.59	176.68	176.79	176.87	176.94	176.94	176.90	176.79	176.70	176.66	176.68	176.76
1919	176.57	176.55	176.58	176.68	176.78	176.82	176.75	176.68	176.57	176.54	176.46	176.36	176.61
1920	176.34	176.35	176.39	176.51	176.58	176.62	176.66	176.67	176.62	176.52	176.43	176.37	176.51
1921	176.31	176.30	176.33	176.47	176.53	176.53	176.48	176.39	176.34	176.30	176.24	176.19	176.37
1922	176.12	176.11	176.18	176.35	176.49	176.52	176.56	176.53	176.47	176.34	176.21	176.07	176.33
1923	176.06	175.98	176.04	176.11	176.24	176.30	176.32	176.27	176.24	176.16	176.06	175.97	176.15

1924	175.89	175.96	175.96	176.03	176.12	176.17	176.20	176.24	176.20	176.12	175.97	175.87	176.06
1925	175.82	175.80	175.83	175.88	175.87	175.88	175.91	175.89	175.83	175.70	175.63	175.57	175.80
1926	175.54	175.58	175.61	175.69	175.80	175.87	175.91	175.95	175.92	175.84	175.83	175.81	175.78
1927	175.80	175.81	175.90	176.00	176.11	176.18	176.22	176.18	176.11	176.07	176.01	175.96	176.03
1928	175.93	175.99	176.02	176.21	176.34	176.41	176.48	176.52	176.47	176.49	176.53	176.55	176.33
1929	176.51	176.56	176.55	176.80	176.97	177.03	177.07	177.02	176.90	176.82	176.68	176.60	176.79
1930	176.53	176.52	176.56	176.60	176.65	176.67	176.73	176.69	176.54	176.43	176.29	176.17	176.53
1931	176.10	176.06	176.10	176.06	176.09	176.11	176.08	176.03	175.94	175.88	175.83	175.82	176.01
1932	175.83	175.78	175.79	175.87	175.93	175.95	175.92	175.89	175.80	175.76	175.71	175.63	175.82
1933	175.64	175.62	175.66	175.76	175.92	175.96	175.97	175.90	175.81	175.70	175.64	175.60	175.77
1934	175.59	175.59	175.58	175.65	175.72	175.75	175.78	175.75	175.74	175.64	175.63	175.65	175.67
1935	175.62	175.65	175.69	175.78	175.82	175.88	175.94	175.93	175.86	175.78	175.79	175.75	175.79
1936	175.74	175.71	175.76	175.82	175.92	175.98	175.96	175.92	175.94	175.87	175.77	175.69	175.84
1937	175.70	175.71	175.74	175.82	175.92	175.95	175.97	175.96	175.91	175.82	175.73	175.67	175.83
1938	175.69	175.79	175.84	175.99	176.10	176.18	176.24	176.23	176.28	176.20	176.10	176.01	176.05
1939	175.99	175.99	176.03	176.08	176.21	176.34	176.37	176.37	176.36	176.24	176.17	176.07	176.19
1940	175.99	176.01	175.96	175.98	176.06	176.13	176.17	176.22	176.19	176.12	176.00	175.98	176.07
1941	176.02	175.98	175.98	176.02	176.09	176.12	176.09	176.03	175.98	176.02	176.07	176.06	176.04
1942	176.02	176.06	176.11	176.22	176.33	176.44	176.43	176.41	176.35	176.28	176.23	176.16	176.25
1943	176.19	176.17	176.26	176.36	176.51	176.70	176.80	176.84	176.77	176.73	176.66	176.51	176.54
1944	176.47	176.45	176.48	176.53	176.59	176.63	176.63	176.59	176.57	176.53	176.48	176.33	176.52
1945	176.27	176.25	176.30	176.38	176.49	176.66	176.70	176.66	176.63	176.54	176.54	176.49	176.49
1946	176.45	176.49	176.59	176.62	176.66	176.69	176.72	176.64	176.54	176.41	176.31	176.21	176.53
1947	176.20	176.16	176.16	176.32	176.51	176.68	176.72	176.74	176.70	176.69	176.58	176.49	176.50
1948	176.38	176.33	176.42	176.56	176.65	176.67	176.66	176.58	176.52	176.34	176.26	176.16	176.46
1949	176.11	176.12	176.12	176.18	176.24	176.28	176.32	176.28	176.11	176.04	175.93	175.83	176.13
1950	175.85	175.93	175.94	176.12	176.22	176.25	176.34	176.39	176.39	176.32	176.24	176.25	176.19
1951	176.26	176.28	176.36	176.52	176.69	176.76	176.83	176.90	176.84	176.89	176.88	176.88	176.67
1952	176.89	176.93	176.94	177.06	177.12	177.17	177.18	177.23	177.13	176.95	176.88	176.85	177.03
1953	176.80	176.73	176.79	176.88	176.97	177.02	177.05	177.05	176.94	176.88	176.74	176.64	176.87
1954	176.60	176.56	176.59	176.68	176.77	176.88	176.90	176.90	176.88	176.93	176.89	176.85	176.79
1955	176.77	176.74	176.70	176.79	176.82	176.86	176.81	176.73	176.57	176.47	176.37	176.30	176.66
1956	176.28	176.24	176.30	176.32	176.45	176.51	176.57	176.56	176.50	176.41	176.30	176.21	176.39
1957	176.13	176.14	176.13	176.17	176.26	176.30	176.36	176.33	176.27	176.20	176.11	176.09	176.21
1958	176.10	176.07	176.08	176.09	176.04	176.05	176.11	176.04	175.98	175.91	175.80	175.73	176.00
1959	175.70	175.70	175.78	175.90	176.05	176.08	176.06	176.07	176.03	176.06	176.06	176.09	175.97
1960	176.08	176.14	176.13	176.21	176.48	176.60	176.67	176.73	176.70	176.58	176.48	176.38	176.43
1961	176.33	176.30	176.34	176.35	176.40	176.40	176.43	176.42	176.38	176.32	176.26	176.19	176.34
1962	176.12	176.17	176.20	176.24	176.33	176.36	176.32	176.29	176.19	176.15	176.03	175.91	176.19
1963	175.83	175.81	175.84	175.91	175.99	176.03	176.01	176.00	175.98	175.86	175.73	175.66	175.89
1964	175.57	175.54	175.57	175.62	175.70	175.73	175.77	175.74	175.70	175.64	175.60	175.58	175.65
1965	175.56	175.58	175.67	175.77	175.92	175.99	175.99	176.01	176.04	176.06	176.01	176.06	175.89
1966	176.06	176.06	176.13	176.20	176.23	176.25	176.24	176.20	176.17	175.99	176.00	176.04	176.13
1967	176.01	176.04	176.04	176.21	176.33	176.43	176.46	176.45	176.40	176.31	176.29		176.27
1968		176.21	176.26	176.33	176.42	176.46	176.51	176.53	176.57	176.51	176.49	176.46	176.43
1969	176.42		176.46	176.55	176.70	176.80	176.92	176.89	176.84	176.74	176.66	176.62	176.69
1970	176.56	176.51	176.53	176.57	176.67	176.74	176.76	176.73	176.72	176.70	176.67	176.65	176.65
1971	176.57	176.58	176.66	176.73	176.84	176.93	176.89		176.86	176.81	176.72	176.71	176.75
1972	176.61	176.63	176.66	176.74	176.88	176.92	176.96	177.03	177.03	176.98	176.98	176.93	176.86
1973	176.92	176.96	177.01	177.12	177.20	177.27	177.26	177.25	177.17	177.12	177.00	177.01	177.11
1974	176.91	176.98	176.99	177.09	177.18	177.27	177.27	177.21	177.10	177.00	176.94	176.89	177.07
1975	176.84	176.83	176.88	176.92	177.05	177.12	177.10	177.08	177.06	176.92	176.85	176.81	176.96
1976	176.72	176.72	176.87	177.02	177.10	177.13	177.12	177.06	176.92	176.78	176.57	176.45	176.87
1977	176.37	176.36	176.44	176.57	176.57	176.54	176.52	176.49	176.51	176.49	176.48	176.50	176.49
1978	176.48	176.44	176.42	176.54	176.62	176.65	176.67	176.64	176.72	176.65	176.60	176.49	176.58
1979	176.48	176.50	176.55	176.72	176.90	176.94	176.98	176.98	176.93	176.88	176.79	176.77	176.79
1980	176.74	176.72	176.68	176.79	176.84	176.90	176.92	176.91	176.87	176.79	176.69	176.63	176.79
1981	176.58	176.55	176.59	176.68	176.77	176.79	176.83	176.83	176.81	176.74	176.66	176.56	176.70
1982	176.49	176.45	176.44	176.55	176.64	176.66	176.68	176.68	176.65	176.59	176.57	176.64	176.59
1983	176.67	176.68	176.75	176.80	176.92	177.03	177.00	176.98	176.88	176.86	176.81	176.71	176.84
1984	176.68	176.73	176.75	176.86	176.91	177.01	177.04	177.04	177.00	176.94	176.90	176.84	176.89
1985	176.89	176.87	177.03	177.18	177.27	177.26	177.23	177.20	177.20	177.14	177.26	177.16	177.14
1986	177.13	177.14	177.14	177.27	177.30	177.35	177.40	177.38	177.40	177.52	177.34	177.24	177.30
1987	177.18	177.14	177.13	177.12	177.09	177.08	177.03	177.00	176.91	176.76	176.70	176.67	176.98
1988	176.58	176.58	176.59	176.68	176.72	176.67	176.61	176.54	176.46	176.40	176.43	176.37	176.55
1989	176.36	176.31	176.36	176.43	176.46	176.59	176.61	176.55	176.47	176.36	176.24	176.18	176.41
1990	176.13	176.17	176.2	176.27	176.38	176.45	176.52	176.52	176.46	176.41	176.36	176.38	176.35
1991	176.32	176.3	176.38	176.52	176.63	176.69	176.66	176.62	176.46	176.41	176.36	176.38	176.48
1992	176.38	176.4	176.44	176.49	176.56	176.56	176.58	176.55	176.51	176.5	176.56	176.51	176.50
1993	176.55	176.55	176.53	176.66	176.74	176.85	176.92	176.9	176.82	176.74	176.71	176.64	176.72
1994	176.6	176.6	176.62	176.66	176.72	176.76	176.83	176.81	176.79	176.7	176.64	176.6	176.69
1995	176.53	176.49	176.51	176.55	176.62	176.68	176.63	176.67	176.57	176.44	176.44	176.4	176.54
1996	176.41	176.42	176.44	176.52	176.69	176.81	176.86	176.87	176.87	176.82	176.79	176.8	176.69
1997	176.81	176.85	176.92	176.97	177.1	177.17	177.22	177.21	177.15	177.03	176.91	176.8	177.01
1998	176.8	176.79	176.81	176.96	176.97	176.93	176.9		176.69	176.57	176.44	176.33	176.74
1999	176.309	176.308	176.285	176.335	176.336	176.374	176.404	176.397	176.257	176.144	176.036	175.973	176.26
2000	175.939	175.905	175.941	175.985	176.042	176.122	176.173	176.164	176.107				

