UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS LABORATORY

Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 466

Lake of the Woods Shoreline Erosion: Analysis of Historical Shorelines, Climate and Lake Level

By

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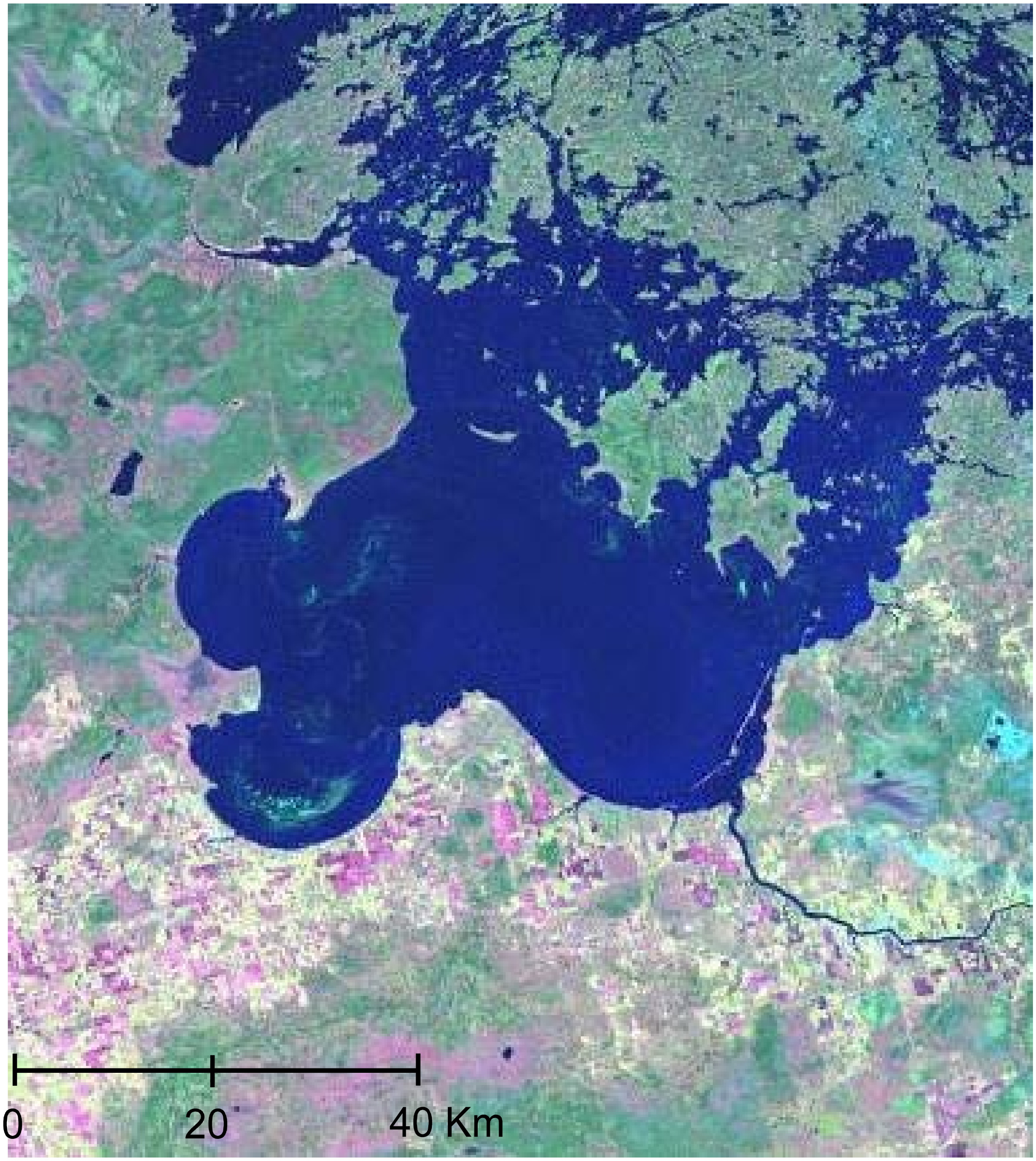

Landsat7 image of Lake of the Woods, 7/16/2000.

Abstract

This report summarizes the results of Phase I of a study of erosion of the Minnesota shoreline of Lake of the Woods. The overall objectives of this study are (a) to determine the causes and to estimate the magnitude of the shoreline recession rates in the US shorelines of Lake of the Woods, and (b) to recommend management practices for shoreline protection against erosion. In Phase I, we collected historical data on wind and water levels at Lake of the Woods, flow and suspended sediment input from the Rainy River, and information on the shoreline, including aerial photos, satellite images, and soil surveys. Analyses of aerial photos from 1940 to 2003 show rapid erosion of several undeveloped wetland areas of the shoreline and relatively slow erosion of developed areas along Sandy Shores and Birch Beach. Analysis of Pine and Sable Islands show a combination of erosion, rebuilding, and shifting from 1940 to 2003, so that the present state of the islands may represent either a long term loss or a loss/rebuilding cycle. Since long term wind records for Lake of the Woods were not found, a synthetic wind record was constructed from regional wind records. Analysis of wind and water level data from the 1950's to the present show a relatively uniform distribution of high wind and high water events. Recent high water events appear as typical events that take place several times per decade. Wind and wave data were also collected at two locations on the southern side of Big Traverse Bay, with record lengths of 4 – 5 weeks. The on-lake wind data and wave data will be useful to calibrate wave models in Phase II, and have been used in Phase I to correlate on-lake wind with local and regional off-lake wind measurements. Field measurements of near-shore bathymetry were made and sediment samples were collected to determine size distribution were also collected in preparation for Phase II. Preliminary analyses of data for the Rainy and the Little Fork rivers do not show distinct trends in flow rate or suspended sediment concentration for the period of record.

Acknowledgments

We would like to acknowledge the Minnesota Pollution Control Agency for funding this project, Nolan Baratono and Bruce Wilson were instrumental in setting up the project. We wish to thank Nolan Baratono for his help in coordinating field trips and meetings. We would like to extend special thanks to Mike Larson, Tom Heinrich, and Joe Stewig at Minnesota DNR Fisheries in Baudette and Mike Hirst at the Lake of the Woods Soil and Water Conservation District for their generous help with field measurements. Finally, we would like to acknowledge Ben Erickson, Dick Christopher and Chris Ellis of the St. Anthony Falls Lab, University of Minnesota for their help in designing, building, and setting up the field measurement stations.

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I. Introduction: Overall Project Goals

Erosion on the southern shores of Lake of the Woods has been a concern since the early 1900's (Phillips and Rasid, 1996). Water levels of Lake of the Woods have been controlled since 1887, primarily by the Norman Dam at Kenora, Ontario. The dam has increased the mean lake level by 3.5 feet over the natural mean level, and periods of above normal precipitation have led to high water events with water levels above normal lake levels. We shall examine if observed erosion rates in regions of the southern shoreline can be related to lake levels and wind.

The overall objectives of this study are (a) to determine the causes and to estimate the magnitude of the shoreline recession rates in the US shorelines of Lake of the Woods, and (b) to recommend management practices for shoreline protection against erosion. The project is divided into Phase I and Phase II, as given below.

I.1. Phase I. Historical Data and Analysis of Erosion, Lake Level and Wind.

Historical weather data for Lake of the Woods will be assembled and analyzed for annual trends in wind speed and direction. The historical rate of erosion of the US shoreline of Lake of the Woods will be characterized via GIS analysis of aerial photos. These analyses will quantify long term erosion rates, identify problem areas for further study, and serve to calibrate and verify a shoreline change model. A field trip will be made to further characterize the shoreline erosion processes, and to install wind and wave field measurement equipment.

I.2. Phase II. Shoreline Change Model and Erosion Control Strategies.

A numerical model study will include a wind setup model, a wave generation model to calculate the characteristics of deep water waves; a wave transformation model to calculate wave propagation, breaking, and run-up in the near shore environment, and an erosion model to estimate shoreline erosion. The shoreline change model will be used to identify the relative importance of controllable and uncontrollable processes in shoreline erosion rates. Based on the results of the historical erosion and model studies, possible erosion control strategies will be suggested, including alternative lake level control strategies and shoreline protection strategies.

This report summarizes the results of Phase I of the project.

I.3. Background

Shoreline change in coastal/marine environments is typically studied in terms of (1) the erosion, transport and deposition of sediment and (2) the erosion of consolidated shoreline. 'Sediment' typically includes granular, non-cohesive material ranging from fine to coarse sizes (silt, sand and gravel), and is found on beaches, islands, and other areas at the edge of the water. 'Consolidated shorelines' are made of materials that can range from igneous rocks to consolidated sedimentary materials such as breccia, and cohesive clays that have geotechnical strength, i.e. they can transmit and resist forces, before they eventually disintegrate into granular materials under the actions of water waves and currents, wind, and ice.

The transport, erosion and deposition of sediments on beaches depends strongly on long shore currents which are typically generated by waves impinging on a shoreline, and by Corriolis effects due to the rotation of the earth. The near shore bathymetry influences the development of long shore currents strongly. Storm events can cause significant short term changes in the beach profile through cross shore transport. In studies of shoreline erosion of the Great Lakes, man-made artificial structures have been shown to have an influence on local sediment transport budgets and shoreline change (Wood and Meadows 1997).

Supply is an important element in the sediment budget of a beach. Even if the long shore transport rate is high, a beach will not experience significant erosion if the sediment supply rate is as high as the removal rate. Problems arise when the sediment supply is disrupted. It is therefore important to identify sediment sources as well as erosion and transport rates in a shore erosion problem. Reductions in sediment supply from river systems, e.g. due to dams, can lead to erosion of coastal beaches (Willis and Griggs 2003).

The loss of sandy beaches can lead to increased erosion of a consolidated shoreline, as consolidated features become exposed directly to wave energy. Depending on the composition of the shoreline material, eroded material may stay in the nearshore zone and contribute to the reestablishment of a stable profile, or may be carried into deeper water as suspension or as bed load. While eroded beaches may be replenished by natural processes or by human intervention ("beach nourishment") erosion of consolidated shoreline features represents a loss of land that is usually permanent. Wave energy is often the primary mechanism of consolidated shoreline erosion, but freeze/thaw cycles and ice erosion can also erode consolidated shoreline (Newbury and McCullough 1984). Figure 1.1, taken from the Wisconsin Sea Grant program Coastal Processes Manual (1998) gives a schematic of consolidated shoreline erosion processes on the Great Lakes.

Long term increase in water levels has been shown to lead to an 'inward readjustment' or erosion of the shoreline in lakes and in reservoirs (Lorang et al. 1993, Newbury and McCollough 1984, Wood and Meadows 1997). The shore line response to a long term change in water level may stabilize if eventually bedrock is exposed, or if a stable offshore profile is established that reduces wave energy incident on the consolidated features. In studies of the Great Lakes, there is some evidence that long term changes in weather patterns caused simultaneous local increases in both wave energy and lake level (Wood and Meadows 1997).

Shoreline/coastal erosion is not a new problem. It is, however a complex problem.

The US Army Corps of Engineers is charged with the protection of U.S. coastlines, and has published the 'Shore Protection Manual' (US Army Corps of Engineers, 1984) and, more recently, the 'Coastal Engineering Manual' (US Army Corps of Engineers, 2002). They provide information on wave and erosion analyses, and potential shoreline protection measures. A much shorter and simpler manual for the coastlines of India was published by Bruun and Nayak (1980). For the protection of the Great Lakes Coastline, various state and provincial agencies have provided some guidance in manuals (e.g. UW Sea Grant, 1998). Unfortunately, most suggested measures are engineered and costly.

The mechanics of sediment transport by waves, and to some extent the coastal erosion processes are explained briefly in these same manuals. A discussion of sediment/wave interaction can also be found in an authoritative Chinese book (translated into English) on sediment transport by Chien and Wan (1999). Some early insights are described in classical papers by Bagnold (1988).

If the sediment is cohesive, a set of proceedings papers edited by Mehta (1986) can provide information.

Since Lake of the Woods is located in a northern/cold climate region, the effects of a lake ice cover on the erosion of a lake's shorelines cannot be ignored. The expansion of ice as it forms, and the impingement and pile-up of ice plates on the shore during break-up in spring are two mechanisms that can cause lake shore scouring and facilitate subsequent erosion. The freeze/thaw cycles in the consolidated banks of a lake can also be a significant cause of erosion (Newbury and McCullough 1984). A review of these effects observed on the shores of northern reservoirs was given by Lawson (1985) from the Cold Regions Research and Engineering Laboratory of the US Army Corps of Engineers. Some of the information provided is most likely applicable to lake shores in northern regions such as Lake of the Woods.

For Lake of the Woods a two-phased approach has been proposed. The first phase is an assembly and analysis of available historical data on the southern shoreline configurations, on lake stages, on wind and on sediment input from the Rainy River. The purpose of this phase 1 study is to document historical changes, and to prepare for the analysis of lake stage and wind effects on southern shoreline erosion in phase 2.

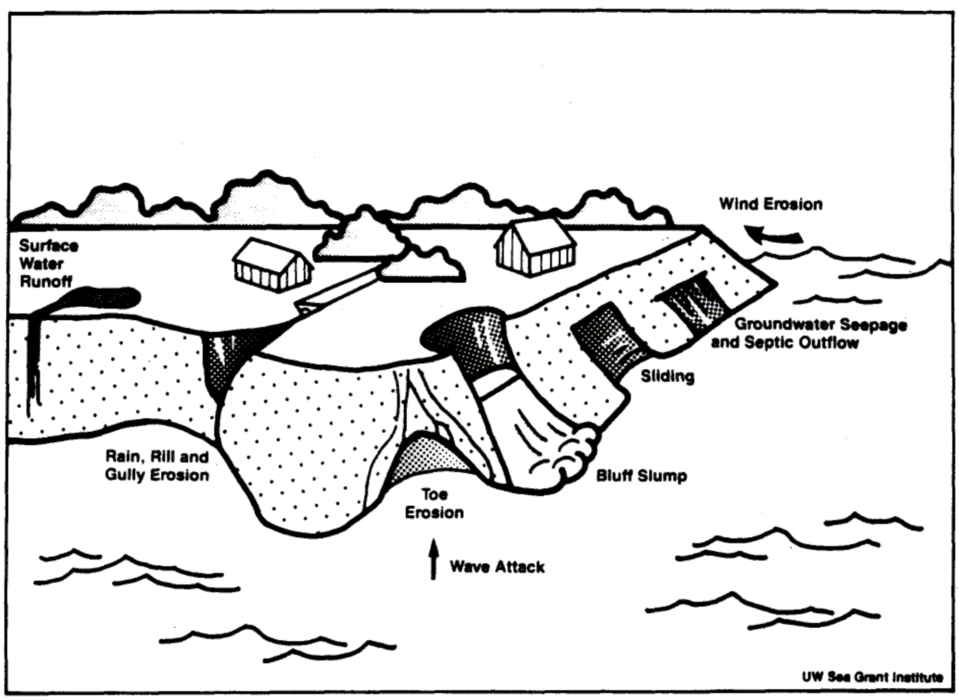


Figure 1.1. Diagram of consolidated coastline erosion processes (taken from UW Sea Grant, 1998).

II. Assembly of Historical Data

II.1 Southern Shoreline Change Data

For this part of the study, four sets of rectified aerial photos were provided by the Minnesota Pollution Control Agency (MPCA). The aerial photos were taken in 1975, 1985, 1991 and 1996 and were prepared by the Minnesota Department of Natural Resources (MnDNR) and the US Geological Survey. The delineated shoreline and waterline on these aerial photos and the associated shape files were prepared by the MnDNR. In addition to these aerial photos, a series of black and white aerial photos from the 1940s and 1960s were obtained from the University of Minnesota Library (Government Publications Archives). These photos were converted to electronic files and rectified for comparison. The oldest available aerial photos were from September 1940. Furthermore, the 2003 electronic aerial photos of the US shoreline of Lake of the Woods (georeferenced) were downloaded from the web. These photos were prepared by the National Agricultural Imagery Program (NAIP). Table 2.1 gives the average lake levels at the time the above aerial photos were taken. Average lake levels will be introduced in section II.2.

Table 2.1. Average lake levels at the time of the aerial photos

Aerial Photo	Average Lake Level (m)	Average Lake Level (ft)
1940	322.3	1057.3
1961	322.6	1058.3
1975	323.35	1060.9
1985	323.6	1061.7
1991	322.54	1058.2
1996	323.05	1059.9
2003	322.4	1057.6

During the site visit and the review of the aerial photos, four main regions were identified for shoreline erosion processes along the US shoreline: 1) Between Rocky Pt. and Long Pt., 2) some sections along the Birch Beach and Sandy Shore areas, 2) along the south shore of Fourmile Bay, and 4) Pine Island (Figure 2.1).

II.1.1. The Rocky Pt./Long Pt. Shoreline

There has been progressive erosion in two areas between Rocky Pt. and Long Pt. Figure 2.2 displays the 1940 aerial photo of the area and the 1996 delineated shoreline. It is evident that the shoreline in those two areas has receded by about 500 m (1600 ft). Figure 2.3 shows the 1961 aerial photos of the area in comparison with the 1996 shoreline, which indicates most of the western area was eroded between 1940 and 1961. The 1975, 1985, 1991, and 1996 delineated shorelines of the area are displayed in Figure 2.4. A progressive recession of the shoreline of the eastern area is evident during the 1975-1996 periods. However, it seems that nearly no shoreline erosion has occurred in the western area. The NRCS soil maps show that black muck and clay, i.e. consolidated materials, are the predominant soil types of the area. Therefore, erosion has been an irreversible process in those areas. Nevertheless, the 1975-1996 aerial photos show that a sandy peninsula has been rebuilt from Rocky Pt. (Figure 2.4). Figure 2.5 shows the 2003 aerial photo in comparison to the 1996 shoreline. It is evident that there has been some local shoreline erosion in the eastern area and more deposition (shoreline buildup) along the peninsula in the western area.

Figure 2.1. ASTER satellite image for 5/19/2000 and the US shoreline areas exhibiting erosion. (1 ASTER satellite image has been obtained at no cost from the USGS web site at edcdaac.usgs.gov/datapool/datatypes.asp for 5/19/2002.

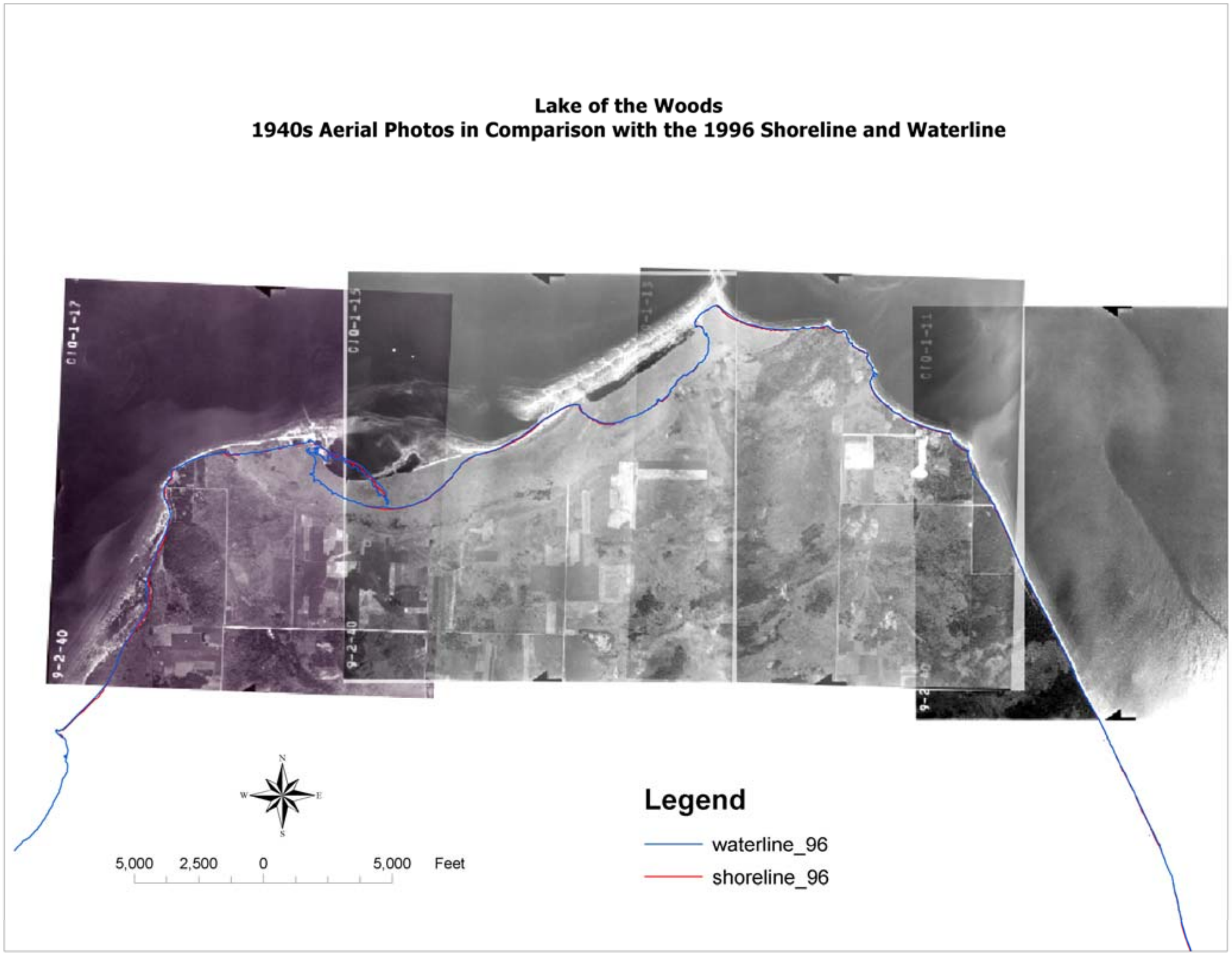


Figure 2.2. The Lake of the Woods shoreline area between Rocky Pt. and Long Pt. on 9/2/1940 in comparison with the 1996 shoreline delineated by MnDNR.

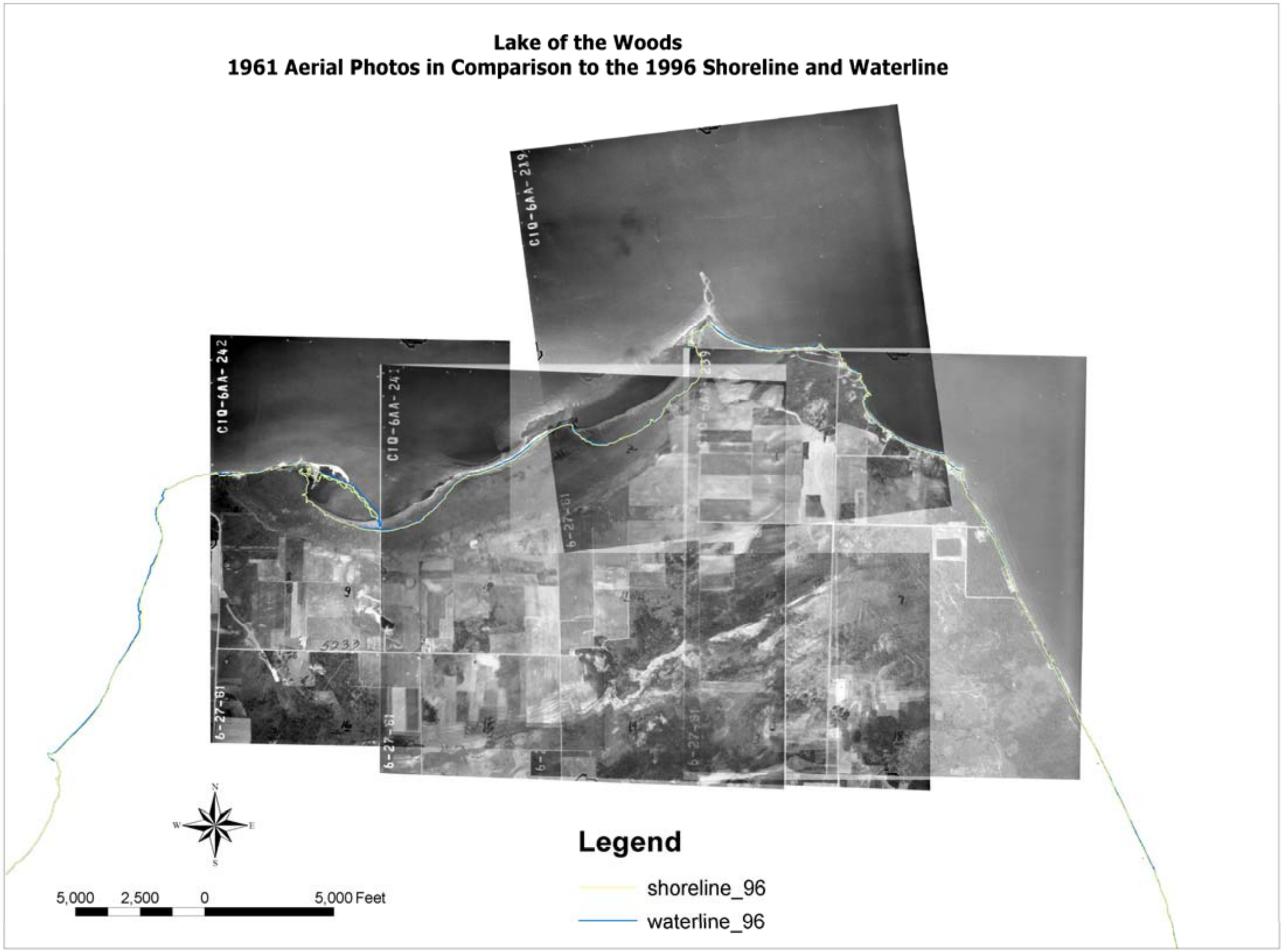


Figure 2.3. The Lake of the Woods shoreline area between Rocky Pt. and Long Pt. on 6/27/1961 in comparison with the 1996 shoreline.

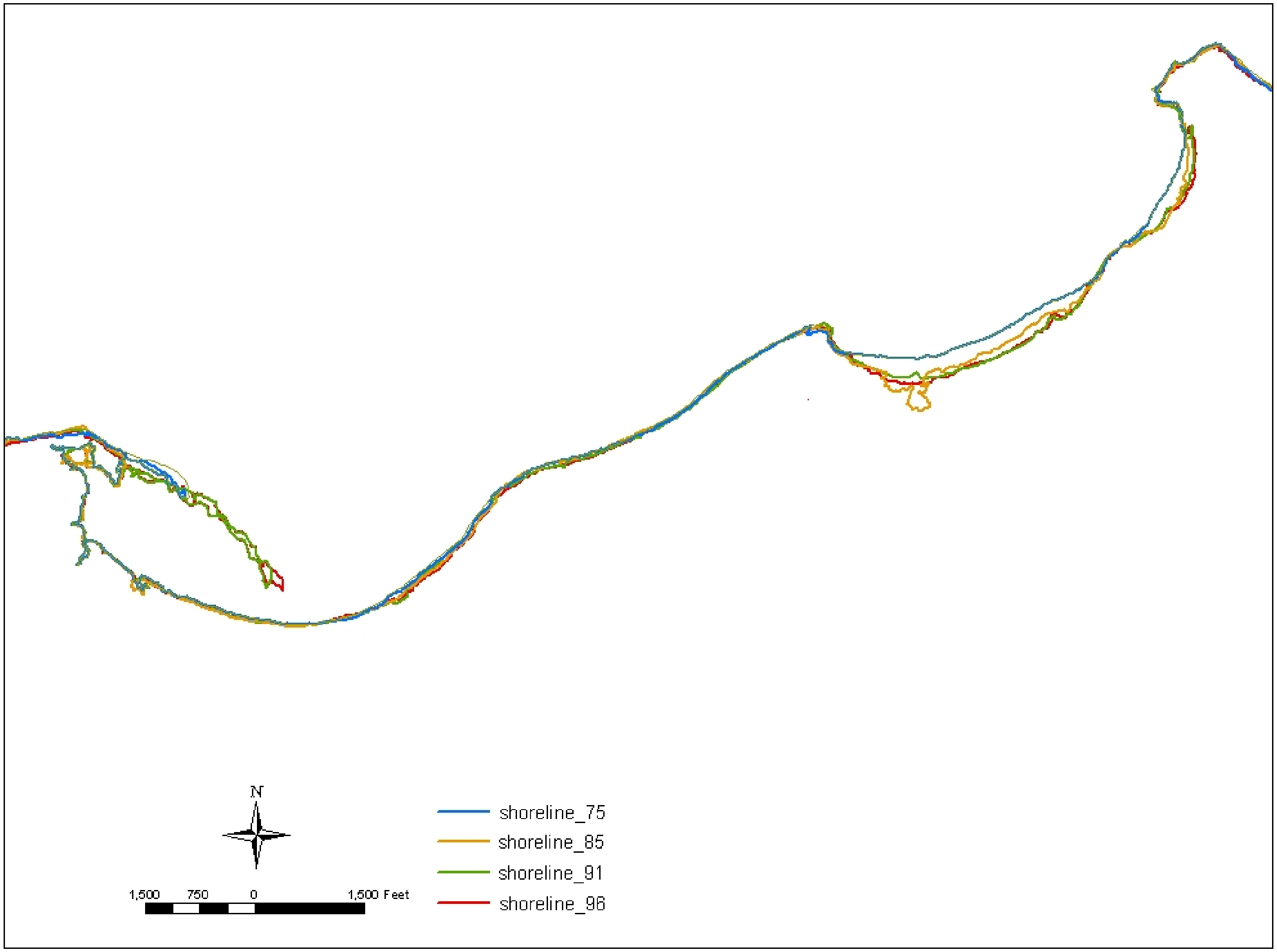


Figure 2.4. The Lake of the Woods shorelines along Rocky Pt. and Long Pt. in 1975, 1985, 1991 and 1996.

Figure 2.5. The Lake of the Woods shoreline area between Rocky Pt. and Long Pt. in 2003 and in comparison with the 1996 shoreline.

II.1.2. The Birch Beach and Sandy Shore Area

No significant shoreline erosion is evident from 1940 to 1996 in the Birch Beach area (Figures 2.2. and 2.3). No aerial photos from 1940 and 1960 were available for the Sandy Shores area. Considering the inherent error in rectifying and delineating the shoreline of the 1975, 1985, 1991 and 1996 photos, no significant shoreline erosion is evident in that period. However, during the site visit, it became obvious that the sandy beach areas have been eroded during recent years and the local communities have been placing riprap and similar materials to protect their properties. According to the NRCS soil maps, black loamy fine sand and fine sandy loam are the predominant soil types of the area which were protected by narrow sandy beaches. Erosion of sandy beaches creates favorable conditions for erosion of the consolidated materials of the shore. Referring to the historical data, it seems that shoreline erosion has been a recent problem and cannot be detected back in the 40s, 60s or 70s.

