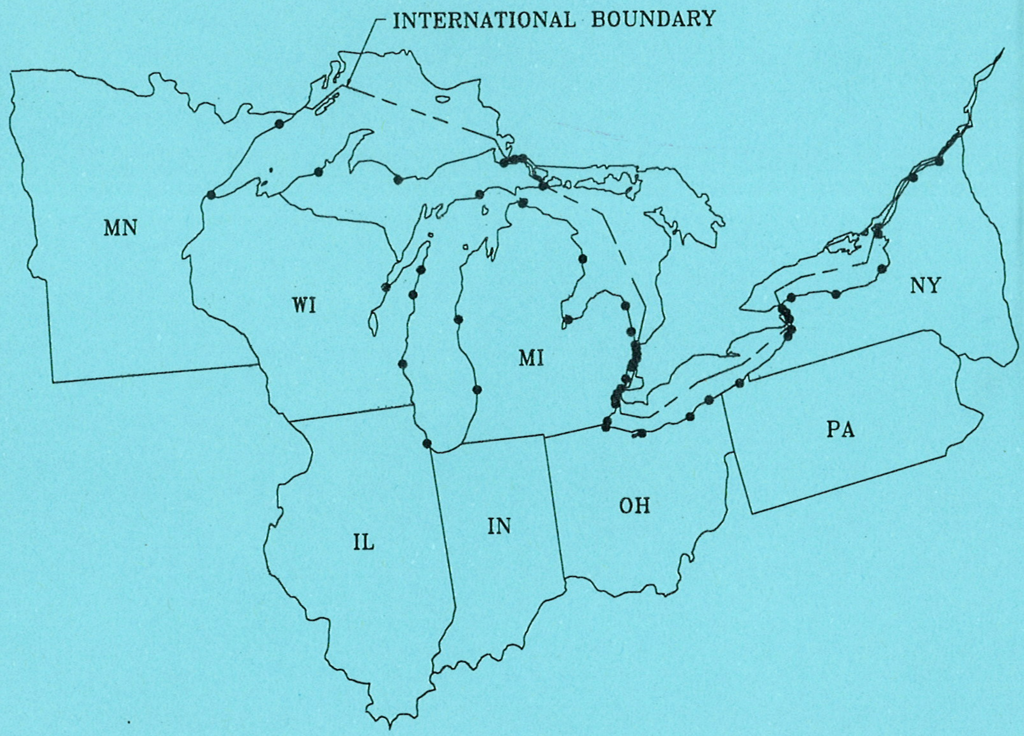
NWLON GREAT LAKES SIZING STUDY

NWLON STATIONS
GREAT LAKES



Prepared by

The Oceanographic Products and Services Division
National Ocean Service
National Oceanic and Atmospheric Administration

September 1998

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

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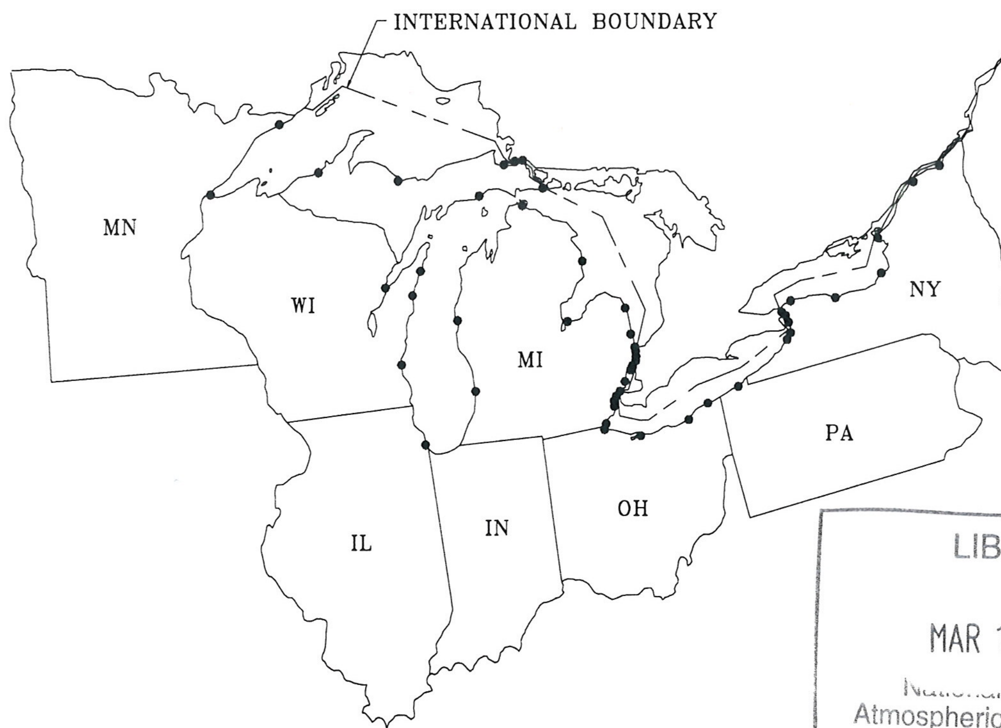

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BACKGROUND

The Oceanographic Products and Services Division (OPSD) of the National Ocean Service (NOS) operates and maintains the National Water Level Observation Network (NWLON) and the Physical Oceanographic Real-Time Systems (PORTS). Each of these highly operational programs is managed to be a source of coastal operational oceanographic products and services for the National Oceanic and Atmospheric Administration (NOAA). The PORTS program is a newer activity and builds upon the functionality of the NWLON. It has emerged due to new user requirements for real-time data, and the availability of new data collection, communication, and computer technology that can be implemented to satisfy real-time needs. The NWLON program is the oldest activity and has provided water level and tide observations and predictions for over a century. Emerging technologies have also impacted how the data from these programs are collected, processed, disseminated, and applied.

The OPSD manages these programs through base and supplemental program budgets. Available monetary resources to manage the NWLON program have not historically been sufficient to fully operate the programs while at the same time attempting to modernize and upgrade them completely. For instance, the NWLON funding decreased in FY95 by approximately $2.0M and the program has been level funded since. Because the management of these operational programs is typically carried out under limited budgets, OPSD and predecessors have periodically carried out program requirements studies and user requirement studies to make sure that the programs are the most efficient and effective possible. It necessarily follows for operational programs that the requirements studies review the specific requirements down to the individual observation location level as well as the program level.

The NWLON in particular has been frequently scrutinized as to its size and application. The operational size of the tidal component has decreased significantly over the last ten years due to losses from storms and other operational considerations. Of the 140 tide station locations in the NWLON, only approximately 125 are operational at present. Those that have not yet been upgraded with Next Generation Water Level Measurement System (NGWLMS) systems will not be due to funding limitations. The OPSD, through a private contract, has undertaken a two phase study of a network sizing and requirements study for the tide station portion. Phase I of the study is complete, and after investigation of various scientific analytical tools to perform a scientific analysis from the data themselves, Phase I identified the tools necessary to be implemented in Phase II to complete the study. The analytical tools are now being peer reviewed by the science community and should soon be published in the literature. A separate scientific analysis was assigned to the NOS Coast Survey Development Laboratory for the Great Lakes portion of the

NWLON because the inherent difference between geophysical data from the tidal portion and the great lakes portion led to different analysis strategies.

The OPSD takes the results of the scientific analyses of the data, the results of user requirement analyses, and the reality of budgetary resources to make operational decisions in managing the observational network programs. In a true operational sense, OPSD has to make frequent decisions as to continuation or discontinuation of individual and/or groups of stations. The costs associated with the operation, maintenance, and data processing required for each water level station is significant, therefore, any reduction in the number of operational stations would reduce operating costs.

OBJECTIVE

This particular study is being conducted because of numerous coincident factors. These include funding shortfalls for carrying out operations, the lack of sufficient updated data collection platforms and sensors to upgrade all stations with new technology, and an aging data management system required for old technology data that is not Y2K compliant.

The goal of this particular study is to carefully assess current NOS requirements for water level information on the Great Lakes and, based on that assessment, determine if the size of the network could be reduced while still meeting NOS' obligations.

This report makes recommendations as to an overall size of the network and specific recommendations as to which stations should remain in operation to meet the primary missions of NOS. This report will be distributed to the user community for feedback and comment before any operational decisions are made. The feedback from known U.S. significant stakeholders, such as the COE and the NOAA Great Lakes Environmental Research Laboratory (GLERL) will be especially important. The report will also be provided to the appropriate international community for evaluation and review.

THE NETWORK

The OPSD operates and maintains the National Water Level Observation Network (NWLON) which consists of approximately 189 water level stations located along the U.S. Coasts, in the Pacific and Atlantic Ocean Island Possessions and in the Great Lakes. The role of the NWLON, including the Great Lakes component, is one of an effective reference network of long-term continuously operating stations. The long-term monitoring capability and the data collection technology of the NWLON provides baseline information for all users, from real-time to decadal time frames. The design of such a reference network includes the strategic geographic densification of long-term stations such that water level and datum information can be extrapolated from existing NWLON stations to locations where stations are not operated continuously. The reference network then is used as the fundamental building block for specific surveys, projects, and studies that are typically local in geographic scope and have shorter time frames for measurement. With a scientifically and operationally strong reference network in place, OPSD would be in a better position to enter into partnerships with other local, state, and federal agencies to carry-out these special projects.

OPSD currently operates a Great Lakes component of the NWLON which is made up of 49 water level stations located on the five Great Lakes and their connecting channels. This observational component became the responsibility of NOS when operation of the water level network was transferred to NOAA from the U.S. Army Corps of Engineers (COE) in the early 1970's. The COE remains a major user of the data and information from the network and OPSD works closely with them on an operational basis to ensure their needs are met. The Great Lakes component also has a significant international linkage with Canada, as the Canadian Government also maintains a network of stations along the Canadian shoreline of each lake. The U.S and Canada manage the Great Lakes system under the auspices of an International Joint Commission (IJC) and OPSD sends representatives to the yearly meetings.

The Great Lakes water level measurement systems include a mix of Next Generation Water Level Measurement Systems (NGWLMS) with GOES satellite radio data transmission (34), older telephone data telemetry systems (3), and obsolete analog strip-chart or punch paper tape water level measurement systems (12). The stations typically consist of a small structure housing the gauges sitting on top of a sump in which the float operated sensors follow the water level variations. The structures are located several yards from shore and the sumps are connected to the water with a horizontal underground pipe so that the orifices are located under the ice cover during winter.

The users of Great Lakes data obtain data by one of five methods: 1) dialing into the OPSD-maintained Great Lakes Database; 2) directly from the Internet via the OPSD WEB page; 3) telephone requests; 4) letters of request; or 5) by monthly routine product mailing. The modernization effort underway will result in the WEB being the primary mode of remote access to the data base and will be augmented by real-time access to specific stations by specific real-time users. Five of the Great Lakes stations are configured for access to the data in real-time for dissemination to specific local users.

APPROACH

The guideline for determining the number of stations required was based on specific NOS mandates (generally covered under 33 U.S.C. §§ 883 a-k) and current treaty obligations for monitoring the Great Lakes water levels. At a minimum, the remaining network must satisfy mandated requirements for:

- Navigation Safety. NOAA is responsible for nautical chart products and maintenance of nautical chart datum on the Lakes and interconnecting waterways and for the delivery of real-time information from these stations to support operational navigational decisions.

- Lake Level Datums. NOAA is responsible for the U.S. commitment to maintaining the International Great Lakes Datum (IGLD) and for establishing and maintaining official lake datums and interrelationships.

-U.S. Treaty Responsibilities. Through operational linkages with the COE and the IJC community, the network must support the international commitments to manage water quantity and water quality along the boundary between Canada and the U.S.

A three-prong approach was taken to perform this sizing study. First, OPSD conducted a practical assessment of its funding levels, the operational status of the network, and the resources necessary to modernize the network. Second, the water level station requirements were assessed by determining the primary users of the data from each Great Lakes station. And third, a scientific assessment was made of the Great Lakes Network (excluding the interconnecting waterways) based on correlation analyses of simultaneous data from the stations.

1. Operational Assessment

A significant factor is the need to decrease operating costs in response to years of level funding for the NWLON. Numerous factors were considered as part of an operational assessment, including whether the station has been equipped with NGWLMS equipment, the physical status of the station including vertical stability of the gauge, and whether major well/intake maintenance is required.

A primary consideration is the urgent need to eliminate all of the older, obsolete measurement systems which require regular manual gauge/Electric Tape Gauge (ETG) comparisons. In addition, these old systems require payment to local station observers, labor intensive data reduction, and an old, specialized data management system which is not Y2k compliant. OPSD does not have available the 15 additional NGWLMS field units required to upgrade all of the existing network stations. The sensor associated with the NGWLMS hardware procurement is the air acoustic water level sensor. This sensor is not appropriate to the Great Lakes station operational environment due to air temperature dependancies in the sounding tube air column. The NGWLMS systems for the Great Lakes are being configured with absolute shaft angle encoder/float sensor systems for the primary water level measurements and with pressure sensor backup sensors. The shaft angle encoders add another $3,000 to the cost of each station upgrade. Without planned modernization and operational reduction across the NWLON, OPSD will not have the ability to maintain sufficient levels of spare components and supplies to successfully operate old or new technology systems.