APPENDIX III Monthly Precipitation Measured at Milwaukee, WI

Precipitation Statistics
Monthly Totals
Measured at : Milwaukee Airport

Year	Month	Date Fraction	Precip. (inches)
1950	2	1950.199543	2.16
1950	3	1950.282877	1.39
1950	4	1950.36621	2.50
1950	5	1950.449543	3.58
1950	6	1950.532877	2.04
1950	7	1950.61621	5.11
1950	8	1950.699543	6.07
1950	9	1950.782877	3.29
1950	10	1950.86621	1.75
1950	11	1950.949543	0.55
1950	12	1951.032877	1.60
1951	1	1951.11621	2.62
1951	2	1951.199543	2.38
1951	3	1951.282877	1.87
1951	4	1951.36621	3.33
1951	5	1951.449543	4.91
1951	6	1951.532877	3.87
1951	7	1951.61621	2.97
1951	8	1951.699543	3.12
1951	9	1951.782877	2.56
1951	10	1951.86621	2.75
1951	11	1951.949543	4.42
1951	12	1952.032877	1.99
1952	1	1952.11621	2.26
1952	2	1952.199543	2.08
1952	3	1952.282877	0.82
1952	4	1952.36621	3.67
1952	5	1952.449543	2.95
1952	6	1952.532877	2.86
1952	7	1952.61621	4.03
1952	8	1952.699543	6.69
1952	9	1952.782877	3.59
1952	10	1952.86621	0.36
1952	11	1952.949543	0.17
1952	12	1953.032877	3.37
1953	1	1953.11621	2.10
1953	2	1953.199543	1.16
1953	3	1953.282877	1.62
1953	4	1953.36621	1.18
1953	5	1953.449543	2.81
1953	6	1953.532877	1.77
1953	7	1953.61621	2.65
1953	8	1953.699543	2.78
1953	9	1953.782877	4.34
1953	10	1953.86621	1.65
1953	11	1953.949543	0.46
1953	12	1954.032877	0.58
1954	1	1954.11621	1.87
1954	2	1954.199543	0.92
1954	3	1954.282877	1.31
1954	4	1954.36621	1.65
1954	5	1954.449543	3.27
1954	6	1954.532877	1.83
1954	7	1954.61621	8.28
1954	8	1954.699543	5.13
1954	9	1954.782877	3.86
1954	10	1954.86621	2.78
1954	11	1954.949543	3.18
1954	12	1955.032877	1.06
1955	1	1955.11621	2.64
1955	2	1955.199543	0.62
1955	3	1955.282877	1.32
1955	4	1955.36621	1.05
1955	5	1955.449543	2.43
1955	6	1955.532877	4.29
1955	7	1955.61621	4.58
1955	8	1955.699543	2.10
1955	9	1955.782877	3.62
1955	10	1955.86621	2.36
1955	11	1955.949543	3.57
1955	12	1956.032877	0.87
1956	1	1956.11621	1.09
1956	2	1956.199543	0.57
1956	3	1956.282877	1.43
1956	4	1956.36621	2.36
1956	5	1956.449543	4.14
1956	6	1956.532877	4.55
1956	7	1956.61621	3.87
1956	8	1956.699543	5.37
1956	9	1956.782877	2.96
1956	10	1956.86621	0.30
1956	11	1956.949543	0.15
1956	12	1957.032877	1.62
1957	1	1957.11621	1.03
1957	2	1957.199543	0.88
1957	3	1957.282877	0.96
1957	4	1957.36621	1.59
1957	5	1957.449543	2.70
1957	6	1957.532877	3.82
1957	7	1957.61621	4.01
1957	8	1957.699543	1.50
1957	9	1957.782877	2.03
1957	10	1957.86621	0.88
1957	11	1957.949543	1.34
1957	12	1958.032877	2.88
1958	1	1958.11621	2.36
1958	2	1958.199543	1.41
1958	3	1958.282877	0.15
1958	4	1958.36621	0.46
1958	5	1958.449543	1.84
1958	6	1958.532877	2.07
1958	7	1958.61621	1.71
1958	8	1958.699543	1.02
1958	9	1958.782877	1.71
1958	10	1958.86621	2.85
1958	11	1958.949543	3.24
1958	12	1959.032877	3.37
1959	1	1959.11621	0.34
1959	2	1959.199543	2.48
1959	3	1959.282877	1.98
1959	4	1959.36621	3.03
1959	5	1959.449543	3.29
1959	6	1959.532877	1.28
1959	7	1959.61621	1.67
1959	8	1959.699543	6.82
1959	9	1959.782877	3.47
1959	10	1959.86621	2.31
1959	11	1959.949543	6.42
1959	12	1960.032877	2.08

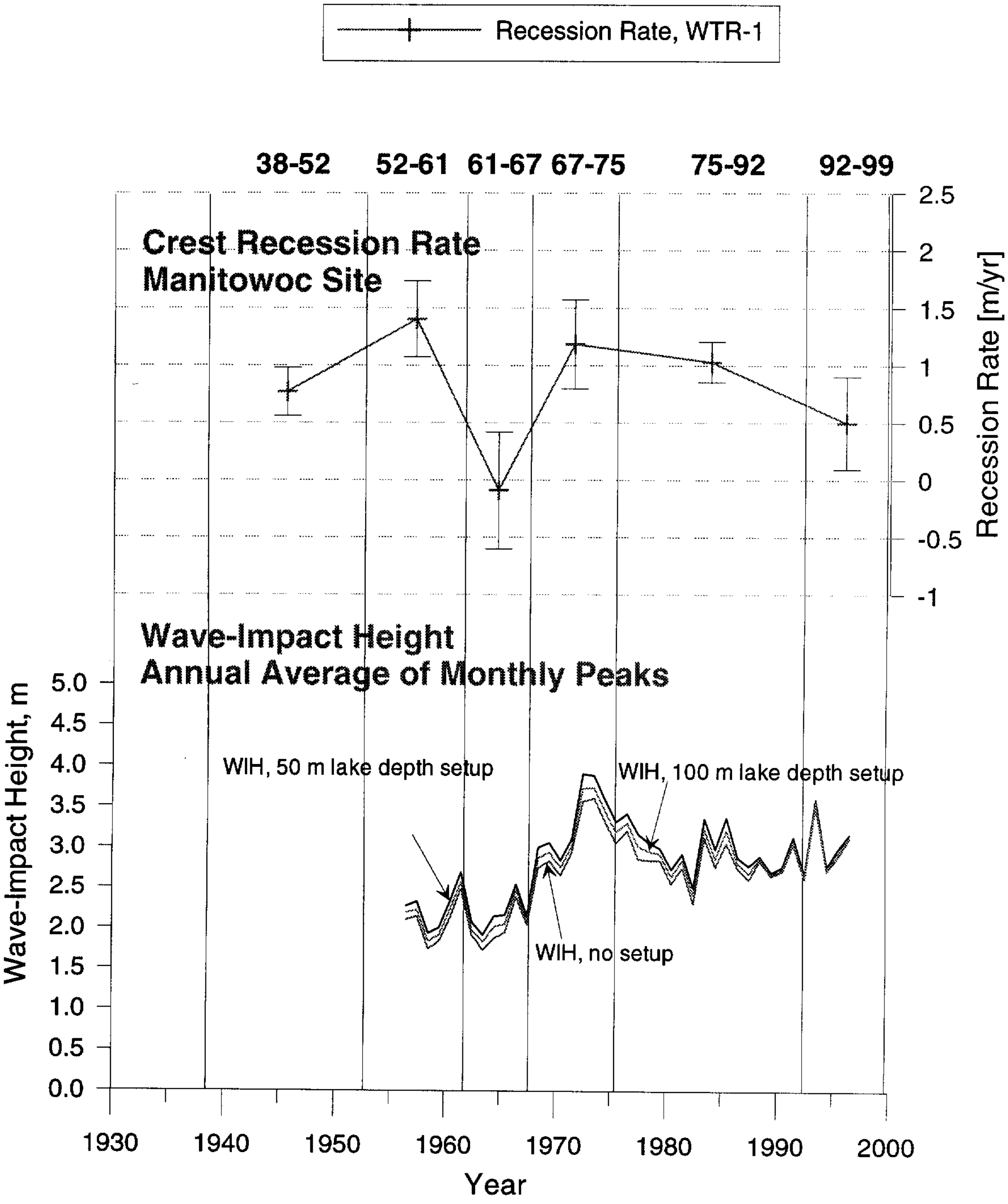
Year	Month	Date Fraction	Precip. (inches)
1960	1	1960.11621	2.85
1960	2	1960.199543	4.04
1960	3	1960.282877	3.05
1960	4	1960.36621	3.80
1960	5	1960.449543	2.92
1960	6	1960.532877	4.27
1960	7	1960.61621	3.28
1960	8	1960.699543	3.50
1960	9	1960.782877	7.07
1960	10	1960.86621	3.25
1960	11	1960.949543	3.06
1960	12	1961.032877	2.12
1961	1	1961.11621	0.35
1961	2	1961.199543	0.31
1961	3	1961.282877	1.22
1961	4	1961.36621	3.80
1961	5	1961.449543	3.89
1961	6	1961.532877	1.25
1961	7	1961.61621	1.53
1961	8	1961.699543	2.91
1961	9	1961.782877	2.35
1961	10	1961.86621	9.41
1961	11	1961.949543	2.75
1961	12	1962.032877	2.37
1962	1	1962.11621	1.02
1962	2	1962.199543	2.48
1962	3	1962.282877	2.04
1962	4	1962.36621	1.69
1962	5	1962.449543	1.49
1962	6	1962.532877	2.17
1962	7	1962.61621	1.33
1962	8	1962.699543	3.74
1962	9	1962.782877	1.98
1962	10	1962.86621	1.49
1962	11	1962.949543	2.14
1962	12	1963.032877	0.81
1963	1	1963.11621	0.55
1963	2	1963.199543	0.66
1963	3	1963.282877	0.42
1963	4	1963.36621	2.20
1963	5	1963.449543	2.54
1963	6	1963.532877	1.95
1963	7	1963.61621	1.50
1963	8	1963.699543	2.36
1963	9	1963.782877	2.48
1963	10	1963.86621	1.78
1963	11	1963.949543	0.34
1963	12	1964.032877	2.17
1964	1	1964.11621	0.70
1964	2	1964.199543	1.18
1964	3	1964.282877	0.41
1964	4	1964.36621	3.05
1964	5	1964.449543	3.81
1964	6	1964.532877	2.57
1964	7	1964.61621	1.70
1964	8	1964.699543	7.66
1964	9	1964.782877	2.62
1964	10	1964.86621	1.74
1964	11	1964.949543	0.17
1964	12	1965.032877	2.29
1965	1	1965.11621	0.98
1965	2	1965.199543	3.33
1965	3	1965.282877	1.04
1965	4	1965.36621	3.61
1965	5	1965.449543	3.47
1965	6	1965.532877	2.12
1965	7	1965.61621	0.85
1965	8	1965.699543	2.64
1965	9	1965.782877	6.15
1965	10	1965.86621	6.85
1965	11	1965.949543	2.68
1965	12	1966.032877	2.02
1966	1	1966.11621	3.73
1966	2	1966.199543	2.06
1966	3	1966.282877	1.27
1966	4	1966.36621	3.61
1966	5	1966.449543	2.67
1966	6	1966.532877	2.00
1966	7	1966.61621	1.68
1966	8	1966.699543	3.32
1966	9	1966.782877	3.27
1966	10	1966.86621	0.48
1966	11	1966.949543	1.76
1966	12	1967.032877	2.70
1967	1	1967.11621	2.31
1967	2	1967.199543	1.49
1967	3	1967.282877	1.31
1967	4	1967.36621	1.35
1967	5	1967.449543	2.70
1967	6	1967.532877	1.80
1967	7	1967.61621	7.38
1967	8	1967.699543	1.35
1967	9	1967.782877	1.23
1967	10	1967.86621	1.69
1967	11	1967.949543	2.70
1967	12	1968.032877	1.52
1968	1	1968.11621	1.33
1968	2	1968.199543	0.98
1968	3	1968.282877	0.56
1968	4	1968.36621	0.31
1968	5	1968.449543	2.90
1968	6	1968.532877	3.28
1968	7	1968.61621	7.79
1968	8	1968.699543	3.59
1968	9	1968.782877	2.59
1968	10	1968.86621	3.36
1968	11	1968.949543	0.94
1968	12	1969.032877	2.56
1969	1	1969.11621	2.65
1969	2	1969.199543	1.83
1969	3	1969.282877	0.05
1969	4	1969.36621	1.05
1969	5	1969.449543	3.42
1969	6	1969.532877	3.05
1969	7	1969.61621	7.53
1969	8	1969.699543	6.61
1969	9	1969.782877	0.53
1969	10	1969.86621	2.18
1969	11	1969.949543	4.48
1969	12	1970.032877	1.14