The precipitation data obtained from the Minnesota State Climatologist for Baudette and Morris Point area, south of Sandy Shore, show that precipitation events exceeding 2 inches per day have occurred 28 times since 1940. 9 events have occurred since 1996, and the storm event of June 11 and 12 with a total rainfall of 8.3 inches is a record for the area since 1940. The average lake level since 1918 has been about 322.87 m (1058.6 ft). Even though storm events exceeding 2 inches per day have occurred more frequently within the past 8 years than in the rest of the record since 1940 (Figure 2.6), the lake level does not show a significant difference. To study erosion in the Birch Beach and Sandy Shore area, a wind set-up model and a wave model will be required.

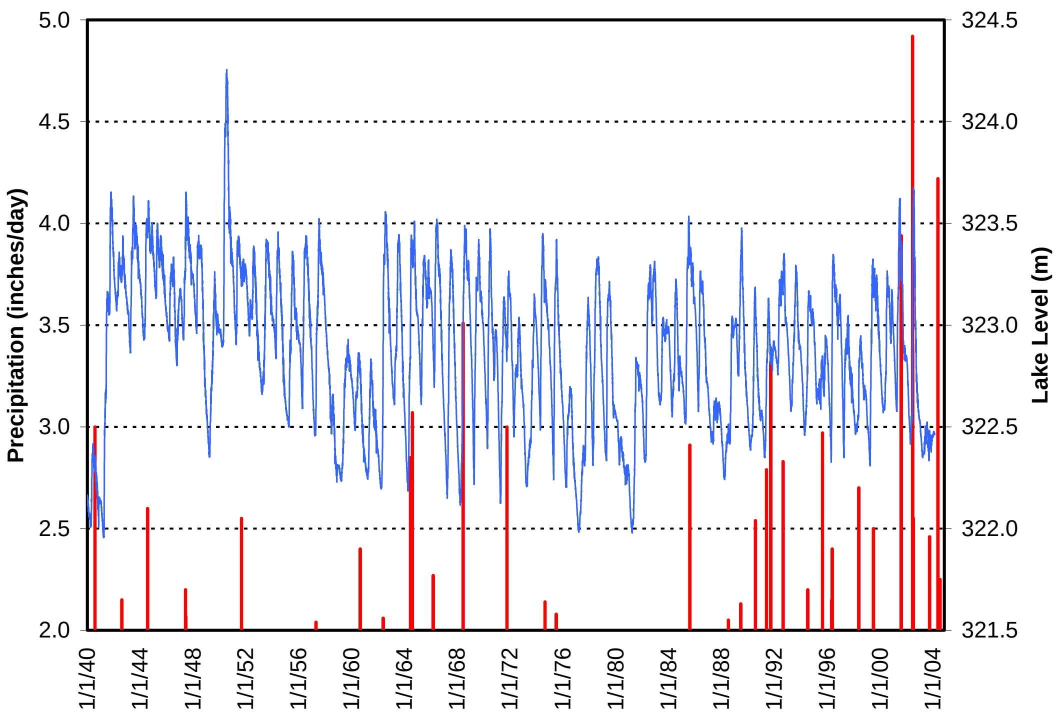


Figure 2.6. Daily precipitation events in excess of 2 inches since 1940 and the corresponding lake levels. The blue line is the average lake level for the past 90 years.

II.1.3. The Fourmile Bay Area

Similar to the Rocky Pt. and Long Pt. area, there has been progressive erosion of the south shore of Fourmile Bay. Figure 2.7 displays the 1941 aerial photos of the area and the 1996 delineated shoreline. It is evident that in some areas the shoreline has receded by about 600 m (2000 ft). Figure 2.8 shows 1961 aerial photos of the area in comparison to the 1996 shoreline, indicating that a significant portion of erosion occurred between 1941 and 1961. The 1975, 1985, 1991, and 1996 delineated shorelines of the Fourmile Bay area show a total of 150 ft shoreline recession as displayed from 1975 to 1996 (Figure 2.9). Shoreline erosion from 1996 to 2003 has been confined to a small portion of the area (Figure 2.10).

The NRCS soil maps show that black muck is the predominant soil types of the area, therefore, erosion has been an irreversible process in the area.

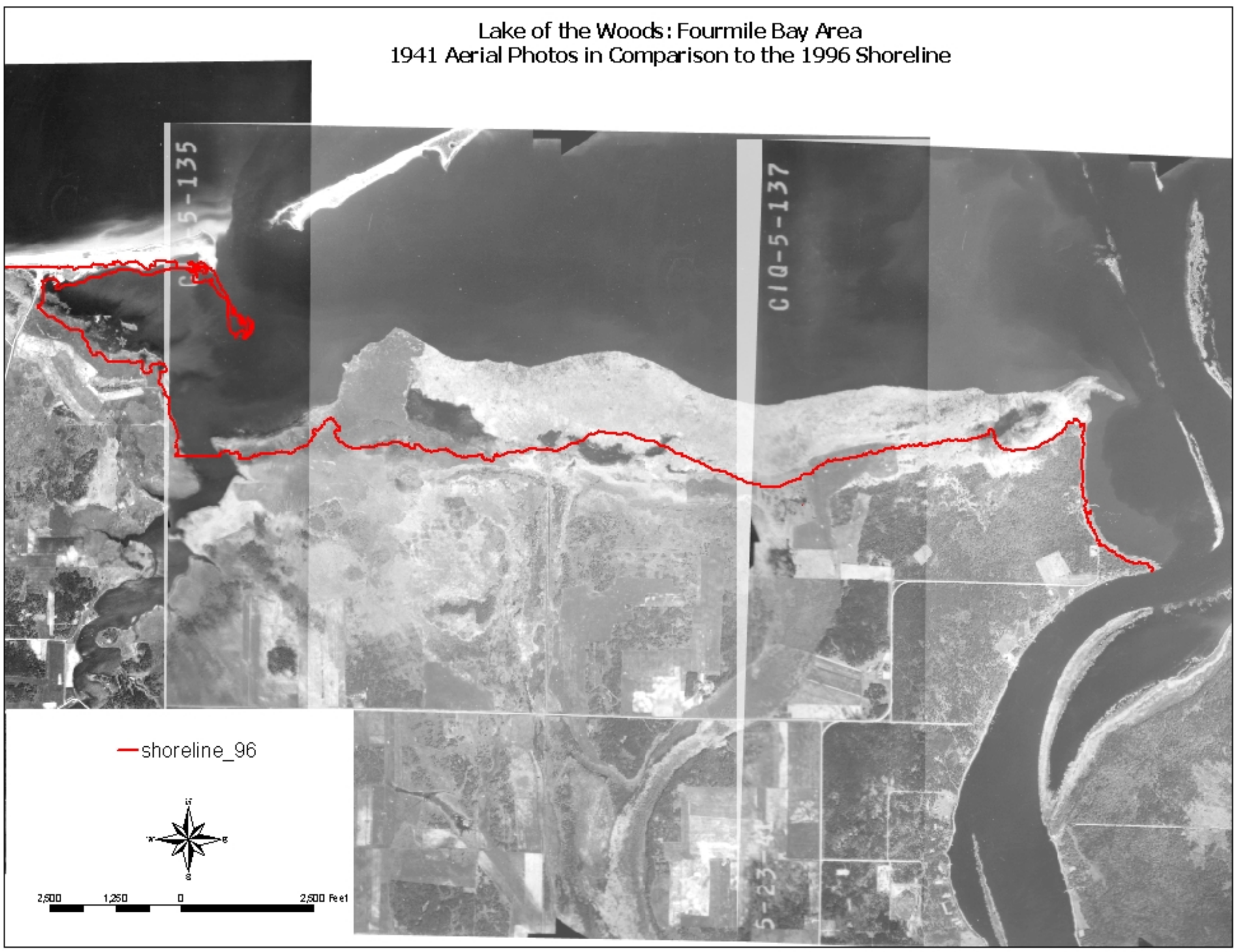


Figure 2.7. The Lake of the Woods shorelines south of Fourmile Bay in 1941 in comparison to the 1996 shoreline.

Lake of the Woods: Fourmile Bay
1961 Aerial Photos in Comparison to the 1996 Shoreline

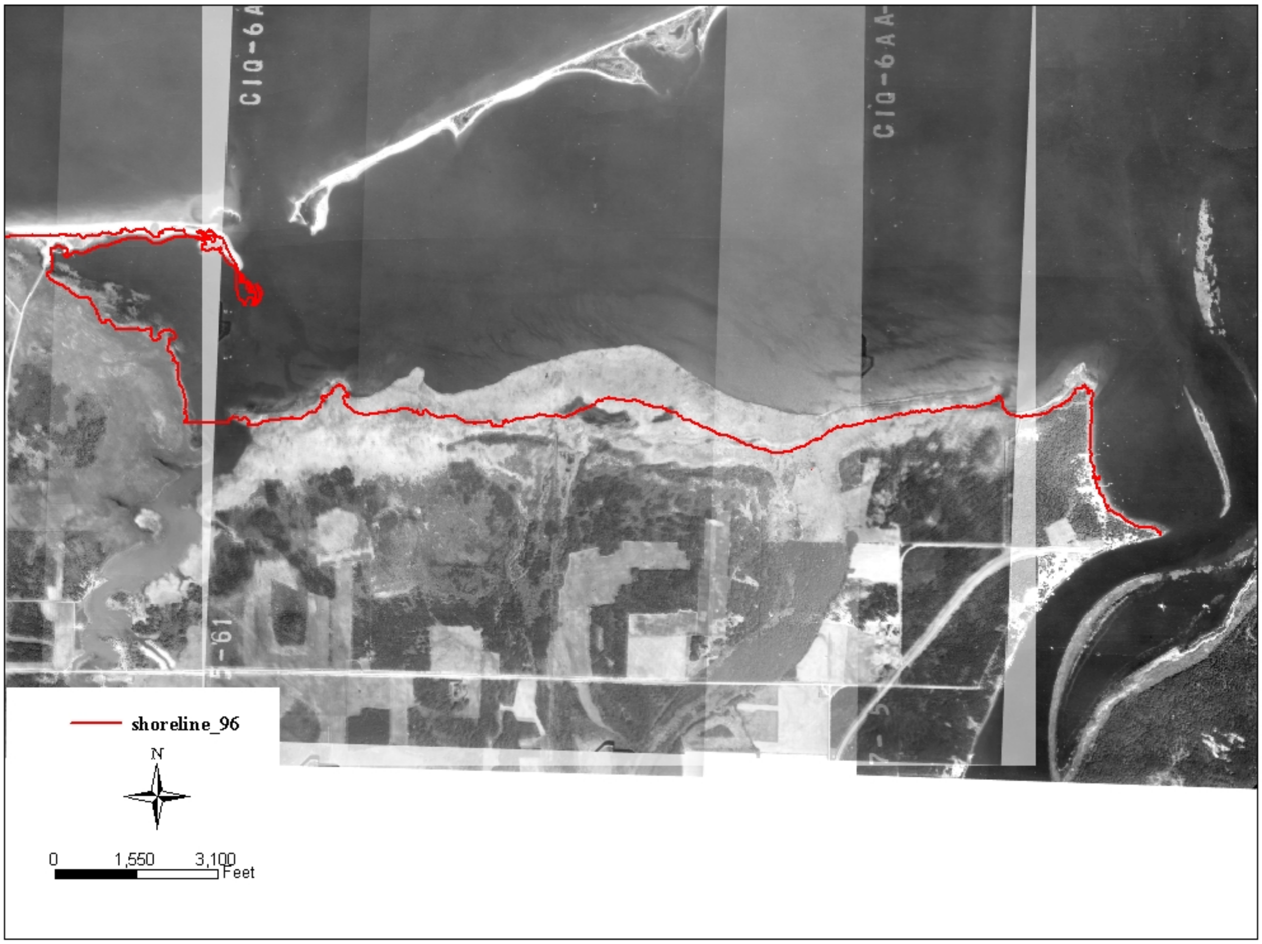


Figure 2.8. The Lake of the Woods shorelines south of Fourmile Bay in 1961 in comparison to the 1996 shoreline.

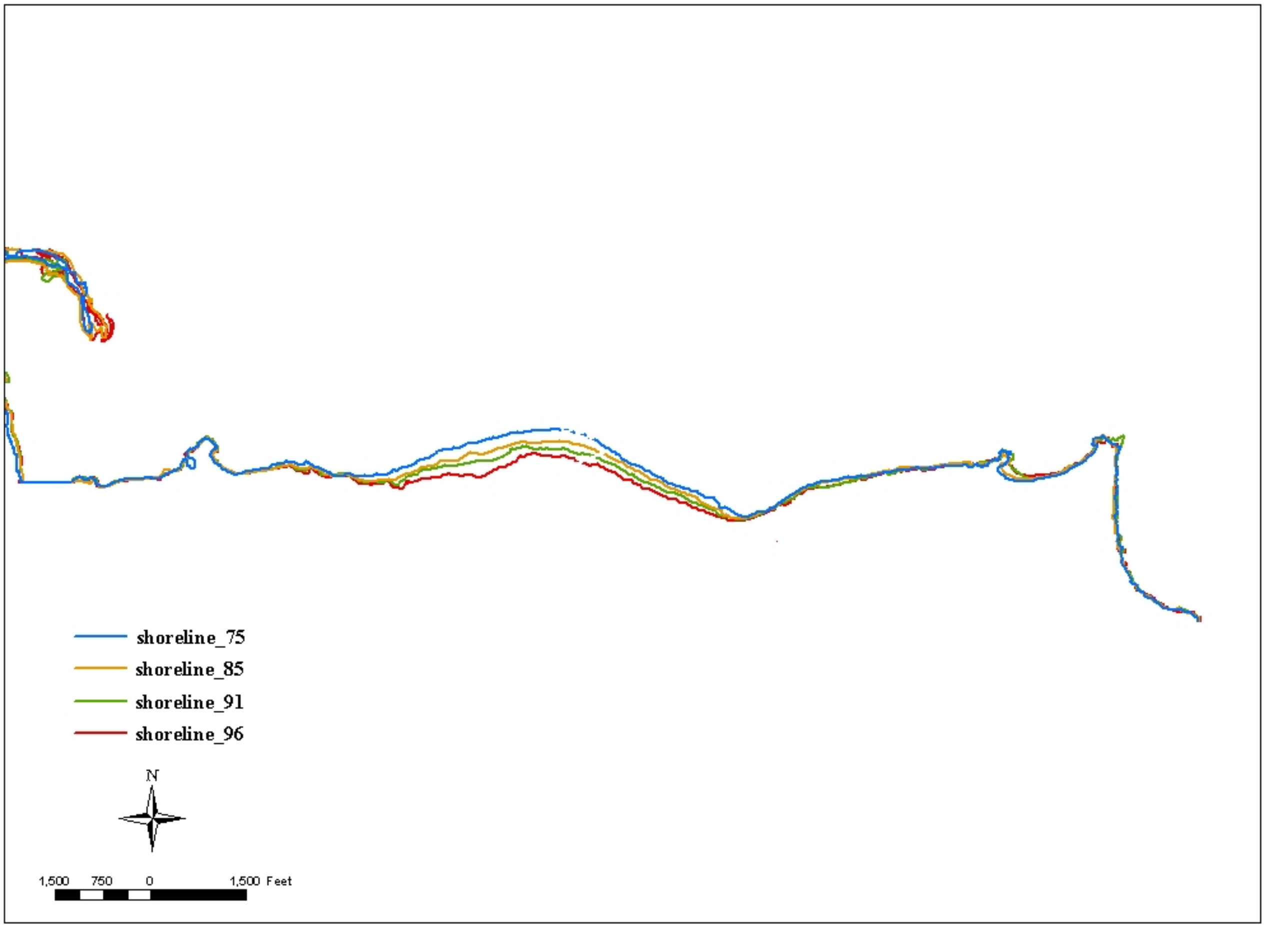


Figure 2.9. The Lake of the Woods shorelines south of Fourmile Bay in 1975, 1985, 1991 and 1996.

Lake of the Woods: Fourmile Bay
2003 Aerial Photos in Comparison to the 1996 shoreline

Figure 2.10. The Lake of the Woods shorelines south of Fourmile Bay in 2003 in comparison to the 1996 shoreline.

II.1.4. Pine Island

Pine Island is a narrow sandy island on the northern part of Fourmile Bay with a width of less than 100 m (300 ft) in the middle section of the island. The aerial photos of 1940s and 1960s could not be accurately georeferenced and compared to the aerial photos of 1975 to 2003 due to lack of fixed features and references in the photos. Therefore, those photos were not compared with the aerial photos of 1975 to 2003.

The 1975 aerial photo did not cover the entire island, therefore only the western half of the island is delineated and presented in Figure 2.11. Figures 2.11 indicates some changes in the width of the island, and breaches and partial erosion of the western tail of the island. The change of the width can be partially attributed to the water level at the time of the aerial photos (Table 2.1). For example, the water level in 1985 was high at 323.6 m (1061.7 ft), therefore, the island seemed to be thinning, while the water level in 2003 was low, 322.4 m (1057.6), and the island seemed to be widening. Due to lack of detailed topography of the island it would be difficult to compare these photos regarding the general erosion or reconstruction of the main web of the island. However, it is evident from Figure 2.11 that there has been progressive erosion in the western tail of the island near Morris Point since 1985, and about 1500 m (5000 ft) of the island has disappeared. Since Pine Island is a sandy island, erosion is not necessarily an irreversible process. The 1941 and 1961 aerial photos show that the western tail of the island was not breached then.

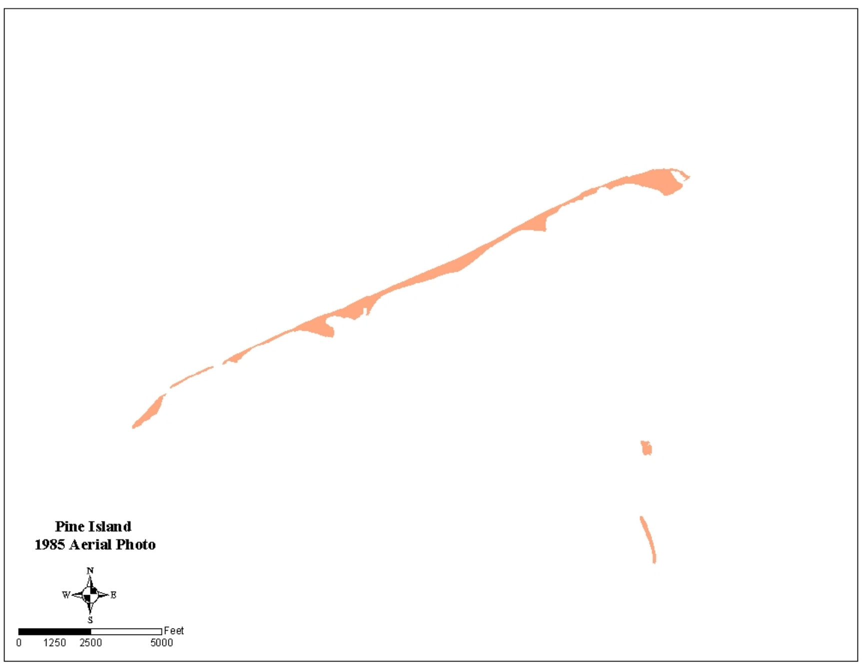
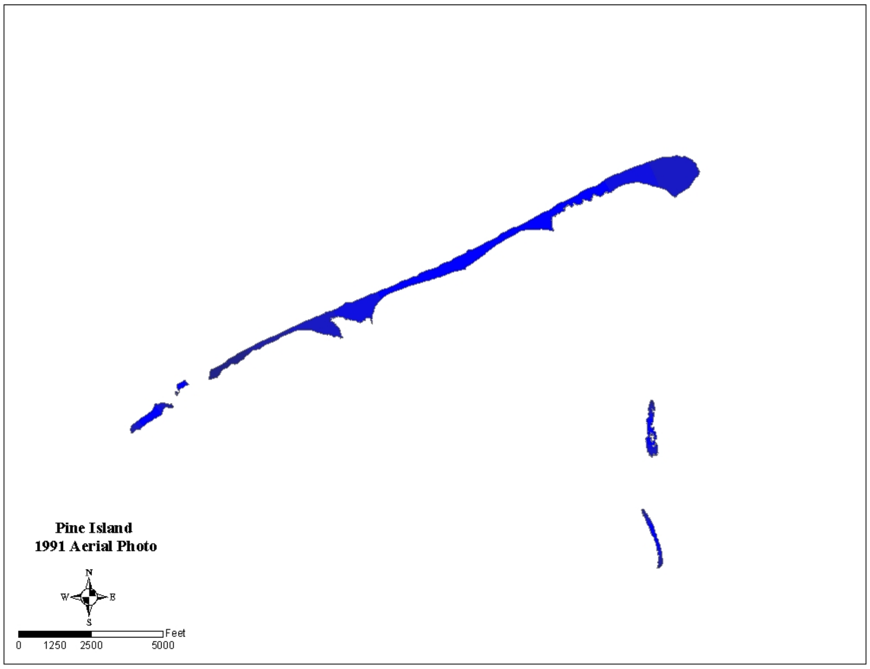


Figure 2.11. The Pine Island delineated shorelines in 1975 and 1985.



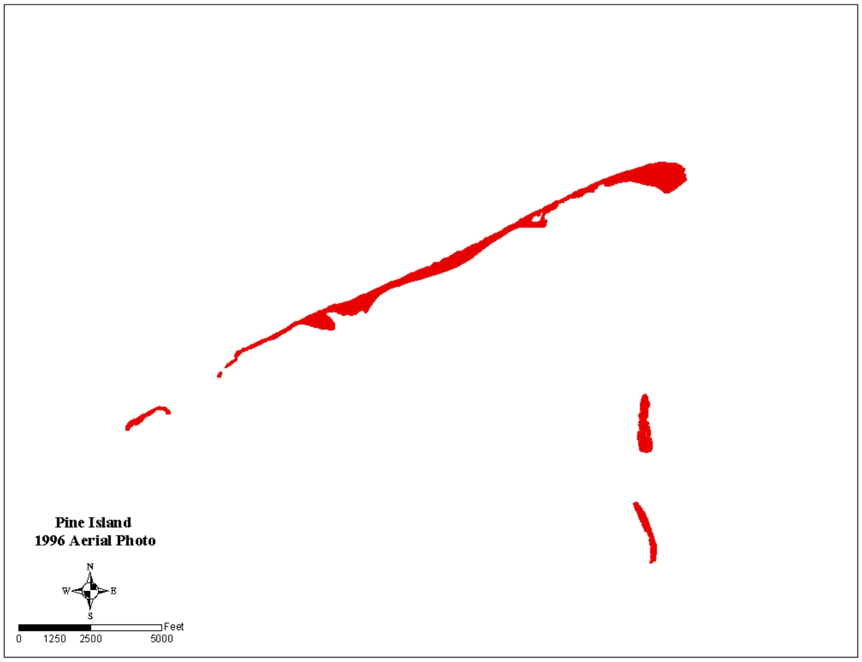


Figure 2.11 continued. The Pine Island delineated shorelines in 1991 and 1996.

Figure 2.11 continued. The Pine Island aerial photo of 2003.

II.2. Lake Level Data

Both long term mean lake level and seasonal lake level fluctuations can influence shoreline erosion rates by exposing different shoreline material to wave energy [Newbury and McCullough 1984, Lorang et al. 1993] and by influencing the formation and destruction of protective beaches [Rosen 1977, Wood and Meadows 1997]. We procured Lake of the Woods lake level records to characterize long term trends and seasonal fluctuations, and as input for future shoreline erosion models. Lake level data were obtained for eight locations on Lake of the Woods, with records of up to 100 years. Long term daily level data were obtained from the Hydat CD (Environment Canada), while hourly records were obtained from the Lake of the Woods Control Board. Figure 2.12 gives the relative locations of the lake level measurement stations, and Table 2.2 summarizes the record length and the type of lake level records that have been procured for these stations.

Table 2.2: Summary of Water Level Data for Lake of the Woods.

Location	Record Length	Records Obtained	
		Hourly	Daily
Warroad	1916 - present	1999 - 2003	1916 - 2003
Hanson Bay	1962 - present	1998 - 2003	1962 - 2003
Clearwater Bay	1963 - present	1998 - 2003	1963 - 2003
Cyclone Island	1983 - present	1998 - 2003	1983 - 2003
Sioux Narrows	1983 - 1985		1983 - 1985
Keewatin	1913 - present	1998 - 2003	1913 - 2003
Kenora	1915 - 1954		1915 - 1954
Springsteel Point	- present	1998 - 2003	1998 - 2003

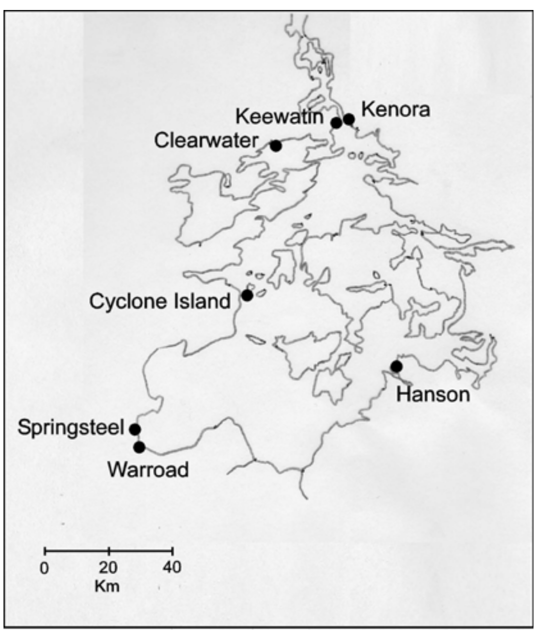


Figure 2.12. Lake level measurement stations on Lake of the Woods.

II.3. Wind Data

Wind velocity and direction have a strong influence on wave climate and shoreline erosion. Surface wave height varies with wind speed, the duration of wind events, and the fetch over which the wind acts on the water surface. Historical wind data records can be used directly to qualitatively examine the wave energy available for erosion over the period of record. Historical wind data records can also be used to hindcast a corresponding wave climate as input for quantitative erosion models. Wind data have been obtained from local weather stations with shorter records near Lake of the Woods, e.g. Warroad and Baudette, and from regional sites with longer records, e.g. International Falls and Winnipeg. Figures 2.13 shows the relative locations of permanent wind measurement stations and the two temporary stations installed for this study. Table 2.3 summarizes the wind data records that have been procured for the permanent stations.

Table 2.3: Summary of Wind Data Records obtained for stations near Lake of the Woods.

Location	Record Length (Resolution)	Records Obtained (Source)
International Falls, MN	1948 – 2004, (1 – 3 hour)	All (1, 2)
Baudette, MN	1997-2004, (1 hour)	All (1, 2)
Warroad, MN	1998 – 2000, 2003 - 2004 (1 hour)	All (1, 2)
Flag Island, MN	1998 – 2000, 2003 - 2004 (1 hour)	All (1, 2)
Royal Island, ON	2000 - 2001, 2003 - 2004 (1 hour)	All (3)
Kenora, ON	1953 – 2004 (1 hour)	1996-2003 (3)
Winnipeg, MB	1953 – 2004 (1 hour)	All (3)

Sources: (1) NOAA (nndc.noaa.gov) (2) State of Minnesota Climatology Office (Greg Spoden) (3) Environment Canada (www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html)

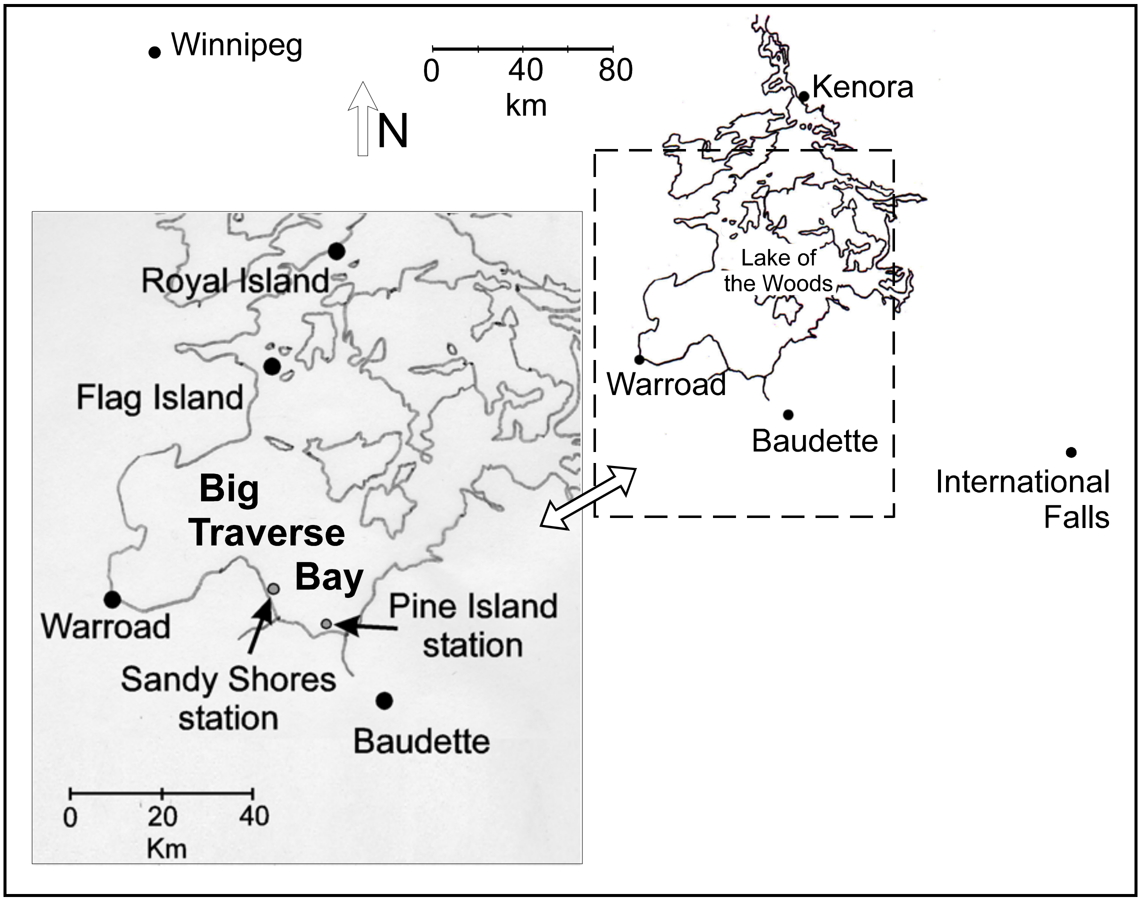


Figure 2.13. Wind measurement stations on Lake of the Woods. Baudette, Flag Island, Kenora, Royal Island, Warroad, and Winnipeg are government weather stations, while the Pine Island and Sandy Shores stations were installed for this study.