2. User Requirements

A detailed user assessment was prepared that identified the various organizations, government, private industry, and academia. The results of the user assessment are summarized in Appendix A of this report.

An important factor in determining essential Great Lakes stations was the identification of stations that are considered critical for enhancing navigation safety. The Lake Carriers' Association (LCA) represents the vast majority of the commercial navigation community on the Lakes and they were requested to provide a list of the stations that they feel are essential for safe navigation on the Great Lakes. The Lake Carriers' Association (LCA) identified 19 stations as critical for navigation.

Their written response is included with this study (Appendix B). Other NOS data obligations were also considered such as U.S./Canadian treaties. A description of the 1909 Boundary Waters Treaty and the 1950 Niagara Treaty are contained in Appendix D. The 1909 Treaty is general in nature, however, the Niagara Treaty explicitly mentions the need for information to manage the flow of water over the Falls. In addition, the operational importance of each station to the needs of the COE was taken into account and is detailed in the user survey (Appendix B.)

The Master Stations for each Lake which provide the long term historical control for lake level datums and monitoring were not considered for removal.

3. Scientific Assessment

The third key element of this study was the NOAA Technical Report (NOS CS-1) titled "The Accuracy of Great Lakes Mean Water Level Computations Using Reduced Network Configurations" prepared by Chris Zervas in August 1997. In this study, empirical orthogonal function (EOF) analysis was employed to evaluate the effect of reducing the number of stations on the accuracy of mean lake level calculations. One significant element of this report was the calculated correlation coefficients between the various U.S. and Canadian water level stations on each lake. A high correlation coefficient between stations indicates that the determination of lake level would not be adversely affected by the removal of one of these stations. Analyses of the EOF modes also provided important analyses of potential errors using various network configurations. This report is included with this study and is found in Appendix C.

NETWORK SIZING RECOMMENDATIONS

Following a careful review of all available information, consideration of user requirements, and organizational funding restrictions, a station by station assessment was made to evaluate which of the currently operating stations could be removed while not adversely impacting NOS' ability to meet critical program and user needs.

The resulting recommended network would provide a base network for meeting the NOS mandated hydrographic surveying, nautical charting, and navigation needs.

The recommended network would provide an adequate reference network which has been referenced to the current water level datum, IGLD85, and would be maintained to provide the necessary information for monitoring Great Lakes levels. Although updated datums have not been established at several historic stations and harbors on the Great Lakes, datums can be established based on the reference network, and through differential GPS surveys or short term water level gauge installation. These datum determinations can be carried out in partnership with other agencies and organizations on a special project basis.

It is recognized that requirements for data and information from stations recommended for removal still exist and are important to the specific user needing the information. However, the present program cannot hope to fulfill everyone's existing or potential requirements for a station. For instance, the recommended network should provide the baseline information needed by the COE and GLERL to produce traditional routine products, but may not provide the network necessary to provide enhanced products. The recommended sizing is designed to provide the best network based on the considerations in the previous section.

Table 1 contains the result of this sizing study. In summary, it is recommended that the number of stations be reduced from the current 49 to 36. Thirteen stations are proposed to be eliminated:

St. Lawrence River, Proposed for removal - Alexandria Bay

The current Great Lakes network consists of two stations on the St. Lawrence River, Ogdensburg and Alexandria Bay. It is proposed that the Alexandria Bay station be removed as part of the network resizing. The user survey indicated the Ogdensburg station has significantly more organizations utilizing this station compared with Alexandria Bay. In addition, Ogdensburg is one of the joint U.S./Canadian monitoring stations.

Lake Ontario, Proposed for removal - Olcott

The Olcott station is currently equipped with old technology and would be extremely difficult to upgrade. In addition, the user survey found this station was not relied on by federal or state agencies. The conclusion was that the three remaining NWLON stations in conjunction with existing Canadian stations would provide an adequate lake network for lake level determinations.

Niagara River, Proposed for removal - Niagara Intake

The network consists of stations above and below Niagara Falls, i.e. Ashland Ave. and American Falls. These stations provide data that is used to regulate flow over the Falls, thereby, meeting U.S./Canadian treaty obligations. The Niagara Intake station is equipped with old technology and, because of its current configuration with only a vault below grade and no gauge house, would be extremely expensive to upgrade to the NGWLMS technology.

Lake Erie, Proposed for removal - Sturgeon Point and Fermi Power Plant

The current network on Lake Erie consists of eight stations. The analysis contained in NOS Technical Report CS-1 indicates that the network could be reduced by two stations while not significantly affecting the accuracy of lake level determination.

The Sturgeon Point station is geographically close to the Buffalo station and as a result, the lake level data from this station is nearly identical to that measured at Buffalo. The correlation coefficient as determined from the NOS Technical Report CS-1 was 0.99, indicating that Sturgeon Point station is redundant and could be removed with minimum impact.

The user assessment indicated that the majority of Fermi Power Plant station users are other than federal or state agencies. In addition, the correlation coefficient for Fermi when compared with the Toledo station was 0.97 which indicates minimal impact if this station were removed.

Detroit River, Proposed for removal - Fort Wayne and Windmill Point

The current network includes four stations along the Detroit River. As a result of the network sizing study, it has been proposed to eliminate two of the Detroit River stations. These stations were selected to minimize the impact of the network resizing. In addition, the Windmill Point station has not been upgraded with NGWLMS equipment.

Lake St. Clair, Proposed for removal - None

St. Clair River, Proposed for removal - Algonac, Dry Dock, Mouth of the Black River, and Dunn Paper

The current network consists of six stations along the St. Clair River. As a result of the network sizing study, it has been proposed to eliminate four stations. The stations at Algonac, Dry Dock, Mouth of the Black River, and Dunn Paper were selected in order to minimize the impact of the network resizing. Measurements from the remaining network stations are supplemented by Canadian stations including a real-time station at Point Edward. Of the stations proposed for removal, three of the four stations have not been upgraded with NGWLMS equipment.

Lake Huron, Proposed for removal - None

Lake Michigan, Proposed for removal - Kewaunee

The current network on Lake Michigan consists of eight stations. The Kewaunee station was selected for removal in part because its data series correlates well with the near-by Sturgeon Bay Canal station with a 0.96 correlation coefficient. Fewer users were identified compared to most other stations on this lake. In addition, this station has not been upgraded with NGWLMS equipment and would require expensive construction to upgrade.

St. Mary's River, Proposed for removal - None

Lake Superior, Proposed for removal - Ontonagon

The current network consists of five stations on Lake Superior. The recommendation of the sizing study is to remove the Ontonagon station. The data series from this station correlates well with the station at Grand Marais with a 0.96 correlation coefficient. In addition, this station has not been upgraded with NGWLMS equipment and analysis of station level records indicate this station structure is subsiding, which degrades the station measurements.

NETWORK MODERNIZATION PLAN

An essential benefit of the resizing of the Great Lakes network is to complete the modernization of the Great Lakes stations with up-to-date technology. As stated earlier, the network presently consists of a variety of measurement systems including several analog recorders. These analog systems require a local observer to reference the measurements to the local datum and the data processing is extremely time consuming. The elimination of the antiquated and obsolete equipment is required to provide a cost effective water level network.

The proposed resized network consists of 36 stations, of which, 29 are equipped with NGWLMS field units. Five of the stations proposed for removal currently have NGWLMS field units; these systems will be moved to those network stations which have not been upgraded. In addition, two NGWLMS field units from the OPSD inventory will be used to complete the modernization of the network.

In addition to improving the performance, reliability, and efficiency of field operations, the modernization will also permit data from all the Great Lakes network to be routinely collected and processed by the new OPSD Data Processing and Analysis System (DPAS). This will substantially improve efficiency of data processing and analysis and provide data from the Great Lakes network in near real-time through the OPSD Internet web site at www.opsd.nos.noaa.gov. Several of the unique data products requested by Great Lakes users such as timely computation of daily means based on local standard time are being incorporated into DPAS and will be available directly from the OPSD web site. In addition, all NWLON data with NGWLMS technology will be undergoing 24 hour/day by 7 day/week data quality review using OPSD's Continuous Operational Real-Time Monitoring System (CORMS). Older technology systems are not capable of having the data put through CORMS prior to application by the user.

Another long-term advantage of the modernization is that this will eliminate the requirement of station observers which are currently necessary to support the older measurement systems. In order to assure reliable, continuous water level data from Great Lakes stations, backup electronic water level measurement systems will be installed at all stations to provide redundancy should the primary system fail. This configuration, a primary and backup measurement system, is consistent with the NGWLMS field unit installations at coastal stations. An initial investment to procure additional backup systems will be required by, however, the installation of the backup systems will reduce operating costs by approximately $1,500 per year per station by removing the need for local observers.

PROJECT SCHEDULE

- Notification of users of NOS' plan to remove water level stations.	Nov. 1998
- Review of user comments; finalizing Great Lakes network stations.	Jan. 1999
- Begin the elimination of observers at stations scheduled to be removed.	Feb. 1999
- Removal of stations during FY 99 field season.	Mar-Nov. 1999
- Complete modernization of Network.	Nov. 1999

SUMMARY

The proposed resizing and modernization of the NOS Great Lakes water level measurement network represents a cost-effective approach toward meeting NOS' water level measurement requirements for the Great Lakes while improving the availability of Great Lakes data products. The recommended resizing of the network was based on: 1) a comprehensive user requirements study, especially taking into account LCA needs and COE needs; 2) a scientific EOF analysis of the Great Lakes data; and 3) an operational assessment of the present network and what it would take to modernize.

This effort will effectively reduce the number of stations that NOS operates from 49 to 36, modernize all of the remaining Great Lakes stations, and eliminate the need for special data handling currently required for the non-NGWLMS stations. The resulting recommended size provides for a strong reference network of stations that effectively monitors the water levels and provides datum control for the Great Lakes while providing the baseline for special projects on partnership basis.

The resulting network size will position OPSD to operate a strong, sustainable base program upon which partnerships can grow and new product applications developed. The pending reorganization of NOS, and the resulting broadening of NOS missions and potential data application beyond traditional surveying, mapping, engineering, and navigation needs will present new opportunities for the Great Lakes program. OPSD is eager to develop partnerships that can explore avenues for funding special projects and special applications of the Great Lakes Network.

Table 1. PROPOSED GREAT LAKES SIZING

STATION		Gauge Type	River Gauge	Master Station	Lake Level	Lake Carriers' Assoc.	Treaty	Proposed for Removal
8311030	Ogdensburg, St. Lawrence	NG	X				X	
8311062	Alexandria Bay, St. Lawrence	NG	X					Removal
9052000	Cape Vincent, Lake Ontario	NG			X			
9052030	Oswego, Lake Ontario	NG		X	X			
9052058	Rochester, Lake Ontario	NG			X			
9052076	Olcott, Lake Ontario	Digit						Removal
9063007	Ashland Ave., Niagara Falls, Niagara R.	NG	X				X	
9063009	American Falls, Niagara Flls, Niagara R.	NG	X				X	
9063012	Niagara Intake, Niagara Falls, Niagara R	Digit	X					Removal
9063020	Buffalo, Lake Erie	NG			X	X		
9063028	Sturgeon Point, Lake Erie	NG						Removal
9063038	Erie, Lake Erie	Prog			X			
9063053	Fairport, Lake Erie	NG		X	X	X		
9063063	Cleveland, Lake Erie	NG				X		
9063079	Marblehead, Lake Erie	Digit			X	X		
9063085	Toledo, Lake Erie	NG				X		
9063090	Fermi Power Plant, Lake Erie	NG						Removal
9044020	Gibraltar, Detroit River	NG	X			X		
9044030	Wyandotte, Detroit River	NG	X			X		
9044036	Fort Wayne, Detroit River	NG	X					Removal
9044049	Windmill Point, Detroit River	Prog	X					Removal
9034052	St Clair Shores, Lake St. Clair	NG		X				
9014070	Algonac, St. Clair River	NG	X					Removal
9014080	St Clair State Police, St. Clair River	NG	X					
9014087	Dry Dock, St Clair River	Digit	X					Removal
9014090	Mouth of the Black River, St. Clair Riv	Digit	X					Removal
9014096	Dunn Paper, St. Clair River	Digit	X					Removal
9014098	Fort Gratiot, St. Clair River	NG	X			X		

STATION	Gauge Type	River Gauge	Master Station	Lake Level	Lake Carriers' Assoc.	Treaty	Proposed for Removal
9075002 Lakeport, Lake Huron	Digit			X			
9075014 Harbor Beach, Lake Huron	NG		X				
9075035 Essexville, Lake Huron	NG				X		
9075059 Harrisville	Digit			X			
9075080 Mackinaw City, Straits of Mackinac	NG			X			
9075099 De Tour Village, Lake Huron	NG			X	X		
9076060 U.S. Slip, St. Marys	NG	X			X		
9076070 S.W. Pier, St Marys River	NG	X			X		
9087023 Ludington, Lake Michigan	NG			X			
9087031 Holland, Lake Michigan	Analog				X		
9087044 Calumet Harbor, Lake Michigan	NG			X	X		
9087057 Milwaukee, Lake Michigan	NG			X			
9087068 Kewaunee, Lake Michigan	Digit						Removal
9087072 Sturgeon Bay Canal, Lake Michigan	Digit				X		
9087079 Green Bay, Lake Michigan	NG				X		
9087096 Port Inland, Lake Michigan	NG			X	X		
9099004 Point Iroquois, Lake Superior	NG			X			
9099018 Marquette C.G, Lake Superior	NG		X	X	X		
9099044 Ontonagon, Lake Superior	Digit						Removal
9099064 Duluth, Lake Superior	NG			X	X		
9099090 Grand Marais, Lake Superior	Prog			X			

Summary:

- Of the current 49 stations, 13 are proposed for removal, leaving a network of 36 stations.
- Five of the stations proposed for removal are NGWLMS
- Seven of the remaining 36 are NOT NGWLMS
- Eight of the 13 stations proposed for removal are river gauges.