Year	Month	Date Fraction	Precip. (inches)
1970	1	1970.11621	1.18
1970	2	1970.199543	0.41
1970	3	1970.282877	0.13
1970	4	1970.36621	1.62
1970	5	1970.449543	2.71
1970	6	1970.532877	3.41
1970	7	1970.61621	3.92
1970	8	1970.699543	1.93
1970	9	1970.782877	0.64
1970	10	1970.86621	6.94
1970	11	1970.949543	2.09
1970	12	1971.032877	2.03
1971	1	1971.11621	3.02
1971	2	1971.199543	1.37
1971	3	1971.282877	2.50
1971	4	1971.36621	2.83
1971	5	1971.449543	1.31
1971	6	1971.532877	0.90
1971	7	1971.61621	2.67
1971	8	1971.699543	2.60
1971	9	1971.782877	2.28
1971	10	1971.86621	1.30
1971	11	1971.949543	1.90
1971	12	1972.032877	2.45
1972	1	1972.11621	4.34
1972	2	1972.199543	0.75
1972	3	1972.282877	0.86
1972	4	1972.36621	2.57
1972	5	1972.449543	2.76
1972	6	1972.532877	2.33
1972	7	1972.61621	3.33
1972	8	1972.699543	4.60
1972	9	1972.782877	4.82
1972	10	1972.86621	7.57
1972	11	1972.949543	3.28
1972	12	1973.032877	1.34
1973	1	1973.11621	2.47
1973	2	1973.199543	1.12
1973	3	1973.282877	1.51
1973	4	1973.36621	2.86
1973	5	1973.449543	7.31
1973	6	1973.532877	3.39
1973	7	1973.61621	1.96
1973	8	1973.699543	1.55
1973	9	1973.782877	0.95
1973	10	1973.86621	4.50
1973	11	1973.949543	2.97
1973	12	1974.032877	1.83
1974	1	1974.11621	3.80
1974	2	1974.199543	3.61
1974	3	1974.282877	3.10
1974	4	1974.36621	4.29
1974	5	1974.449543	3.83
1974	6	1974.532877	4.10
1974	7	1974.61621	3.48
1974	8	1974.699543	3.51
1974	9	1974.782877	2.54
1974	10	1974.86621	0.50
1974	11	1974.949543	1.96
1974	12	1975.032877	1.86
1975	1	1975.11621	2.10
1975	2	1975.199543	2.25
1975	3	1975.282877	2.53
1975	4	1975.36621	3.01
1975	5	1975.449543	4.08
1975	6	1975.532877	2.01
1975	7	1975.61621	3.99
1975	8	1975.699543	1.14
1975	9	1975.782877	3.89
1975	10	1975.86621	1.00
1975	11	1975.949543	0.72
1975	12	1976.032877	2.83
1976	1	1976.11621	1.70
1976	2	1976.199543	1.16
1976	3	1976.282877	2.65
1976	4	1976.36621	6.93
1976	5	1976.449543	5.01
1976	6	1976.532877	3.77
1976	7	1976.61621	2.27
1976	8	1976.699543	2.12
1976	9	1976.782877	2.05
1976	10	1976.86621	1.70
1976	11	1976.949543	2.82
1976	12	1977.032877	0.65
1977	1	1977.11621	0.29
1977	2	1977.199543	0.90
1977	3	1977.282877	0.59
1977	4	1977.36621	4.56
1977	5	1977.449543	2.09
1977	6	1977.532877	0.90
1977	7	1977.61621	5.78
1977	8	1977.699543	5.99
1977	9	1977.782877	3.82
1977	10	1977.86621	4.11
1977	11	1977.949543	2.02
1977	12	1978.032877	2.56
1978	1	1978.11621	3.27
1978	2	1978.199543	2.03
1978	3	1978.282877	0.55
1978	4	1978.36621	1.08
1978	5	1978.449543	4.41
1978	6	1978.532877	4.66
1978	7	1978.61621	4.52
1978	8	1978.699543	5.98
1978	9	1978.782877	3.43
1978	10	1978.86621	6.81
1978	11	1978.949543	2.22
1978	12	1979.032877	2.13
1979	1	1979.11621	2.92
1979	2	1979.199543	3.00
1979	3	1979.282877	0.97
1979	4	1979.36621	4.17
1979	5	1979.449543	5.43
1979	6	1979.532877	1.62
1979	7	1979.61621	2.84
1979	8	1979.699543	1.06
1979	9	1979.782877	4.85
1979	10	1979.86621	0.02
1979	11	1979.949543	1.77
1979	12	1980.032877	2.67
1980	1	1980.11621	2.27
1980	2	1980.199543	1.65
1980	3	1980.282877	1.75
1980	4	1980.36621	0.77
1980	5	1980.449543	4.02
1980	6	1980.532877	1.81
1980	7	1980.61621	4.67
1980	8	1980.699543	3.39
1980	9	1980.782877	5.06
1980	10	1980.86621	3.57
1980	11	1980.949543	1.63
1980	12	1981.032877	1.57
1981	1	1981.11621	3.52
1981	2	1981.199543	0.31
1981	3	1981.282877	2.88
1981	4	1981.36621	0.51
1981	5	1981.449543	4.87
1981	6	1981.532877	3.05
1981	7	1981.61621	2.39
1981	8	1981.699543	4.35
1981	9	1981.782877	4.26
1981	10	1981.86621	5.47
1981	11	1981.949543	2.71
1981	12	1982.032877	2.05
1982	1	1982.11621	1.03
1982	2	1982.199543	2.92
1982	3	1982.282877	0.29
1982	4	1982.36621	3.20
1982	5	1982.449543	4.47
1982	6	1982.532877	2.76
1982	7	1982.61621	3.06
1982	8	1982.699543	3.88
1982	9	1982.782877	3.33
1982	10	1982.86621	0.64
1982	11	1982.949543	3.17
1982	12	1983.032877	4.74
1983	1	1983.11621	4.10
1983	2	1983.199543	0.75
1983	3	1983.282877	2.23
1983	4	1983.36621	4.12
1983	5	1983.449543	4.66
1983	6	1983.532877	5.83
1983	7	1983.61621	1.41
1983	8	1983.699543	1.34
1983	9	1983.782877	4.70
1983	10	1983.86621	2.79
1983	11	1983.949543	2.65
1983	12	1984.032877	4.10
1984	1	1984.11621	2.89
1984	2	1984.199543	0.79
1984	3	1984.282877	1.20
1984	4	1984.36621	2.17
1984	5	1984.449543	5.04
1984	6	1984.532877	4.21
1984	7	1984.61621	4.07
1984	8	1984.699543	3.39
1984	9	1984.782877	2.93
1984	10	1984.86621	2.51
1984	11	1984.949543	5.30
1984	12	1985.032877	3.74
1985	1	1985.11621	4.25
1985	2	1985.199543	1.93
1985	3	1985.282877	2.34
1985	4	1985.36621	4.11
1985	5	1985.449543	1.93
1985	6	1985.532877	2.73
1985	7	1985.61621	1.27
1985	8	1985.699543	2.18
1985	9	1985.782877	2.23
1985	10	1985.86621	3.44
1985	11	1985.949543	5.39
1985	12	1986.032877	7.11
1986	1	1986.11621	2.62
1986	2	1986.199543	0.91
1986	3	1986.282877	3.94
1986	4	1986.36621	1.85
1986	5	1986.449543	1.83
1986	6	1986.532877	2.74
1986	7	1986.61621	4.51
1986	8	1986.699543	6.15
1986	9	1986.782877	8.82
1986	10	1986.86621	7.26
1986	11	1986.949543	2.24
1986	12	1987.032877	0.89
1987	1	1987.11621	1.03
1987	2	1987.199543	1.22
1987	3	1987.282877	1.22
1987	4	1987.36621	1.74
1987	5	1987.449543	4.26
1987	6	1987.532877	3.76
1987	7	1987.61621	2.23
1987	8	1987.699543	4.20
1987	9	1987.782877	9.05
1987	10	1987.86621	2.22
1987	11	1987.949543	1.09
1987	12	1988.032877	2.83
1988	1	1988.11621	5.42
1988	2	1988.199543	3.25
1988	3	1988.282877	1.29
1988	4	1988.36621	1.30
1988	5	1988.449543	3.97
1988	6	1988.532877	0.50
1988	7	1988.61621	0.70
1988	8	1988.699543	1.53
1988	9	1988.782877	3.25
1988	10	1988.86621	4.94
1988	11	1988.949543	2.97
1988	12	1989.032877	5.15
1989	1	1989.11621	1.43
1989	2	1989.199543	0.86
1989	3	1989.282877	0.69
1989	4	1989.36621	3.03
1989	5	1989.449543	1.33
1989	6	1989.532877	2.86
1989	7	1989.61621	1.89
1989	8	1989.699543	6.16
1989	9	1989.782877	5.19
1989	10	1989.86621	3.25
1989	11	1989.949543	2.67
1989	12	1990.032877	1.90
1990	1	1990.11621	0.47
1990	2	1990.199543	2.57
1990	3	1990.282877	1.90
1990	4	1990.36621	2.75
1990	5	1990.449543	2.67
1990	6	1990.532877	7.56
1990	7	1990.61621	4.97
1990	8	1990.699543	3.02
1990	9	1990.782877	4.68
1990	10	1990.86621	1.89
1990	11	1990.949543	2.65
1990	12	1991.032877	3.54