III. Wind and Wave Measurements in Lake of the Woods

Two instrumented stations (Figure 3.1) were installed in Lake of the Woods (LOW) during the summer of 2004. The stations were installed primarily to provide short term wave height measurements to calibrate wave hindcast simulations. The stations provided short term wind velocity measurements directly on Big Traverse Bay, to help identify which permanent measurement wind station or stations can be used to represent the wind velocity and direction over the bay.

One station was installed near Pine Island (48º 53.060', 94º 42.567') approximately ¾ mile offshore in 20 ft of water on June 16. The second was installed off of the Sandy Shores area (48º 56.252', 94º 53.914') approximately ½ mile offshore in 20 ft of water on July 20. The approximate location of the two stations is shown in Figure 2.2. Each station was equipped with the following instrumentation:

1. Wave height measured with pressure sensor (Northwest Instrumentation model PS9805, measured at 10 minute intervals + 1 to 3 bursts per hour of 1 to 5 minute length, 8 Hz)

2. Water temperature (Northwest Instrumentation model PS9104E, 10 minute interval)

3. Wind speed (Met One 014A cup anemometer, 10 minute interval)

4. Wind direction (RM Young 03001, 10 minute interval)

5. Data logger (Campbell Scientific CR10X)

Thirty four days of data were recorded by the Pine Island station, including several days of data with peak winds exceeding 10 m/s (22 mph). The recorded wind speed, wind direction, and wave height are shown in Figure 3.2. Several windy days were recorded from June 18 to June 24, with wind speeds in excess of 12 m/s (26 mph) and uncorrected wave heights of 1.2 to 1.5 m (4 to 5 ft). The station was heavily damaged in August, probably by a storm on August 18, so that all data recorded after June 24 was lost. 42 days of data were recorded by the Sandy Shores station, including several days of data with peak winds exceeding 10 m/s (22 mph), and one day with peak wind speed of 17.2 m/s (38.5 mph). The recorded wind speed, wind direction, and wave height at the Sandy Shores station are shown in Figure 3.3.

A sample wave burst measurement from the Pine Island station (5 minutes at 8 Hz) and the corresponding frequency spectrum are given in Figure 3.4, with a maximum wave height of 1.75 m. The data shown in Figure 3.4 has been corrected for pressure attenuation with depth, using equations from the USACOE Shoreline Protection Manual.

Preliminary analysis of the wind and wave data from the Pine Island measurement station shows a strong relationship between wind velocity and wave height, with a directional dependence. Figure 3.5 gives uncorrected wave height versus wind speed, for the full set of 10 minute wind/wave measurements from Pine Island. While the expected relationship exists between wave height and wind speed (wave height $\propto$ (wind speed)^2), there is substantial scatter. The relationship was improved by applying a direction dependent correction function to wind velocity, as given in Figure 3.6. The function takes into account the effect of varying fetch with direction. The resulting relationship between wave height and wind speed is given in Figure 3.5, with R^2 improved from 0.6 to 0.73. The relationship between wind velocity and wave height also improved at longer time scales. Figures 3.7 and 3.8 give the relationship between wind speed and wave height for 1 hour averaged data, using raw (Figure 3.8) and corrected (Figure 3.9) wind.

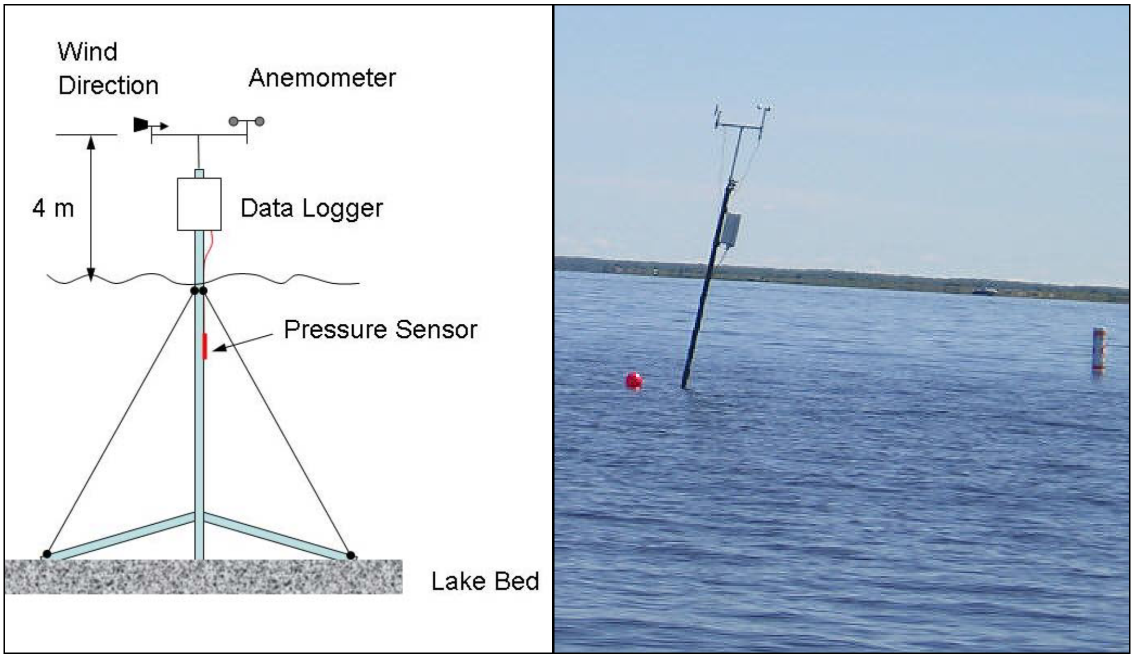


Figure 3.1. Schematic drawing and photograph of the Pine Island wind/wave measurement station.

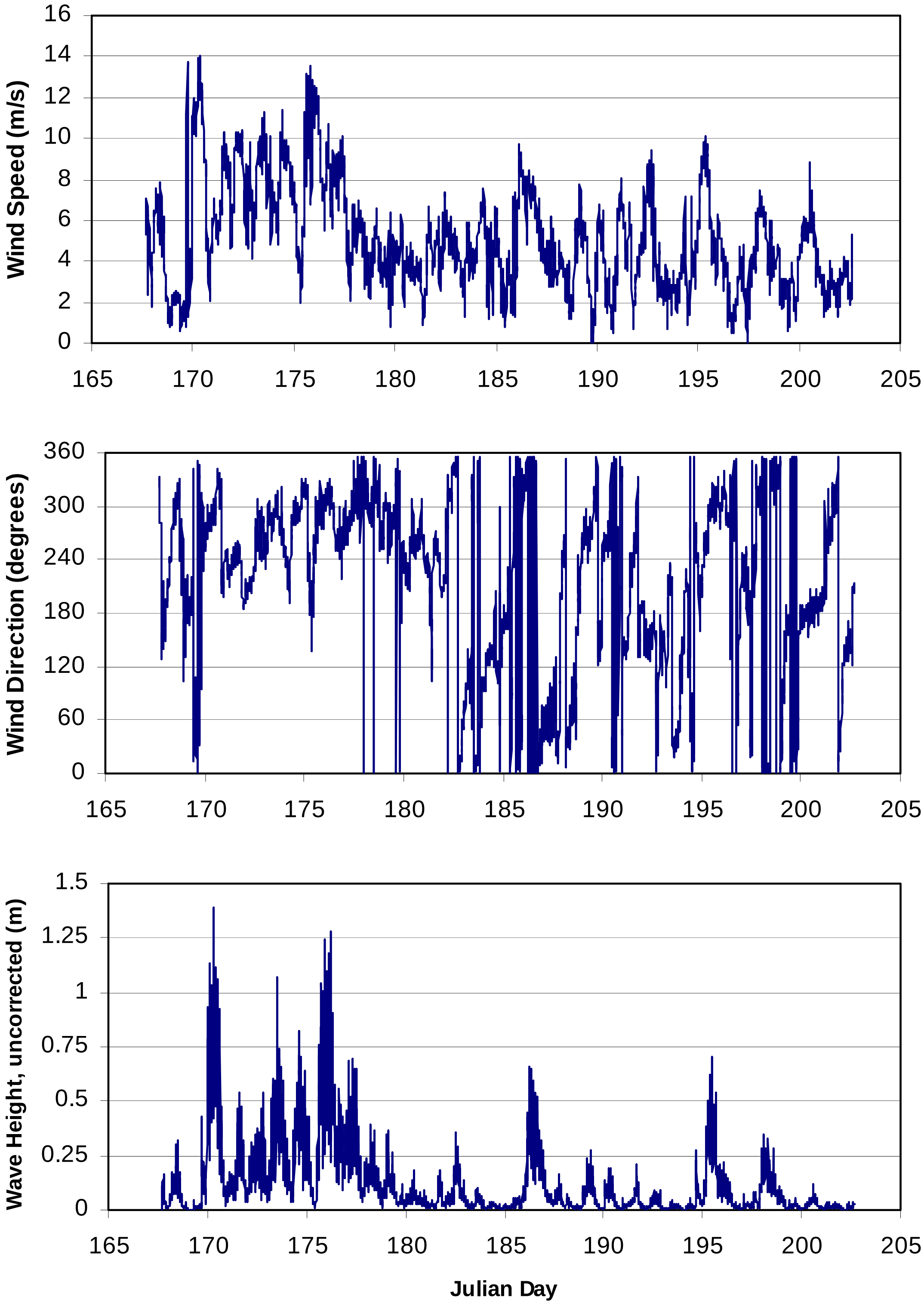


Figure 3.2. 10 minute wind speed, wind direction, and wave height data (uncorrected) for the Pine Island station, June 16 to July 20, 2004.

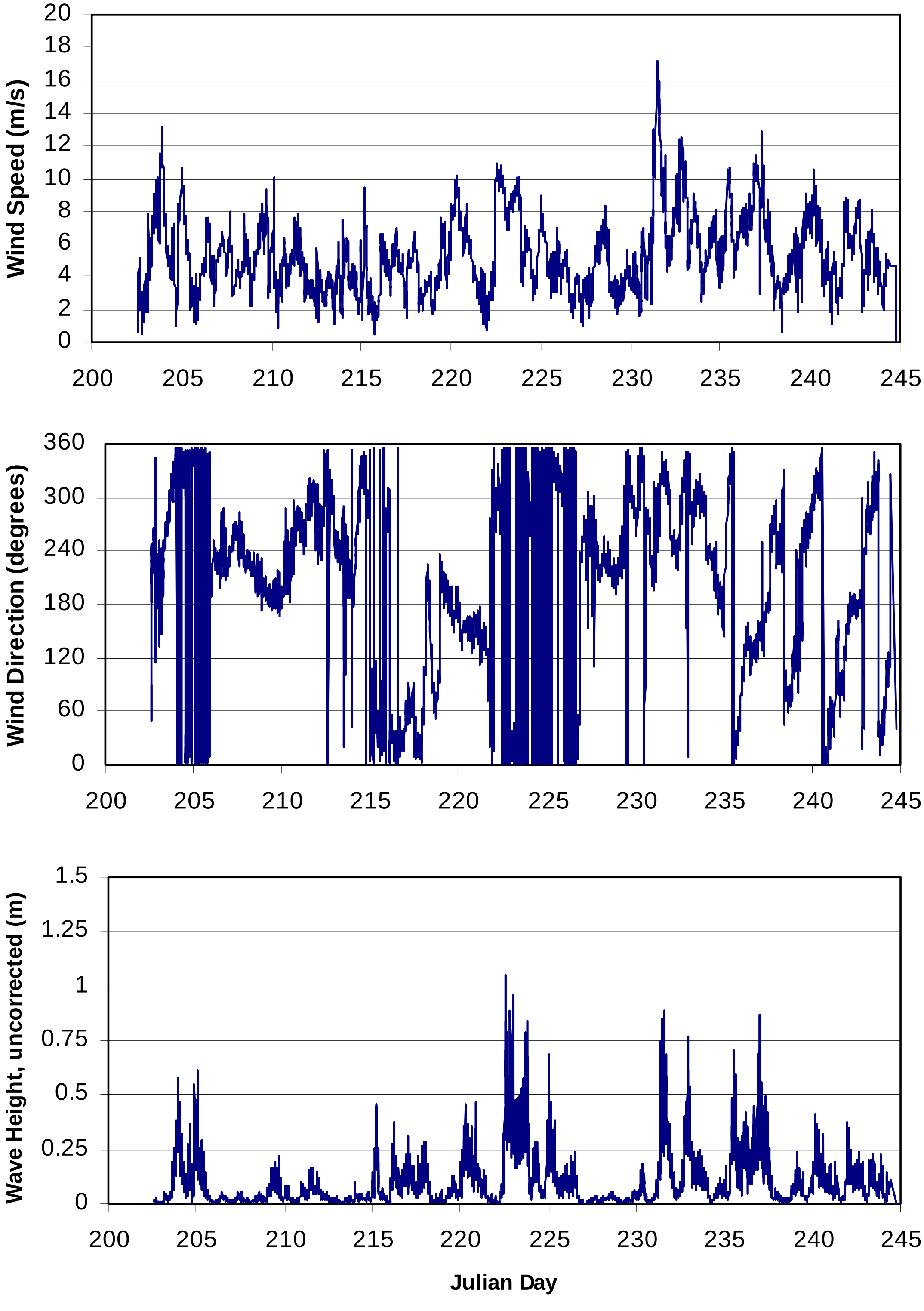
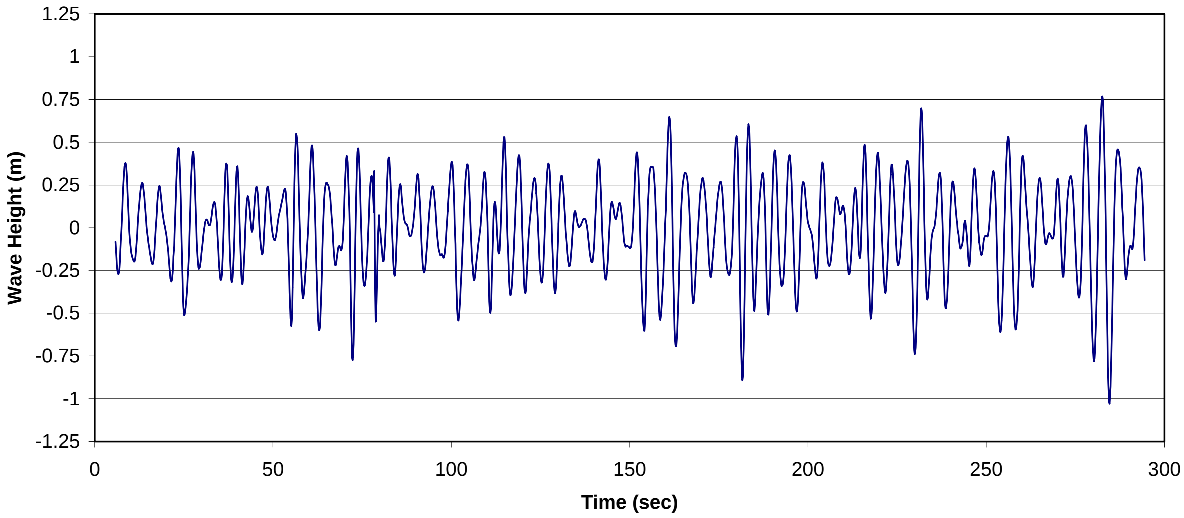


Figure 3.3. 10 minute wind speed, wind direction, and wave height data (uncorrected) for the Sandy Shores station, July 20 to August 31, 2004.



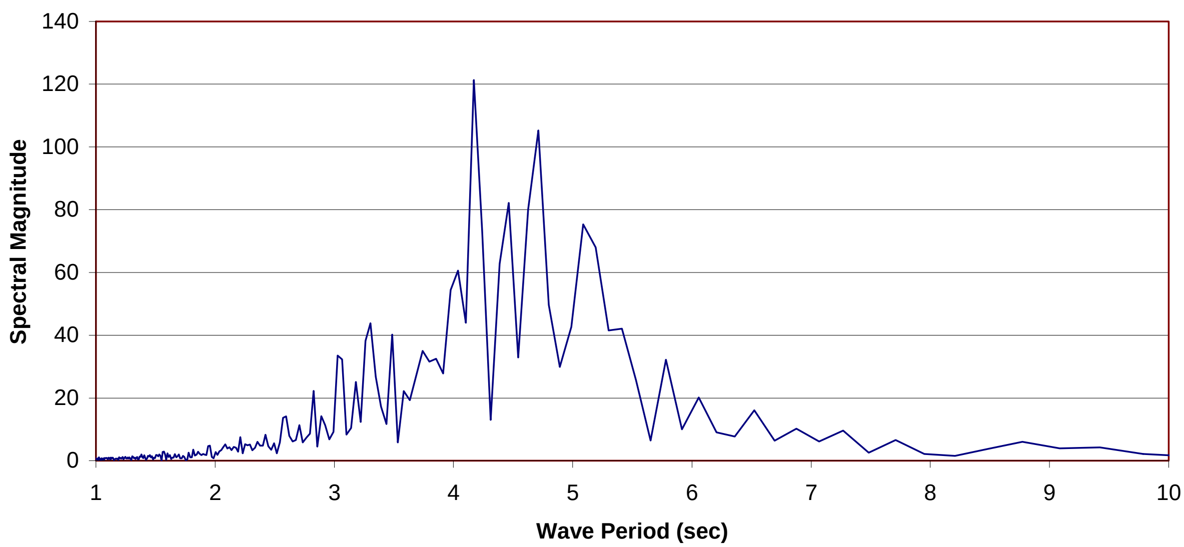


Figure 3.4. Sample wave burst data in time domain (upper panel) and frequency domain (lower panel) for the Pine Island station, June 18, 2004 (Julian day 170).

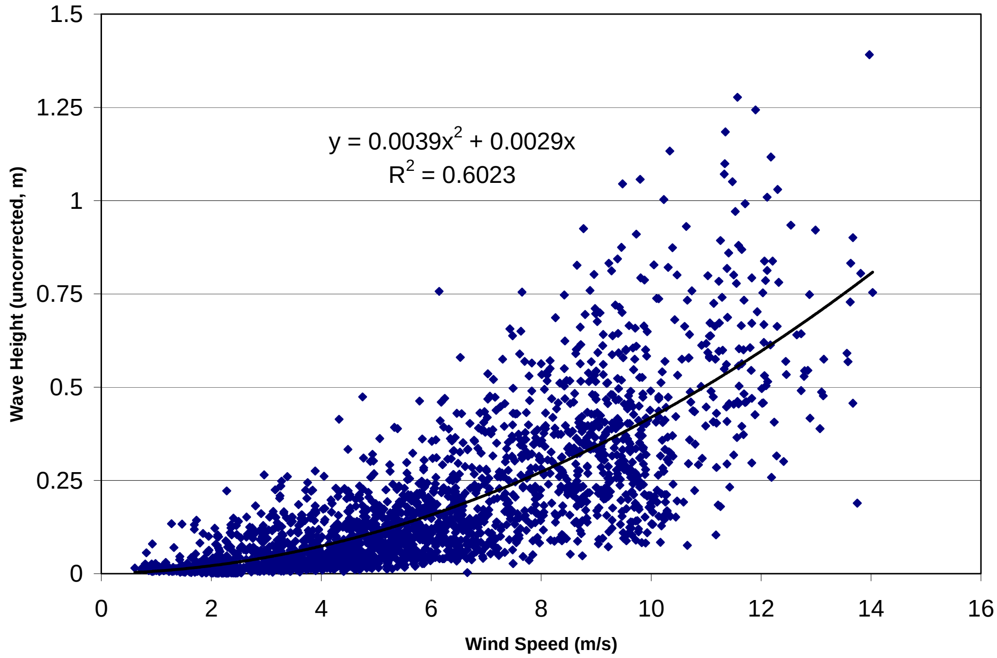


Figure 3.5. Raw station wind speed versus wave height for the Pine Island station. Wind speed values are 10 minute averaged, while wave height values are instantaneous measurements at 10 minute intervals.

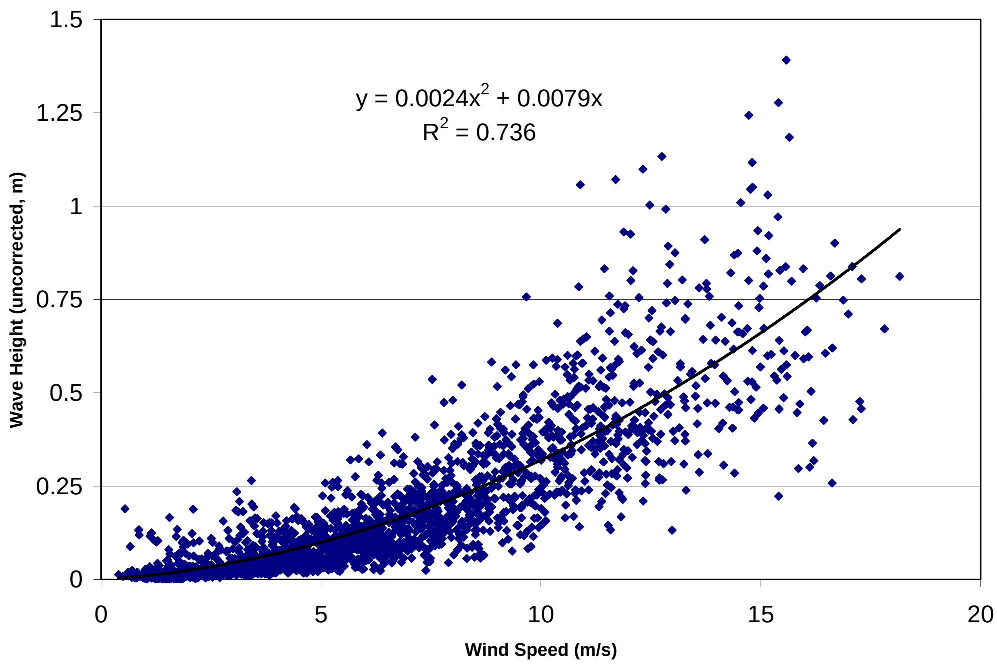


Figure 3.6. Fetch adjusted station wind speed versus wave height for the Pine Island station. Wind speed values are 10 minute averaged, while wave height values are instantaneous measurements at 10 minute intervals.

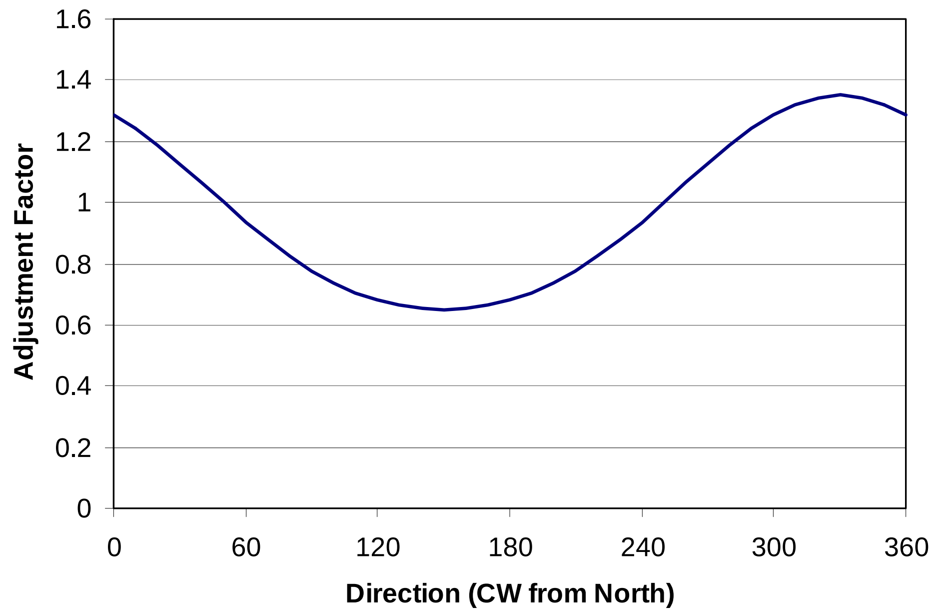


Figure 3.7. Wind speed adjustment factor versus wind direction for the Pine Island station.

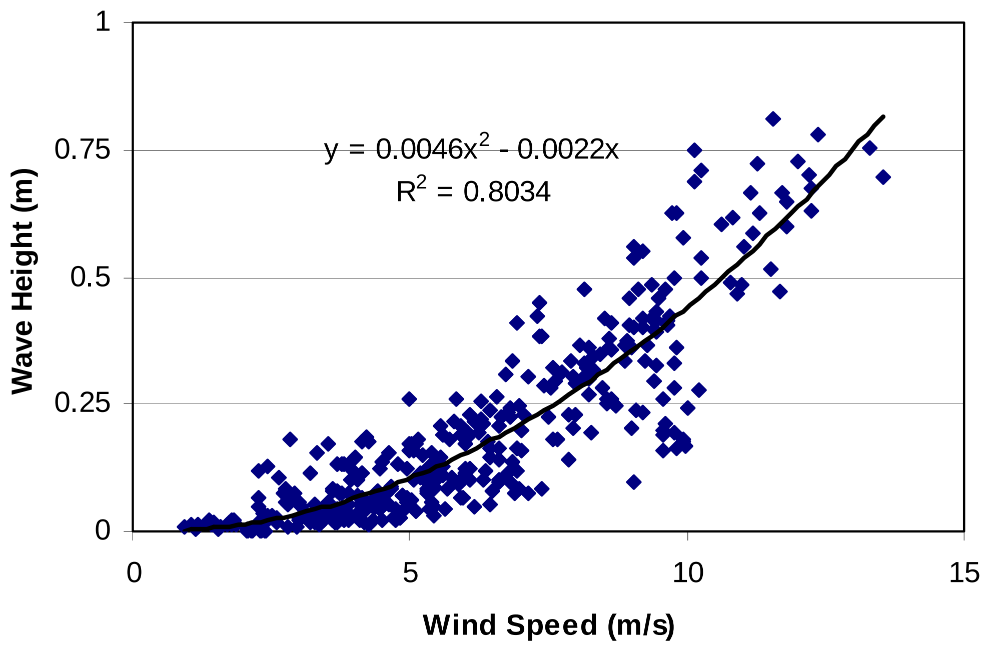


Figure 3.8. Raw station wind speed versus wave height for 1 hour averaging for the Pine Island station.

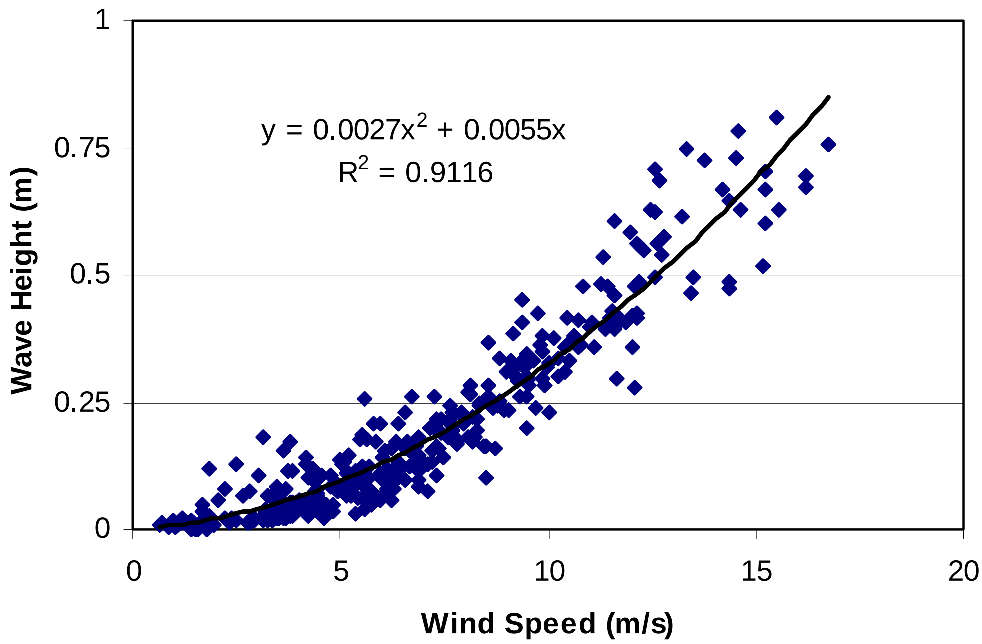


Figure 3.9. Adjusted station wind speed versus wave height for 1 hour averaging for the Pine Island station.

IV. Lake Level Analysis

The lake level data records were examined to characterize seasonal and long term trends in the record, and to compare recent high water events with high water evens over the last hundred years. The record of monthly averaged lake level at four measurement stations on Lake of the Woods is shown in Figure 4.1. There are offsets between the stations of up to 5 cm, e.g differences in long term averaged lake level between stations. These offsets were removed from the data prior to combining the station data to calculate average lake level, using long term (5 - 10 year) averaging of winter lake level data. In addition, the Warroad data was corrected for an offset of 3.3 cm occurring in November of 1978, believed to be caused by a maintenance problem with the Warroad level station (Tackman 1999). Corrected data from six stations (Clearwater, Cyclone, Hanson, Kenora, Keewatin, and Warroad) were used to calculate monthly average lake level from 1913 to 2003 (Figure 4.2).