NWLON GREAT LAKES SIZING STUDY

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APPENDIX A

Great Lakes Water Level Station Uses and Users

The following section provides additional information, by station, on uses of water level data and a list of the users that are mailed monthly data for that station. The type of user is found before each user; Federal (Fed), Corps of Engineers (CoE), Canadian (Can), State(Sta), Local(Loc), University(Uni), or Private(Pri). Following the type of user is the users name and location.

There are seven users that receive data from all the Great Lakes stations. Those users are:

Fed	US EPA GLNPO, Chicago IL
CoE	U.S. Army Corps of Engineers, North Central Division, Chicago IL
CoE	Great Lakes H&H Branch, Detroit District, Corps of Engineers, Detroit MI
Can	Marine Environmental Data Services Branch, Dept. of Fisheries and Oceans, Ottawa, Ontario
Can	Great Lakes St. Lawrence Study Off. DOE, IWD Ontario Region, Cornwall, Ontario
Pri	Great Lakes Coalition, Saugatuck MI
Pri	Dewberry & Davis/ M.E.T.S. Fairfax VA

St. Lawrence River

Ogdensburg, NY (831-1030) NGWLMS

Lake Ontario Regulation by St. Lawrence Board of Control
CoE Bi-Monthly Forecast
River Profile datum determination
Ontario Hydro/ New York Power Authority backwater gauge for dams
Navigation - if levels fall below datum, stop vessel traffic on river
High water level warning caused by Ice James
Joint works (U.S./CA) river gauge.

Can	Superintendent, Navigable Waters, Canadian Coast Guard, Ontario CANADA
Can	Central Region, Ocean & Aquatic Sciences, Burlington, Ontario CANADA

Can Marine Environmental Data Service, Dept. of Fisheries and Oceans, Ottawa, Ontario Canada
Loc City Engineer, Ogdensburg NY
Pri St. Lawrence Seaway Development Corp., Massena NY

Alexandria Bay, NY (831-1062) NGWLMS (Proposed for removal)

Navigation - CMAN station for NDBC
High water level warning caused by Ice Jams
River Profile datum determination
CoE Bi-Monthly Forecast

Can Central Region, Ocean & Aquatic Sciences, Burlington, Ontario CANADA
Pri St. Lawrence Seaway Development Corp., Massena NY

Lake Ontario

Cape Vincent, NY (905-2000) NGWLMS

Water Level transfer point from level line to lake for IGLD '55
Navigation
CoE Bi-Monthly Forecast
Used by St. Lawrence Seaway Authority to gauge lake elevation at head of river

Loc Town of Hamlin, Hamlin NY
Pri St. Lawrence Seaway Development Corp., Massena NY
Pri Bectel Corporation, Gaithersburg MD

Oswego, NY (905-2030) NGWLMS

Master station for Lake Ontario - Zero for the lake datum determination.
Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast

Lake Ontario Regulation by St. Lawrence Board of Control
CoE Bi-Monthly Forecast
Terminus for level line from New York Harbor
One of the most requested water level data gauges
Nuclear power plant at Nine Mile Point is required to check level on a regular basis
Navigation - Port of Oswego Authority

Fed	U.S. Geological Survey, Ithaca NY
Fed	Hydrologic Information Unit, U.S. Geological Survey, Reston VA
CoE	U.S. Army Engineers, Detroit District, Lake Hydrology, Detroit MI
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington, Ontario Canada
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta	Conservation Department, State of New York, Avon NY
Loc	Town of Hamlin, Hamlin NY
Loc	Executive Director, Port of Oswego Authority, Oswego NY
Loc	Results Department, Niagara Mohawk Power Corp., Oswego Steam Station, Oswego, NY
Pri	International Research & Evaluation, IRE-ITTD, Input Processing Dir, Eagan MN
Pri	Triple ZZZ Cyclotron, Cleveland OH
Pri	John Pauldine, Liverpool NY
Pri	General Electric Company, Corporate Environmental Programs, Albany NY
Pri	Bectel Corporation, Gaithersburg MD

Rochester, NY (905-2058) NGWLMS

Coordinated Lake Level Computation by US and Canada for Joint Lake Level Forecast
Lake Ontario Regulation by St. Lawrence Board of Control
CoE Bi-Monthly Forecast
Daily/Bi-weekly call from local TV station for data to be used on nightly weather report.

CoE	District Engineer, U.S. Engineering District, Buffalo Permits Section, Buffalo NY
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA

Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Loc	Monroe County Water Authority, Shoremont Water Treatment Plant, Rochester NY
Loc	Town of Hamlin, Hamlin NY
Loc	Superintendent, Russell Station,. Rochester NY
Loc	Emergency Preparedness Office, Monroe County, Rochester NY
Uni	SUNY at Buffalo, Dept of Civil Engineering, Buffalo NY
Pri	Robert K. Strong, Hilton NY
Pri	Rose Mack, Rochester NY

Olcott, NY (905-2076) (Proposed for removal)

Water Level transfer point from level line to lake for IGLD '55

Loc	Town of Hamlin, Hamlin NY
Pri	Bectel Corporation,. Gaithersburg MD

Niagara River

Ashland Avenue, Niagara Falls, NY (906-3007) NGWLMS

Treaty Gauge
Niagara River Board of Control
Federal (US/CA) check gauge on diversions by power companies
Ontario Hydro gauge with read out to Control Room to control flow over falls

CoE	District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo, NY
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada Burlington Ontario CANADA
Can	Canada Centre for Inland Waters, Department of Environment, Burlington, Ontario
Can	Ontario Hydro, Cornwall, Ontario Canada
Sta	St. Lawrence Committee on River Gauging, New York Power Authority, Massena, NY
Sta	New York Power Authority, Marcy, NY

American Falls, Niagara Falls, NY (906-3009) NGWLMS

Treaty Gauge
Niagara River Board of Control
Ontario Hydro gauge to Control Room used in winter to monitor ice jams

CoE District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo, NY
Can Canada Centre for Inland Waters, Department of Environment, Burlington, Ontario
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA

Niagara Intake, Niagara Falls, NY (906-3012) (Proposed for removal)

Niagara River Board of Control
Only Federal (US/CA) gauge in the Grass Island Pool
Last datum gauge on the Niagara River

Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Pri RECRA Research Inc., Amherst NY

Lake Erie

Buffalo, NY (906-3020) NGWLMS

Niagara River Board of Control - first gauge on Lake
El Nino study by GLERL
Lake Erie extreme storm recording
Weather Service instrumentation; wind, water level
Corps of Engineers Bristol Water Level to Buffalo Dist. Office
NYPA wind speed & direction
Request for real time water level data by Lake Carriers Association

Fed National Weather Forecast Office, Federal Facilities Building Cleveland Hopkins Int. Airport Cleveland OH

Fed	National Weather Service, Silver Spring MD
Fed	U.S. Geological Survey, Ithaca NY
CoE	District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo, NY
Can	Canada Centre for Inland Waters, Department of Environment, Burlington, Ontario
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta	Ohio Division of Geological Survey, Great Lakes Center, Sandusky OH
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Loc	Buffalo Sewer Authority, Buffalo NY
Loc	Chief Operator, Power Authority of the State of NY, Niagara Falls NY
Loc	Buffalo Sewer Authority, Buffalo NY
Loc	Erie County Dept. of Environment & Planning, Buffalo NY
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	Department of Geology State University College, Fredonia NY
Uni	OSU/Dept of Civil Engineering, Columbus OH
Uni	Dept Geog & Earth Science, Bloomsburg University, Bloomsburg PA
Pri	Hayden-Wegman Inc., Amherst NY
Pri	Calocerinos & Spina Consulting Engineers, Buffalo NY
Pri	The Great Lakes Towing Company, Cleveland OH

Sturgeon Point, NY (906-3028) NGWLMS (Proposed for removal)
Harbor of refuge

CoE	District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo, NY
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	Department of Geology, State University College, Fredonia NY
Uni	OSU/Dept of Civil Engineering, Columbus OH

Erie, PA (906-3038)

Major Shipping port & Harbor of refuge
PA Sea Grant has ask that we install a 9000 with a display at the State Park visitor center
Flooding at State Park

Fed	U.S.G.S., Pittsburgh PA
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Sta	Presque Isle State Park, Erie PA
Sta	Pennsylvania Geological Survey, Harrisville PA
Loc	Erie Co. Department of Health, Erie PA
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	Department of Geology, State University College, Fredonia NY
Uni	OSU/Dept of Civil Engineering, Columbus OH
Uni	Dept Geog & Earth Science, Bloomsburg University, Bloomsburg PA
Pri	Jones and Henry Engineering, Toledo OH
Pri	Consor Townsend Envirodyne, Erie PA
Pri	Harbormaster, Erie Yacht Club, Erie PA

Fairport, OH (906-3053) NGWLMS

Master station for Lake Erie- Zero for the lake datum determination.
Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast
Request for real time water level data by Lake Carriers Association

Fed	U.S. Fish and Wildlife Service, Reynoldsburg OH
CoE	District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo NY
Sta	Ohio Division of Geological Survey, Great Lakes Center, Sandusky OH
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	OSU/Dept of Civil Engineering, Columbus OH
Uni	Dept Geog & Earth Science, Bloomsburg University, Bloomsburg PA

Pri Morton Salt Company, Grand River OH

Cleveland, OH (906-3063) NGWLMS

Original Master gauge for Lake Erie for '03, '35, and IGLD '55 datums
Longest continuous record on Lake Erie
CoE Bristol Water Level to Cleveland office
Request for real time water level and current data by Lake Carriers Association

Fed U.S. Fish and Wildlife Service, Reynoldsburg OH
Fed Area Manager, National Weather Forecast Office, Cleveland Hopkins Airport, Cleveland OH
Fed Chief, Hydrologic Information Unit, U.S. Geological Survey, Reston VA
CoE U.S. Army Engineers, Detroit District, Lake Hydrology, Detroit MI
CoE Corps of Engineers, Cleveland Projects Office, Cleveland OH
CoE District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo NY
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can Canada Centre for Inland Waters, Burlington Ontario CANADA
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta Ohio Division of Geological Survey, Great Lakes Center, Sandusky OH
Sta Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Loc Huron - Clinton Metropolitan Authority, Brighton MI
Uni Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni OSU/Dept of Civil Engineering, Columbus OH
Uni Dir. CLEAR, The Ohio State University, Columbus OH
Pri Don Izold, Cleveland OH
Pri Jospeh A. Friess, Sheffield Lake OH
Pri International Research & Evaluation, IRE-ITTD, Input Processing Dir, Eagan MN
Pri George B. Kasik Attorney at Law, Bay Village OH
Pri Walter J. Stalzer, Havens and Emerson, Cleveland OH
Pri The Great Lakes Towing Company, Cleveland OH
Pri General Electric Company, Corporate Environmental Programs, Albany NY

Marblehead, OH (906-3079)

Harbor of refuge
ODNR uses data
Request for real time water level data by Lake Carriers Association

Fed	U.S. Fish and Wildlife Service, Reynoldsburg OH
Fed	Area Manager, National Weather Forecast Office, Cleveland Hopkins Airport, Cleveland OH
CoE	District Engineer, U.S. Engineering District, Buffalo, Water Control Section, Buffalo NY
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Ohio Division of Geological Survey, Great Lakes Center, Sandusky OH
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Loc	Ottawa County Engineer, Port Clinton OH
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	Dir. CLEAR Ohio State University, Columbus OH
Uni	OSU/Dept of Civil Engineering, Columbus OH
Pri	Don Izold, Cleveland OH
Pri	Engineering Manager, United States Gypsum Company, Gypsum OH

Toledo, OH (906-3085) NGWLMS

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
El Nino study by GLERL
CoE Bi-Monthly Forecast
Bristol to Coast Guard - used for Navigation (West end of Lake & Maumee River)
Bristol to CoE for dredging
CoE Telemark for Water Level - used by Cleveland Weather Service Office
Correlation coefficient less that .90 in NOAA Tech Report NOS CS 1
Request for real time water level data by Lake Carriers Association

Fed	National Weather Forecast Office, Federal Facilities Building, Cleveland Hopkins Int. Airport, Cleveland OH
Fed	U.S. Fish and Wildlife Service, Reynoldsburg OH