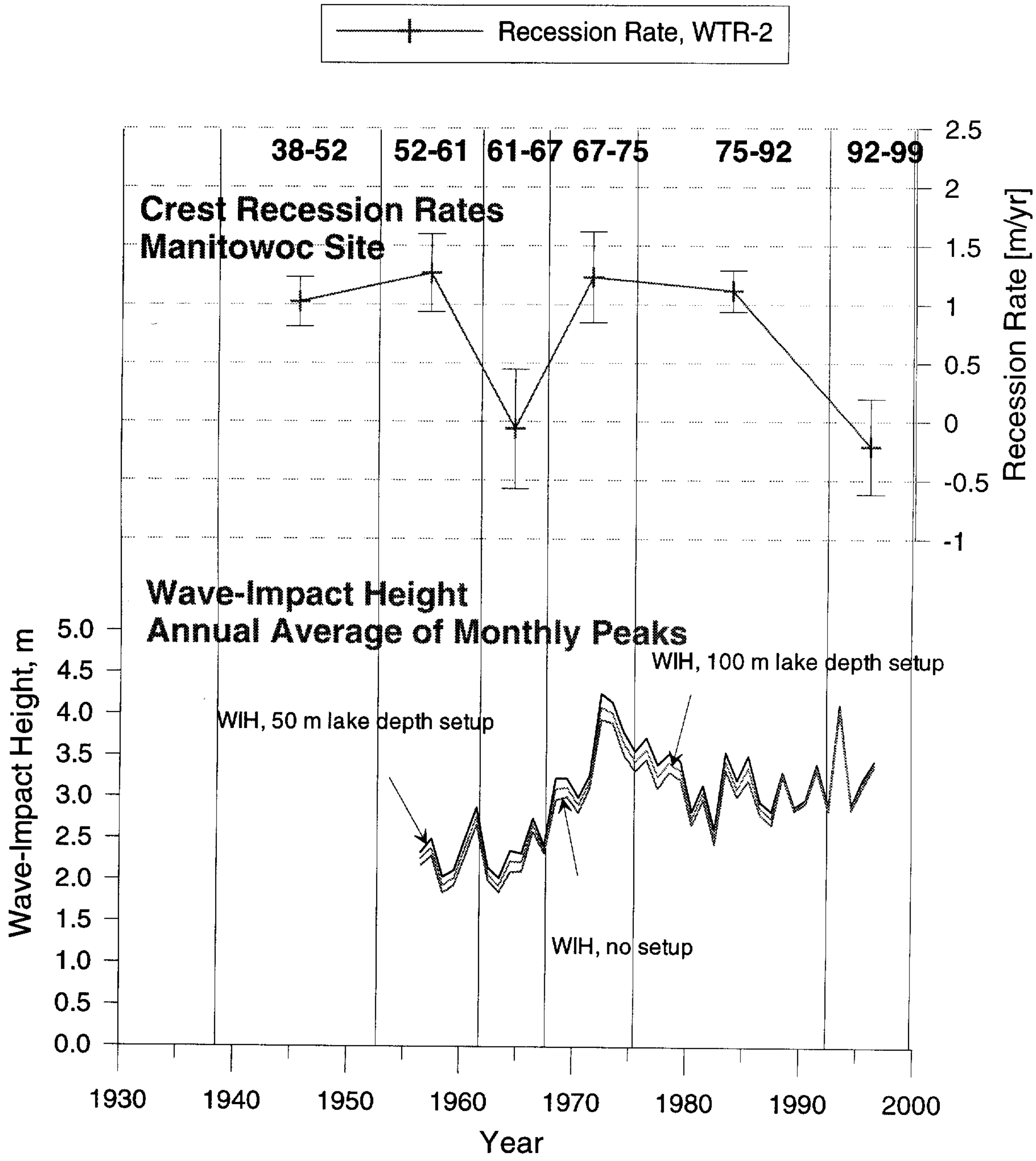
Year	Month	Date Fraction	Precip. (inches)
1991	1	1991.11621	2.66
1991	2	1991.199543	1.55
1991	3	1991.282877	0.38
1991	4	1991.36621	4.06
1991	5	1991.449543	3.70
1991	6	1991.532877	4.25
1991	7	1991.61621	2.13
1991	8	1991.699543	4.34
1991	9	1991.782877	2.27
1991	10	1991.86621	4.34
1991	11	1991.949543	7.03
1991	12	1992.032877	3.36
1992	1	1992.11621	1.94
1992	2	1992.199543	1.09
1992	3	1992.282877	1.54
1992	4	1992.36621	2.61
1992	5	1992.449543	2.41
1992	6	1992.532877	0.60
1992	7	1992.61621	3.13
1992	8	1992.699543	5.64
1992	9	1992.782877	3.50
1992	10	1992.86621	4.13
1992	11	1992.949543	1.45
1992	12	1993.032877	5.40
1993	1	1993.11621	2.45
1993	2	1993.199543	2.63
1993	3	1993.282877	0.98
1993	4	1993.36621	3.19
1993	5	1993.449543	6.64
1993	6	1993.532877	1.56
1993	7	1993.61621	6.39
1993	8	1993.699543	4.22
1993	9	1993.782877	4.20
1993	10	1993.86621	3.91
1993	11	1993.949543	0.44
1993	12	1994.032877	1.98
1994	1	1994.11621	0.70
1994	2	1994.199543	2.20
1994	3	1994.282877	3.52
1994	4	1994.36621	1.21
1994	5	1994.449543	2.35
1994	6	1994.532877	0.67
1994	7	1994.61621	3.08
1994	8	1994.699543	2.51
1994	9	1994.782877	4.91
1994	10	1994.86621	1.68
1994	11	1994.949543	0.78
1994	12	1995.032877	3.31
1995	1	1995.11621	1.14
1995	2	1995.199543	2.14
1995	3	1995.282877	0.25
1995	4	1995.36621	1.76
1995	5	1995.449543	3.86
1995	6	1995.532877	3.41
1995	7	1995.61621	1.46
1995	8	1995.699543	3.52
1995	9	1995.782877	5.82
1995	10	1995.86621	0.79
1995	11	1995.949543	2.44
1995	12	1996.032877	4.20
1996	1	1996.11621	0.89
1996	2	1996.199543	1.41
1996	3	1996.282877	0.51
1996	4	1996.36621	0.73
1996	5	1996.449543	3.00
1996	6	1996.532877	2.63
1996	7	1996.61621	5.13
1996	8	1996.699543	1.38
1996	9	1996.782877	1.19
1996	10	1996.86621	1.71
1996	11	1996.949543	2.84
1996	12	1997.032877	0.47
1997	1	1997.11621	1.01
1997	2	1997.199543	1.26
1997	3	1997.282877	2.37
1997	4	1997.36621	0.63
1997	5	1997.449543	1.97
1997	6	1997.532877	1.76
1997	7	1997.61621	7.44
1997	8	1997.699543	3.27
1997	9	1997.782877	3.47
1997	10	1997.86621	1.72
1997	11	1997.949543	1.11
1997	12	1998.032877	1.02
1998	1	1998.11621	0.70
1998	2	1998.199543	1.78
1998	3	1998.282877	1.87
1998	4	1998.36621	3.08
1998	5	1998.449543	4.13
1998	6	1998.532877	2.47
1998	7	1998.61621	2.79
1998	8	1998.699543	1.07
1998	9	1998.782877	5.98
1998	10	1998.86621	2.17
1998	11	1998.949543	2.47
1998	12	1999.032877	2.44
1999	1	1999.11621	0.81
1999	2	1999.199543	3.44
1999	3	1999.282877	0.88
1999	4	1999.36621	0.20
1999	5	1999.449543	6.03
1999	6	1999.532877	3.74
1999	7	1999.61621	6.78
1999	8	1999.699543	5.08

APPENDIX IV Wave-Impact Heights with Wind Setup Considered

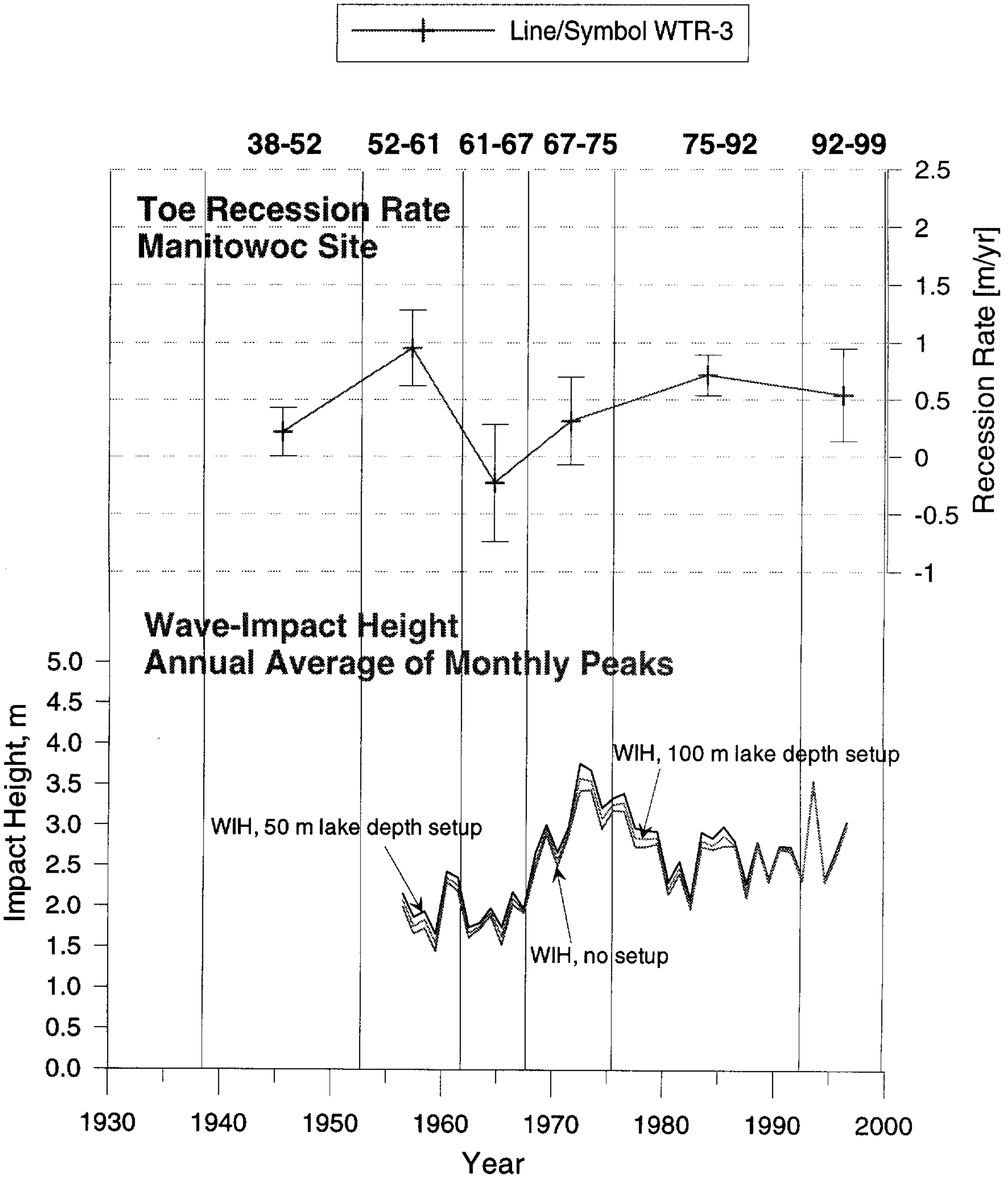
Crest-Recession Rate and Wave-Impact Height
Manitowoc Site
Profile WTR-1