A linear fit of the entire record gives a slight downward trend (0.2 mm/year), while a 10 year running average shows that long term (10 year) fluctuations were more pronounced before 1960. A linear fit of the last 30 years has a slight upward trend of 0.6 mm/year (Figure 4.3). The North-South differential measure (Keewatin-Warroad) shows a more significant trend, of about 1 mm/year (Figure 4.4). This has been attributed to large scale geologic processes (glacial rebound) in other studies (Tackman 1999), and results in a steady increase in apparent lake level at the south end of the lake of about 0.5 mm/year. The monthly mean lake levels averaged over multiple stations are plotted versus month in Figure 4.5. There is a clear seasonal trend, with the highest water levels in June and July, but with significant scatter from year to year. The highest mean lake level occurs in July (323.1 m), while the lowest mean lake level occurs in March (322.6 m). Standard deviations of lake level from year to year are on the order of 0.5 m (1.6 ft).

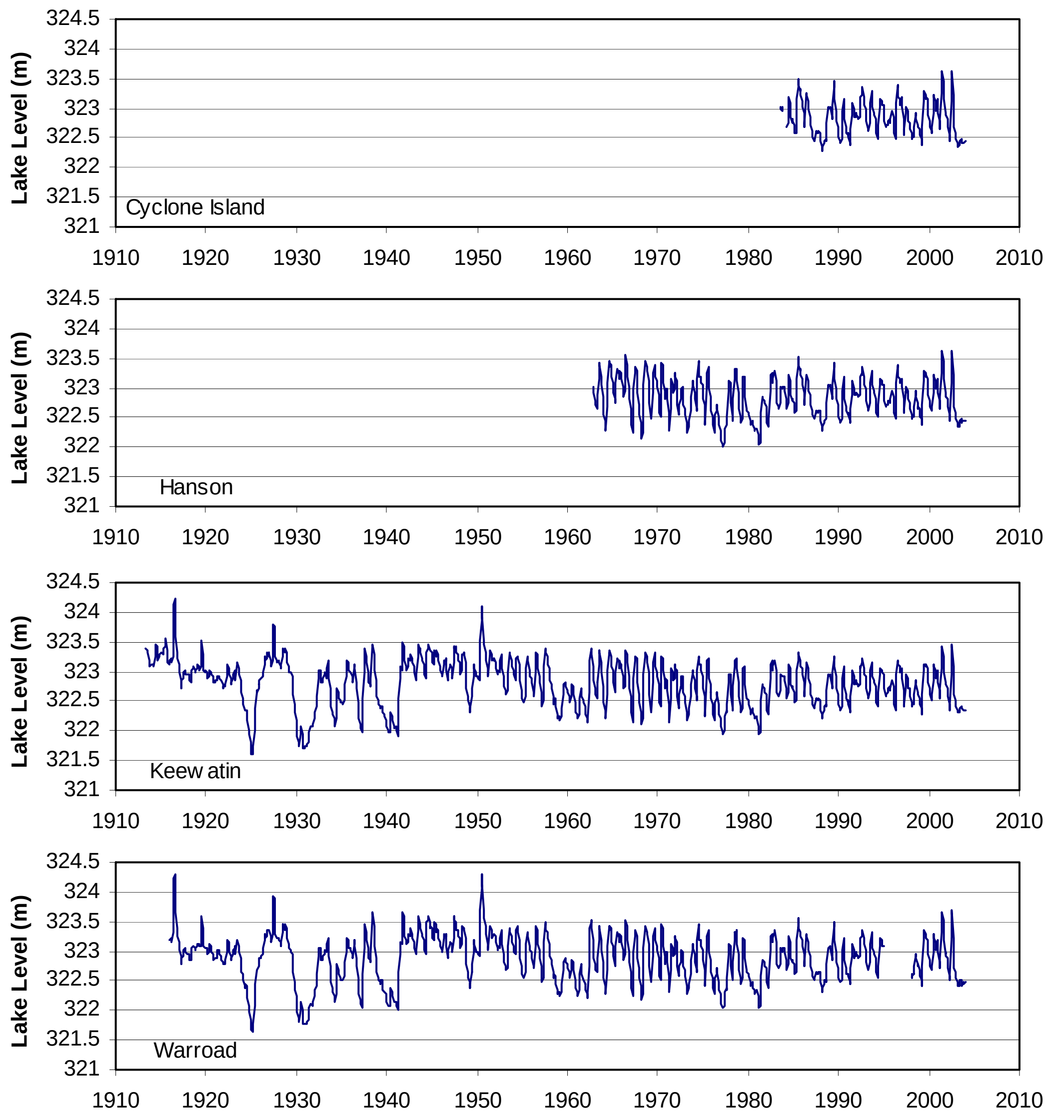


Figure 4.1. Monthly mean lake level for four Lake of the Woods measurement stations, 1913 to 2003.

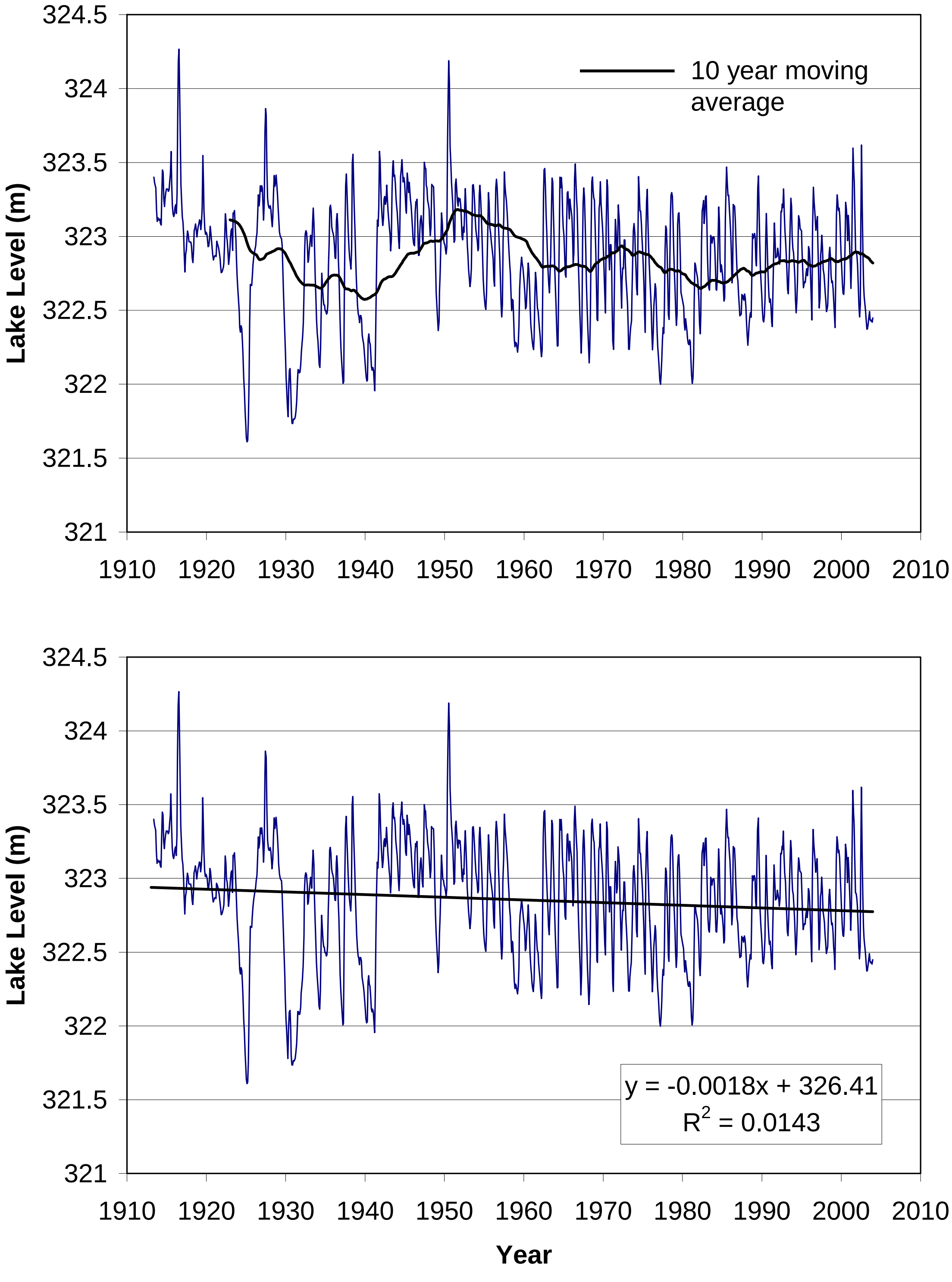


Figure 4.2. Monthly mean lake level for 1913 to 2003 with 10 moving average (upper panel) and linear fit (lower panel).

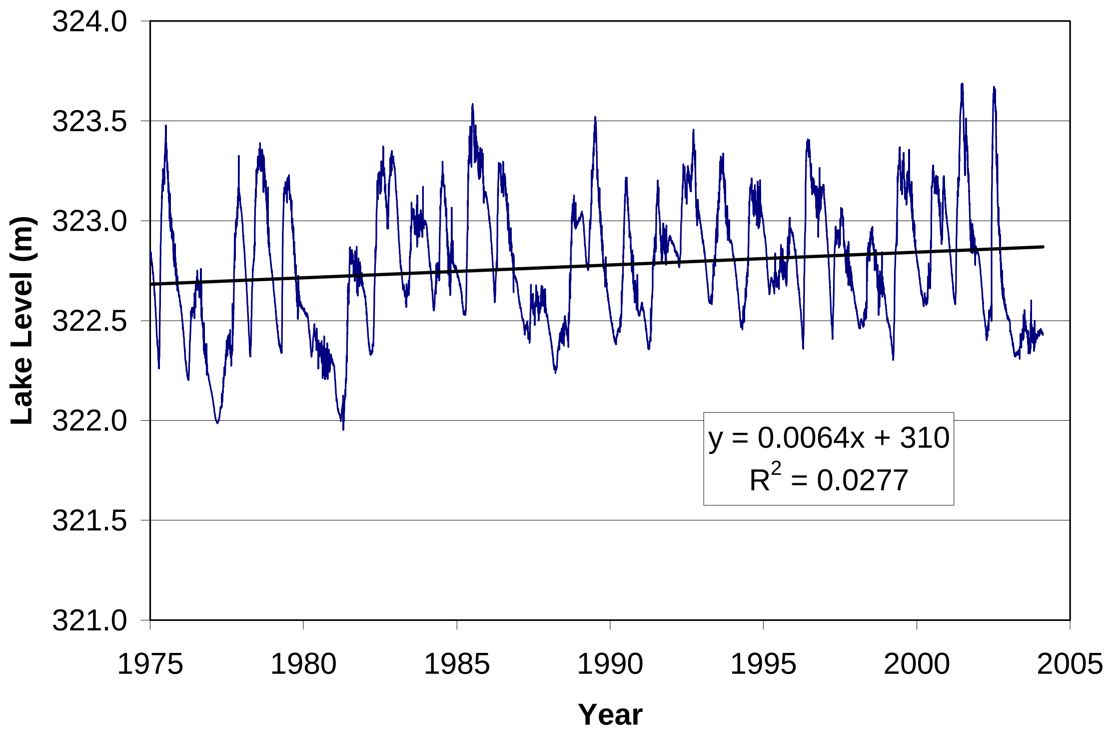


Figure 4.3. Lake level at Hanson station for 1975 to 2003 with linear fit.

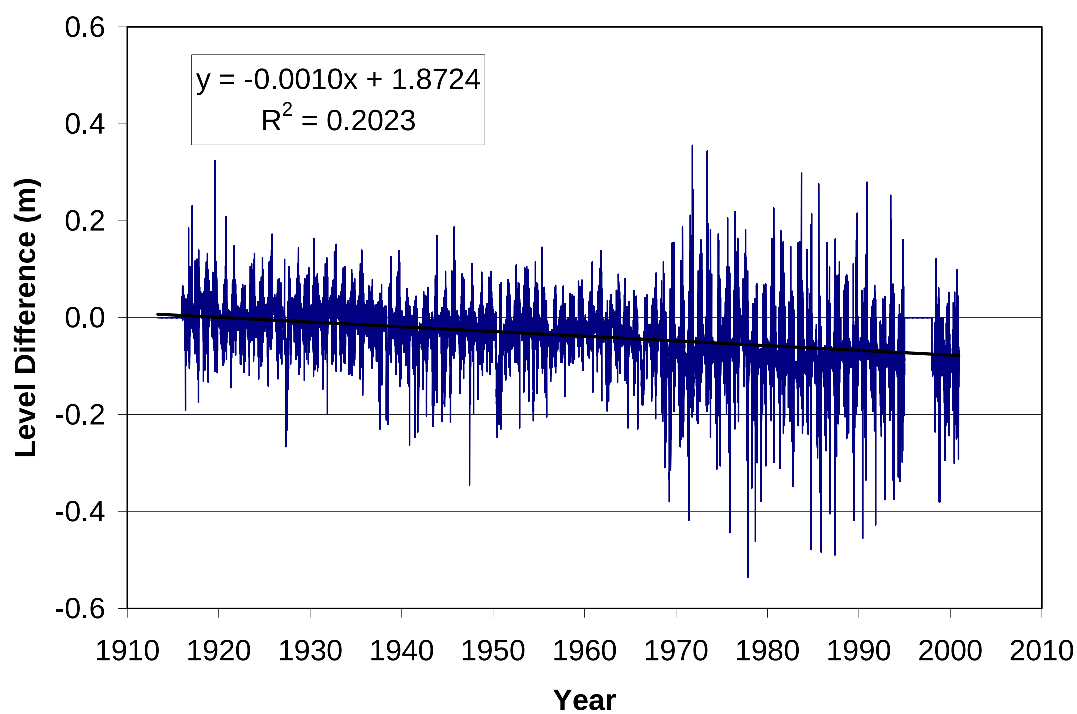


Figure 4.4. Lake level difference (Warroad-Keewatin) for monthly mean values, 1916-2003.

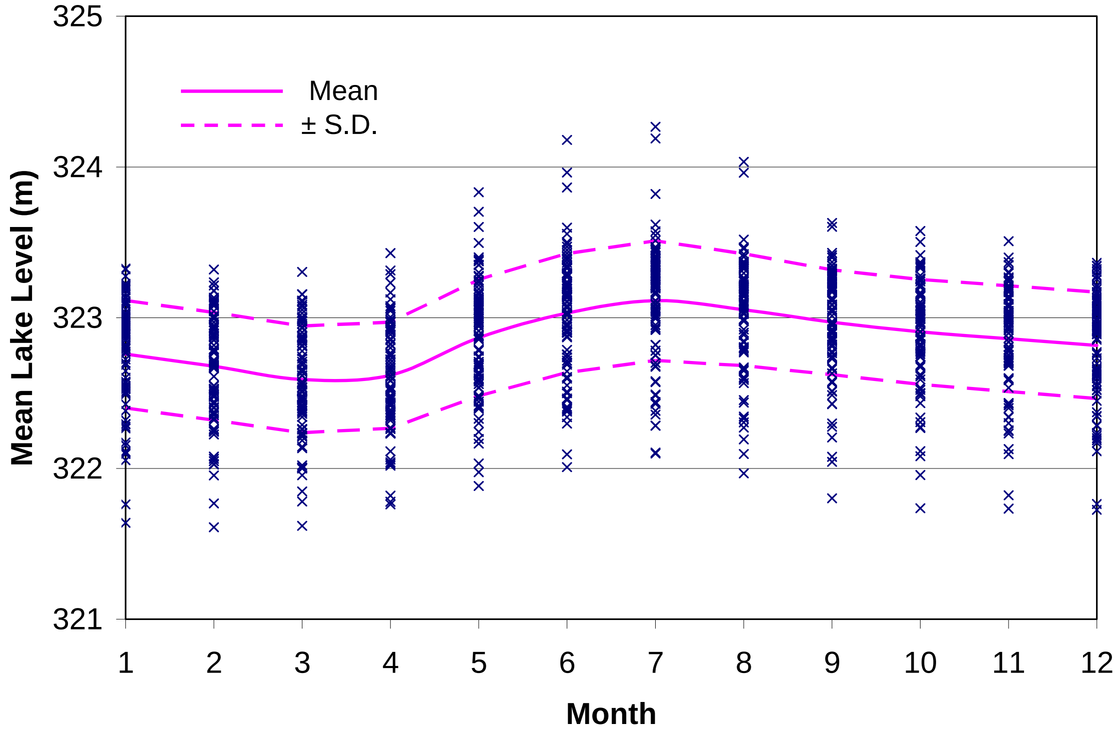


Figure 4.5. Seasonal variation in monthly mean lake level, averaged over multiple stations. Monthly mean values are plotted as a solid line with ± 1 STD as a dashed line.

V. Wind Data Correlations

To achieve a realistic historical model for wave energy and erosion on the southern shores of Lake of the Woods, it is important to determine if wind data records exist that can be used to represent the wind velocity over Big Traverse Bay. The four local stations close to Big Traverse Bay (Baudette, Warroad, Flag Island, Royal Island) have record lengths on the order of 5 to 10 years and measurement intervals of 1 hour or longer. Three regional stations (Kenora, Winnipeg and International Falls) have long term wind records going back to the 1950s with measurements at 1-3 hour intervals. Several years of wind data from these seven stations, plus data from the Pine Island wind/wave station, were analyzed in this task to determine:

1) The correlations of wind data between local stations at different time scales

2) The correlation of wind data from the Pine Island measurement station to local and regional wind stations

3) The correlation of wind data from the Pine Island measurement station to averaged wind velocities from local and regional wind measurement stations.

V.1. Correlation of wind data between stations

Table 5.1 summarizes the correlation coefficients calculated for time scales of 1 hour to 24 hours. The table includes local wind stations (Baudette, Flag Island, and Warroad), regional wind stations (International Falls, Kenora, and Winnipeg) and a synthesized local wind record (Big Traverse). The wind record for Big Traverse Bay was synthesized by vector averaging the hourly wind velocity and direction from the Baudette, Warroad, and Flag Island stations. The results given in Table 5.1 are for data from 2003. Analysis of other years gave similar results (not shown). Correlation improves consistently as the time scale is increased from 1 hour to 24 hours. In general, the local stations are better correlated to each other than to the regional stations. The averaged Big Traverse wind record was, in general, slightly better correlated to the regional stations than the individual local stations. Figures 5.1 and 5.2 give examples of linear regressions between local and regional wind stations (Baudette and International Falls) at 24 hour and 3 hour time scales, respectively.

Table 5.2 summarizes the correlation of each wind record to the 34 day wind record from the Pine Island wave/wind station, for 1 hour time scale. The local wind records were better correlated to Pine Island than the regional wind records. Of the local records, Flag Island had the best wind velocity correlation to Pine Island (R=0.74). The averaged local wind record (Big Traverse) had only slightly better correlation to Pine Island (R=0.75). Of the regional wind records, International Falls and Winnipeg had better correlation to Pine Island (R=0.55), while Kenora was somewhat lower (R=0.46). Figures 5.3 and 5.4 give examples of linear regressions between the Pine Island and Flag Island wind stations for hourly wind data. Correlation is improved by considering only winds coming from the northwest quadrant (270 - 360º), as shown in Figure 5.4.

Table 5.1. Velocity and direction correlation coefficient (R) for local and regional measurements sites around Lake of the Woods for 2003, using 1, 3, 6, and 24 hour averaging times. Big Traverse is the average of Baudette, Flag Island, and Warroad.

Station 1 – Station 2	24 hour average		6 hour average	
	Velocity	Direction	Velocity	Direction
Warroad-Intern Falls	0.81	0.84	0.73	0.86
Baudette-Intern Falls	0.86	0.83	0.80	0.84
Flag Island-Intern Falls	0.72	0.84	0.63	0.83
Warroad-Baudette	0.86	0.83	0.80	0.86
Warroad-Flag Island	0.73	0.86	0.68	0.89
Baudette-Flag Island	0.77	0.86	0.70	0.86
Warroad-Kenora	0.79	0.80	0.70	0.72
Baudette-Kenora	0.79	0.83	0.73	0.74
Flag Island-Kenora	0.77	0.88	0.70	0.75
Big Traverse – Intern Falls	0.87	0.78	0.80	0.81
Big Traverse – Kenora	0.75	0.81	0.77	0.69

Station 1 – Station 2	3 hour average		1 hour average	
	Velocity	Velocity	Velocity	Direction
Warroad-Intern Falls	0.68	0.86	0.66	0.68
Baudette-Intern Falls	0.76	0.82	0.73	0.65
Flag Island-Intern Falls	0.58	0.82	0.58	0.67
Warroad-Baudette	0.76	0.86	0.73	0.64
Warroad-Flag Island	0.64	0.88	0.62	0.73
Baudette-Flag Island	0.64	0.85	0.62	0.68
Warroad-Kenora	0.64	0.73	0.62	0.58
Baudette-Kenora	0.67	0.73	0.62	0.61
Flag Island-Kenora	0.64	0.77	0.61	0.65
Warroad-Winnipeg			0.62	0.58
Baudette-Winnipeg			0.62	0.60
Flag Island-Winnipeg			0.61	0.66
Big Traverse – Intern Falls	0.76	0.82	0.69	0.69
Big Traverse – Kenora	0.71	0.72	0.68	0.63
Big Traverse – Winnipeg			0.68	0.63

Table 5.2. Correlation coefficient (R) of seven wind measurement stations to Pine Island wind/wave station at hurly time scale for June 16 to July 20, 2004. The lead/lag time applied to each wind station to maximize correlation to the Pine Island station is also given. Big Traverse is the average of Baudette, Flag Island, and Warroad.

Station	R	lag/lead (hours)
Baudette	0.59	1
Big Traverse	0.75	-1
Flag Island	0.74	-2
International Falls	0.55	2
Kenora	0.46	0
Warroad	0.63	-2
Winnipeg	0.55	-10

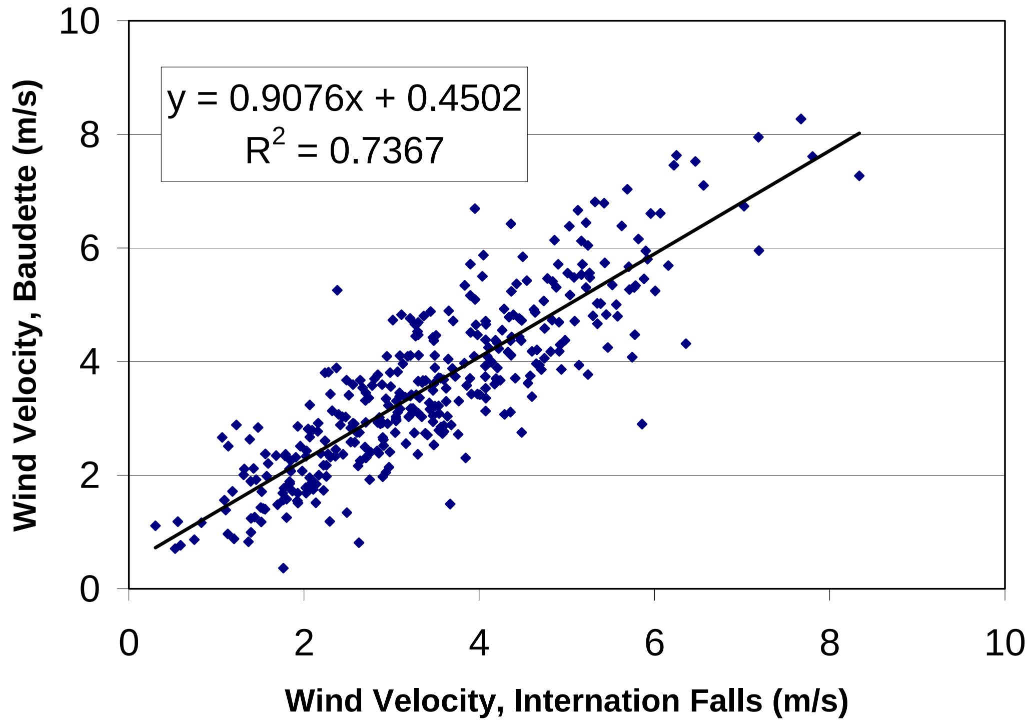


Figure 5.1. Daily averaged wind velocity for Baudette versus International Falls, 2003.

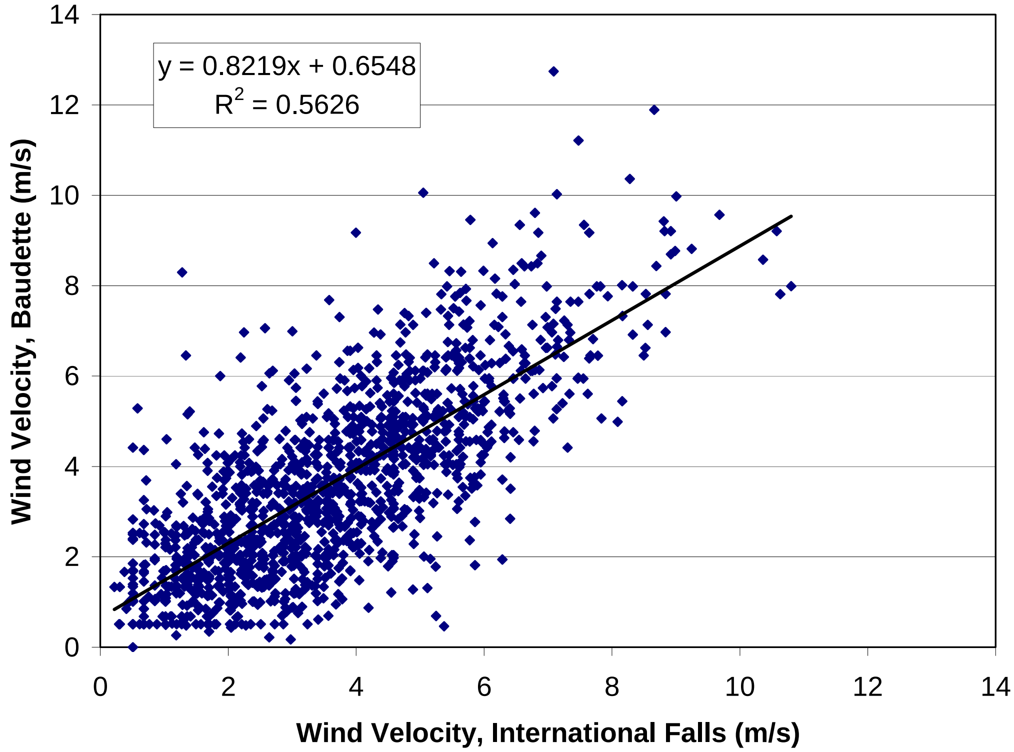


Figure 5.2. Three hour averaged wind velocity for Baudette versus International Falls, 2003.

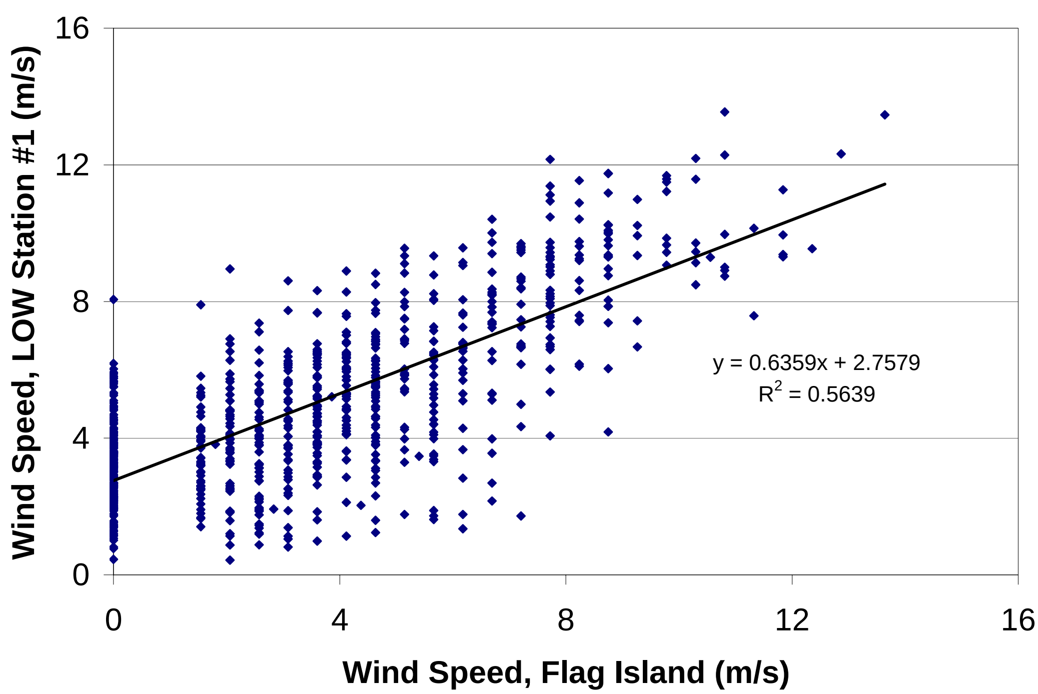


Figure 5.3. Pine Island station wind speed versus Flag Island wind speed for 1 hour averaged data, all directions, June 16 to July 20, 2004.

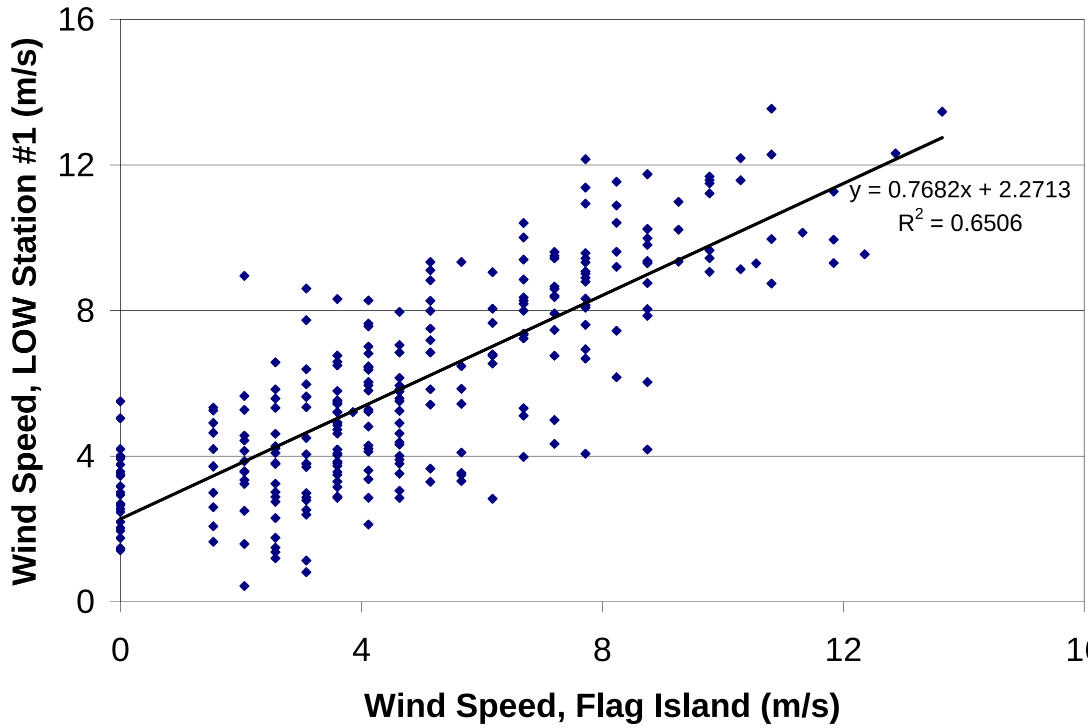


Figure 5.4. Pine Island station wind speed versus Flag Island wind speed for 1 hour averaged data, West to North winds only.