Fed	National Weather Service, Silver Spring MD
CoE	Corps of Engineers, Toledo Area Office, Toledo OH
CoE	Detroit District, CoE Regulatory Branch, Enforcement Section, Detroit MI
CoE	District Engineer, U.S. Engineering District, Buffalo Water Control Section, Buffalo NY
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Sta	Department of Natural Resources, Pointe Mouillee State Game Area, Rockwood MI
Sta	Ohio Division of Geological Survey, Great Lakes Center, Sandusky OH
Sta	Office of Chief Engineer, Ohio Department of Natural Resources, Columbus OH
Loc	Executive Director, Lake Erie Office, Toledo OH
Uni	Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni	OSU/Dept of Civil Engineering, Columbus OH
Uni	Dept Geog & Earth Science, Bloomsburg University Bloomsburg PA
Pri	Jones and Henry Engineering, Toledo OH
Pri	The Great Lakes Towing Company, Cleveland OH
Pri	Toledo Edison Co., Toledo OH
Pri	Joseph J. Paprocki, S.S.O.E. Inc., Toledo OH
Pri	John Kohler, Architect, Monroe MI
Pri	Finkbeiner, Pettis & Strout, Toledo OH

Fermi Power Plant, Stoney Point, MI (906-3090) NGWLMS (Proposed for removal)

Civil Defense high water indicating gauge to City of Monroe
Fermi Nuclear Power plant as check on their other gauges

CoE	Detroit District, CoE Regulatory Branch, Enforcement Section, Detroit MI
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc	Monroe Co. Office of Civil Defense, Monroe MI
Loc	Supervisor, Compliance Licensing, 270 TAC, Newport MI

Loc Chief Engineer, Huron-Clinton Metropolitan Authority, Brighton MI
Loc Reference Department, Monroe County Library System, Monroe MI
Uni Department of Geological Sciences, Case Western Reserve University, Cleveland OH
Uni OSU/Dept of Civil Engineering, Columbus OH
Pri Detroit Edison, Enrico Fermi Power Plant, Newport MI
Pri John Kohler, Architect, Monroe MI

Detroit River

Gibraltar, MI (904-4020) NGWLMS

Bristol to City of Gibraltar for flood warning
Bristol to Coast Guard Group Detroit for Navigation
Determine International Coordinated flows in Detroit River
CoE Bi-Monthly Forecast
River datum determination
Canadian Coast Guard for deep water draft forecast
Request for real time water level data by Lake Carriers Association

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Can Golder Associates, Windsor, Ontario CANADA
Sta Department of Natural Resources, Pointe Mouillee State Game Area, Rockwood MI
Loc Director of Public Safety, City of Gibraltar, Gibraltar MI
Loc Chief of Police, City of Gibraltar, Gibraltar MI
Loc Chief Engineer, Huron-Clinton Metropolitan Authority, Brighton MI
Pri Hubbell, Roth & Clark, Inc., Bloomfield Hills MI

Wyandotte, MI (904-4030) NGWLMS

Determine International Coordinated flows in Detroit River
River datum determination

Canadian Coast Guard for deep water draft forecast
Request for real time water level data and Rouge River current data by Lake Carriers Association

CoE Detroit District, CoE Regulatory Branch, Enforcement Section, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Loc Detroit Water & Sewerage Dept., Detroit MI
Pri BASF Corporation, Wyandotte MI
Pri Hubbell, Roth & Clark, Inc., Bloomfield Hills MI

Fort Wayne, Detroit, MI (904-4036) NGWLMS (Proposed for removal)

Determine International Coordinated flows in Detroit River
River datum determination
Water level for GLERL flow meter
Canadian Coast Guard for deep water draft forecast

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Can Golder Associates, Windsor, Ontario CANADA
Loc Detroit Water & Sewerage Department, Document Control Library,. Detroit MI
Loc Chief Engineer, Huron-Clinton Metropolitan Authority, Brighton MI
Loc Detroit Water & Sewerage Department, Detroit MI
Loc City Engineering Department, Bureau of Surveys, Detroit MI
Pri Hubbell, Roth & Clark, Inc., Bloomfield Hills MI
Pri The Great Lakes Towing Company, Cleveland OH

Windmill Point, Detroit, MI (904-4049) (Proposed for removal)

Determine International Coordinated flows in Detroit River
CoE Bi-Monthly Forecast
River datum determination
Canadian Coast Guard for deep water draft forecast

CoE Detroit District, CoE Regulatory Branch, Enforcement Section, Detroit MI
CoE Department of the Army, Detroit District Corps of Engineers Boat Yard, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Can Golder Associates, Windsor, Ontario CANADA
Loc Detroit Department of Health, Detroit MI
Loc Chief Engineer, Huron-Clinton Metropolitan Authority, Brighton MI
Loc Detroit Water & Sewerage Dept., Detroit MI
Loc City Eng. Department, Bureau of Surveys, Detroit MI
Pri Hubbell, Roth & Clark, Inc., Bloomfield Hills MI

Lake St. Clair

St. Clair Shores, MI (903-4052) NGWLMS
Master station for Lake St. Clair - Zero for the lake datum determination.
Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast
Water level Telemark for Macomb County

Fed 127 Tactical Fighter Wing, Selfridge ANG Base MI

St. Clair River

Algonac, MI (901-4070) NGWLMS (Station in need of major repairs) (Proposed for removal)
Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan
CoE Bi-Monthly Forecast
Monitor for Ice Jams & flooding in St. Clair River
River datum determination

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI

CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta Division of Environ. Health, Michigan DPH, Lansing MI
Loc Sewage Treatment Plant, Port Huron MI
Pri Hubbell, Roth & Clark, Inc., Bloomfield Hills MI

St. Clair State Police, MI (901-4080) NGWLMS

Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan
Monitor for Ice Jams & flooding in St. Clair River
CoE Bi-Monthly Forecast
River datum determination
Canadian Coast Guard for deep water draft forecast

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
CoE Department of the Army ,Detroit District Corps of Engineers Boat Yard, Detroit MI
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Loc Sewage Treatment Plant, Port Huron MI

Dry Dock, Port Huron, MI (901-4087) (Proposed for removal)

Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan
River datum determination

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Loc Sewage Treatment Plant, Port Huron MI

Mouth of Black River, Port Huron, MI (901-4090) (Proposed for removal)

Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan

River datum determination

CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Loc Sewage Treatment Plant, Port Huron MI

Dunn Paper, Port Huron, MI (901-4096) (Proposed for removal)

Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan
River datum determination

CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Loc Sewage Treatment Plant, Port Huron MI
Pri Dunn, P.E., R.L.S., Port Huron MI

Fort Gratiot, Port Huron, MI (901-4098) NGWLMS

Unsteady Flow Models to provide daily flows for US/CA - water balance between lakes Huron and Michigan
Monitor for Ice Jams & flooding in St. Clair River
CoE Bi-Monthly Forecast
River datum determination
Request for real time water level and current data by Lake Carriers Association

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Loc Sewage Treatment Plant, Port Huron MI
Pri Dunn, P.E., R.L.S., Port Huron MI

Lake Huron

Lakeport, MI (907-5002)

Monitor for Ice Jams & flooding in St. Clair River

Fed National Weather Service, Silver Spring MD
CoE Detroit District, COE Regulatory Branch, Enforcement, Detroit MI
CoE Department of the Army Detroit District, Corps of Engineers Boat Yard, Detroit MI
Can Canada Centre for Inland Waters, Burlington Ontario CANADA
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc Chief Pumping Plant Engineer, Fort Gratiot MI
Pri Dunn, P.E., R.L.S., Port Huron MI

Harbor Beach, MI (907-5014) NGWLMS

Master station for Lakes Huron and Michigan - Zero for the lake datum determination.
Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast

Fed U.S. Geological Survey, WRD, Lansing MI
Fed Chief, Hydrologic Information Unit, U.S. Geological Survey, Reston VA
CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
CoE U.S. Army Engineers, Detroit District, Lake Hydrology, Detroit MI
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can Canada Centre for Inland Waters, Burlington Ontario CANADA
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Can Rand Monk, Caledonia, Ontario CANADA
Sta Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc Huron Clinton Metropolitan Auth, Brighton MI
Pri National Gypsum Company, National City MI
Pri International Research & Evaluation, IRE-ITTD Input Processing Dir, Eagan MN
Pri K & K Warehousing, Menominee MI
Pri General Electric Company, Corporate Environmental Programs, Albany NY
Pri Gary Culver, Grand Rapids MI

Essexville, MI (907-5035) NGWLMS

REALDATA to Coast Guard Station Saginaw Bay
Correlation coefficient less that .90 in NOAA Tech Report NOS CS 1
Request for real time water level and current data by Lake Carriers Association

Fed	U.S. Geological Survey, WRD, Lansing MI
Fed	National Weather Service, Silver Spring MD
Fed	U.S.G.S., Grayling MI
CoE	Saginaw Projects Office, Corps of Engineers, Essexville MI
CoE	Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Pri	Hubbell, Roth & Clark, Inc., Bloomfield Hills MI
Pri	Wade-Trim/Edmands, Bay City MI

Harrisville, MI (907-5059)

Harbor of refuge

CoE	Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI

Mackinaw City, MI (907-5080) NGWLMS (In need of major sump repairs)

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast

CoE	Area Engineer, Soo Area, St. Marys Falls Canal Sault St. Marie MI
CoE	Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI

Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Pri	Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL

De Tour Village, MI (907-5099)	NGWLMS

Located at foot of St Mary's river
Request for real time water level data by Lake Carriers Association

CoE	Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
CoE	Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA

St. Marys River

U.S. Slip, Sault Ste. Marie, MI (907-6060)	NGWLMS

Navigation - Approach to locks at Sault St Marie (below)
Lake Superior Board of Control
Continual readout water level gauge to Control Tower for locks
CoE Bi-Monthly Forecast
Request for real time water level data by Lake Carriers Association

CoE	Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA

S.W. Pier, Sault Ste. Marie, MI (907-6070)	NGWLMS

Navigation - Approach to locks at Sault St Marie (above)
Lake Superior Board of Control
Continual readout water level gauge to Control Tower for locks
CoE Bi-Monthly Forecast
Request for real time water level data by Lake Carriers Association

CoE Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington Ontario CANADA
Can Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA

Lake Michigan

Ludington, MI (908-7023) NGWLMS

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast
El Nino study by GLERL
Harbor of refuge

Fed U.S. Geological Survey, WRD, Lansing MI
CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
CoE U.S. Army Engineers Detroit District Lake Hydrology Box 1027 Detroit MI
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington, Ontario Canada
Can Rand Monk, Caledonia, Ontario CANADA
Sta Land and Water Management Division, Department of Natural Resources, Lansing MI
Uni Civil Engineering Department, University of Massachusetts, Amherst MA
Pri James C. Kelley, Redmond WA
Pri Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri Bectel Corporation, Gaithersburg MD

Holland, MI (908-7031)

El Nino study by GLERL
Harbor of refuge
Request for real time water level data by Lake Carriers Association

CoE	Corps of Engineers, CENCC-ED-H, Chicago IL
CoE	Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Sta	Division of Water, Department of Natural Resources, Michigan City IN
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc	American Electric Power, Columbus OH
Loc	Holland Water Treatment Plant, Holland MI
Uni	Great Lakes Coastal Research Lab, Dept. of Civil Engineering, Purdue University, West Lafayette IN
Uni	University of Maryland Balt. Co., Geography Department, Baltimore MD
Pri	Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri	Ted and Myra Zwiep, Holland MI
Pri	Bectel Corporation, Gaithersburg MD

Calumet Harbor, Chicago, IL (908-7044) NGWLMS

Navigation - Major shipping point
Correlation coefficient less that .90 in NOAA Tech Report NOS CS 1
Southern most gauge on Lake Michigan
Request for real time water level data by Lake Carriers Association

Fed	USGS , Indianapolis IN
CoE	Corps of Engineers, CENCC-ED-H, Chicago IL
CoE	Kewaunee Project Office, Corps of Engineers, Kewaunee WI
Sta	Illinois State Geological Survey, Champaign IL
Sta	Division of Water, Department of Natural Resources, Michigan City IN
Sta	Illinois Dept. of Transportation, Division of Water Resources, Chicago IL
Sta	Illinois State Water Survey, Champaign IL
Loc	Director of Engineering, Chicago Park District, Chicago IL

Loc Water Quality Surveillance Section, Water Purification Division, Chicago IL
Uni Great Lakes Coastal Research Lab, Dept. of Civil Engineering, Purdue University, West Lafayette IN
Pri Woodward-Clyde Consultants, Chicago IL
Pri Burns and McDonnell, Kansas City MO
Pri Water Resources, Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri The Great Lakes Towing Company, 1800 Terminal Tower, Cleveland OH
Pri LTV Steel Company, Engineering Dept., East Chicago IN
Pri Orbital Engineering, Pittsburgh PA
Pri Burns and McDonnell, Kansas City MO
Pri STS Consultants Limited, Deerfield IL
Pri Bectel Corporation, Gaithersburg MD
Pri Frank Pranschke, Chicago, IL

Milwaukee, WI (907-7057) NGWLMS

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
CoE Bi-Monthly Forecast
Harbor of refuge