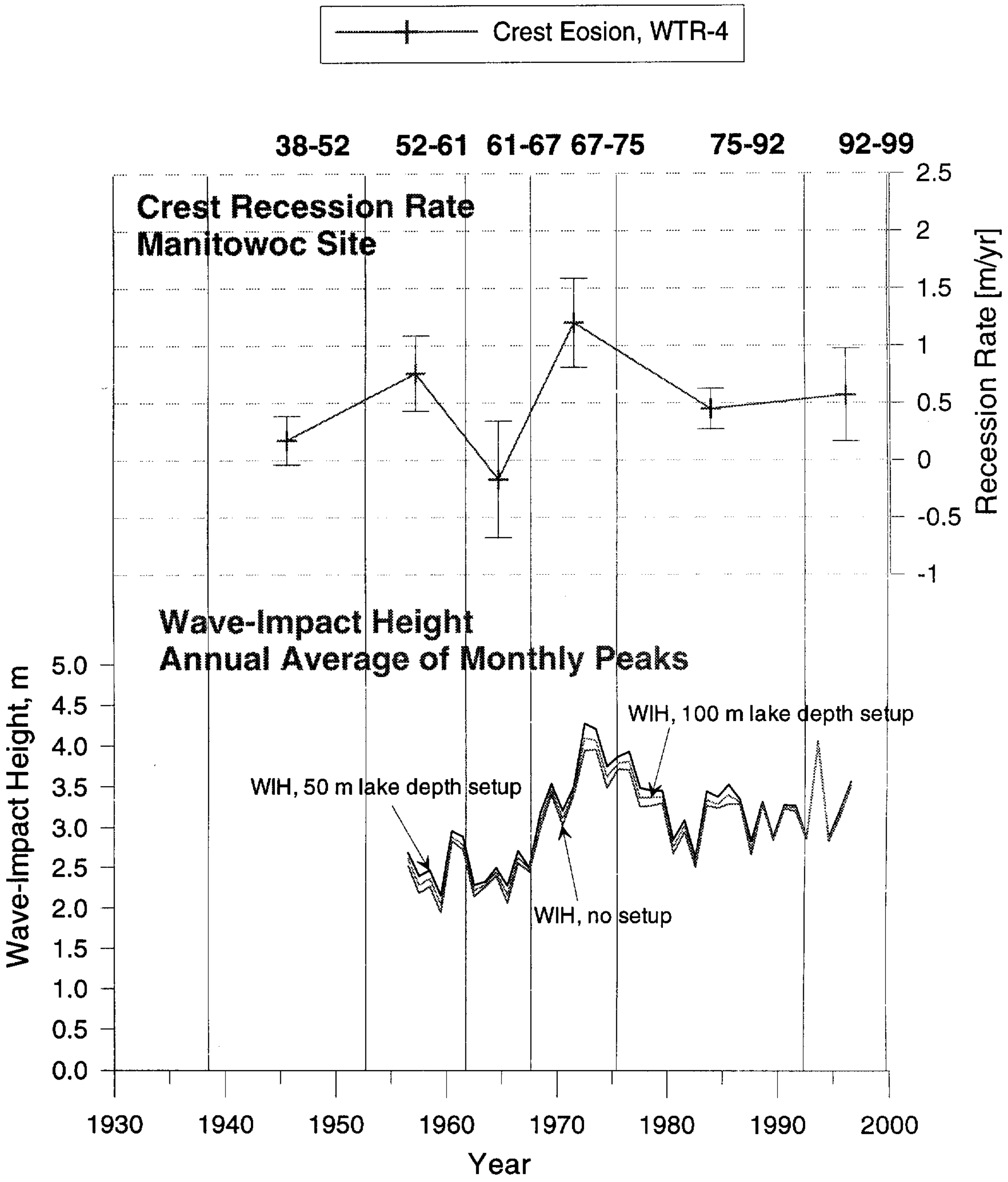
Crest-Recession Rate and Wave-Impact Heights
Manitowoc Site
Profile WTR-2



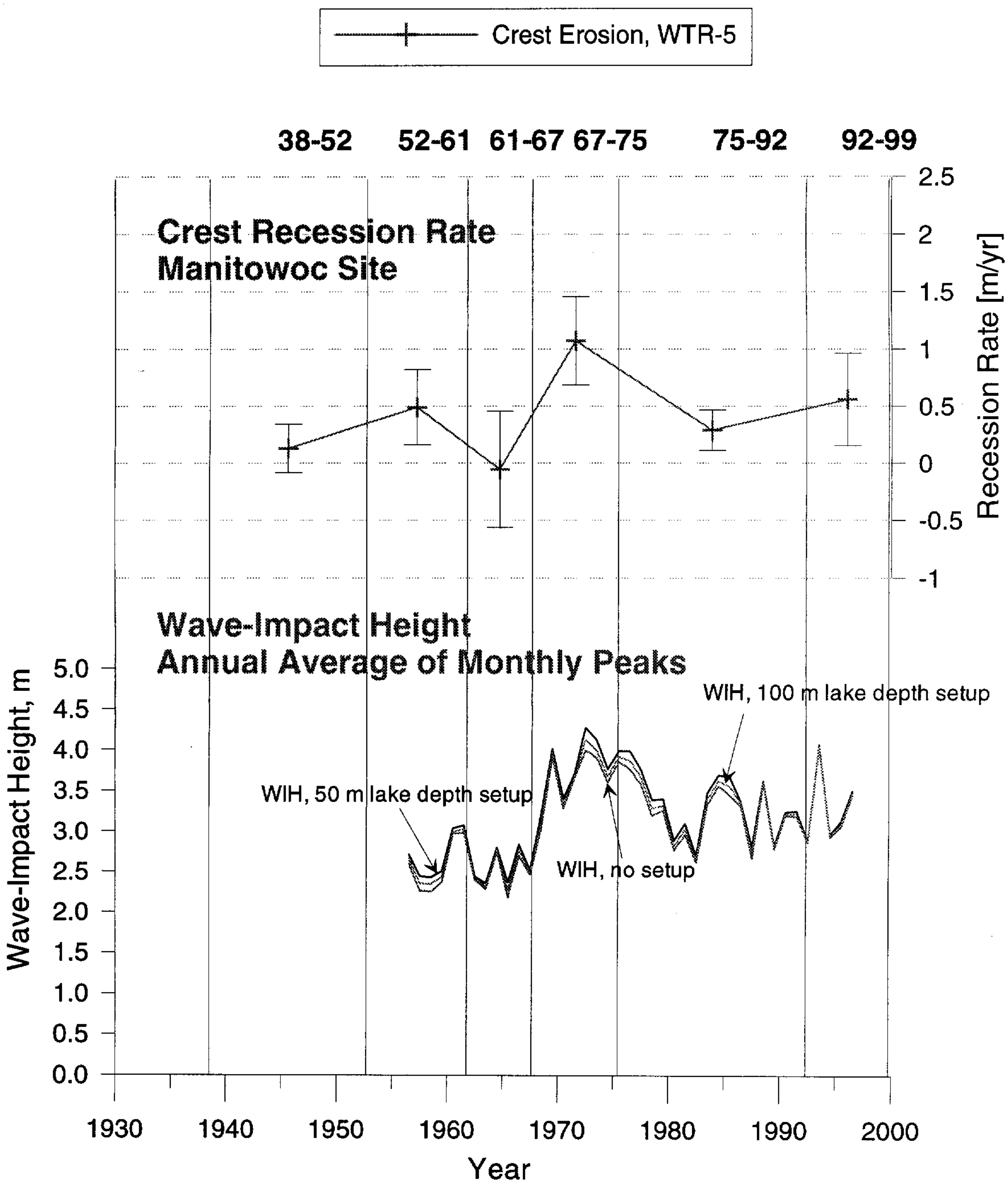
Crest-Recession Rate and Wave-Impact Height
Manitowoc Site
Profile WTR-3



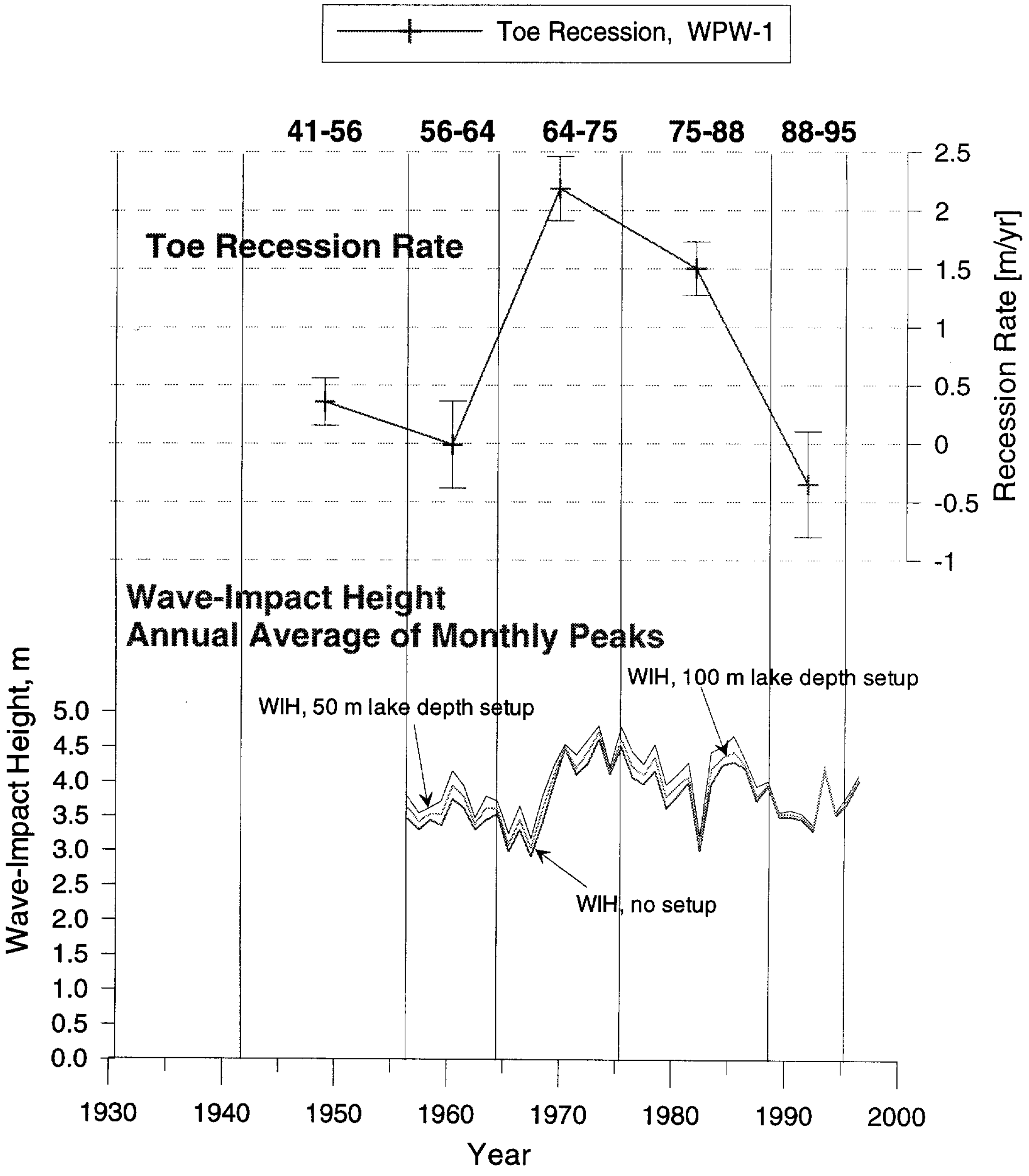
Crest-Recession Rate and Wave-Impact Height
Manitowoc Site
Profile WTR-4