V.2. Constructing a Long Term Wind Data Record for Big Traverse Bay

Because there are no long term (>10 years) wind data records for locations close to Big Traverse Bay, the regional wind data records were considered for constructing a historical wind record for Lake of the Woods. The average of International Falls and Winnipeg was found to have reasonable correlation to wind measured at the Pine Island and Sandy Shores wind stations, but somewhat lower average and peak wind speed. By further applying linear fit coefficients to the average International Falls/Winnipeg wind data, a simulated LOW data set was constructed that has the same average wind speed as the measured data sets, and a similar distribution of high wind events.

Considered individually, Winnipeg and International Falls wind speed both have intermediate correlation (R=0.55) to the Pine Island measurement station, while Kenora has relatively poor correlation (Table 5.2). Winnipeg and International Falls data combined in a scalar average was found to be better correlated to Pine Island than the individual stations. Using an average of Winnipeg, International Falls, and Kenora did not improve the correlation coefficient compared to an average of Winnipeg and International Falls only. 1 hour averaged wind velocity readings from the Pine Island and Sandy Shores stations are plotted against the average of International Falls and Winnipeg in Figures 5.5 and 5.6. Figure 5.5 gives wind measurements in all directions, while Figure 5.6 gives only winds from the northwest quadrant. The slope and intercept of the linear regressions shown are slightly different for the two cases, but the relationships are very similar for the two different measurement stations. Since winds from the northwest quadrant are the most significant for erosion at the southern shore and have the best correlation between locations (Table 5.3), the linear fit coefficients for the northwest quadrant (Figure 5.6) were used to synthesize a wind record for Big Traverse Bay from the average Winnipeg/International Falls velocity readings, as given in Equation 5.1:

$$V_s(t) = 0.63 \cdot \left[V_{int}(t + \delta_{int}) + V_{win}(t + \delta_{win})\right] + 0.46 \qquad (5.1)$$

where V_{int} and V_{win} are the wind velocity (m/s) at International Falls and Winnipeg, respectively, and t is time. δ_{int} and δ_{win} are the time offsets used for International Falls and Winnipeg. For the time period for which wind was measured at Pine Island, offsets of δ_{int} = 2 hours and δ_{win} = 10 hours gave the best correlation of simulated wind to measured wind. The simulated wind record given by Equation 5.1 is compared to the Pine Island wind record in Figure 5.7, and the correlation coefficients are given in Table 5.3.

To further evaluate the validity of the synthetic LOW wind record, the synthetic record was also compared to Flag Island for longer records, e.g. 1 year of hourly readings. The synthetic LOW wind record was found to be reasonably well correlated to Flag Island, again with the best correlation for winds coming from the northwest quadrant (Table 5.3).

The characteristics of peak wind events at Flag Island, Pine Island, and the simulated LOW record were also compared, as peak winds give the highest wave and erosion potential. Figure 5.8 gives the duration and frequency of wind events ranging from 4 m/s to 10 m/s. The frequency of wind events has a similar distribution for Pine Island, Flag Island, and the simulated wind. However, the wave station has significantly longer wind event duration, particularly for events exceeding 8 and 10 m/s. The timing, duration, and direction of 8 m/s wind events are plotted in Figure 5.9 for the Pine Island station and the simulated LOW wind, over the period of record for the wind station. The number, timing, and direction of wind events are similar for the two wind records, but the actual station data again shows longer duration events than the simulated wind.

Wind roses (Figures 5.10 – 5.12) are very similar for the Pine Island station and the simulated LOW wind, with dominant winds from the West to Northwest. The wind rose for Flag Island is also dominated by winds from the West to Northwest, but has stronger components from the North and South compared to the wave station.

Table 5.3. Correlation coefficients (R) of 1 hour averaged simulated LOW wind data and measured wind velocities for Flag Island and Pine Island.

Direction Range	Simulated LOW to Pine Island	Simulated LOW to Flag Island	Flag Island to Pine Island
0 to 90	0.57	0.64	0.30
90 to 180	0.57	0.58	0.60
180 to 270	0.71	0.63	0.75
270 to 360	0.74	0.76	0.81
0 to 360	0.70	0.65	0.71

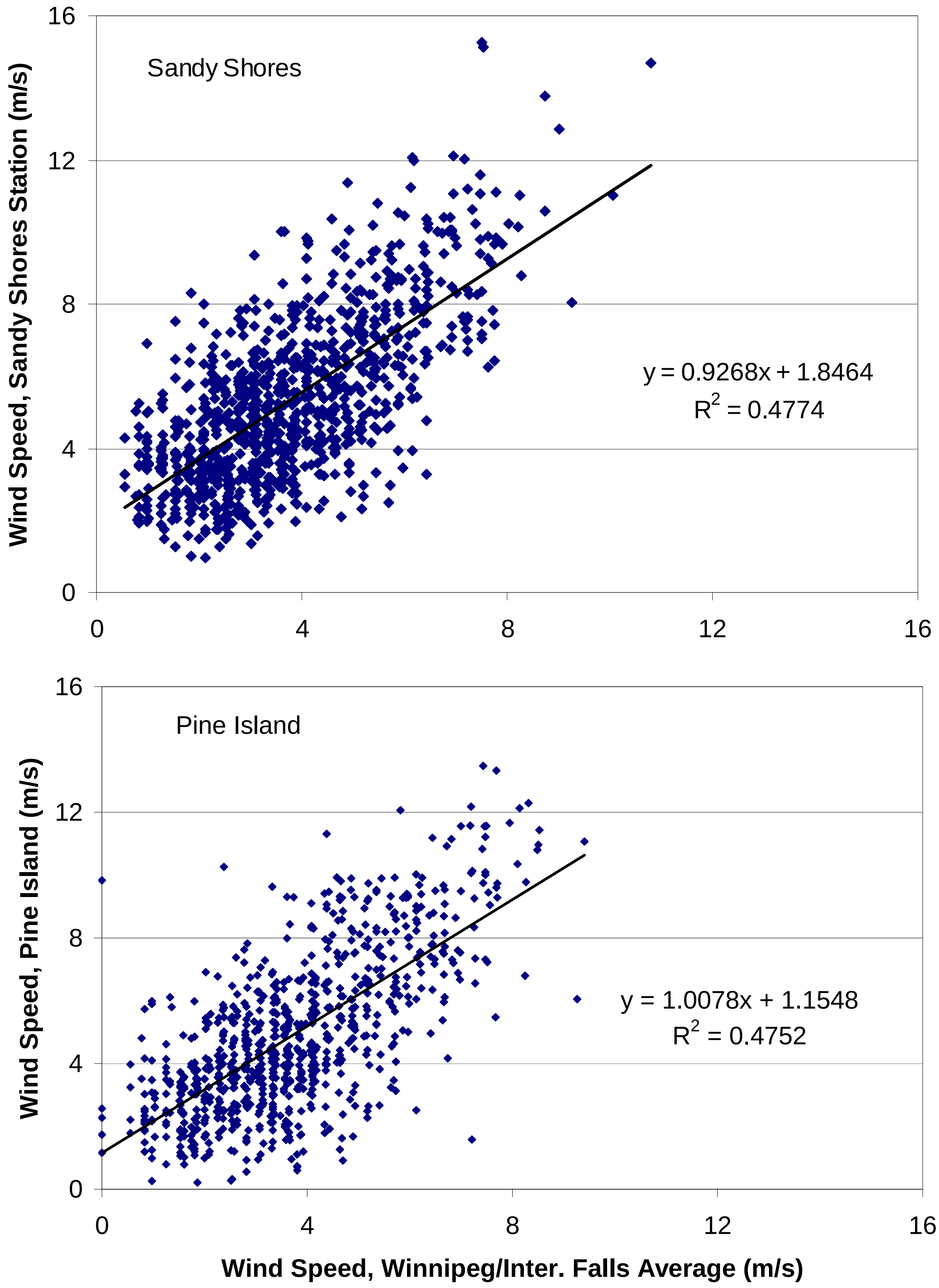


Figure 5.5. Measured wind speed versus averaged Winnipeg-International Falls wind speed for Sandy Shores (upper panel) and Pine Island (lower panel) for 1 hour averaged data, all directions.

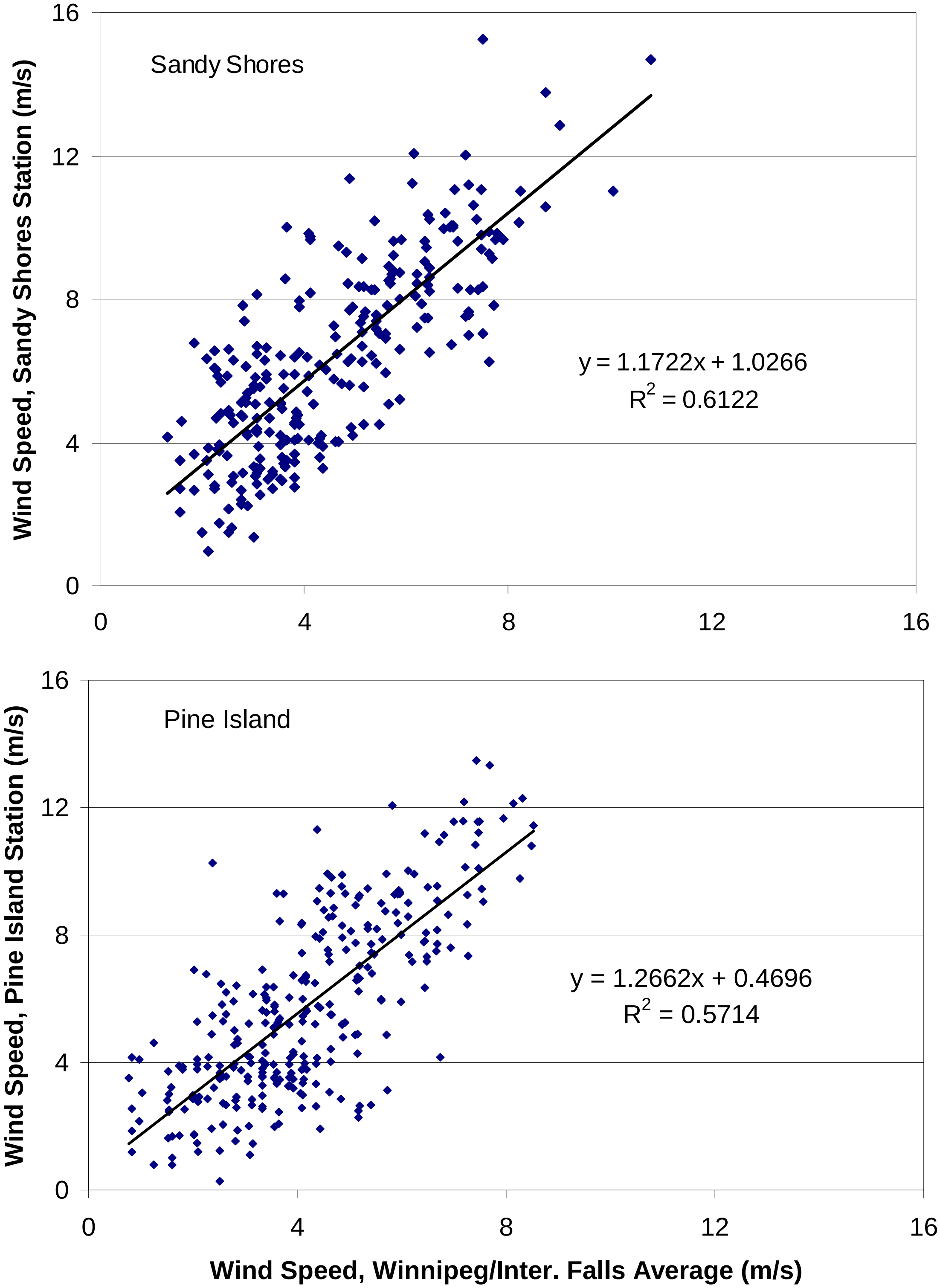


Figure 5.6. Measured LOW wind speed versus average Winnipeg-International Falls wind speed for Sandy Shores (upper panel) and Pine Island (lower panel) for 1 hour averaged winds from the northwest quadrant (270°-360°) only.

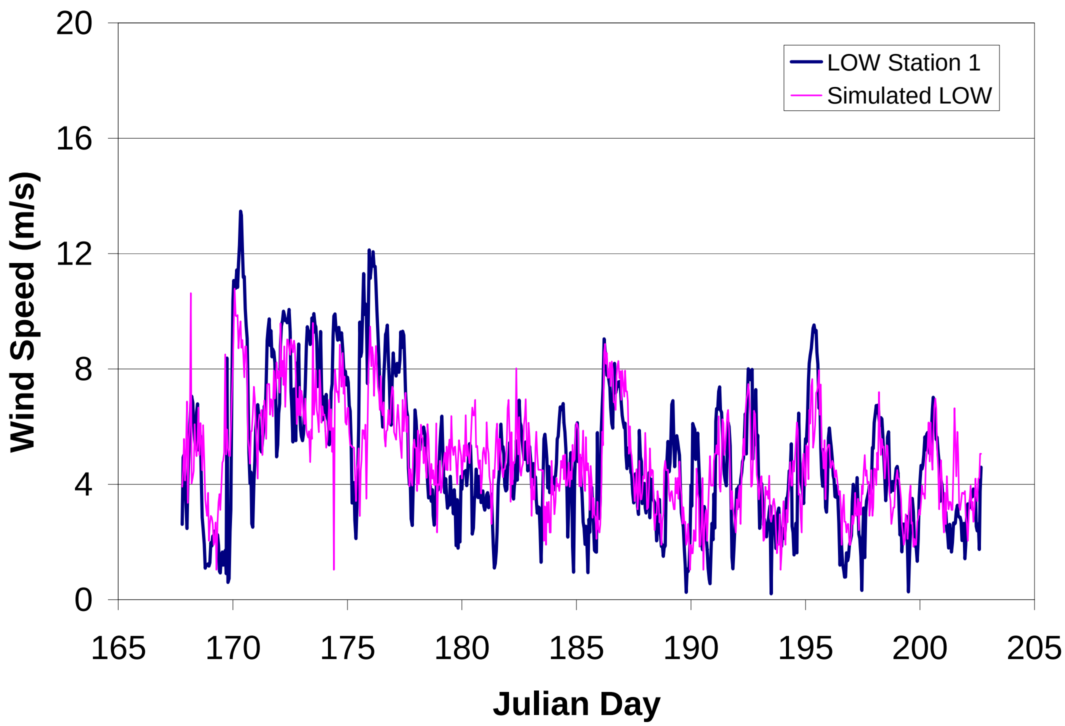


Figure 5.7. One hour averaged wind speed versus time for LOW station #1 (Pine Island) and simulated LOW.

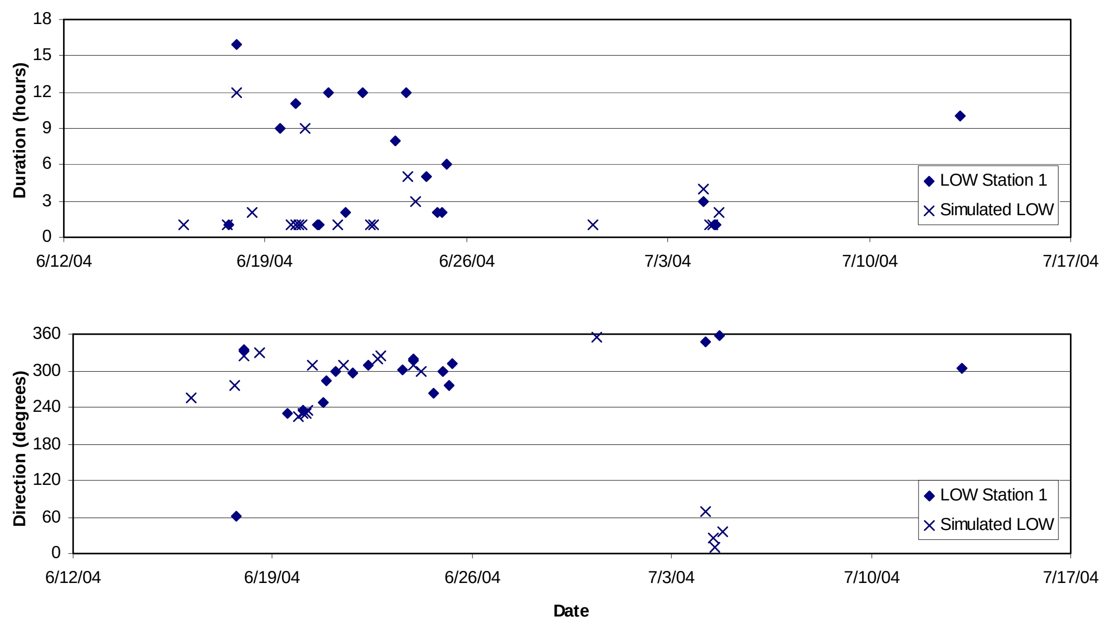


Figure 5.8. Duration and mean direction versus time for wind events exceeding 8 m/s for LOW Station 1 and simulated LOW, June 16 to July 20, 2004.

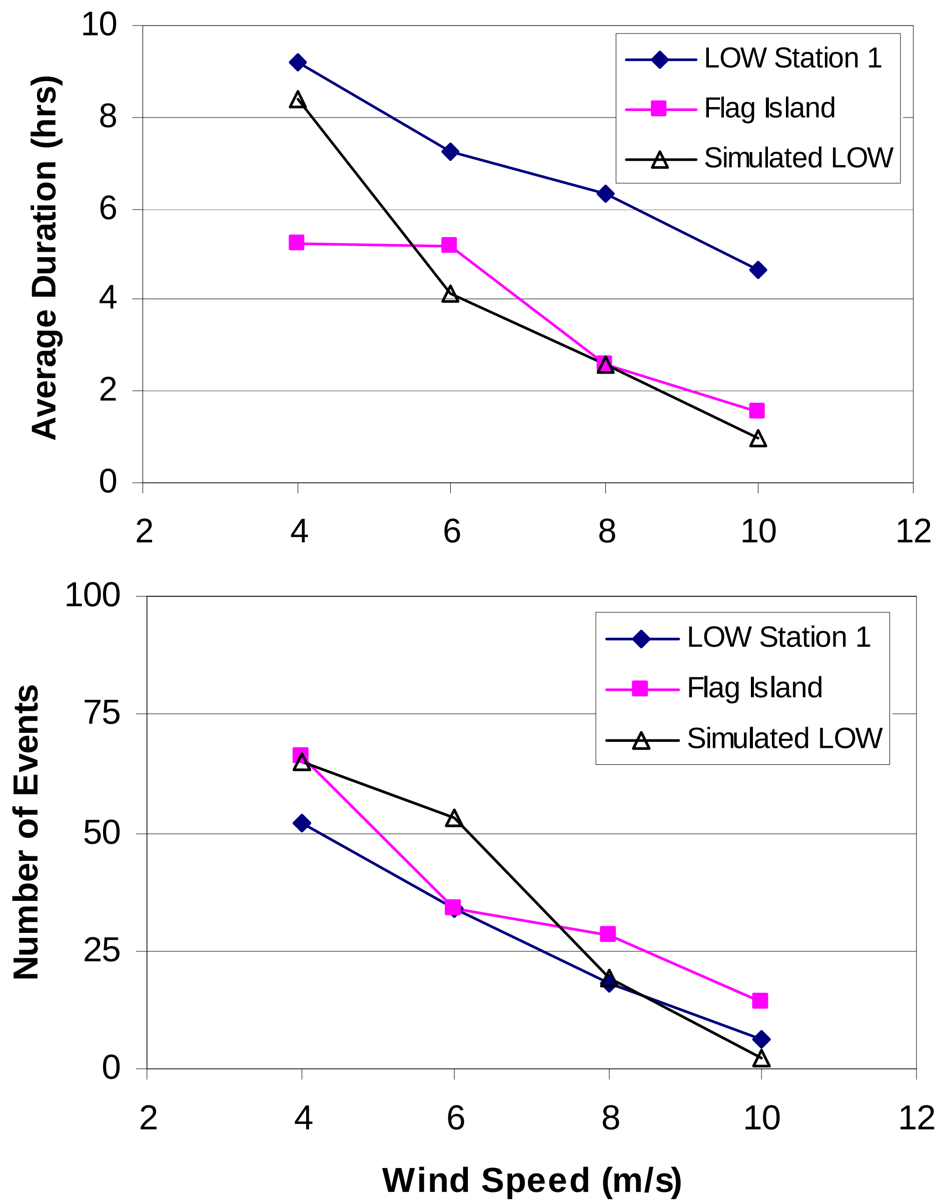
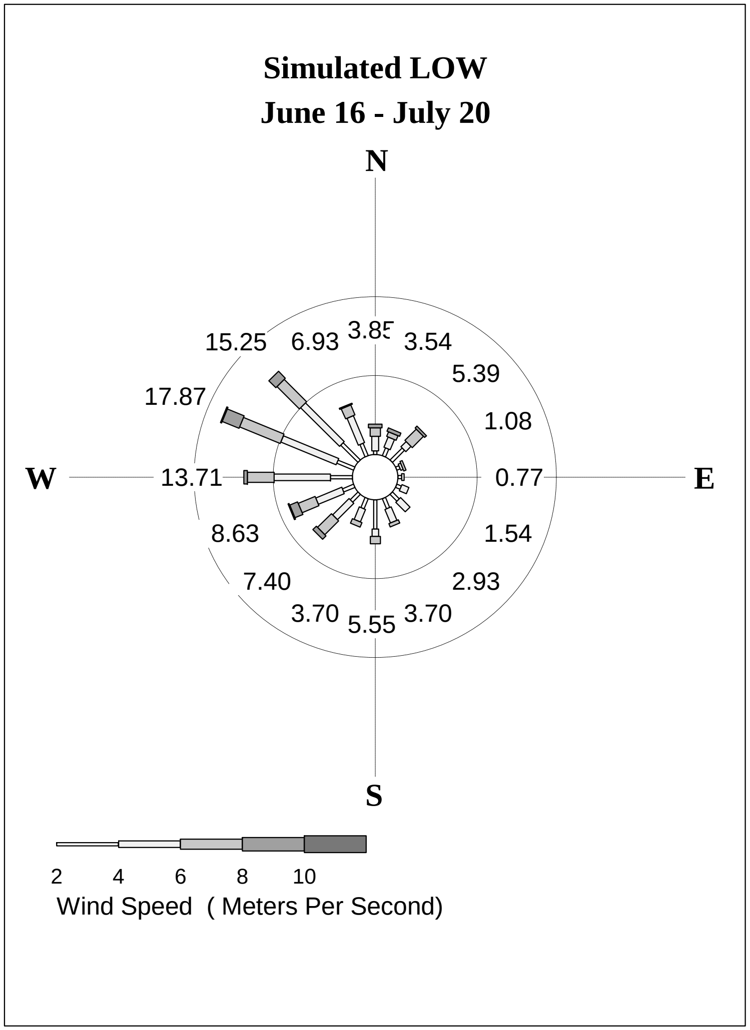


Figure 5.9. Average duration (upper panel) and number of events (upper panel) versus wind speed for LOW Station 1, simulated LOW, and Flag Island, June 16 to July 20, 2004.



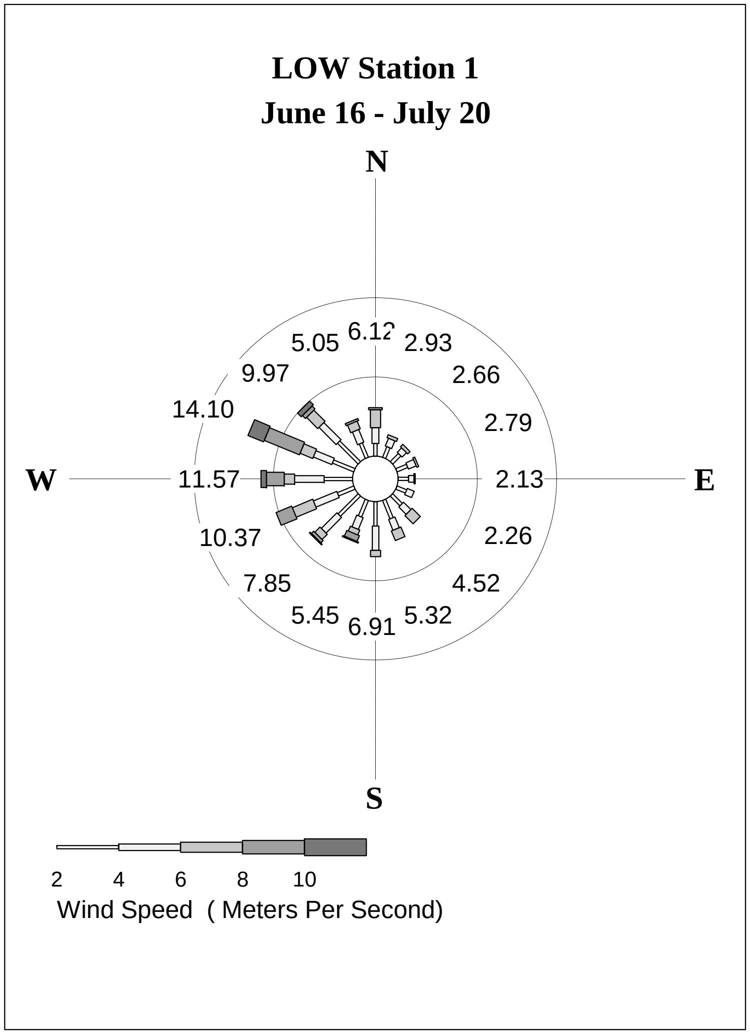


Figure 5.10. Wind rose plots for simulated LOW hourly wind record (Equation 5.1) and LOW station 1 (Pine Island) for June 16 to July 20, 2004.

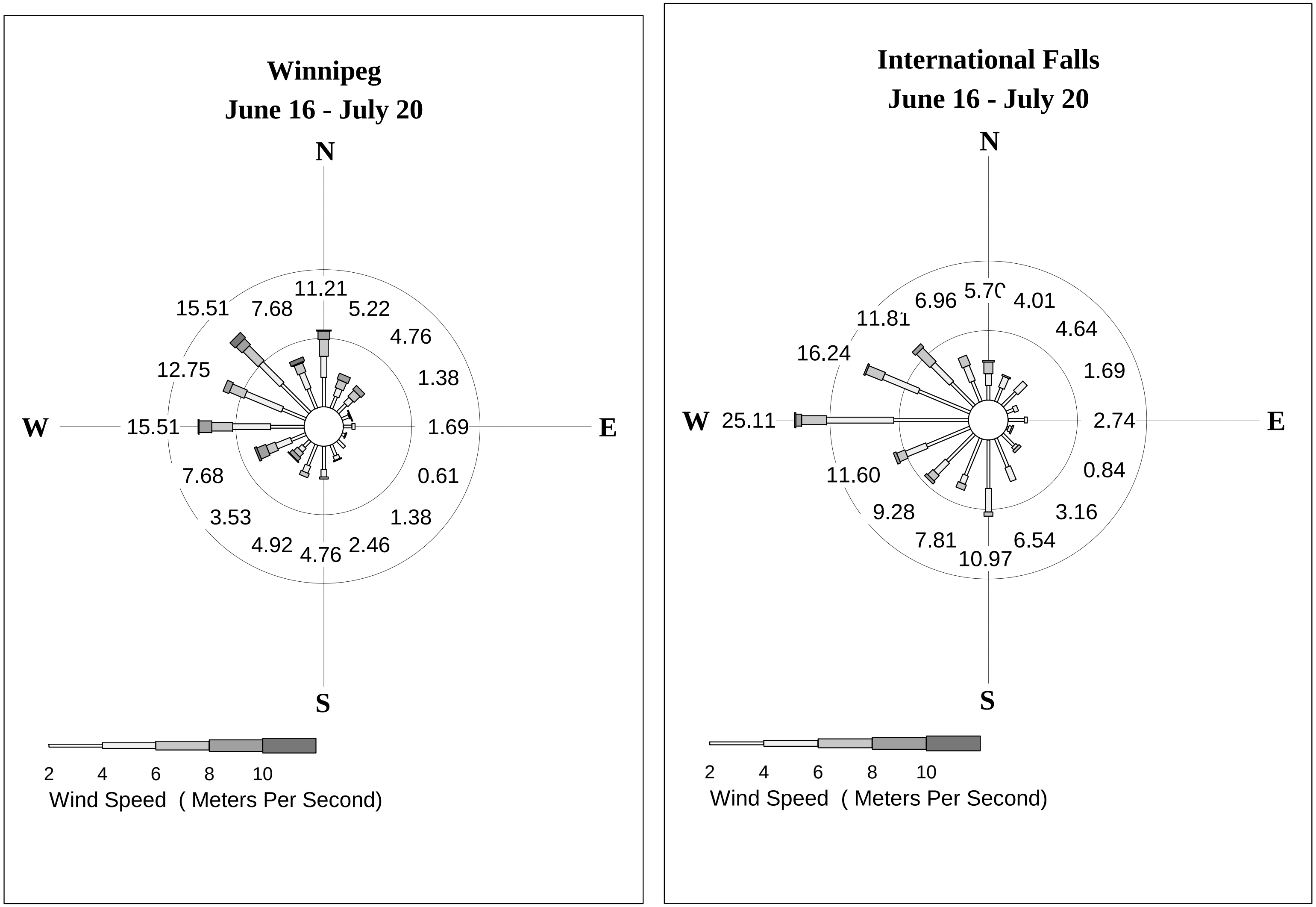


Figure 5.11. Wind rose plots for Winnipeg and International Falls wind records for June 16 to July 20, 2004.