Fed Chief, Hydrologic Information Unit, U.S. Geological Survey, Reston VA
CoE Kewaunee Project Office, Corps of Engineers, Kewaunee WI
Can Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington, Ontario Canada
Can Rand Monk, Caledonia, Ontario CANADA
Sta Illinois State Geological Survey, Champaign IL
Sta Port of Milwaukee, Engineering Dept., Milwaukee WI
Sta Division of Water, Department of Natural Resources, Michigan City IN
Sta Land and Water Management Division, Department of Natural Resources, Lansing MI
Sta Chief Environmental Planner, S.E. Wisc. Regional Planning Commission, Waukesha WI
Sta Illinois State Water Survey, Champaign IL
Sta Illinois State Geological Survey, Champaign IL
Sta STS Consultants LTD, Milwaukee WI
Pri Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL

Pri Woodward-Clyde Consultants, Stoughton WI
Pri Milwaukee Metro Sewerage Dist., Milwaukee WI
Pri Greenly and Hansen Engineers Library, Chicago IL
Pri Bectel Corporation, Gaithersburg MD
Pri Frank Pranschke, Chicago, IL

Kewaunee, WI (908-7068) (Proposed for removal)

CoE Kewaunee Project Office, Corps of Engineers, Kewaunee WI
Pri Bectel Corporation, Gaithersburg MD
Pri Pt. Beach Nuclear Plant, Two Rivers WI
Pri Alpha Terra Science, Plymouth WI

Sturgeon Bay Canal, WI (908-7072)
Determine flow between Green Bay & Lake Michigan
Request for real time water level data by Lake Carriers Association

CoE Kewaunee Project Office, Corps of Engineers, Kewaunee WI
Pri Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri K & K Warehousing, Menominee MI
Pri Bectel Corporation, Gaithersburg MD

Green Bay, WI (908-7079) NGWLMS
Bristol water level to Power Plant
Correlation coefficient less that .90 in NOAA Tech Report NOS CS 1
Only gauge on Green Bay and is at mouth of Fox River
Request for real time water level and current data by Lake Carriers Association

Fed National Weather Service, Silver Spring MD

CoE Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
CoE Kewaunee Project Office, Corps of Engineers, Kewaunee WI
Sta W.D.N.R.,Green Bay WI
Loc Green Bay Metro Sewage District, Green Bay WI
Uni University of Wisconsin, GB Sea Grant, Green Bay WI
Pri Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri James River Corporation, Green Bay WI

Port Inland, MI (908-7096) NGWLMS

Northern most gauge on Lake Michigan
Harbor of refuge
Request for real time water level data by Lake Carriers Association

Sta Land and Water Management Division, Department of Natural Resources, Lansing MI
Pri Water Resources Site Development Div., Sargent & Lundy Engineers, Chicago IL
Pri Sand Products Corporation, Detroit MI

Lake Superior

Point Iroquois, MI (909-9004) NGWLMS

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
Lake Superior Board of Control
CoE Bi-Monthly Forecast

CoE Detroit District, COE Regulatory Branch, Enforcement Section, Detroit MI
Sta Land and Water Management Division, Department of Natural Resources, Lansing MI

Marquette, MI (909-9018) NGWLMS

Master station for Lake Superior - Zero for the lake datum determination.

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
Lake Superior Board of Control
CoE Bi-Monthly Forecast
Request for real time water level data by Lake Carriers Association

Fed	Chief, Hydrologic Information Unit, U.S. Geological Survey, Reston VA
CoE	Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
CoE	U.S. Army Engineers, Detroit District, Lake Hydrology, Detroit MI
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington, Ontario Canada
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Can	Operations Branch, St. Lawrence Seaway Authority, Cornwall, Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Pri	Woodward-Clyde Consultants, Stoughton WI
Pri	International Research & Evaluation, IRE-ITTD, Input Processing Dir, Eagan MN
Pri	General Electric Company, Corporate Environmental Programs, Albany NY
Pri	Steve Benda, Cokato MN

Ontonagon, MI (909-9044) (Structure subsidence) (Proposed for removal)

CoE	Area Engineer, Soo Area, St. Marys Falls Canal, Sault St. Marie MI
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Pri	Superior Seawall, Houghton MI

Duluth, MN (909-9064) NGWLMS

Coordinated Lake Level Computation by US and Canada for joint Lake Level Forecast
Lake Superior Board of Control
CoE Bi-Monthly Forecast
Request for real time water level and current data by Lake Carriers Association

Fed	Group Commander, U.S. Coast Guard Group Duluth, Duluth MN
Can	Water Planning and Management Br., IWD/Ontario Region, Environment Canada, Burlington, Ontario Canada
Can	Canada Centre for Inland Waters, Burlington Ontario CANADA
Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc	City Engineer, City of Duluth, Duluth MN
Loc	Apostle Island National Lakeshore, Bayfield WI
Pri	The Great Lakes Towing Company, Cleveland OH
Pri	Maintenance of Way, DM&IR Railway Company, Proctor MN

Grand Marais, MN (909-9090)

Harbor of refuge

Sta	Land and Water Management Division, Department of Natural Resources, Lansing MI
Loc	City Clerk, Grand Marais MN

NWLON GREAT LAKES SIZING STUDY

Prepared by

The Oceanographic Products and Services Division
National Ocean Service
National Oceanic and Atmospheric Administration

APPENDIX B

Lake Carriers' Association Letter dated June 5, 1998

Lake Carriers' Association

RICHARD W. HARKINS
VICE PRESIDENT - OPERATIONS
Direct Dial: 216-861-0591
E-Mail: harkins@lcaships.com
Website: www.lcaships.com

June 5, 1998

Mr. James Dixon
Field Operations Branch Chief
Atlantic Regional Office
808 Principal Court
Chesapeake, Va. 23320

Dear Mr. Dixon,

At our Annual Captains Committee meeting in January, you requested Lake Carriers' Association to review the current locations of NOAA water level meters through the Great Lakes and provide you an analysis of which gages should be given priority and/or additional capability. We have completed a survey of 35 LCA vessel masters and advise that of the listing you provided of 43 NOAA gages on the Great Lakes we recommend that 19 be retained. We also evaluated additional features that are desireable for those 19 gages and have recommended that the addition of current meters be examined for 6 of those gages. The list is ordered by the number of votes each location received therefore we also advise that this is the priority of importance of these gages.

1. Duluth, Minn. (add current meter)
2. S.W. Pier above Locks, Soo, Mi.
3. U.S. Slip below Locks, Soo, Mi.
4. Gibralter, Mi.
5. Toledo, Ohio
6. Cleveland, Oh. (add current meter)
7. Essexville, Mi. (add current meter)
8. Wyandotte, Mi (add current in Rouge)
9. Detour Village, Mi.
10. Buffalo, NY
11. Sturgeon Bay Canal, Wi.
12. Port Inland, Mi.
13. Fort Gratiot, Mi (add current meter)
14. Fairport, Oh.
15. Green Bay, Wi. (add current meter)
16. Marquette, Mi.
17. Marblehead, Oh.
18. Calumet Hbr, Il.
19. Holland, Mi

The gages at Ludington, Mi., Milwaukee, Wi., and Ontonogan, Mi., Fermi Power Plant, Mi., and Haarbor Beach, Mi., also received one or two votes and we suggest that these gages be phased out last. All other NOAA gages on the Great Lakes are not serving a useful purpose for the professional mariner.

We look forward to hearing your strategy and plans to develop and install real time capability for these gages.

Sincerely,

R W Harkins

Richard W. Harkins
Vice President - Operations

RWH:lca
cc: Navigation Committee
Bill Willis, Army Corps of Engineers, Detroit

915 Rockefeller Building • 614 Superior Avenue, West • Cleveland, Ohio 44113-1383 • Fax: 216-241-8262

NWLON GREAT LAKES SIZING STUDY

Prepared by

The Oceanographic Products and Services Division
National Ocean Service
National Oceanic and Atmospheric Administration

APPENDIX C

NOAA Technical Report NOS CS 1
"THE ACCURACY OF GREAT LAKES MEAN WATER LEVEL COMPUTATIONS USING REDUCED NETWORK CONFIGURATIONS"

NOAA Technical Report NOS CS 1

THE ACCURACY OF GREAT LAKES MEAN WATER LEVEL COMPUTATIONS USING REDUCED NETWORK CONFIGURATIONS

Silver Spring, Maryland
May 1997

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory
Oceanographic Programs

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ABSTRACT

The mean water level of each of the Great Lakes is required to assess regional hydrological conditions. Since the mean lake level cannot be measured directly with one gauge, it must be calculated as a combination of water levels measured at several stations on each lake. There are presently 31 U. S. and 21 Canadian water level stations on the Great Lakes. The U. S. Army Corps of Engineers uses the Theissen polygon method to derive a weighting factor for each station used in calculating the mean water level for each lake. In this study, empirical orthogonal function (EOF) analysis was employed because it reveals more about the physics of lake level oscillations. The EOF method separates the mean lake level from wind-induced lake surface tilts and other signals in the data. The first EOF mode corresponds to the mean lake level and the second EOF mode corresponds to lake surface tilt along the longer axis of each lake.

The primary object of this investigation was to evaluate the effect of reducing the number of gauges on the accuracy of mean lake level calculations. The analyses in this report were performed on two data sets: 2-day averaged water level time series for 1990 to 1994, and hourly water level time series for 1990. The first data set was used to study the accuracy of beginning-of-month lake levels required by the Army Corps of Engineers for lake level regulation. For each lake, the first EOF mode obtained from the complete network was statistically compared to the first EOF modes obtained from every possible subnetwork. The second data set was used to study the accuracy of monitoring mean lake levels and lake surface tilt on an hourly basis. For each lake, the first and second EOF modes obtained from the complete network were statistically compared to the first and second EOF modes obtained from every possible subnetwork. The lowest error as a function of subnetwork size decreases rapidly before leveling off for subnetwork sizes greater than seven or eight stations.

1. INTRODUCTION

The National Ocean Service (NOS) has been responsible for operating and maintaining the U. S. water level gauges on the Great Lakes and interconnecting waterways since NOAA's inception in 1970. Previously, the gauges were installed and operated by the U. S. Army Corps of Engineers who are charged with regulating water levels on the lakes in cooperation with the Canadian Hydrographic Service. The outflows from Lakes Superior and Ontario are controlled by the International Joint Commission, a committee formed by Canada and the U. S. (Grima and Wilson-Hodges, 1977). All the lakes are affected by diversions and modifications to the waterways between lakes (Hartmann, 1988; David et al., 1988). Effective regulation of the lakes requires timely and accurate measurement of the water level in each lake.

The Army Corps of Engineers (Detroit District) uses the Great Lakes water level data to calculate monthly averages for each lake and publishes the lake levels in the "Monthly Bulletin of Lake Levels for the Great Lakes". The publication also gives a six-month lake level forecast based on future weather conditions (Clites, 1992). The Canadian Hydrographic Services publishes a similiar bulletin. The monthly averages are determined using six stations each for Lake Ontario and the Lake Michigan-Lake Huron system, five stations for Lake Superior, four stations for Lake Erie and two stations for Lake St. Clair. The main reason for averaging over several stations is to minimize the effect of the long-term tectonic uplift of the northern lake shores relative to the southern lake shores due to glacial rebound (Tovell, 1979; Clites, 1992). The water level network was recently releveled in 1985 to account for vertical displacements that had taken place since the previous datums were established in 1955 (Coordinating Committee, 1995).

For regulation of the lake levels, the Corps of Engineers requires a more current lake level value than the monthly value. They use the beginning-of-month lake level, which they obtain by averaging the daily values from the last day of the previous month and the first day of the current month (Quinn and Todd, 1974). This 2-day average is subject to wind set-up errors which can occur when a strong wind stress exists along or across the axis of the lake, tilting the lake's surface (Hamblin, 1987). Therefore to minimize this error, the water levels from a number of stations around the lake are combined using a method called the Theissen polygon method. The beginning-of-month lake levels are then used to obtain the rates of change of lake storage (Quinn and Todd, 1974). These statistics are useful for monitoring lake hydrology, shoreline erosion, navigation, and hydroelectric power generation. They are also used in water budget calculations of evaporation rates and groundwater influx.

This study demonstrates a method for determining the effect of a reduced network size on mean lake level accuracy. In the next section, four different methods of calculating mean lake levels using water level time series at multiple locations are described. Then, the present network configuration and the data sets to be used are introduced. In the subsequent section, 2-day averaged water level data are analyzed to examine the calculation of beginning-of-month mean lake levels. Later, an analysis is carried out with hourly data to evaluate the accuracy of calculating mean lake levels and lake surface tilt on an hourly basis. Finally, the results of these analyses are used in discussing how accurately the hourly water level time series at any individual station may be reproduced by a combination of other stations on the lake.

2. FOUR METHODS FOR ESTIMATION OF MEAN LAKE LEVELS

2.1. AVERAGE

The simplest method of calculating the mean lake level is to add the water level at all available stations together and then divide by the number of stations. This uniform weighting method will work well if there are enough stations available so that any other signals present (at one or more stations) cancel out exactly or are substantially diminished in amplitude. However, during periods of strong wind stress, tilting of the lake surface may cause errors in mean lake levels calculated by simple averaging.