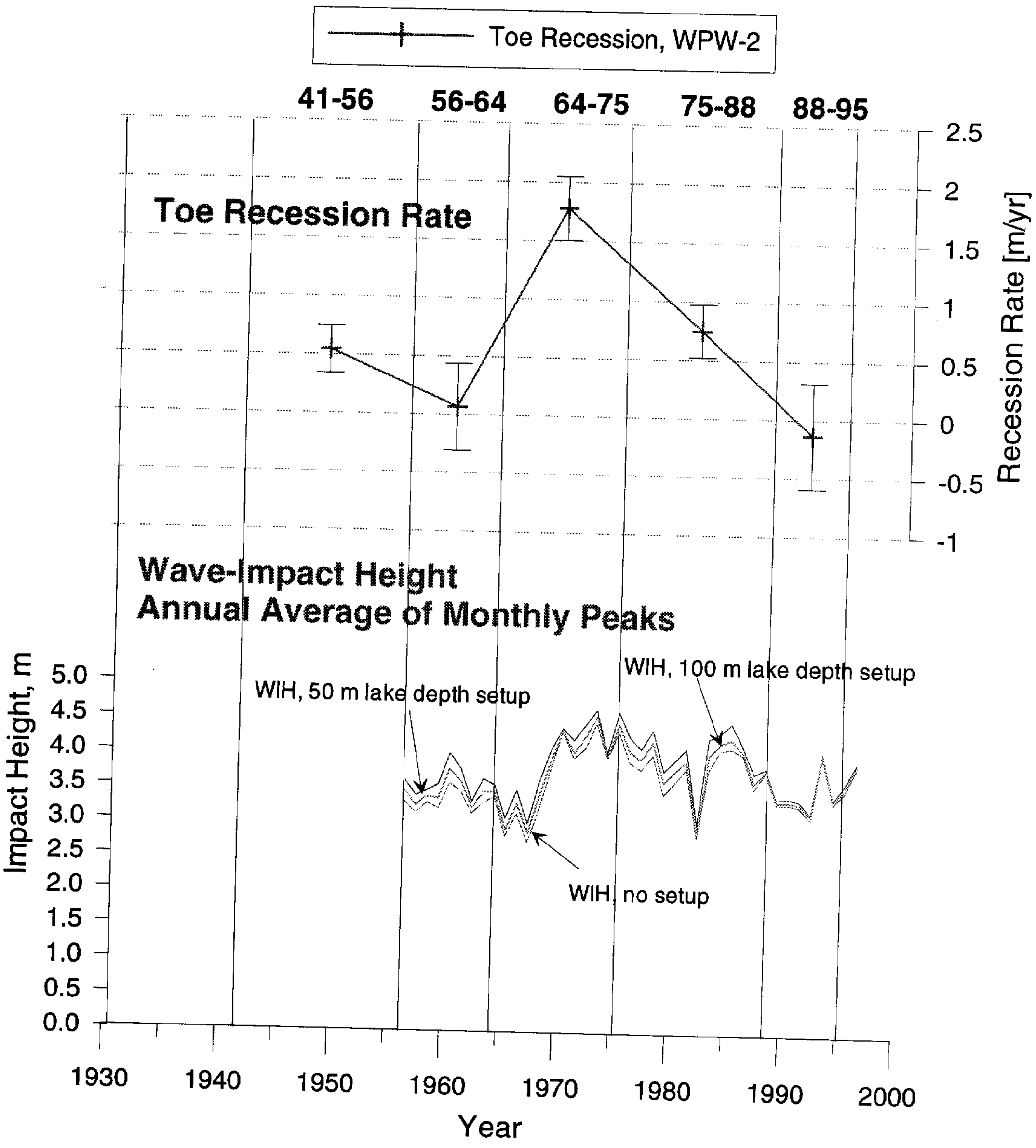
Crest-Recession Rate and Wave Impact Height
Manitowoc Site
Profile WTR-5



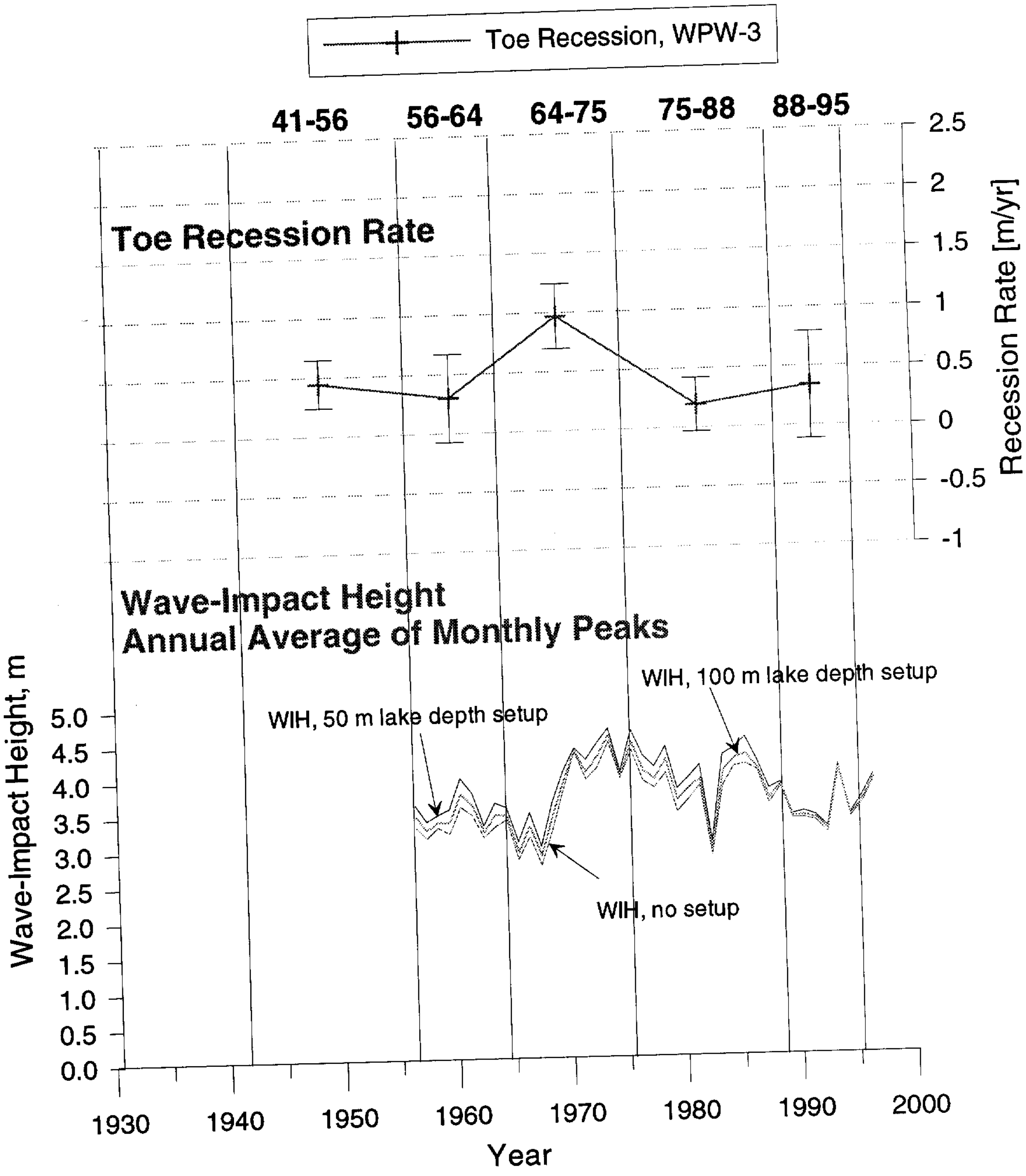
Toe-Recession Rate and Wave-Impact Height
Ozaukee Site
Profile WPW-1



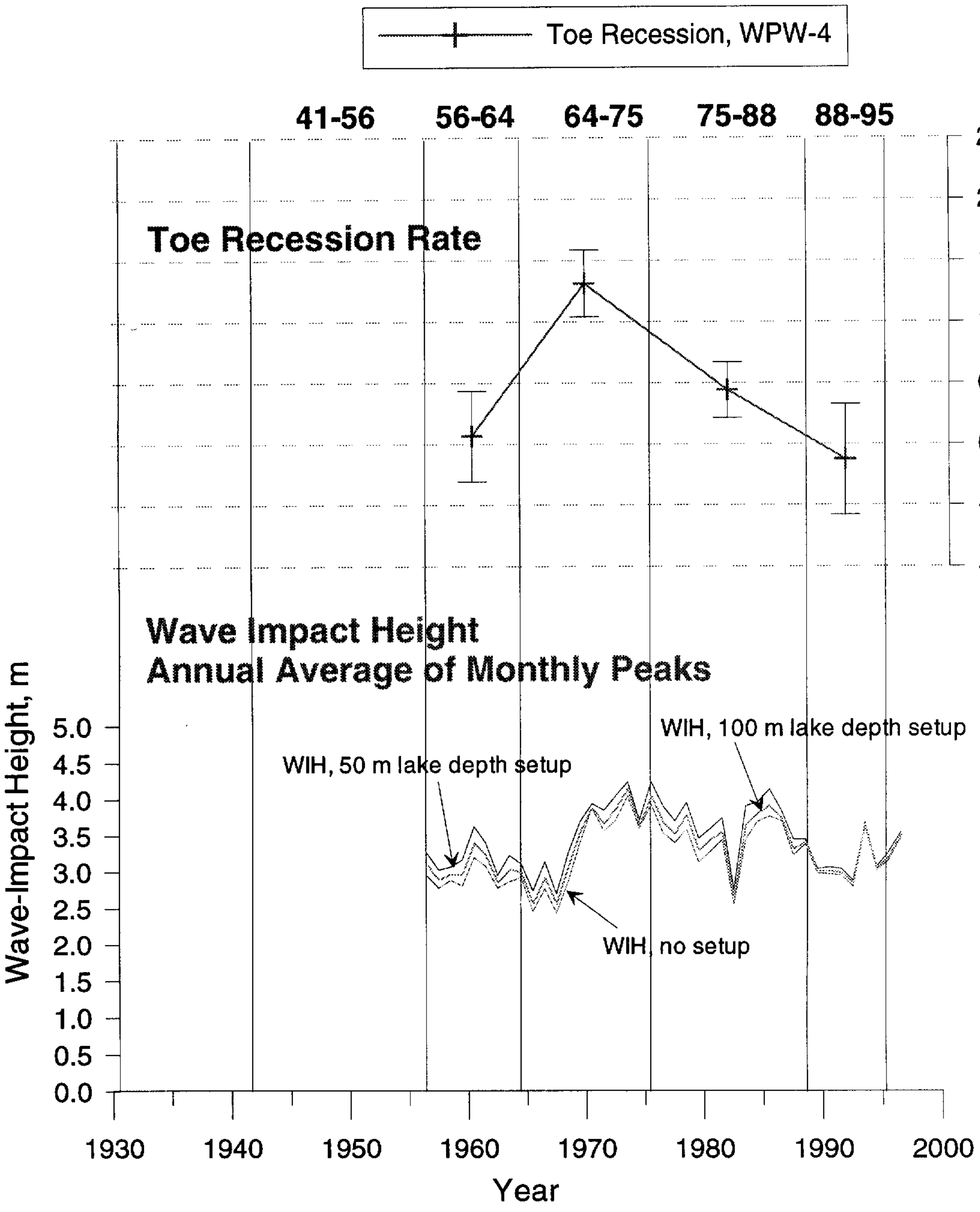
Toe-Recession Rate and Wave-Impact Height
Ozaukee Site
Profile WPW-2