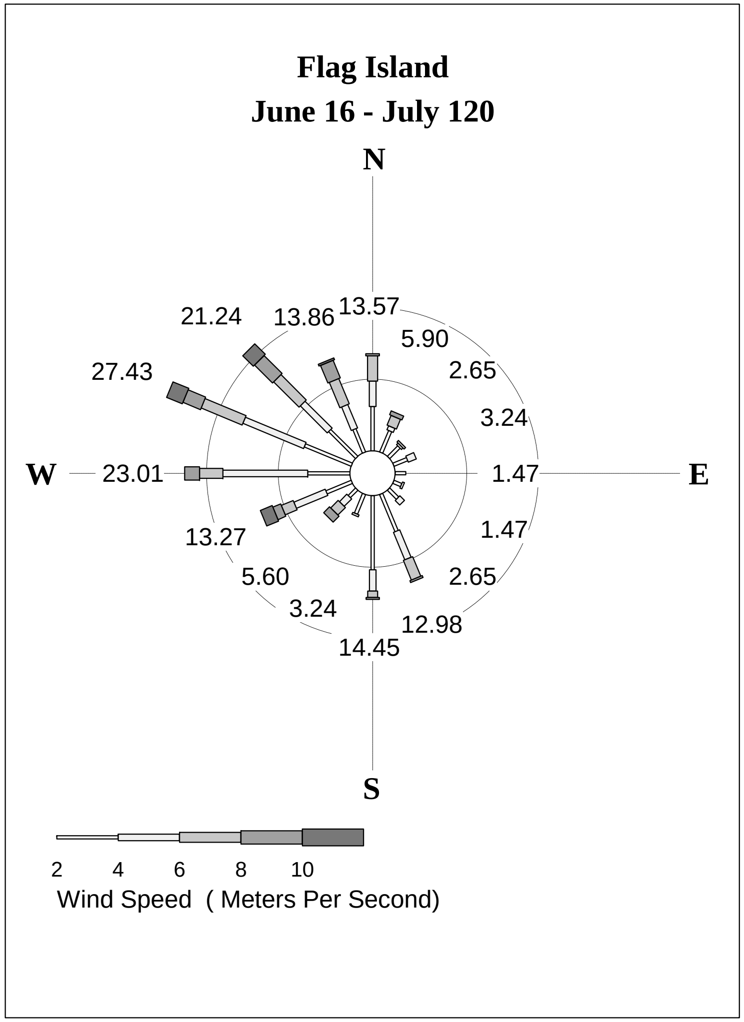


Figure 5.12. Wind rose plot for Flag Island wind records for June 16 to July 20, 2004.

VI. Long Term Trends of Wind over Big Traverse Bay

We extended the wind data analysis to examine if winds had changed over the last 50 years. The data set was constructed from Winnipeg and International Falls wind data for the period 1953 to 2003. For 37 of the 50 years (1956-1964, 1973-1977, 1979, 1982-2003), hourly data is available for both stations, so that the simulated LOW data was calculated at 1 hour time intervals. For the other years, only 3 hour data is available for International Falls, so that the simulated LOW data was calculated at 3 hour time intervals. A number of analyses were performed on the data set for time scales ranging from hourly to yearly, to identify trends in wind patterns on Lake of the Woods over the last 50 years.

Figures 6.1 to 6.3 give the 50 year history of weekly and monthly averaged wind velocity. The 50 year mean wind velocity is 6.06 m/s (13.5 mph), with a standard deviation of 1.2 m/s at a weekly time scale. The windiest week over the 50 year record is in September of 1966, with a weekly average wind of 11.1 m/s (24.8 mph). The simulated LOW data shows more variation prior to 1970 (Figure 6.1). Much of this deviation is from the International Falls wind record, which has a substantial deviations in the annual mean wind velocity from 1958 to 1965 (Figure 6.2). Figure 6.3 gives both the monthly averaged wind velocity and the average of the highest 10% of the wind velocities for each month. The standard deviation of the monthly averaged wind velocity is 0.77 m/s. The monthly averaged wind velocities show a clear seasonal trend (Figure 6.4), with higher average winds in spring and fall, and lower average winds in summer and winter.

Analysis was also performed to characterize individual high wind events at hourly and daily time scales. In all cases, the analysis was performed for May through October only. Figure 6.5 plots the highest hourly wind readings over the 50 year period of simulated LOW wind data, along with the directional quadrant. The highest wind velocity is 21.6 m/s (48.3 mph). Winds coming from the northwest quadrant (270-360º) account for 51% of the upper 1% of the hourly velocities and 35% of the upper 10% (Table 6.1). Figure 6.6 gives similar results for daily averaged wind velocities. Compared to the hourly readings, the highest 10% of daily averaged wind velocities are more evenly distributed over direction, except for the northeast quadrant, which has only 8% of the high wind values.

In the process of averaging hourly wind data from International Falls and Winnipeg, some peak wind events may be reduced in magnitude. The highest hourly wind readings from Winnipeg and International Falls, individually, are shown in Figures 6.7 and 6.8, which may be compared to Figure 6.5. The highest readings from the individual stations (21 to 25 m/s) are comparable to the highest readings from the simulated LOW data. The average of the highest 10% of all readings are 9.0 m/s, 6.6 m/s, and 7.1 m/s for Winnipeg, International Falls, and the simulated LOW data, respectively.

Figure 6.9 gives the distribution of the highest wind days over the 50 year period of record, with the highest year (1965) having 71 windy days, and the lowest year (1987) having 20 windy days. Figure 6.10 gives the seasonal distribution of the windy days. The spring and fall months have a greater number of windy days than the summer months.

Finally, an event duration analysis was performed on the Winnipeg, International Falls, and simulated LOW data sets. The analysis was performed on the 37 years of data with complete hourly data, for May through October. Figure 6.11 plots the average number of events per year and the average event duration versus the lower cutoff velocity. Event duration and the number of events per year both decrease with increasing cutoff velocity in a similar manner for the three data sets. Figure 6.12 gives the number of events per year in the 8, 10, and 12 m/s velocity categories for the 37 years of hourly simulated LOW data. The data appear to show a moderate decreasing trend with time in number of events per year, and little or no trend in event duration.

In summary, the synthetic wind record shows little evidence of major changes in wind characteristics at Lake of the Woods over the last 50 years. There is somewhat more variation in monthly mean wind speed prior to 1970, and less variation from 1970 to the present.

Table 6.1. Directional distribution (%) of the highest 1% and 10% of wind velocities, 1953-2003, for 1 hour and 1 day averaging.

Direction	**1 hour average**		**1 day average**	
	Upper 1%	Upper 10%	Upper 1%	Upper 10%
0-90^o	4.1	7.9	4.3	6.1
90-180^o	22.7	29.3	39.0	37.5
180-270^o	22.2	27.6	16.6	24.9
270-360^o	51.0	35.2	40.1	31.6

0-90^o: winds from the N-E quadrant
90-180^o: winds from the S-E quadrant
180-270^o: winds from the S-W quadrant
270-360^o: winds from the N-W quadrant

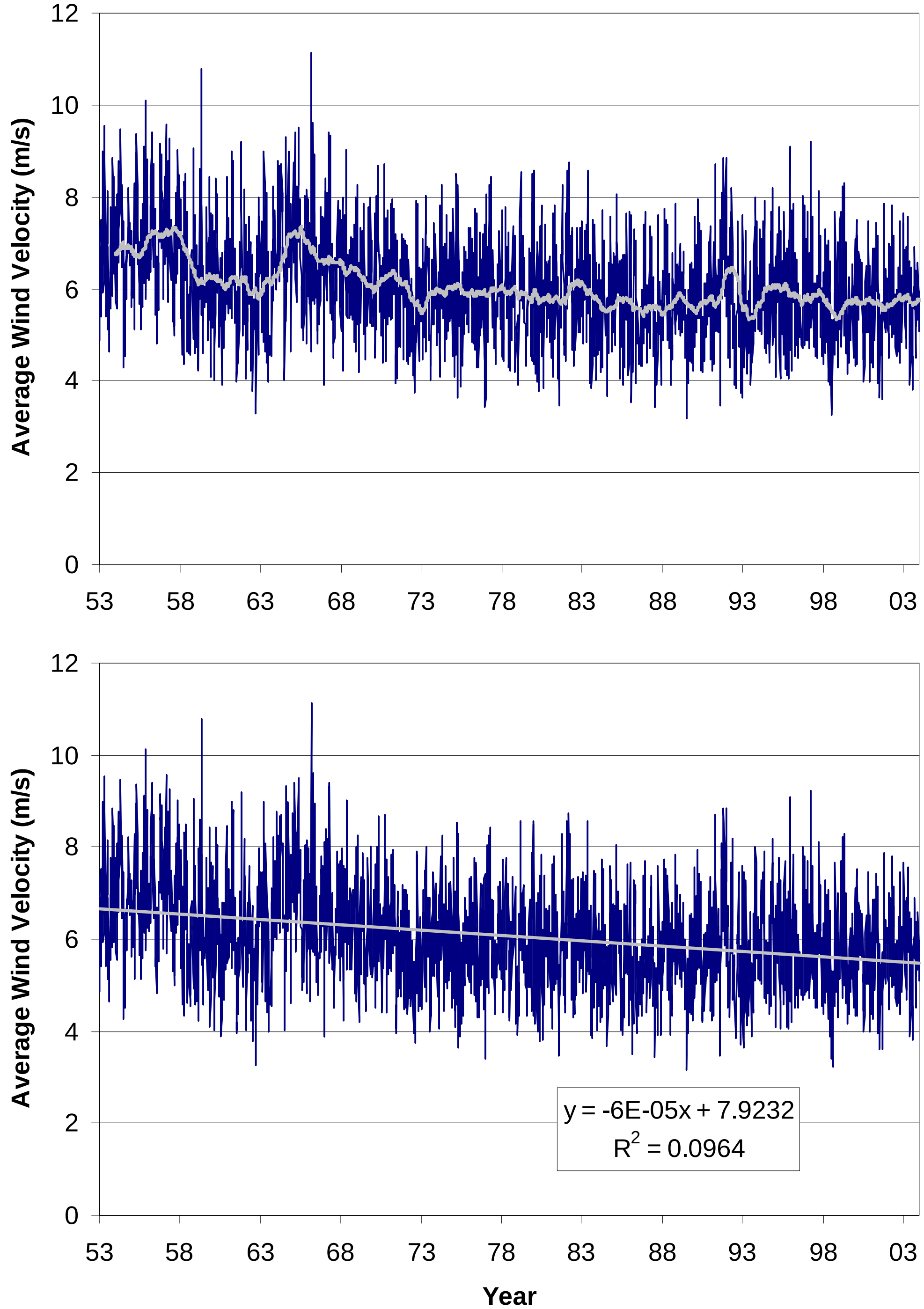


Figure 6.1. Weekly averaged wind velocity versus time for simulated LOW wind data, 1953 – 2003. The upper panel gives the weekly average data with a 52 week running average, while the lower panel gives a linear trend line. The overall mean is 6.06 m/s, with a standard deviation of 1.1 m/s.

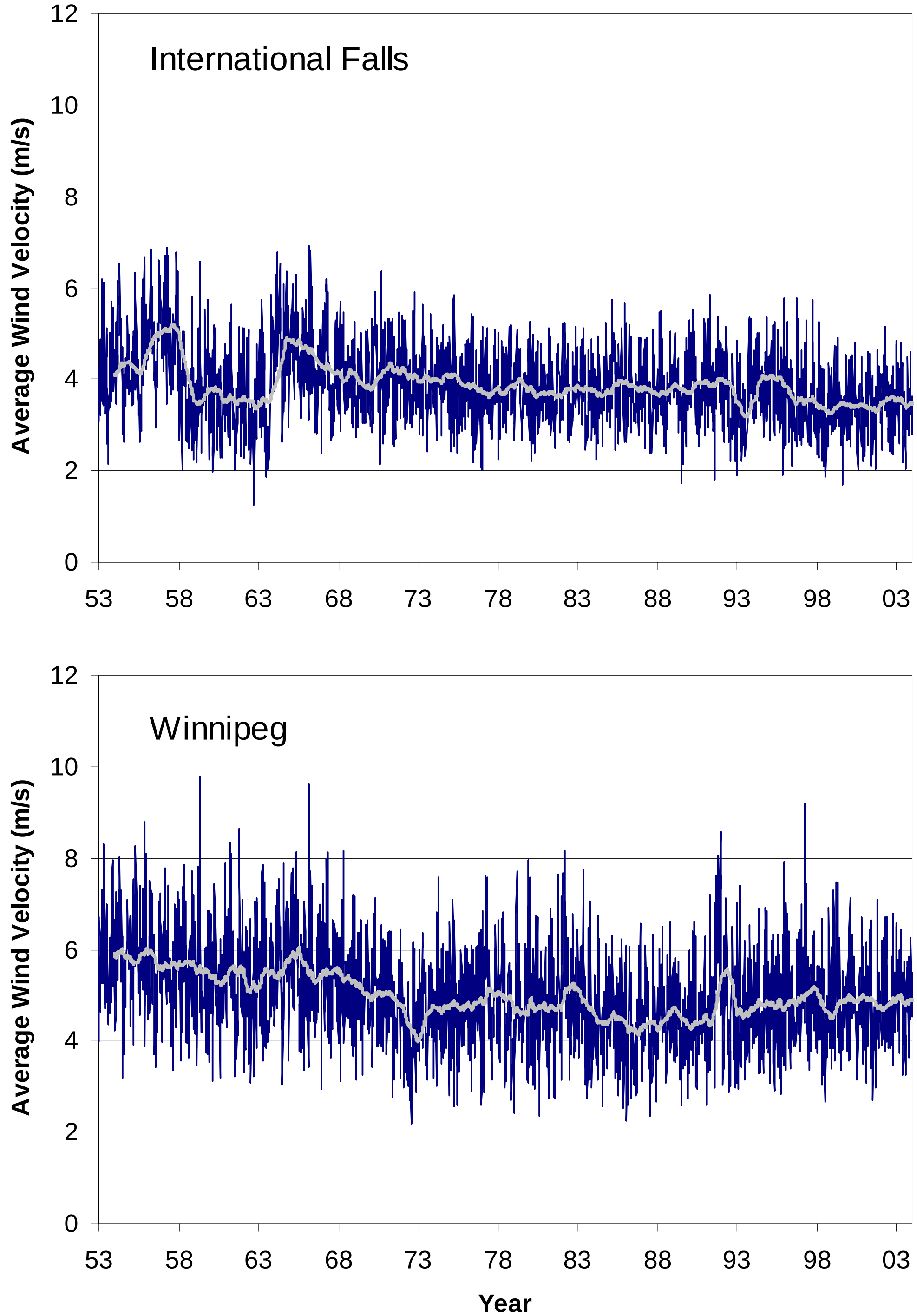


Figure 6.2. Weekly averaged wind velocity versus time for International Falls (upper panel) and Winnipeg (lower panel). The 52 week running average is shown for both locations.

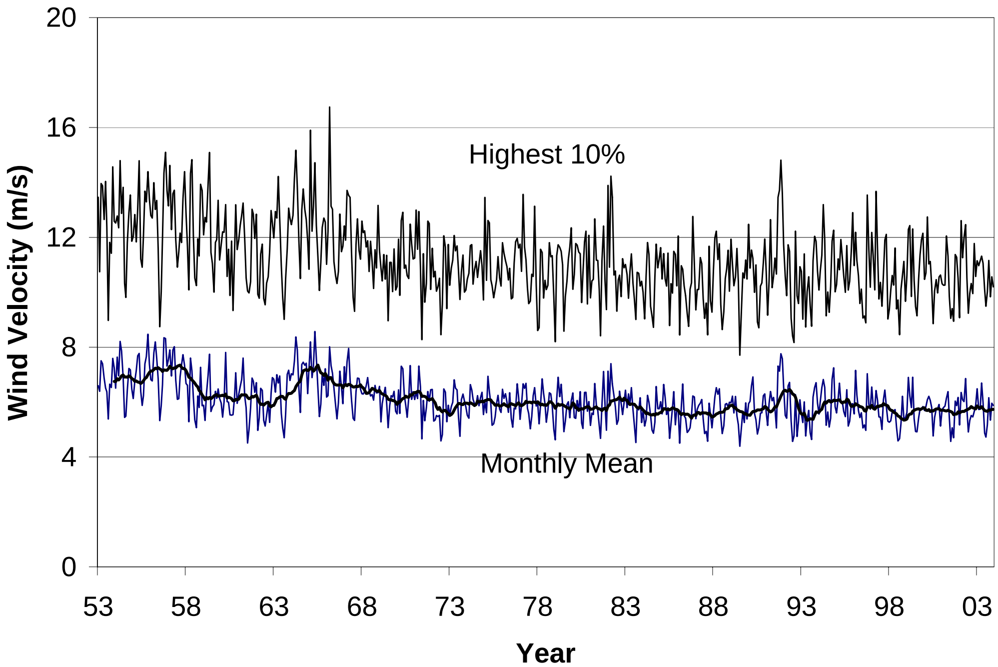


Figure 6.3. Monthly average and monthly average of highest 10% of wind velocity versus time for simulated LOW wind data, 1953 – 2003. The 12 month running average is also shown.

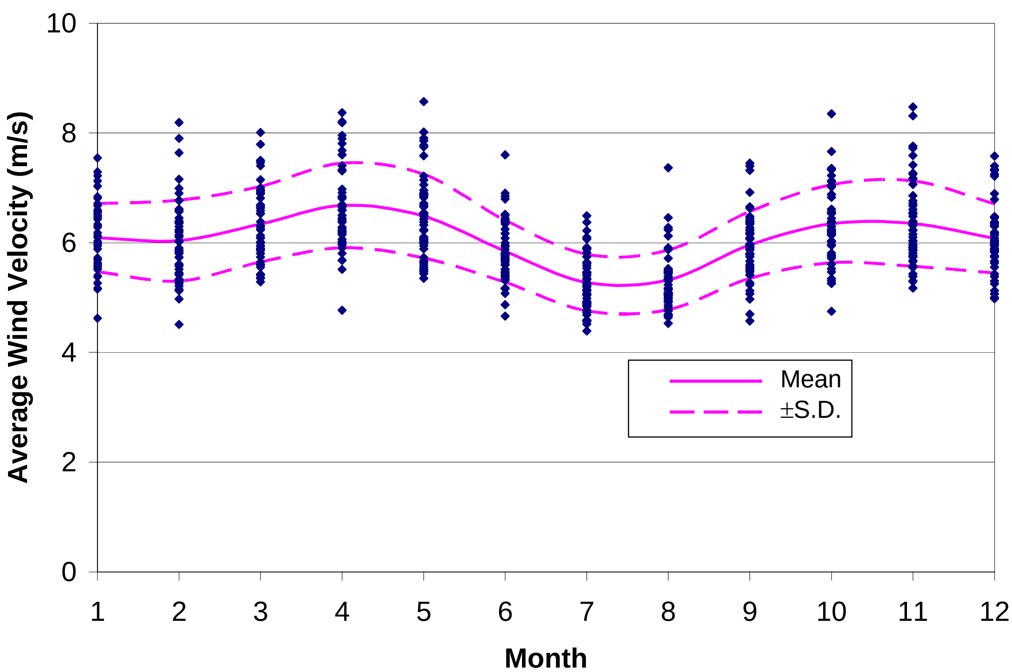


Figure 6.4. Monthly averaged wind velocity versus month for simulated LOW wind data, 1953 – 2003. Monthly mean values are plotted as a solid line with ± 1 STD as a dashed line.

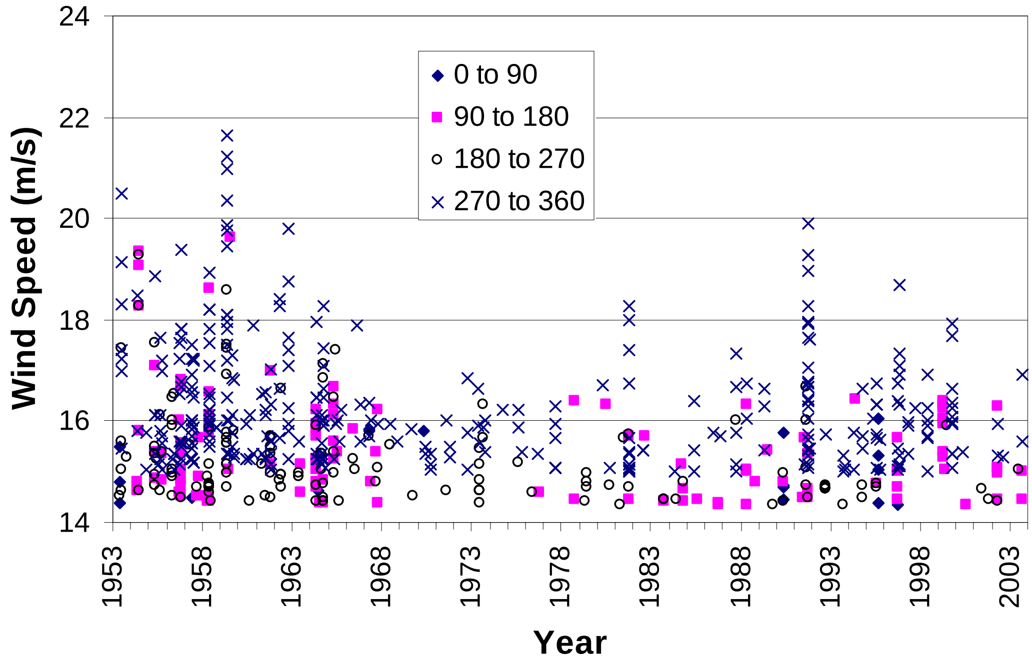


Figure 6.5. Highest hourly wind velocities versus time and direction for simulated LOW wind data, May – October, 1953 – 2003.

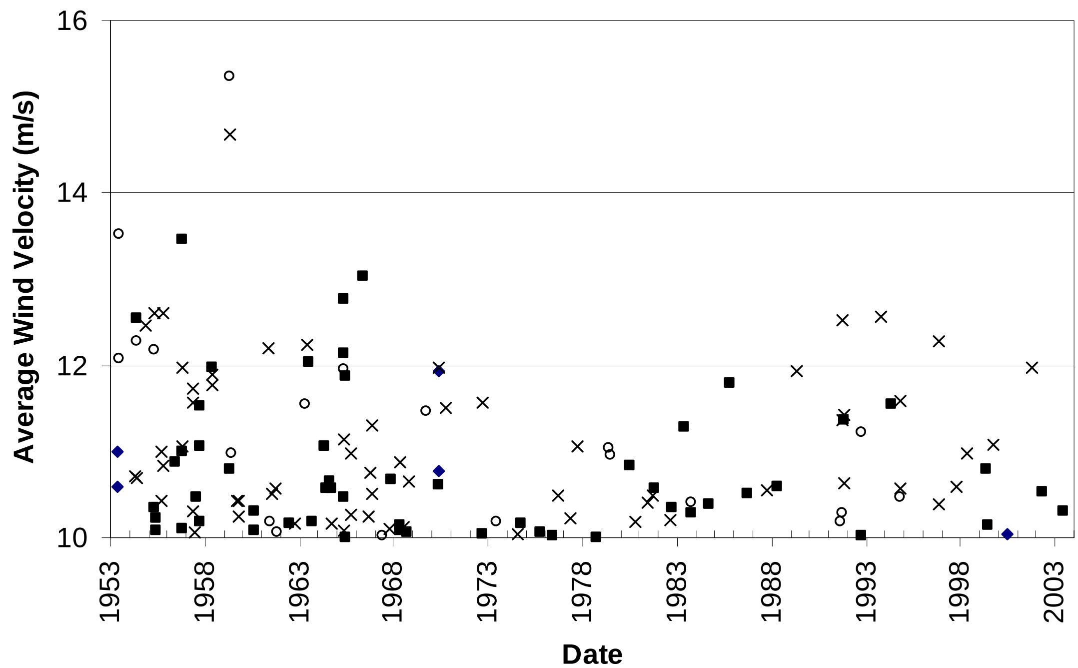


Figure 6.6. Daily averaged wind velocities exceeding 10 m/s versus time and direction for simulated LOW wind data, May – October, 1953 – 2003.

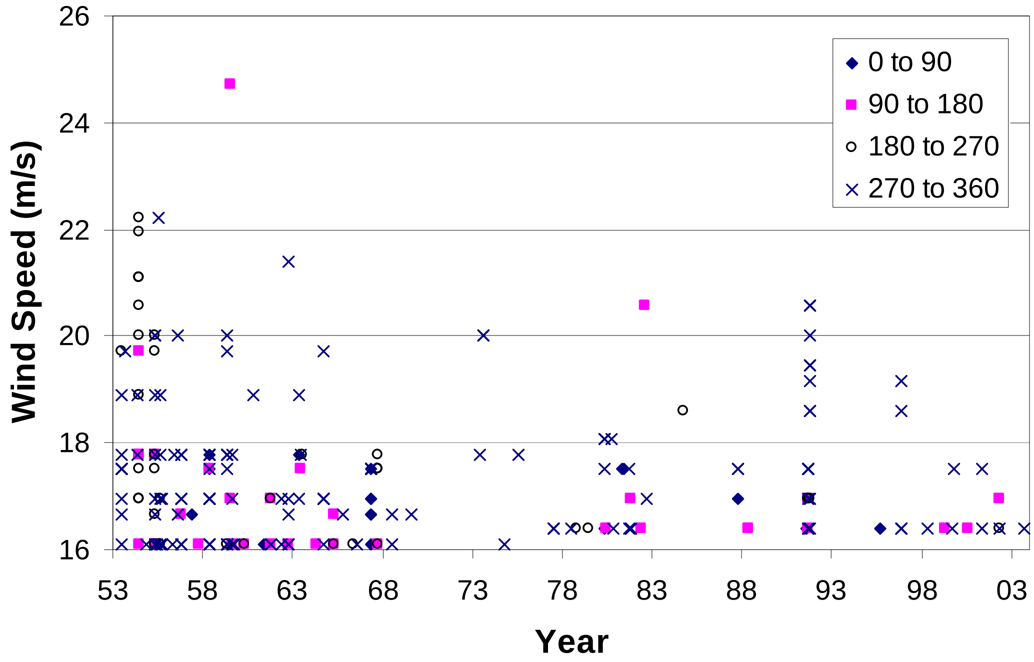


Figure 6.7. Highest hourly wind velocities versus time and direction for Winnipeg, May – October, 1953 – 2003.

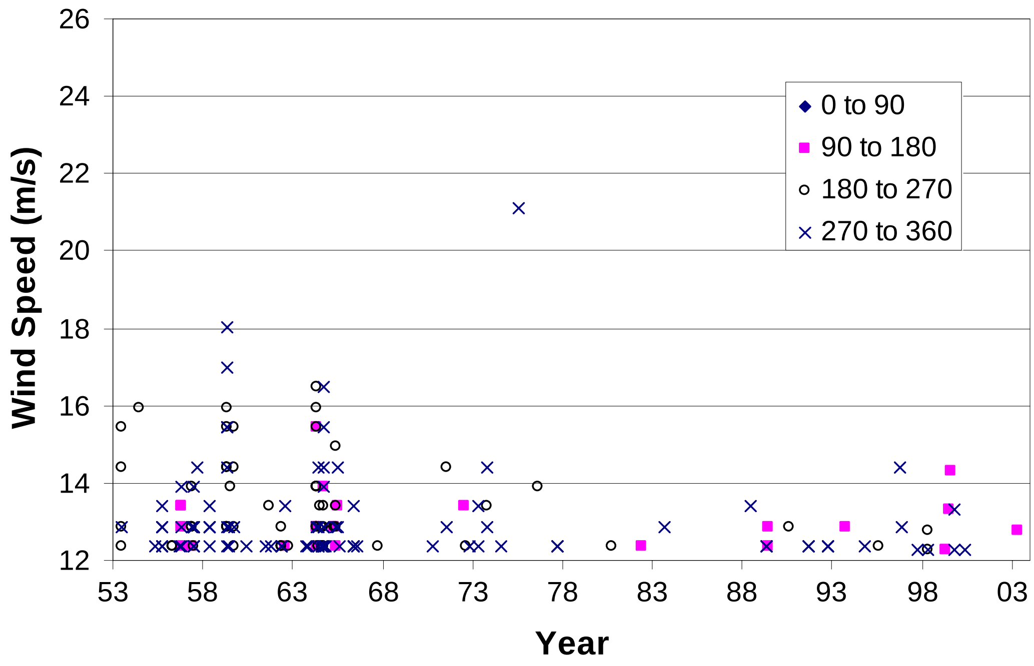


Figure 6.8. Highest hourly wind velocities versus time and direction for International Falls, May – October, 1953 – 2003.

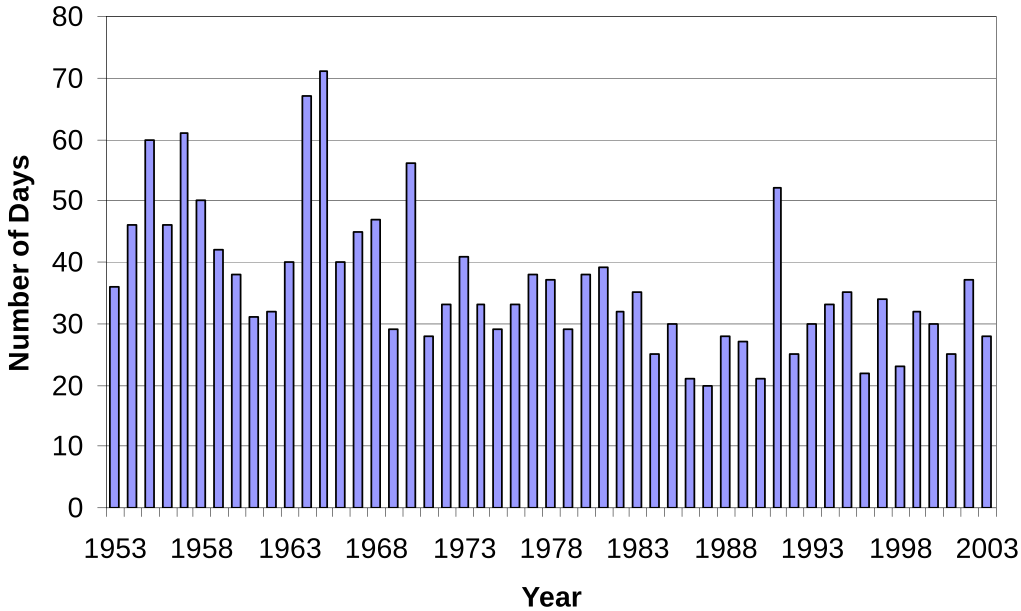


Figure 6.9. Number of days with averaged wind velocity exceeding 6.6 m/s (upper 10% of all daily averages) versus year for simulated LOW wind data, May – October, 1953 – 2003.