2.2. THELSSEN POLYGON METHOD

This method of combining water level data from the periphery of a lake to obtain the mean lake level was described in a series of papers published by the Great Lakes Environmental Research Laboratory (GLERL) in the mid-1970s (Quinn and Todd, 1974; Quinn, 1975a, 1975b; Quinn and Derecki, 1976a, 1976b). The method is a weighted average with the weight for each station given by the Theissen polygon procedure. This procedure was developed by hydrologists to determine the mean precipitation in a basin based on measured precipitation at a limited number of stations (Croley and Hartmann, 1985). Polygons are drawn around each station with the edges of the polygons bisecting lines drawn between each pair of stations. The fractional area of each polygon relative to the area of the whole basin is the weight assigned to the station at the center of the polygon. The weighting is based solely on the geometry of the network and not on the signals recorded at each station.

This method was applied to the Great Lakes water level measurements where, unlike with precipitation data, the stations are all located along the edges of the basin. As a result of the elongated geometry of the lakes, stations near the middle of the lakes are more heavily weighted than stations at the ends of the lakes. The GLERL reports obtained Theissen weights for each new network formed as a new station was added to the existing stations over time and compared the differences in mean lake levels resulting from the addition of one station. When the differences became small, the network was judged to be adequate for measuring mean lake levels. Since the reports were published, two water level stations (Barcelona on Lake Erie and Two Harbors on Lake Superior) have been removed. For the Theissen weights to be used in this paper, the weight for Barcelona has been combined with that of the station at Erie and the weight for Two Harbors has been combined with that of the station at Duluth.

2.3. CROLEY'S SPATAL-OPTIMUM METHOD

In the mid-1980s, Croley (1986, 1987) investigated methods of calculating weighted averages of Lake Erie and Lake Superior station data to eliminate long-term (weekly to monthly) wind set-up error. The theoretical wind set-up for a steady-state wind stress of unit amplitude was calculated for all the stations around the lake based on a numerical hydrodynamic model. Theissen weights were then calculated for every possible subnetwork composed of subsets of the complete network.

The errors in the Theissen mean lake level due to wind set-up were obtained for each subnetwork and minumum error networks were found. Errors were further reduced when weights were obtained without constraining them to be Theissen weights but subject to eliminating the long-term wind set-up error and minimizing the total error for twelve years of daily data. Croley called this the spatial-optimum method.

For smaller networks, the station weights were nearly uniform. However, for the larger networks, the southern shore of Lake Erie was more heavily weighted than the northern shore and the northern shore of Lake Superior was more heavily weighted than the southern shore. Using these Croley spatial-optimum weights to calculate mean lake level could cause errors over the long term due to differential glacial rebound (Clites, 1992). As mentioned in the previous section, for the calculations to be made in this paper, the station weight for Barcelona was combined with Erie and the station weight for Two Harbors was combined with Duluth. In addition, the station weight for Monroe on Lake Erie was combined with the weight for the station at Fermi.

2.4. EMPIRICAL ORTHOGONAL FUNCTIONS

When water levels are measured around the circumference of a lake, the result is a number of non-orthogonal time series. Several signals caused by different physical phenomena are combined in different proportions to form the total signal at each station. The mean lake level is a signal that should be present at each station with equal amplitude. The wind set-up signal (lake surface tilt) should also be present at each station but the amplitude will vary from station to station. The signal will be large in the upwind direction and large (but 180 degrees out of phase) in the downwind direction. The signal will have small amplitudes approaching a nodal line near the middle of the lake where the amplitude goes to zero. Other signals (possibly wind-driven) may be large at one or two of the stations and negligible at the other stations.

The empirical orthogonal function (EOF) method is a way of resolving independent, orthogonal signals from a number of non-orthogonal time series (Kundu et al., 1975; Preisendorfer, 1988). This is done by forming a symmetric matrix composed of the cross-correlations $R(z_i,z_j)$ of each time series $v_k(z_i)$ at station z_i with every other time series at station z_j. Auto-correlations $R(z_i,z_i)$ are along the diagonal of the matrix.

$$R(z_i,z_j) = \frac{1}{K} \sum_{k=1}^{K} v_k(z_i)\ v_k(z_j) \qquad (1)$$

where k is an index for time and i and j are indices for the stations. There are K data points and N stations. This matrix is used to solve for the eigenvalues λ_n and eigenvectors $\phi_n(z_i)$ of the orthogonal signals or modes.

$$\sum_{i=1}^{N} R(z_i,z_j)\ \phi_n(z_i) = \lambda_n\ \phi_n(z_j) \tag{2}$$

where n is an index for the mode. The number of modes will be equal to the number of stations N. The eigenvalues indicate the variance or energy for each mode in the system. The eigenvectors indicate the amplitude or scaling factor for each mode at each station. A time series E_{kn} for each mode is also obtained which is a combination of the input time series at each station.

$$E_{kn} = \sum_{i=1}^{N} v_k(z_i)\ \phi_n(z_i) \tag{3}$$

This method is based on the actual signals recorded at the stations rather than on the geometry of the network. If the empirical orthogonal function analysis is carried out for the complete network and the first mode has nearly the same eigenvector amplitude at each station, the first mode is the mean lake level. It is implicit in this assumption that there are presently enough stations on each lake to closely approximate the mean lake level. Once the mean lake level time series is established, any other time series computed from fewer stations can be statistically evaluated to show how closely it approximates the mean lake level. The two statistics to be considered are the standard error and the maximum error.

3. DATA ASSESSMENT

3.1. DATA

There are presently 52 water level stations on the Great Lakes (NOS, 1994) without including stations on the waterways connecting the lakes. There are 31 U. S. stations and 21 Canadian stations (Figure 1). Archived hourly data for 1990 to 1994 were obtained for all 52 stations. The water level at each station is given to the nearest centimeter. The station at Mackinaw City is located on the Straits of Mackinac which connects Lake Michigan to Lake Huron. Since water can be transported in either direction through the straits, the Mackinaw City station is considered to be part of both the Lake Michigan and the Lake Huron networks.

All of the analyses in this report were carried out for two data sets. An analysis was carried out for 5 years (1990-1994) of 2-day averaged data to evaluate station networks necessary for obtaining the beginning-of-month lake levels used for lake level regulation. Although the beginning-of-month lake levels are dependent on only 2 days of data in a month, mean lake levels can also be calculated for any other 2-day period in a month. All 2-day periods in the 5-year data set were used in the analysis to provide an adequate sampling of high wind stress events that are more likely to occur during the winter months. Further analysis was also carried out with 1990 hourly data to examine the consequences of reduced network size on measuring both mean water levels and lake surface tilt on an hourly basis.

The hourly time series for 1990 for each lake are shown in Figures 2 to 6. Time series are offset to display all the stations. There are fourteen stations on Lake Erie, twelve stations on Lake Huron, and nine stations each on Lakes Superior, Michigan, and Ontario. The 2-day averaged time series for 1990-1994 are shown in Figures 7 to 11. Again, the time series are offset for comparison. Whenever any gaps in the hourly or 2-day averaged data occured at any station, all the data for the other stations on the same lake during the gap were dropped.

3.2. PRELIMINARY ANALYSES

Preliminary EOF analyses of Lake Michigan and Lake Huron data showed that in each lake one station was dominating the second modes; Green Bay for Lake Michigan and Essexville for Lake Huron. When one station dominates the second mode, it indicates that the second mode is not the general wind set-up over the whole lake but rather a large signal that is unique to that station. Each of these stations is at the head of a shallow bay that is at some distance from the main part of the lakes. The signals at these stations have larger amplitudes than the other stations, probably due to large wind set-up in the bays and in the case of Green Bay a resonance or seiche amplified by the bay (Figures 3 and 4). In order that the EOF analyses better represent the lakes as a whole, these two stations were eliminated from subsequent analyses.

Preliminary EOF analysis of the 14 Lake Erie stations showed the effect of strong wind set-up events near the two ends of the lake. The first mode turned out to be a combination of the mean lake level and the wind set-up at stations near the western end of the lake while the second mode was dominated by wind set-up at stations near the eastern end of the lake. This is due to the shallow depth of the western end of the lake which is very responsive to wind events. Only when two of the five western stations are dropped from the EOF analysis does the first mode represent the mean lake level alone and the second mode represent the wind set-up at both ends of the lake. Therefore, the stations at Toledo and Fermi are dropped and the twelve remaining stations are analyzed as the full network. However, the stations at Toledo and Fermi will be considered for possible smaller network configurations.

Figure 1. Great Lakes water level stations. There are 31 U.S. stations and 21 Canadian stations. (PC -- Port Colborne, PW -- Port Weller)

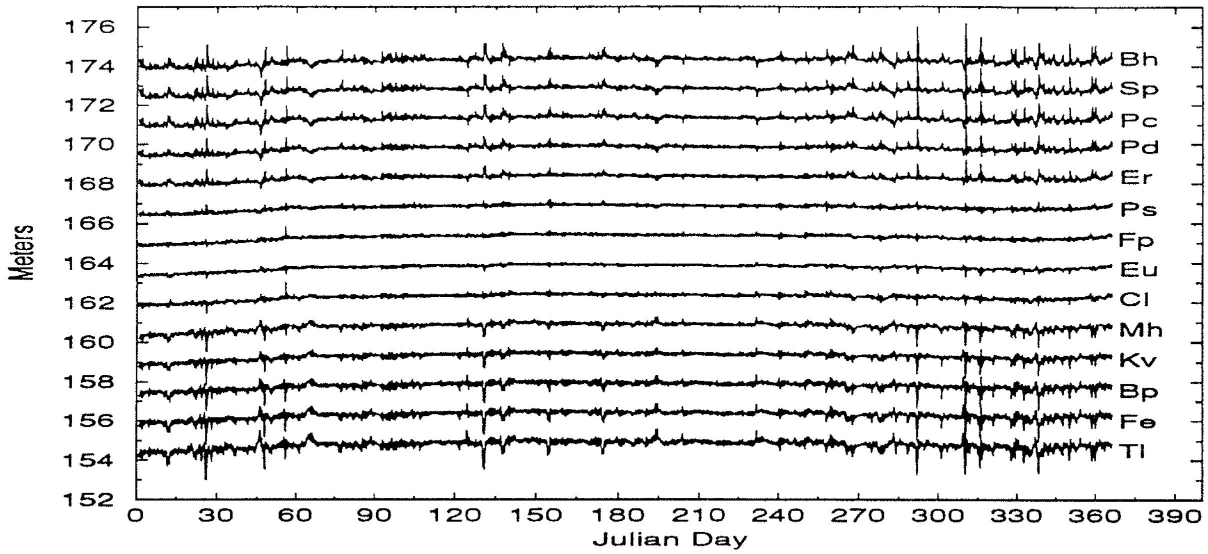


Figure 2. Lake Erie hourly water levels for 1990 (offset for comparison). Bh - Buffalo Harbor, Sp - Sturgeon Point, Pc - Port Colborne, Pd - Port Dover, Er - Erie, Ps - Port Stanley, Fp - Fairport, Eu - Erieau, Cl - Cleveland, Mh - Marblehead, Kv - Kingsville, Bp - Bar Point, Fe - Fermi, Tl - Toledo.

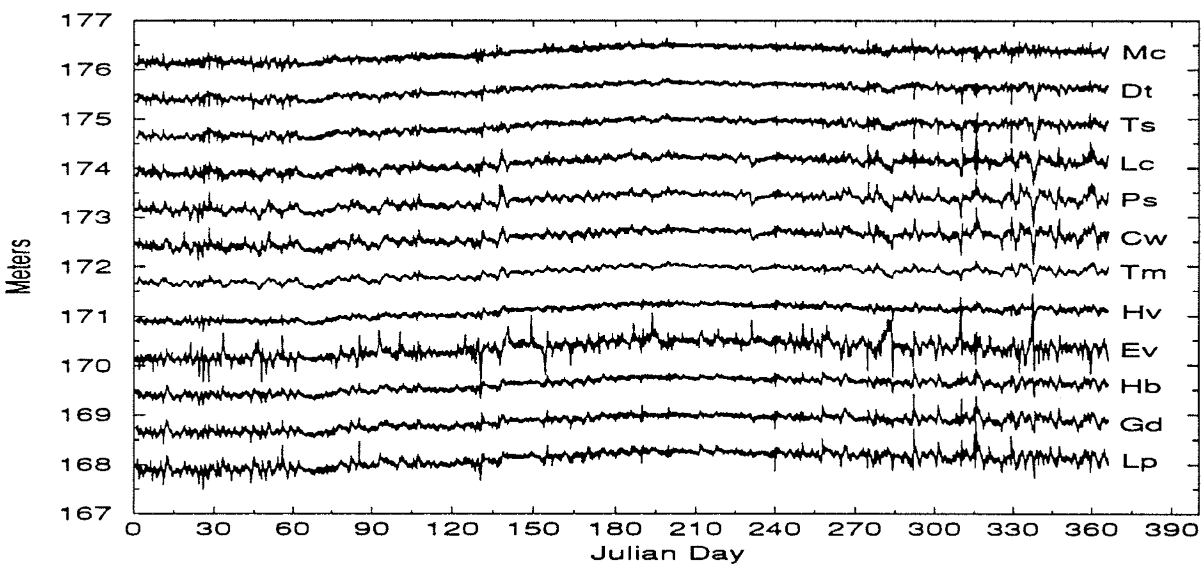


Figure 3. Lake Huron hourly water levels for 1990 (offset for comparison). Mc - Mackinaw City, Dt - De Tour, Ts - Thessalon, Lc - Little Current, Ps - Parry Sound, Cw - Collingwood, Tm - Tobermory, Hv - Harrisville, Ev - Essexville, Hb - Harbor Beach, Gd - Goderich, Lp - Lakeport.