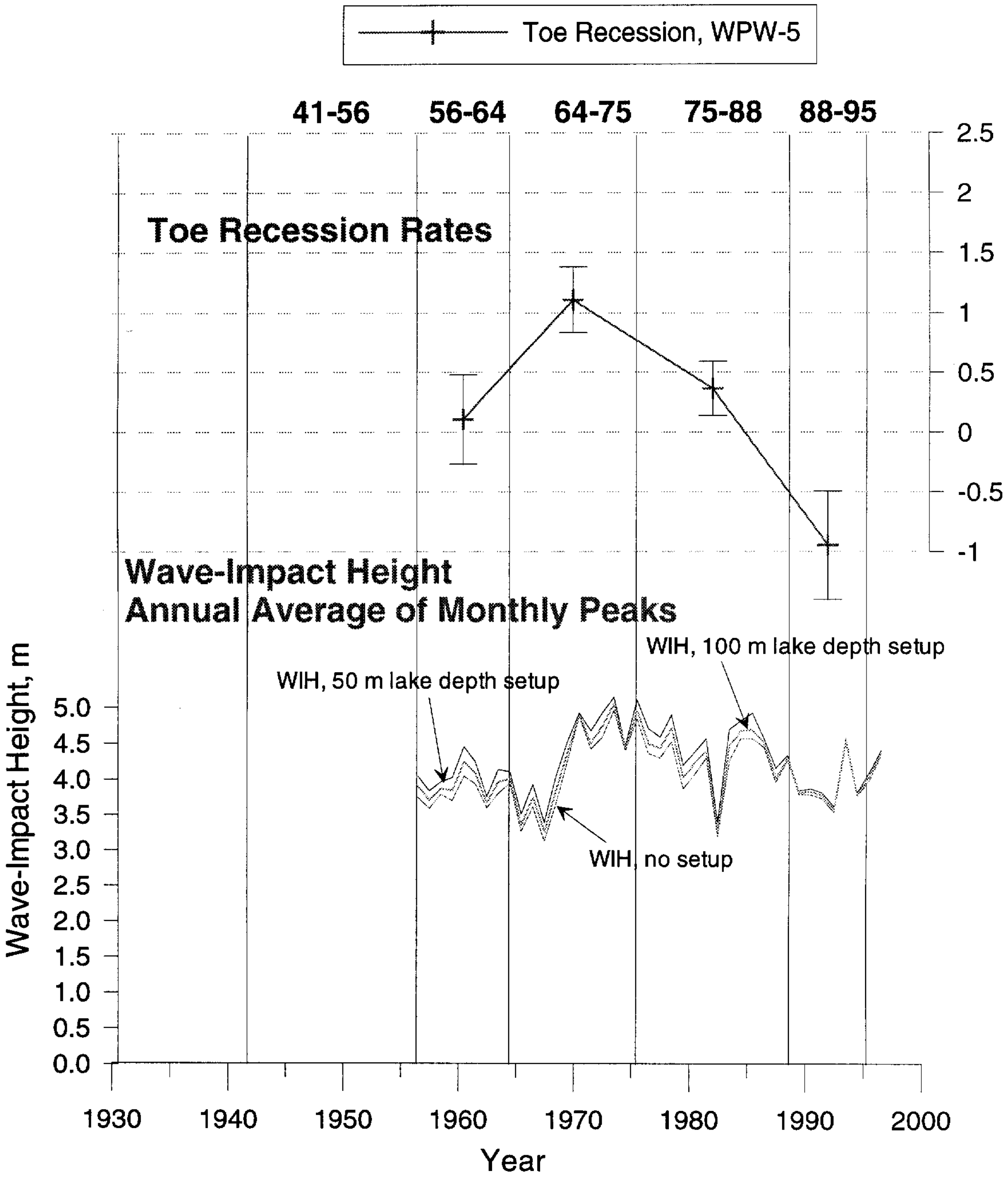
Toe-Recession Rate and Wave-Impact Height
Ozaukee Site
Profile WPW-3



Toe-Recession Rate and Wave-Impact Height
Ozaukee Site
Profile WPW-4



Toe-Recession Rate and Wave-Impact Height
Ozaukee Site
Profile WPW-5



APPENDIX V GPS Positions of Shoreline Profiles

Buoy Locations from UM Field Work, 1999
/GLE2320/USERS/LISA/GLPF WORK/WISCONSIN/LAT_LON1.XLS

Survey Line	Shore Location				State Plane, NAD 27, Wisconsin South-4803		State Plane, NAD 83, Wisconsin South-4803		UTM Zone 16 NAD27	
	Latitude		Longitude		US Survey Feet		US Survey Feet		meters	
	Degrees	Minutes	Degrees	Minutes	Easting [ft]	Northing [ft]	Easting [ft]	Northing [ft]	Northing [m]	Easting [m]
WTR1	44	17.4631	87	32.3419	2,644,372	844,563	2,612,832	844,571	4904125	456994
WTR2	44	17.8951	87	32.4362	2,643,883	847,175	2,612,343	847,183	4904926	456874
WTR3	44	18.7365	87	32.6258	2,642,906	852,261	2,611,366	852,269	4906485	456632
WTR4	44	19.0814	87	32.6246	2,642,849	854,356	2,611,309	854,364	4907123	456638
WTR5	44	19.4610	87	32.6056	2,642,864	856,664	2,611,324	856,672	4907826	456668
									UTM Zone 16 NAD83	
									meters	
									Northing [m]	Easting [m]
WPW1	43	15.0514	87	54.6396	2,556,588	462,865	2,525,049	462,872	4,789,076	426,069
WPW2	43	15.3545	87	54.5476	2,556,950	464,716	2,525,411	464,723	4,789,635	426,200
WPW3	43	16.0601	87	54.3026	2,557,930	469,028	2,526,391	469,035	4,790,938	426,545
WPW4	43	16.4065	87	54.2212	2,558,238	471,141	2,526,699	471,148	4,791,578	426,662
WPW5	43	16.7009	87	54.0830	2,558,806	472,944	2,527,267	472,951	4,792,120	426,855

Shore Locations from UW field work

Survey Line	Shore Location				State Plane, NAD 27, Wisconsin South-4803		State Plane, NAD 83, Wisconsin South-4803		UTM Zone 16 NAD27	
	Latitude		Longitude		US Survey Feet		US Survey Feet		meters	
	Degrees	Minutes	Degrees	Minutes	Easting [ft]	Northing [ft]	Easting [ft]	Northing [ft]	Northing [m]	Easting [m]
WTR1	not available									
WTR2	44	17.9373	87	32.5820					4,905,005	456,681
WTR3	44	18.7612	87	32.7191					4,906,531	456,509
WTR4	44	19.1068	87	32.7294					4,907,171	456,499
WTR5	44	19.4909	87	32.6891					4,907,882	456,557
									UTM Zone 16 NAD83	
									meters	
									Northing [m]	Easting [m]
WPW1	43	15.0800	87	54.7063					4,789,130	425,979
WPW2	43	15.3959	87	54.6363					4,789,714	426,080
WPW3	43	16.1049	87	54.4024					4,791,022	426,411
WPW4	43	16.4428	87	54.3061					4,791,646	426,548
WPW5	43	16.7496	87	54.2167					4,792,213	426,675

APPENDIX VI Storm statistics for profiles WTR-1, WTR-2 and WTR-5. Plots of annual and epoch-averaged deepwater wave power, storm counts and recession rates relevant for WTR-1, WTR-2 and WTR-5

Storm Statistics for Erosion Epochs of the Manitowoc site. Shoreline Orientation for WTR-1 (343°-163°) assumed.

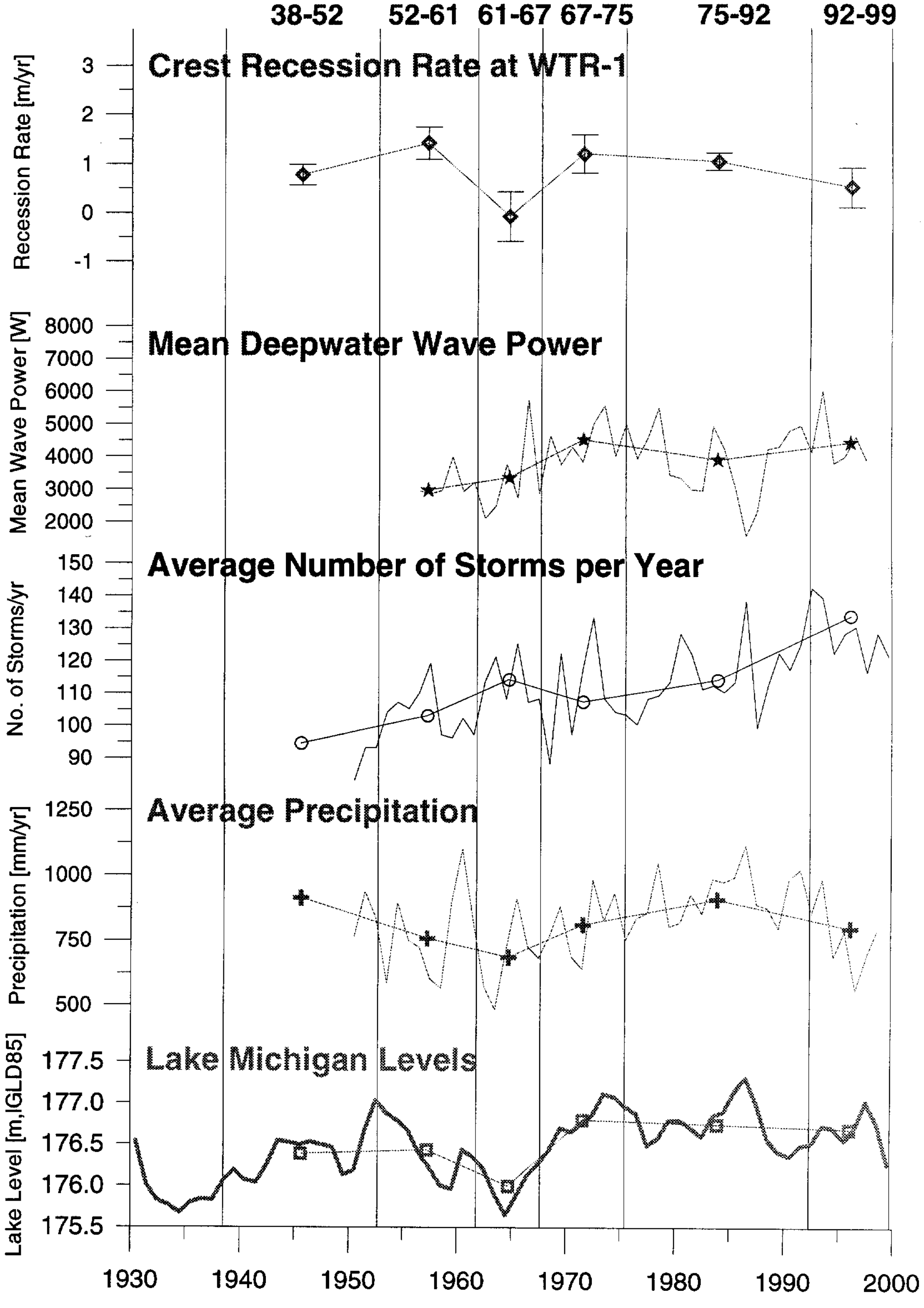
Epoch →	1952-61	1961-67	1967-75	1975-92	1992-99
Total Number of Storms	936	672	832	1926	987
Number of Storms per year	103	114	107	114	133
Total Duration of Storm Activity [hrs]	16799	11958	15368	34701	16487
Weighted Average of Speed During Storms [m/s]	10.6	10.2	11	10.7	9.9
Weighted Average of Wind Directions During Storms [degrees from north]	65.6	69.1	63.8	60.7	61.2
Average Speed of Most Intense Storm [m/s]	19.1	19.3	20.8	22.4	19.9
Maximum Wind Speed [m/s]	38.9	34.3	32.2	53.7	31

Storm Statistics for Erosion Epochs of the Manitowoc site. Shoreline Orientation for WTR-2 (347°-167°) assumed.