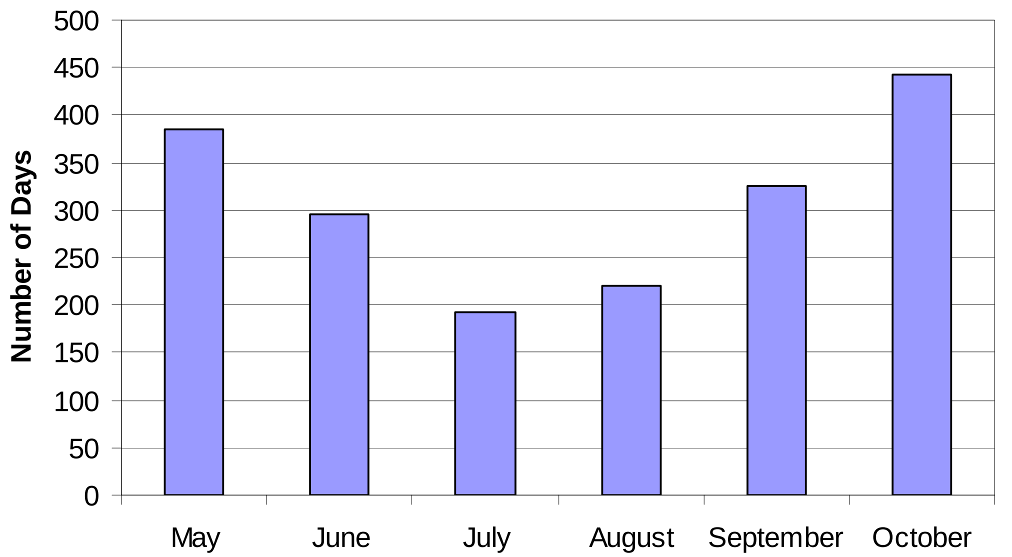


Figure 6.10. Number of days with averaged wind velocity exceeding 6.6 m/s (upper 10% of all daily averages) versus month for simulated LOW wind data, May – October, 1953 – 2003.

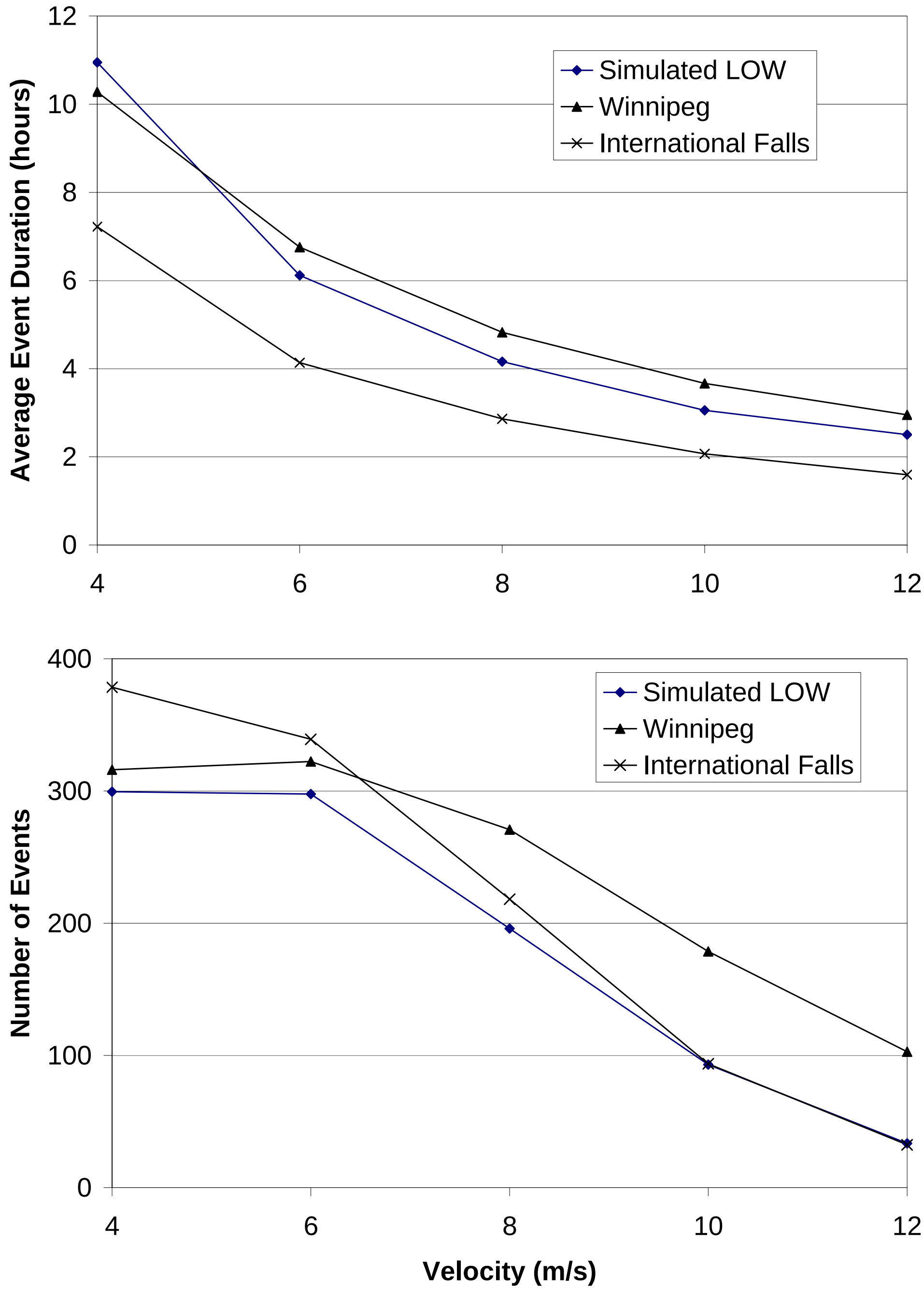


Figure 6.11. Average number of wind events per year and average event duration versus wind velocity for simulated LOW wind data, Winnipeg, and International Falls, 1956 – 2003. Event duration analysis was performed only on years with 1 hour data sets (37 years).

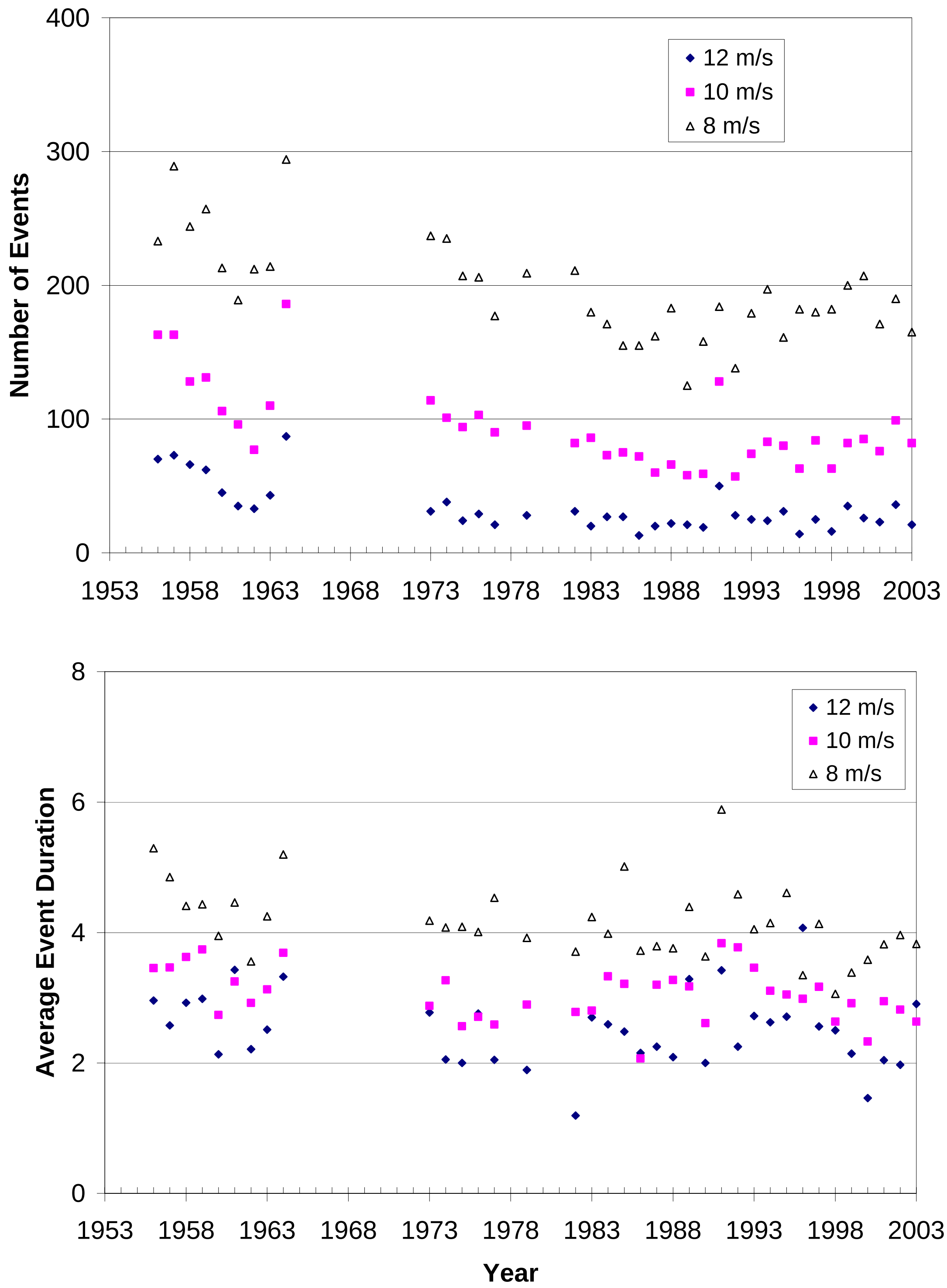


Figure 6.12. Number of wind events exceeding 8, 10, and 12 m/s per year (upper panel) and average event duration (lower panel) for simulated LOW wind data, 1953 – 2003. Event duration analysis was performed only on years with 1 hour data sets (37 years).

VII. Preliminary Analysis of Wind Setup

Wind setup, or storm surge, increases the effective water level on the windward shoreline of a lake. Because wind setup increases water level during periods of high wave energy, it needs to be considered in models of shoreline erosional processes. Analysis of wind setup also gives additional information on wind climate on a lake, if multiple water level measurements are available. Preliminary work was done to analyze wind setup to evaluate the accuracy of very simple wind setup models, and to help validate the simulated LOW wind data. Theoretical wind setup was calculated based on the Saville equation (Saville 1952), which estimates wind setup for a lake basin of uniform depth:

$$(7.1) \quad S = 3.2 \cdot 10^{-6} \frac{V^2 F}{g D}$$

where S is wind setup (m), V is wind velocity (m/s), F is fetch (m), g is the acceleration of gravity = 9.81 m/s^2, and D is average depth. Equation 7.1 was used to calculate wind setup between the Cyclone Island and Warroad level stations (fetch = 59 km), based on hourly values of the simulated LOW wind velocity and direction. The wind velocity component along the line between the two level gauging stations was calculated based on the simulated wind velocity and direction. Measured wind setup values were compiled by taking the difference of Cyclone Island and Warroad lake level readings. The variation of theoretical and measured setup values over time are given in Figure 7.1, for June 1 to July 1, 2000. Hourly theoretical and measured setup values are plotted against each other in Figure 7.2, using both simulated LOW and measured Flag Island wind data. The Flag Island wind data produces setup values in better agreement with measured setup, both in terms of slope and R^2. For both wind data sets, calculated setup tends to underpredict peak values of measured setup.

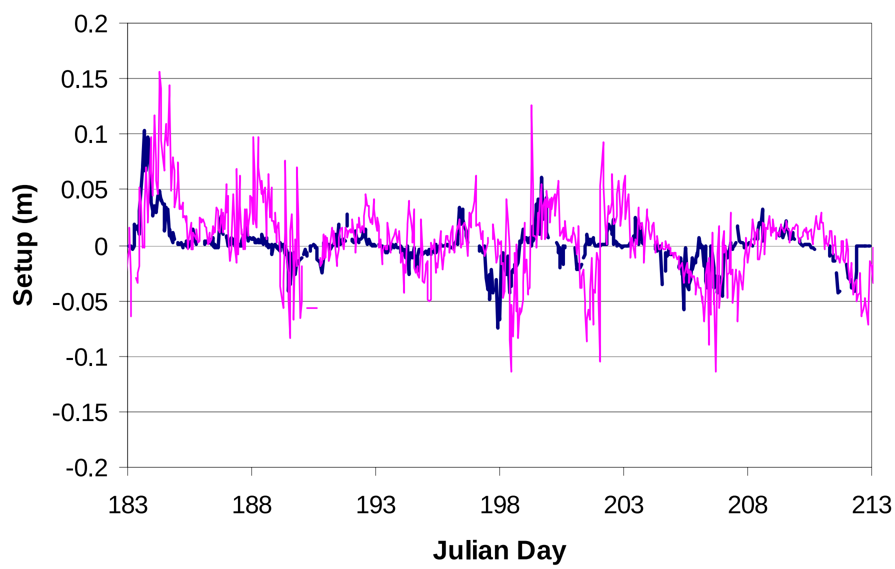


Figure 7.1. Theoretical (dark line) and measured (light line) wind setup vs. time for Warroad and Cyclone Island gages, 1 hour averaging time.

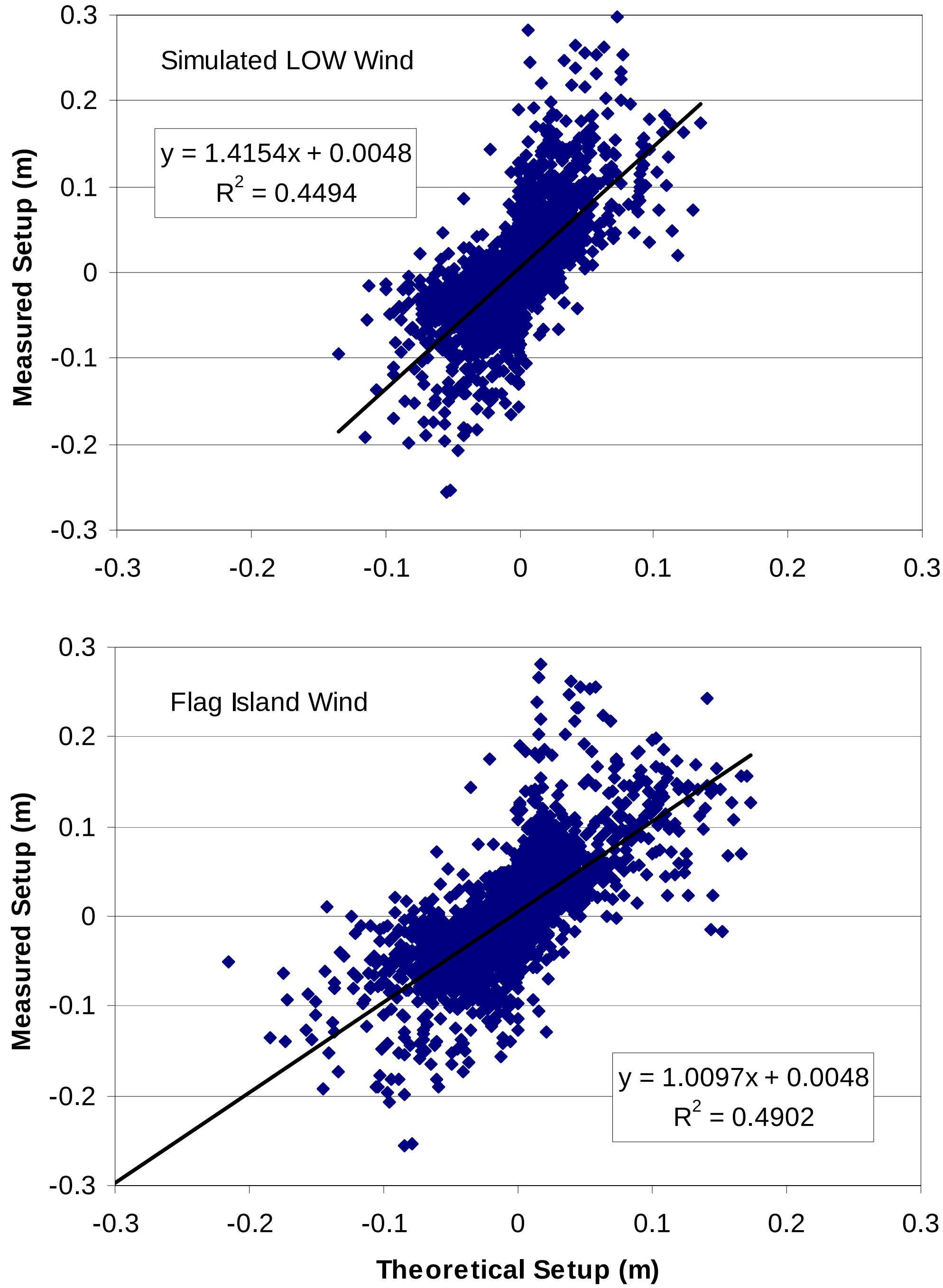


Figure 7.2. Calculated vs. measured wind setup for Warroad and Cyclone Island gages, 1 hour time scale, May 1 to November 1, 2000. Theoretical setup calculated using simulated LOW wind data (upper panel) and Flag Island wind data (lower panel).

VIII. Measurements of near-shore bathymetry and sediment size distribution

Lake sediment samples were taken from six locations in the study area. 500 ml samples were taken by hand by a SCUBA diver. Three samples were taken from shallow water (1.5 to 2 m depth) and three from deeper water (5 to 7 m depth). The three shallow water samples are predominantly sand, and were analyzed for grain size using mesh sieve techniques, with 13 mesh sizes ranging from 0.062 to 16 mm. The cumulative size distributions for the three shallow water samples are given in Figure 8.1. The three deep water samples are predominantly clay, and have not been analyzed. The sampling locations are shown in Figure 8.2.

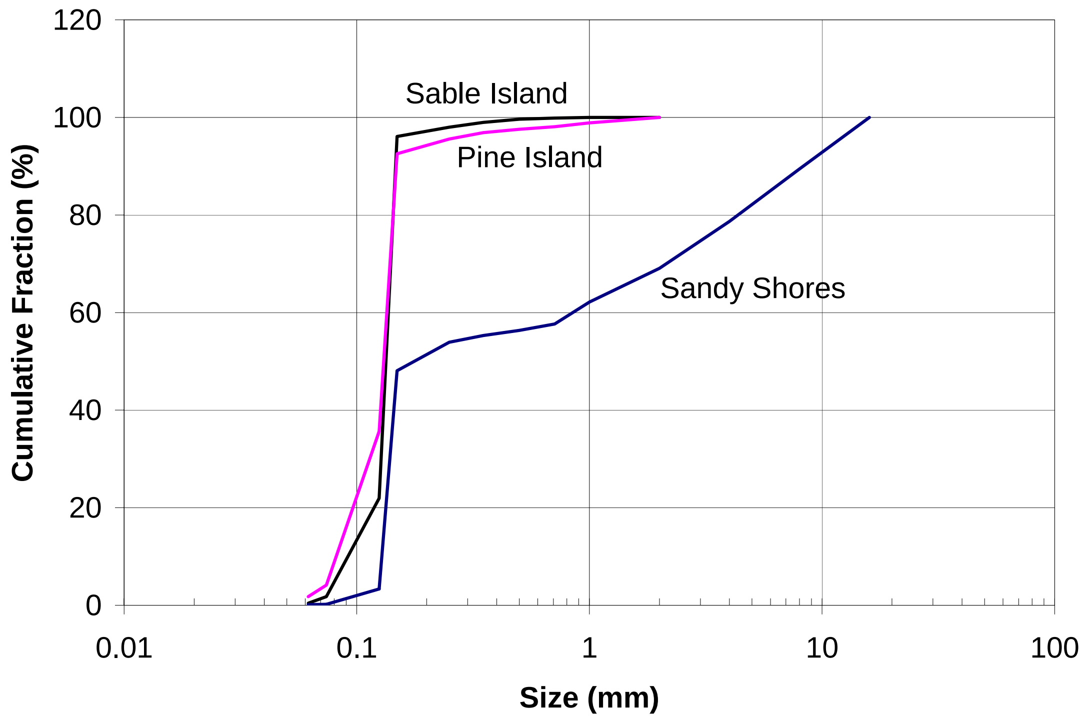


Figure 8.1. Cumulative sediment size distribution for sediment samples from 1.5 to 2 m depth at Sandy Shores, Pine Island, and Sable Island.

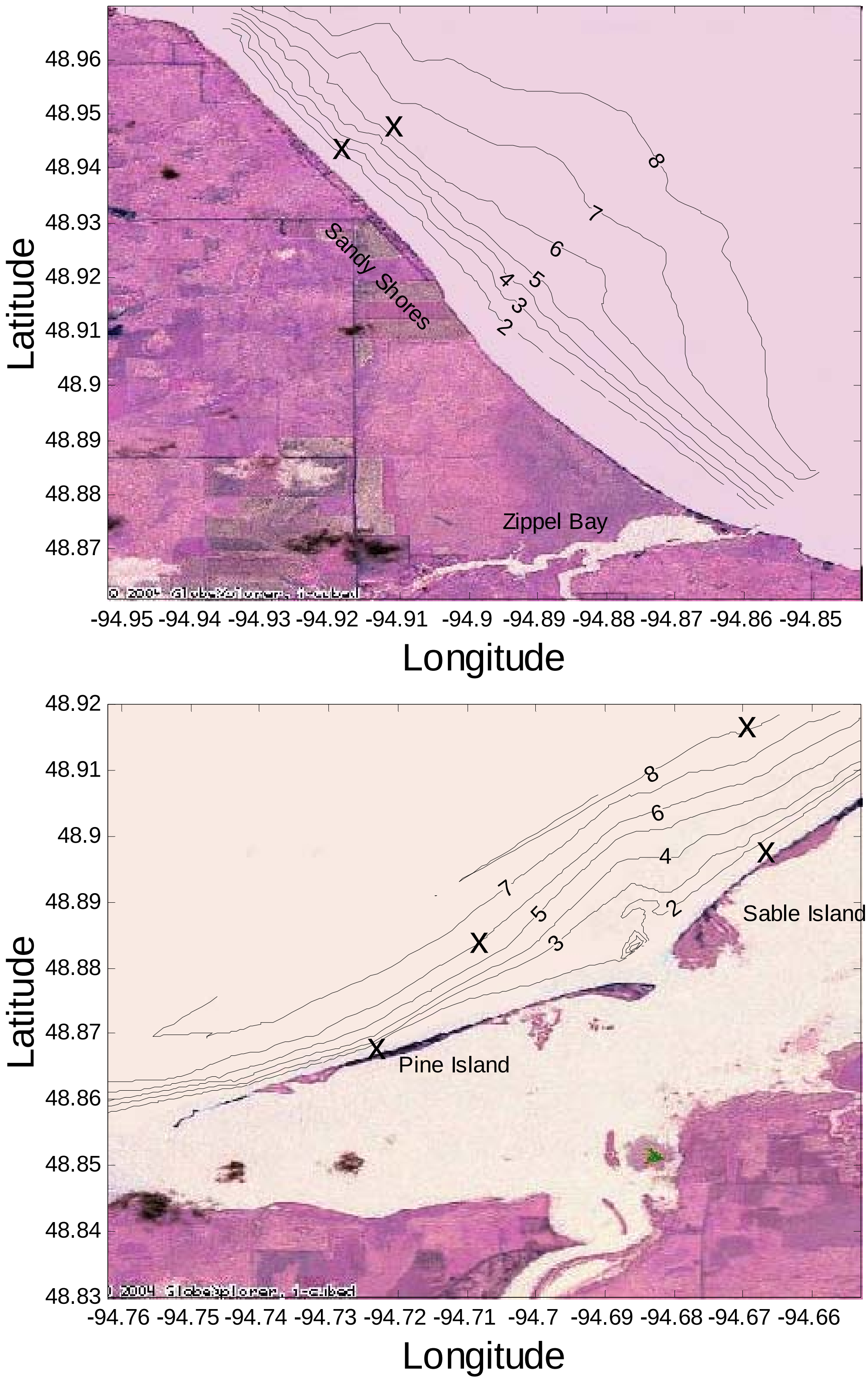


Figure 8.2. Depth contours (in meters) measured on September 1, 2004 for Long Point to Zippel Bay (upper panel) and Morris Point to Sable Island (lower panel). Sediment sampling locations are marked with an "X". Contour plots are overlaid on satellite images taken on 10/5/1999.

IX. Flow and sediment input from the Rainy River

Developing a sediment budget for Big Traverse Bay may be a component of Phase II of the study, because the sediment supply available for longshore transport determines the presence or absence of protective beaches. Preliminary work was done to determine the availability of flow and sediment load measurements for the Rainy River. USGS daily stream flow data have been obtained for the Manitou Rapids measurement station from 1928 to 2001 and for the Little Fork River at Little Fork, MN from 1910 to 2003. MPCA suspended sediment concentration measurements have been obtained for Rainy River at Baudette from 1960 to 1994 and 2002 to 2003 at 1 to 4 month intervals, and for the Little Fork River at Little Fork for 1975 to 1986 at 1 to 4 month intervals. The station locations are shown in Figure 9.1. National Weather Service Precipitation data was also obtained for 5 locations in the Rainy River watershed, as summarized in Table 9.1

Weekly average flow data are given in Figures 9.2 and 9.3 for the Rainy River at Manitou Rapids and the Little Fork River at Little Fork, MN. There is a small positive trend in flow over the period of record (70 years) for the Rainy River, and very little trend for the Little Fork River. 10 year running averages little variation over the period of record (Figure 9.3). Monthly precipitation data for three locations in the Rainy River watershed are given in Figure 9.4. As with the flow data, there is little or no long term trend evident in the precipitation data for the period of record (70 to 100 years).

Suspended sediment data from the Rainy River in Baudette and the Little Fork River at Little Fork is given in Figure 9.5. The trend lines shown appear to show a decrease in sediment concentration over time in both rivers. However, the suspended sediment data are rather sparse and are at irregular intervals. To fill in more data points, power law relationships between sediment concentration and flow rate were developed for the Rainy and Little Fork Rivers. The relationship between sediment concentration and flow was reasonable for the Little Fork River (R^2=0.54), but weak for the Rainy River (R^2=0.23), as shown in Figure 9.6. The relationship shown in Figure 9.6 was used to generate daily sediment concentration values for the Little Fork, based on the measured daily flow rate. The calculated sediment concentrations were then multiplied by flow rate to give daily sediment loading, and summed to give yearly sediment loading, as shown in Figure 9.7. The calculated sediment loading varies considerably from year to year, but has a moderate decreasing trend over the period of record (1975-1986). This decreasing trend in sediment load in the Little Fork River was also noted in a prior study of Minnesota streams (USGS 1985). The sediment loading data analysis was not performed for the Rainy River, because the relationship between sediment concentration and flow rate is weak.

Table 9.1 Summary of Precipitation Records obtained for stations in the Rainy River Watershed.