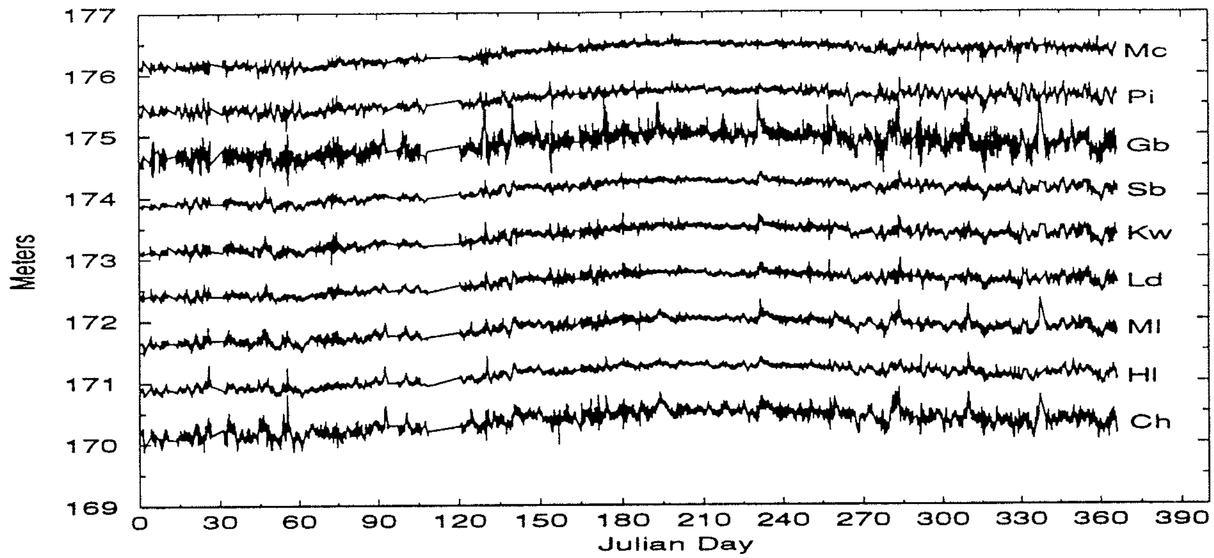


Figure 4. Lake Michigan hourly water levels for 1990 (offset for comparison). Mc - Mackinaw City, Pi - Port Inland, Gb - Green Bay, Sb - Sturgeon Bay, Kw - Kewaunee, Ld - Ludington, Ml - Milwaukee, Hl - Holland, Ch - Calumet Harbor.

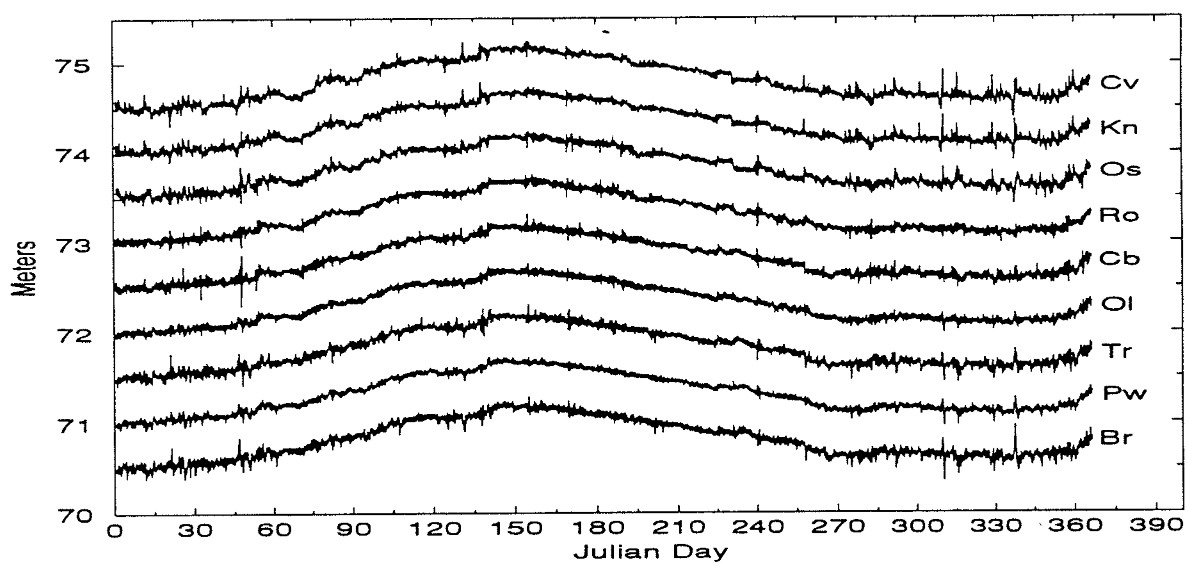


Figure 5. Lake Ontario hourly water levels for 1990 (offset for comparison). Cv - Cape Vincent, Kn - Kingston, Os - Oswego, Ro - Rochester, Cb - Cobourg, Ol - Olcott, Tr - Toronto, Pw - Port Weller, Br - Burlington.

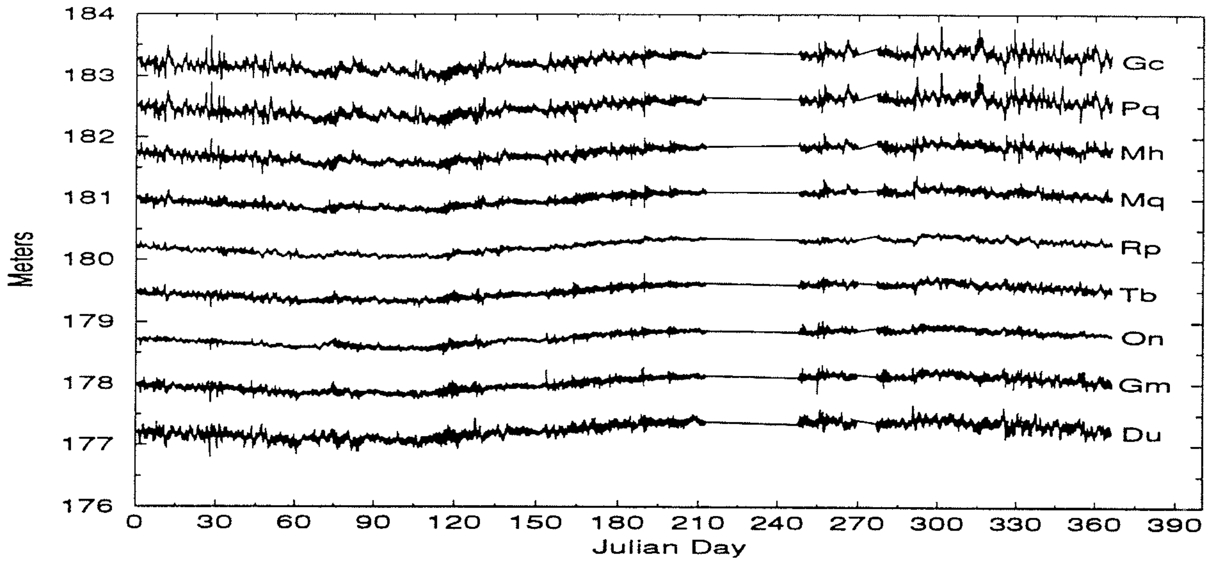


Figure 6. Lake Superior hourly water levels for 1990 (offset for comparison). Gc - Gros Cap, Pq - Port Iroquois, Mh - Michipicoten Harbour, Mq - Marquette, Rp - Rossport, Tb - Thunder Bay, On - Ontonagon, Gm - Grand Marais, Du - Duluth.

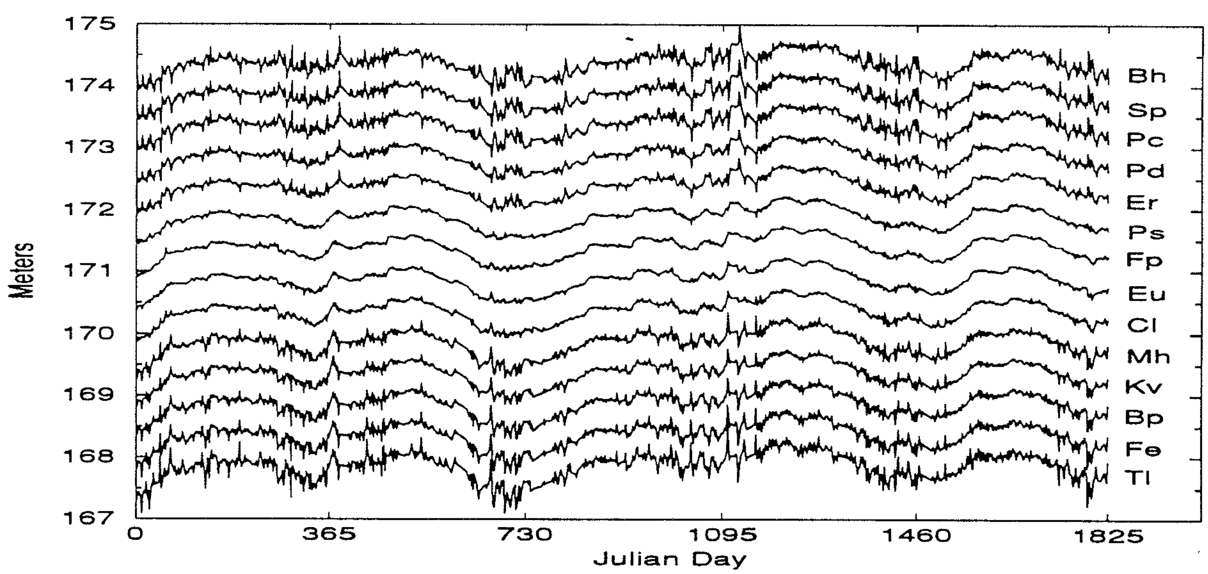


Figure 7. Lake Erie 2-day averaged water levels for 1990-1994 (offset for comparison). Bh - Buffalo Harbor, Sp - Sturgeon Point, Pc - Port Colborne, Pd - Port Dover, Er - Erie, Ps - Port Stanley, Fp - Fairport, Eu - Erieau, Cl - Cleveland, Mh - Marblehead, Kv - Kingsville, Bp - Bar Point, Fe - Fermi, Tl - Toledo.

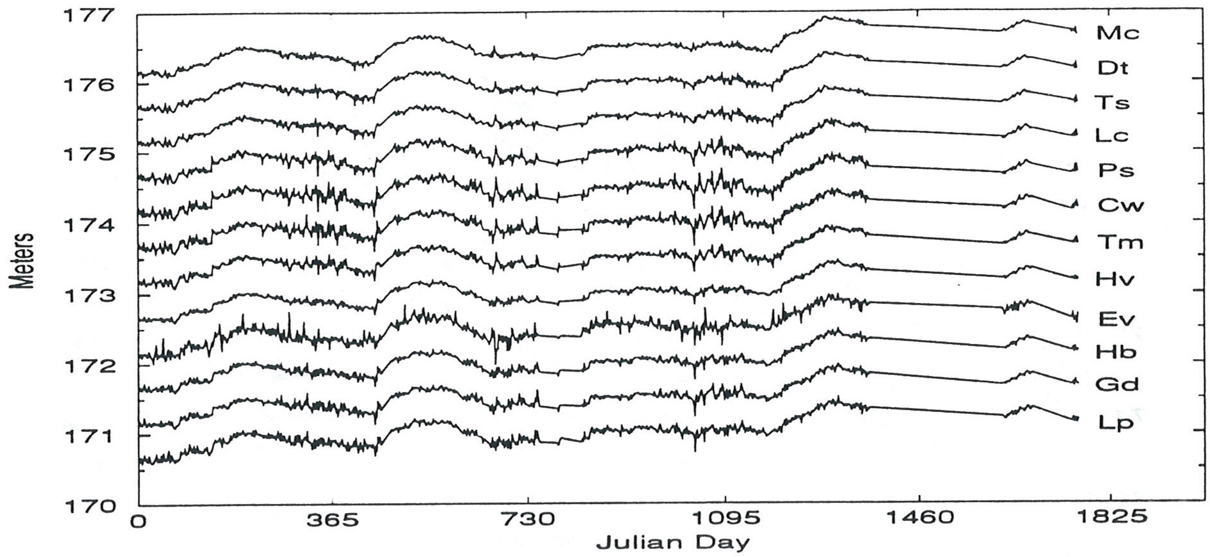


Figure 8. Lake Huron 2-day averaged water levels for 1990-1994 (offset). Mc - Mackinaw City, Dt - De Tour, Ts - Thessalon, Lc - Little Current, Ps - Parry Sound, Cw - Collingwood, Tm - Tobermory, Hv - Harrisville, Ev - Essexville, Hb - Harbor Beach, Gd - Goderich, Lp - Lakeport.