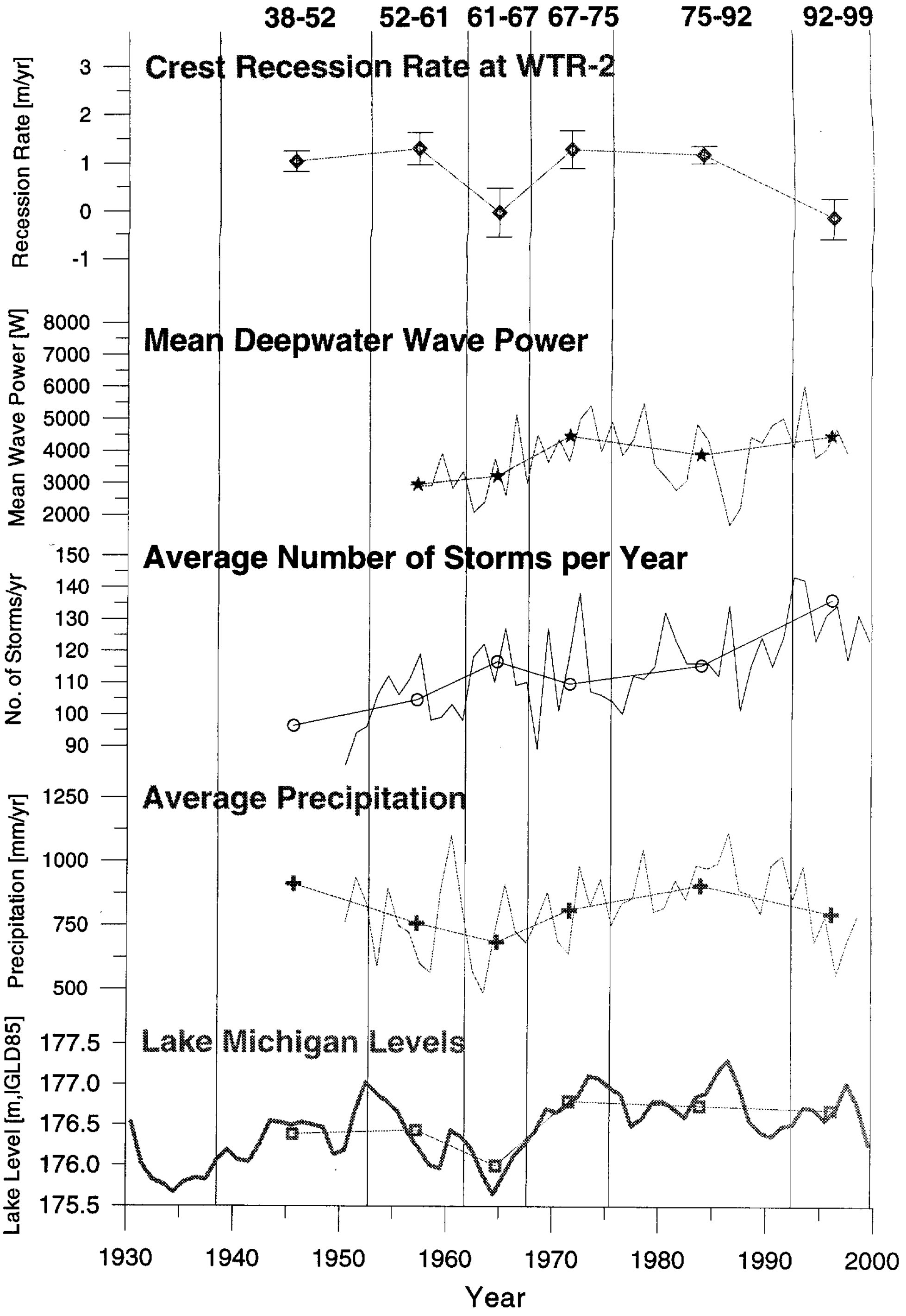
Epoch →	1952-61	1961-67	1967-75	1975-92	1992-99
Total Number of Storms	951	687	850	1952	1004
Number of Storms per year	104	117	109	115	136
Total Duration of Storm Activity [hrs]	17243	12294	15583	35142	16777
Weighted Average of Speed During Storms [m/s]	10.6	10.2	10.9	10.7	9.8
Weighted Average of Wind Directions During Storms [degrees from north]	71.2	73.8	67.9	64.4	63.8
Average Speed of Most Intense Storm [m/s]	19.1	19.3	20.8	22.4	19.9
Maximum Wind Speed [m/s]	38.9	34.3	32.2	53.7	31

Storm Statistics for Erosion Epochs of the Manitowoc site. Shoreline Orientation for WTR-5 (004°-184°) assumed.

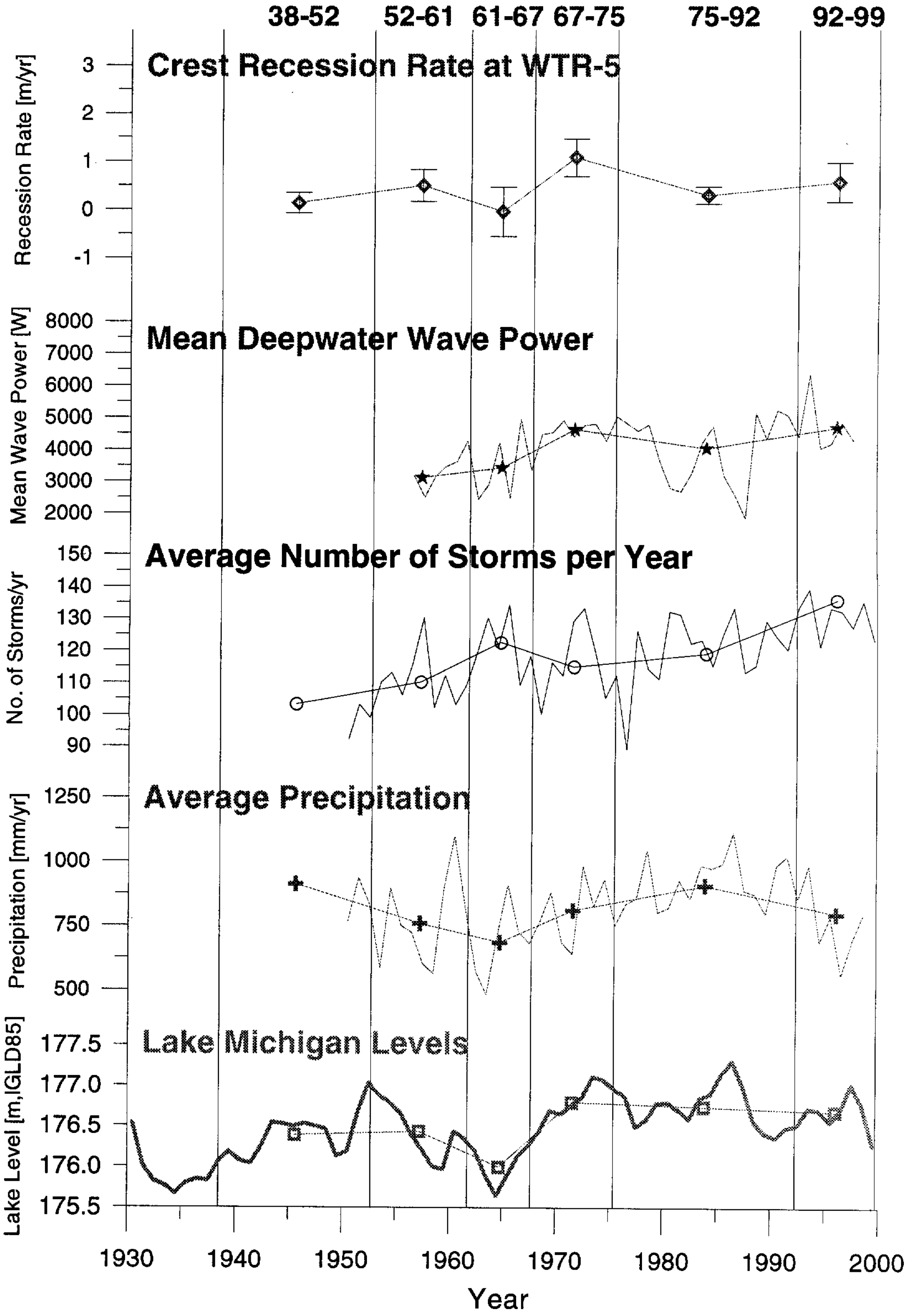
Epoch →	1952-61	1961-67	1967-75	1975-92	1992-99
Total Number of Storms	1001	721	891	2011	1003
Number of Storms per year	110	122	115	119	136
Total Duration of Storm Activity [hrs]	18039	12818	15843	34404	15982
Weighted Average of Speed During Storms [m/s]	10.5	10.1	10.7	10.4	9.6
Weighted Average of Wind Directions During Storms [degrees from north]	93.3	93.9	91.9	86.2	79.5
Average Speed of Most Intense Storm [m/s]	22.4	22.1	20.8	21.4	19.1
Maximum Wind Speed [m/s]	38.9	35.4	32.2	53.7	30



Profile WTR-1, Manitowoc Site - Lake Level, Storms, Precipitation, Wave Power and Recession Rate



Profile WTR-2, Manitowoc Site - Lake Level, Storms, Precipitation, Wave Power and Recession Rate



Profile WTR-5, Manitowoc Site - Lake Level, Storms, Precipitation, Wave Power and Recession Rate

INFLUENCE OF WATER LEVEL, WAVE CLIMATE AND WEATHER ON COASTAL RECESSION ALONG A GREAT LAKES SHORELINE

Approved:

12-14-2000

Signature date

Tuncer B. Edil, Professor

Approved:

12/14/00

Signature Date

David M. Mickelson, Professor