Location	Record Length (Resolution)	Records Obtained (Source)
International Falls, MN	1906 – 1926, 1939 – 2004 (monthly)	All (1)
Baudette, MN	1912-2004 (monthly)	All (1)
Big Falls, MN	1930 - 2004 (monthly)	All (1)
Indus, MN	1943 – 2000 (monthly)	All (1)
Warroad, MN	1913 – 2004 (monthly)	All (1)

Sources: (1) State of Minnesota Climatology Office (www.climate.umn.edu/doc/historical.htm)

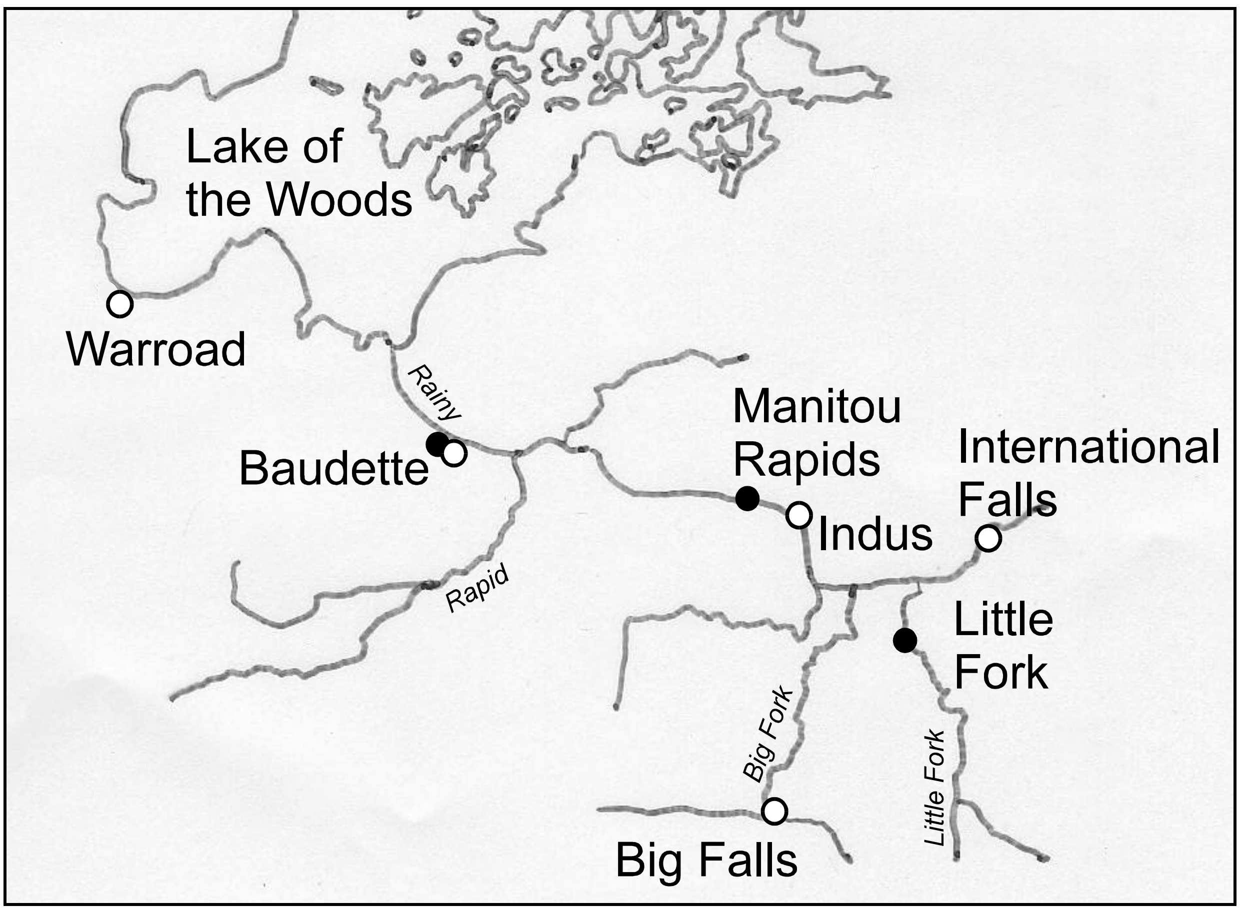
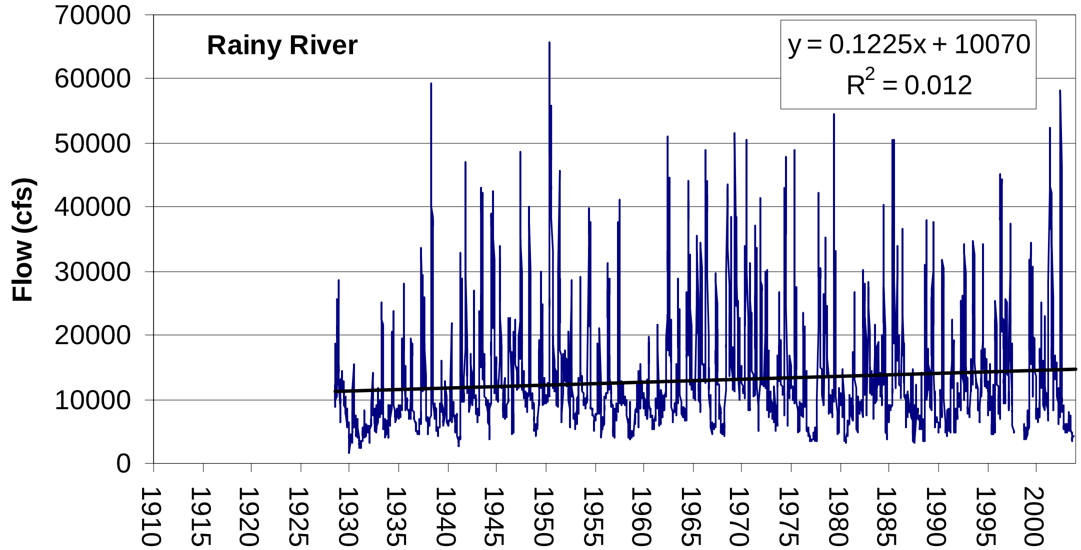


Figure 9.1. Steam gauging stations (solid circle) and precipitation measurement stations (open circle) in the Rainy River watershed.



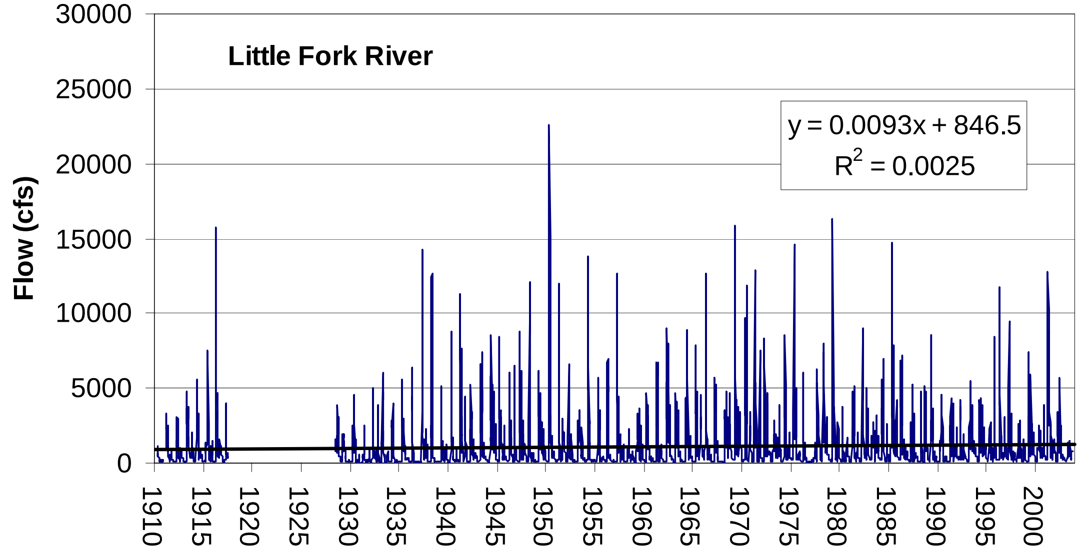


Figure 9.2. Weekly average flow rate for the Rainy River at Manitou Falls and the Little Fork River at Little Fork, MN, from USGS stream gaging stations.

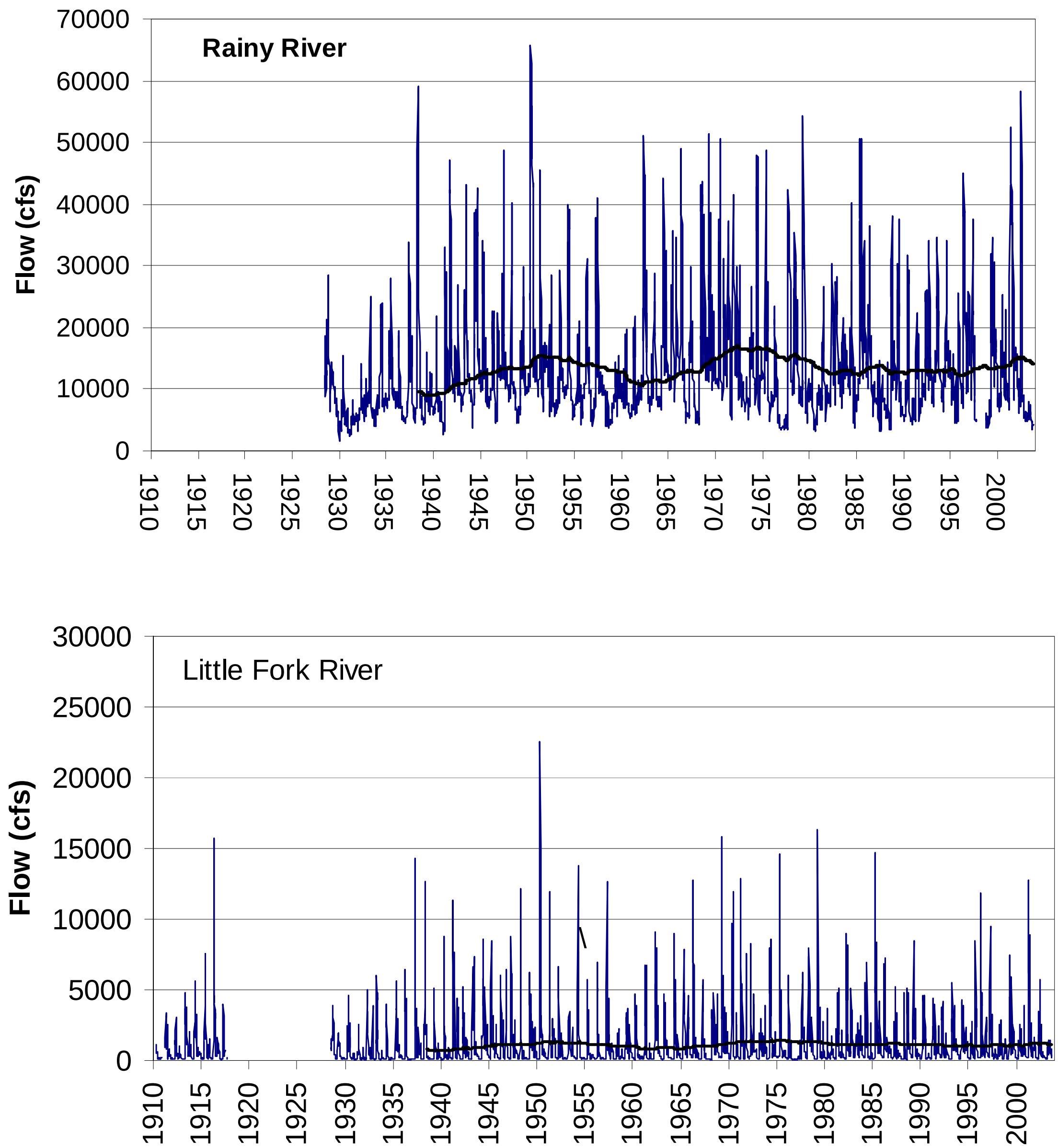


Figure 9.3. Weekly average flow rate and 10 year running average for the Rainy River at Manitou Falls and the Little Fork River at Little Fork, MN, from USGS stream gaging stations.

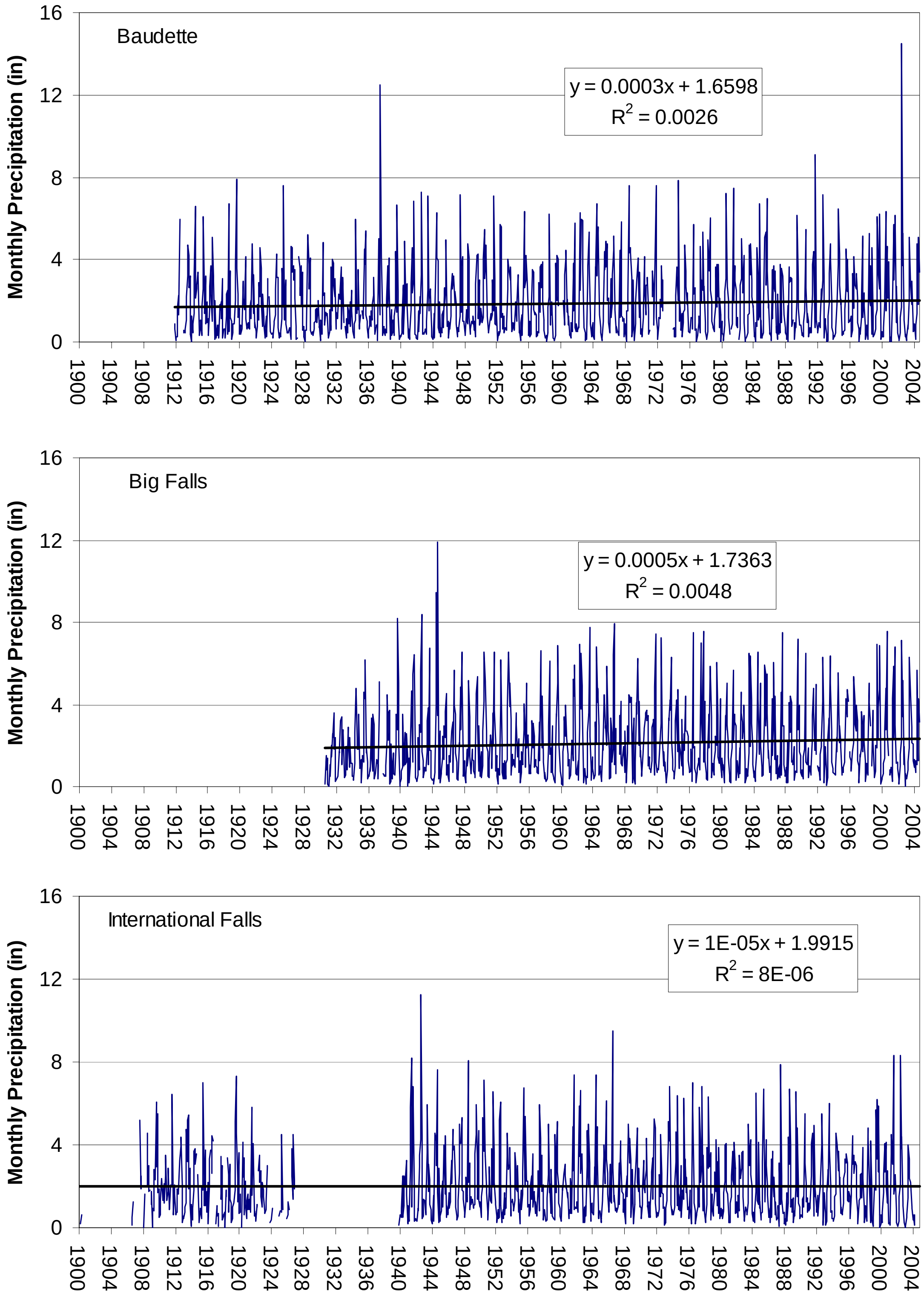


Figure 9.4. Monthly precipitation data records for Baudette, Big Falls, and International Falls for 1900 to 2004.

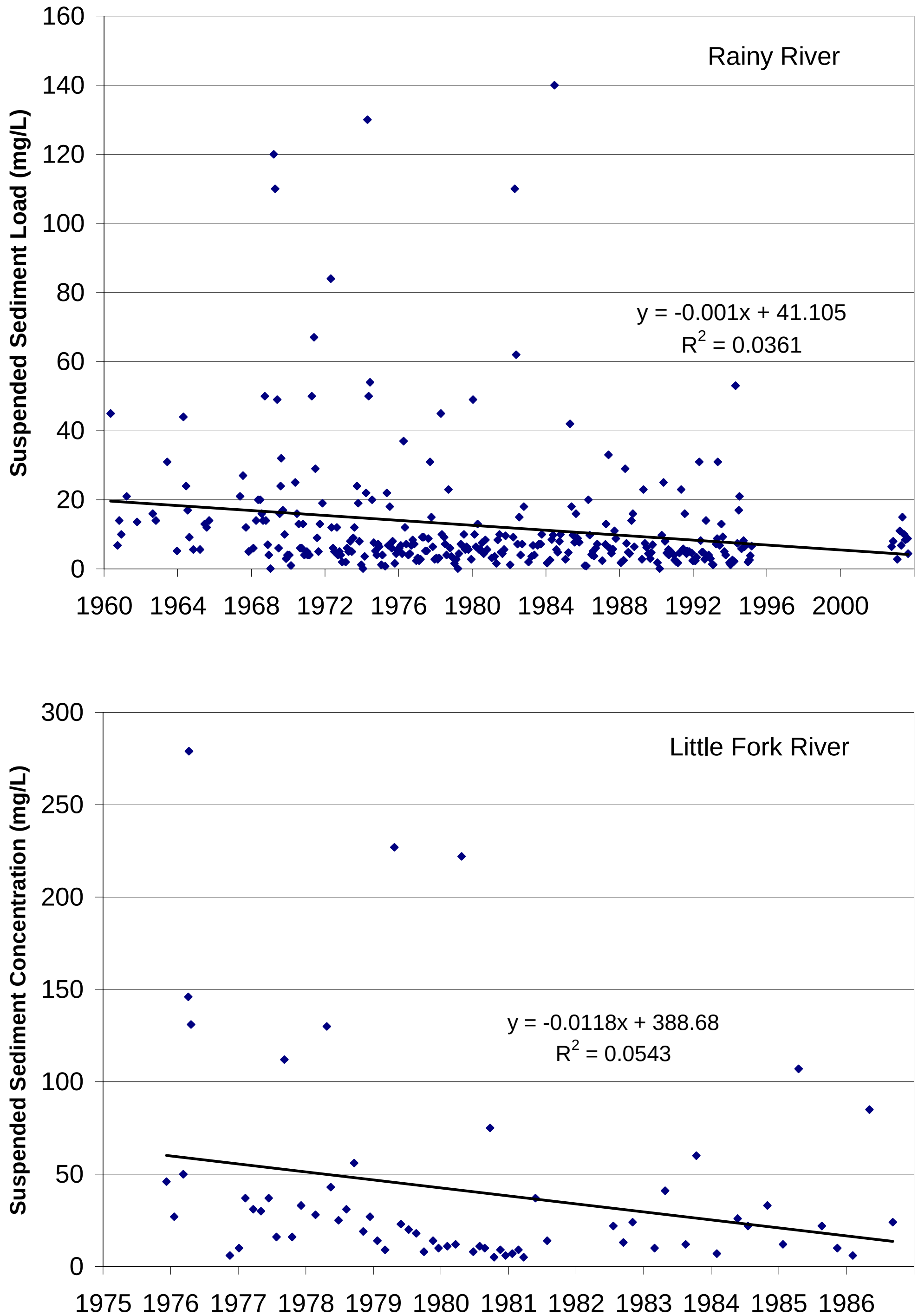


Figure 9.5. Suspended sediment concentration vs. time for the Rainy River at Baudette (upper panel) and Little Fork River at Little Fork, MN.

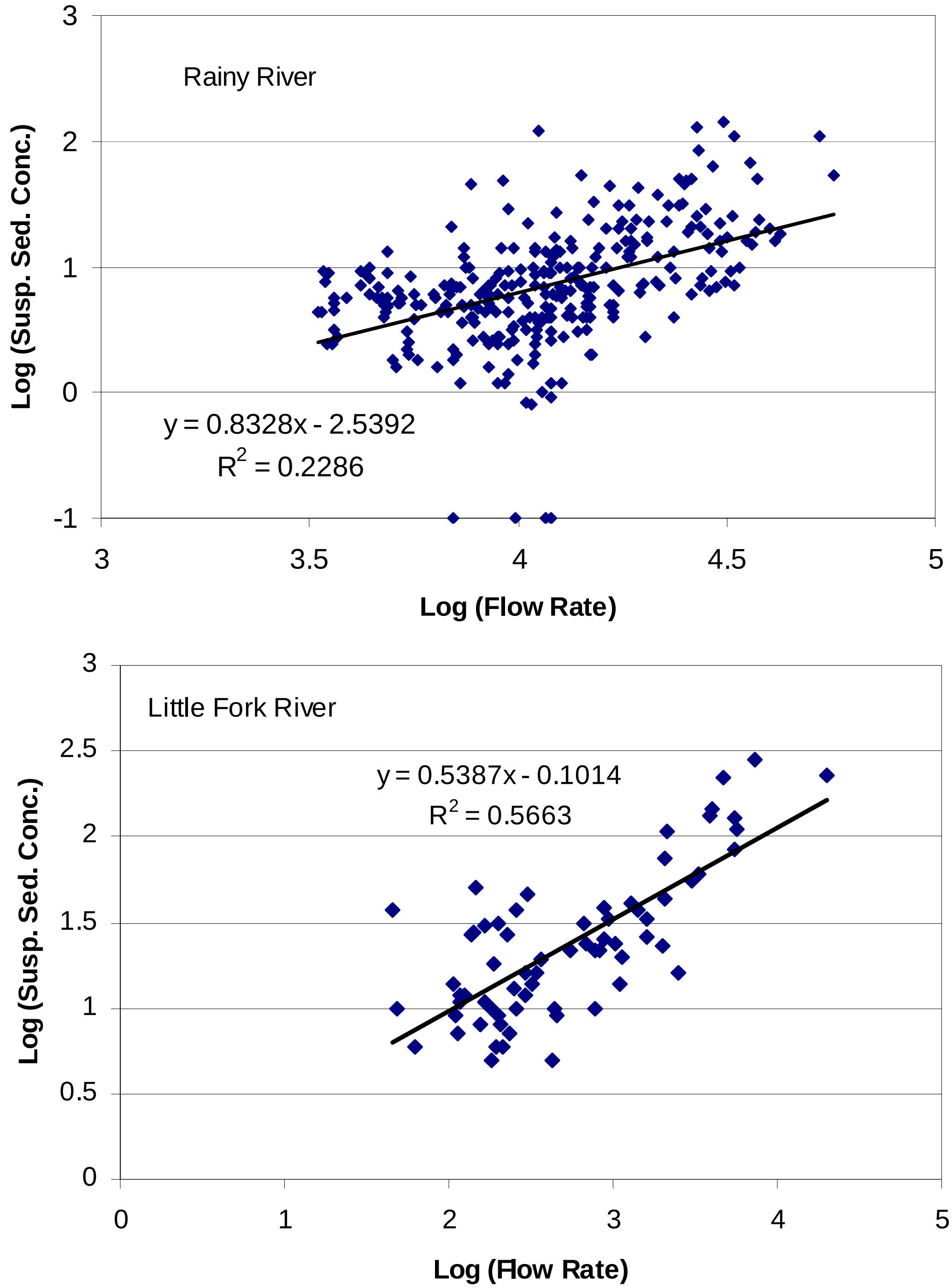


Figure 9.6. Suspended sediment load vs. flow rate for the Rainy River (upper panel) and Little Fork River at Little Fork, MN (lower panel).

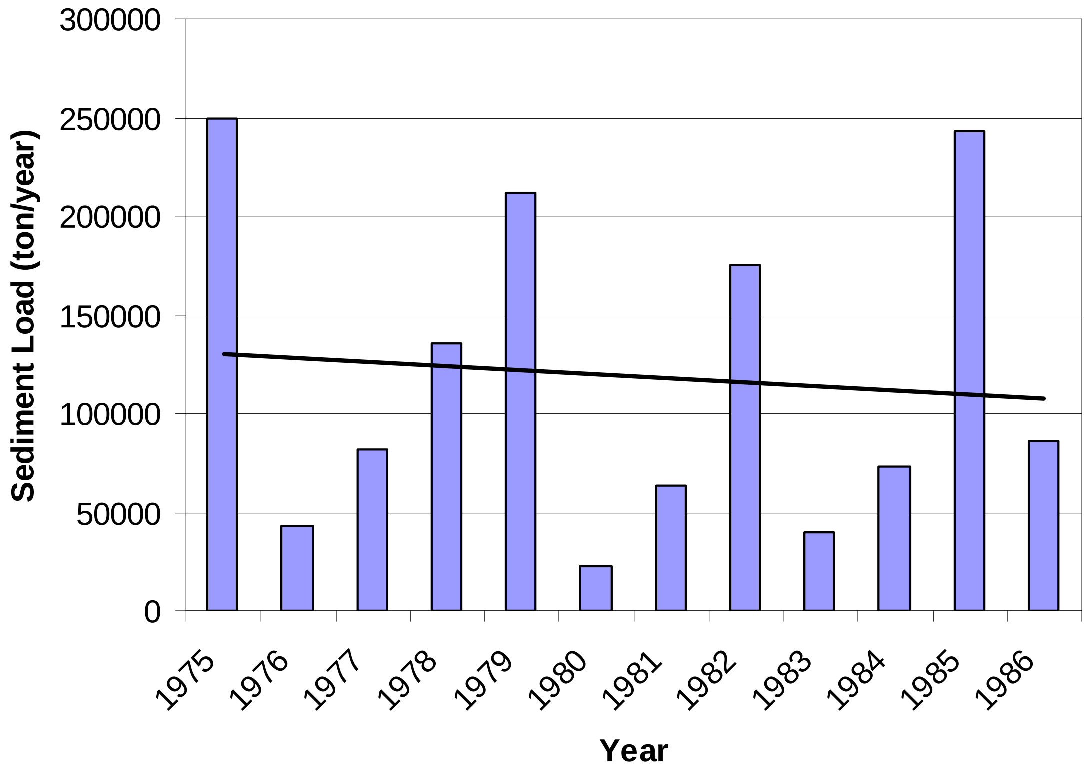


Figure 9.7. Sediment load (ton/year) vs. year for the Little Fork River at Little Fork, MN.

X. Summary and Conclusions

- Lake level data have been collected for Lake of the Woods back to 1913. Over this period of time, there is no indication of a systematic increase in average lake level. Recent high water events in, for example, 2002, do not stand out as being exceptional events when compared to other events in the long term record. Standard deviations of lake level from year to year are on the order of 0.5 m.

- Lake level, on average, is highest in July and lowest in March/April, with an average difference of 0.5 m.

- Higher resolution (1 hour) lake level and wind data have been collected to examine wind setup of the water surface on Lake of the Woods, and to calibrate a simple wind setup models for future application (Phase II).

- Wind data have been collected from seven local and two regional measurement stations. Of the local stations, Flag Island appears to best represent wind velocity and direction on the southern side of Big Traverse Bay. However, local wind stations have insufficient record lengths for historical characterization.

- A composite of wind measurements from Winnipeg and International Falls is reasonably well correlated to wind measurements on Big Traverse Bay, giving the possibility to construct a long term (50 year) historical record.

- Examination of the simulated long term wind record for Big Traverse Bay over a 50 year record does not show any dramatic long term trends. On average, spring and fall are moderately windier (wind speeds are 5.5 to 7.5 m/s), compared to winter and summer (wind speeds are 4.5 to 6.7 m/s).

- Wind and wave data have been collected for two locations on the southern side of Big Traverse Bay. Preliminary analysis shows that wave height varies with wind velocity and fetch in the expected manner, and that local wave height is well correlated to the local wind velocity. The largest waves are produced by winds coming out of the northwest, the direction of maximum fetch for the Pine Island area.

- The suspended sediment data collected for the Rainy and Little Fork Rivers show a decreasing trend in suspended sediment concentration over the last 40 years, with relatively constant flow volume. This may indicate a reduction in the sediment supply to Lake of the Woods.

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Appendix I. Photographs of Lake of the Woods shore

Figure A1.1. Photographs of the lake shore near Morris Point, 6/16/2004, showing sections protected with riprap (upper photo) and unprotected (lower photo).

Figure A1.2. Photographs of Sable Island, 6/16/2004. The upper photo shows a breakthrough during the period of relatively high water.

Figure A1.3. Photographs of the lake shore at Sandy Shores, 6/16/2004, showing a small area of erosion (upper photo) and a protected stretch of shoreline in front of a home (lower photo).

Appendix II. Satellite Images

Four satellite images of Lake of the Woods have been obtained. 3 Landsat7 satellite images have been procured at no cost for the dates 7/16/2000, 9/16/2000, and 10/7/2001 from Natural Resources Canada (geogratis.cgdi.gc.ca). 1 ASTER satellite image has been obtained at no cost from the USGS (edcdaac.usgs.gov/datapool/datatypes.asp) for 5/19/2002. All images have 15 to 30 m resolution. These images will provide additional shoreline information, to augment the aerial photographs discussed in Section II.1. A low resolution version of one of the four satellite images are given below.

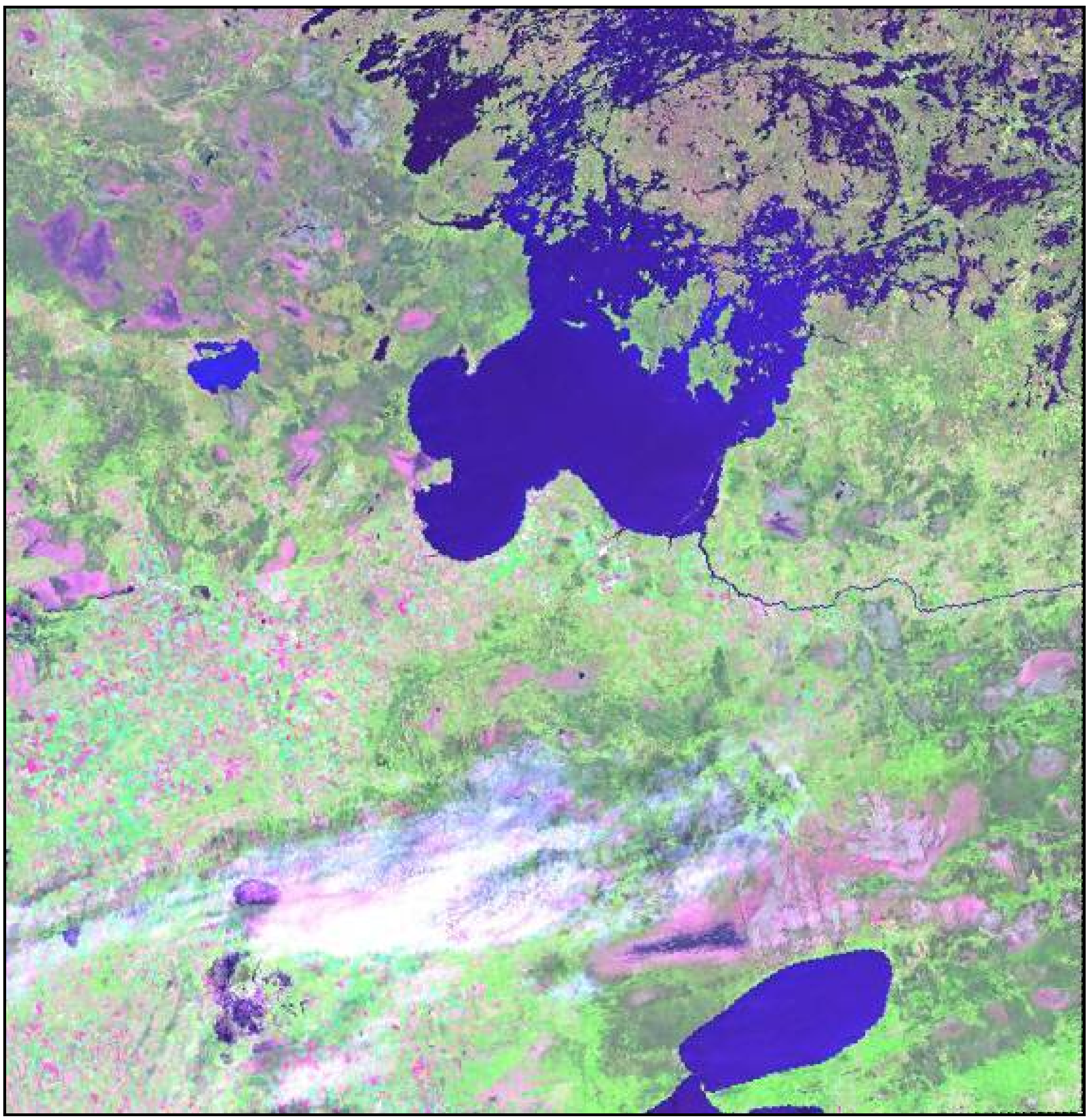

Figure A.2.1. Landsat7 image for 7/16/2000.