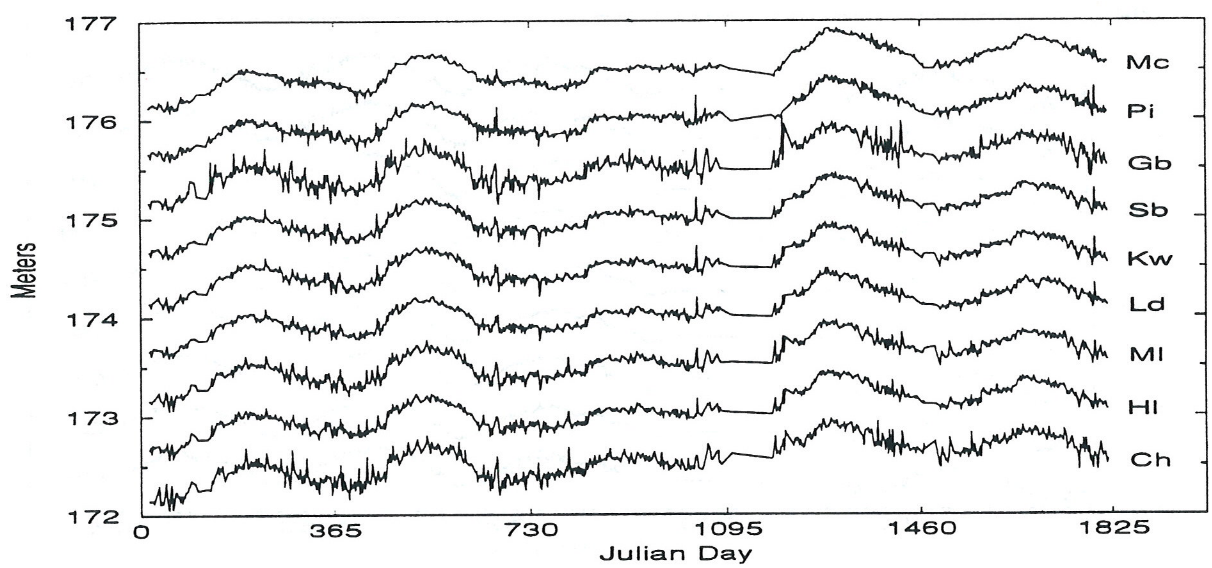


Figure 9. Lake Michigan 2-day averaged water levels for 1990-1994 (offset for comparison). Mc - Mackinaw City, Pi - Port Inland, Gb - Green Bay, Sb - Sturgeon Bay, Kw - Kewaunee, Ld - Ludington, Ml - Milwaukee, Hl - Holland, Ch - Calumet Harbor.

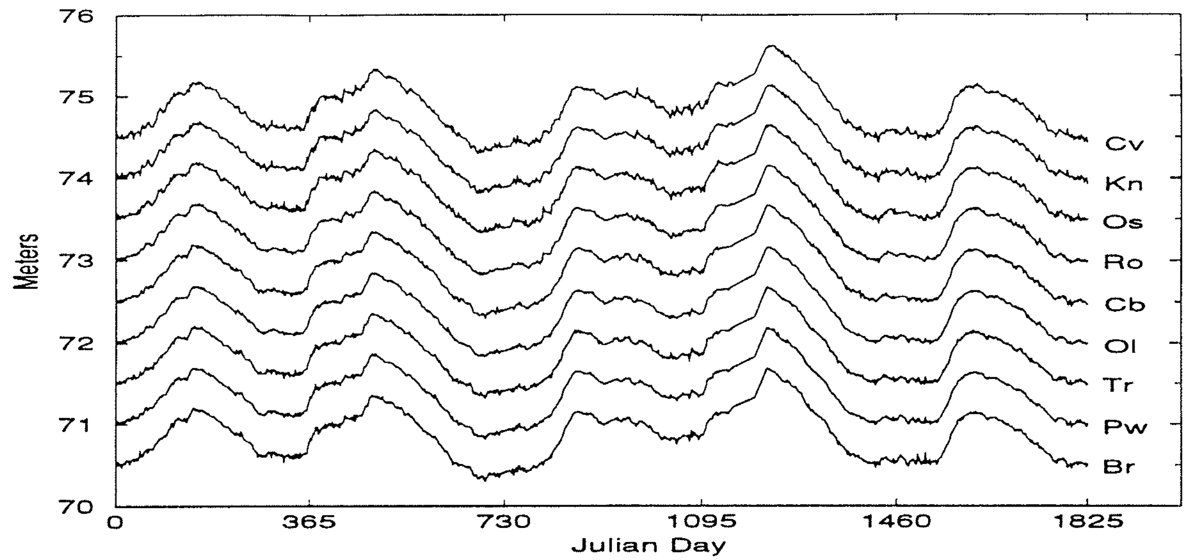


Figure 10. Lake Ontario 2-day averaged water levels for 1990-1994 (offset for comparison). Cv - Cape Vincent, Kn - Kingston, Os - Oswego, Ro - Rochester, Cb - Cobourg, Ol - Olcott, Tr - Toronto, Pw - Port Weller, Br - Burlington.

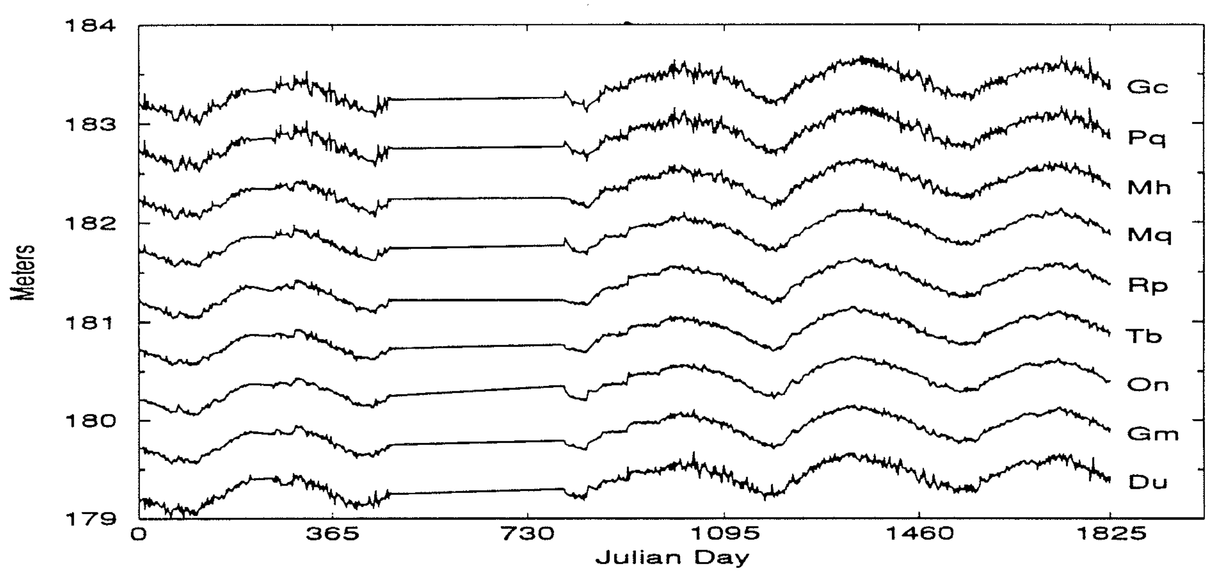


Figure 11. Lake Superior 2-day averaged water levels for 1990-1994 (offset for comparison). Gc - Gros Cap, Pq - Port Iroquois, Mh - Michipicoten Harbour, Mq - Marquette, Rp - Rossport, Tb - Thunder Bay, On - Ontonagon, Gm - Grand Marais, Du - Duluth.

4. ANALYSIS OF 2-DAY AVERAGED DATA

4.1. MEAN LAKE LEVEL COMPARISONS

The four different methods of approximating the mean lake level are shown in Figures 12 to 16 (offset for comparison). The Croley weights were only available for Lakes Erie and Superior. All four methods produce similar mean lake level signals, primarily composed of an annual cycle with a range of 40 to 60 cm and an interannual variability. Lakes Ontario and Erie generally reach their highest levels in the spring, Lakes Huron and Michigan usually peak in the summer, and Lake Superior peaks in the fall. There also appears to be a consistent rise in lake levels for Lakes Superior, Michigan, and Huron during this 5-year period. It is easily seen that Lakes Huron and Michigan mean lake levels have greater high frequency variability than the other lakes, an observation that will be discussed later.

Table 1. Mean Lake Level Difference Statistics (cm) relative to the Theissen Method 1990-1994 2-day averaged data

	Method	Standard error	Maximum error
Lake Erie	Average	0.62	3.10
	Croley	0.65	3.70
	EOF	0.83	3.16
Lake Huron	Average	0.48	2.30
	EOF	0.81	3.09
Lake Michigan	Average	0.31	2.20
	EOF	0.39	2.27
Lake Ontario	Average	0.29	1.20
	EOF	0.29	1.24
Lake Superior	Average	0.32	1.50
	Croley	0.37	2.20
	EOF	0.32	1.19

Since a time series of the true mean lake level is not available, we can only compare the methods with each other. The Theissen method generally gives a slightly smoother curve since the quieter stations near the middle of the lake are more heavily weighted than stations near the ends of the lake which are more affected by wind set-up. If the Theissen method is assumed to produce the closest approximation to real mean lake levels (as the Corps of Engineers does), difference statistics relative to the Theissen method (standard error and maximum error) may be calculated for the other methods (Table 1). All errors are small (less than 1 cm standard error), with the largest errors for Lakes Erie and Huron. The Theissen weights for Lake Huron (Quinn, 1975b) were obtained using only two

Canadian stations on the east side of the lake (Collingwood and Goderich) and therefore may not give the best approximation of the mean lake level. Although the EOF method does not always have the lowest errors, it provides more insight into the main physical processes operating in the lakes.

4.2. MODAL ENERGY DISTRIBUTION

When an EOF analysis was carried out for the full network for each lake, the first mode contained the greatest part of the energy ranging from 90.2% for Lake Erie to 99.7% for Lake Ontario (Table 2). The second mode, with energy percentages ranging from 9.3% for Lake Erie to 0.2% for Lake Ontario, is the lake surface tilt along the longer axis of each lake (i.e. the eigenvectors show that the second mode at one end of the lake is 180 degrees out of phase with the other end). The second EOF mode is shown along with the first EOF mode in Figures 12 to 16. The relative energy of the second mode to the first mode can be observed. The third EOF mode is also shown for Lake Huron since it is comparable in amplitude to the second.

Table 2. EOF Mode Energy Percentage (2-Day Averaged Data)

Mode	1	2	3	≥4
Superior	97.4	2.0	0.4	0.2
Michigan	97.5	1.8	0.3	0.4
Huron	98.0	1.0	0.8	0.2
Erie	90.2	9.3	0.3	0.2
Ontario	99.7	0.2	0.0	0.1

Lake Erie is the shallowest of the Great Lakes and therefore is most responsive to wind stress. The lake surface tilt along the shorter axis of the lake is the third mode for Lakes Superior, Huron, and Ontario and the fourth mode for Lakes Michigan and Erie. The third mode for Lakes Michigan and Erie is a mode with both ends of the lake out of phase with the middle of the lakes. Only for Lake Huron, due to its irregular shape, is the third mode comparable in energy to the second mode.

4.3. NETWORK SIZE

Since the first EOF mode obtained from the complete network is a good measure of the mean lake level, we now statistically compare the first EOF mode obtained from smaller networks to the first EOF mode obtained from the complete network. This is done by examining the standard error and the maximum error for every possible subnetwork (Figures 17 to 21). For the Lake Erie there are 16,382 possible configurations; for Lake Huron there are 2046 possible configurations; for Lakes Superior and Ontario there are 510 possible configurations; and for Lake Michigan there are 254 possible configurations.

For all lakes, it is possible to pick three or four station networks with small errors in mean lake level (standard errors less than 0.5 cm and maximum errors less than 2.5 cm). These networks have stations near the midpoint of the lake or with each station near one end balanced by a station near the other end. However, for Lake Erie (Figure 17), it is also possible to pick a network that will produce mean lake levels with large errors (standard errors greater than 5 cm and maximum errors greater than 25 cm). These networks have most of their stations near one end of the lake. The first mode will be a combination of mean lake level and the lake surface tilt along the longer lake axis. For the other lakes, the worst case networks have much smaller errors due to the fact that the other lakes are much less responsive to wind stress than Lake Erie.

For each subnetwork size, the lowest standard error and the lowest maximum error are shown for each lake in Figure 22. It can be seen that only small reductions in mean lake level error are obtained for networks greater than seven stations. It should be noted that for each network size, there are numerous configurations that give errors only slightly larger than the lowest error subnetwork.

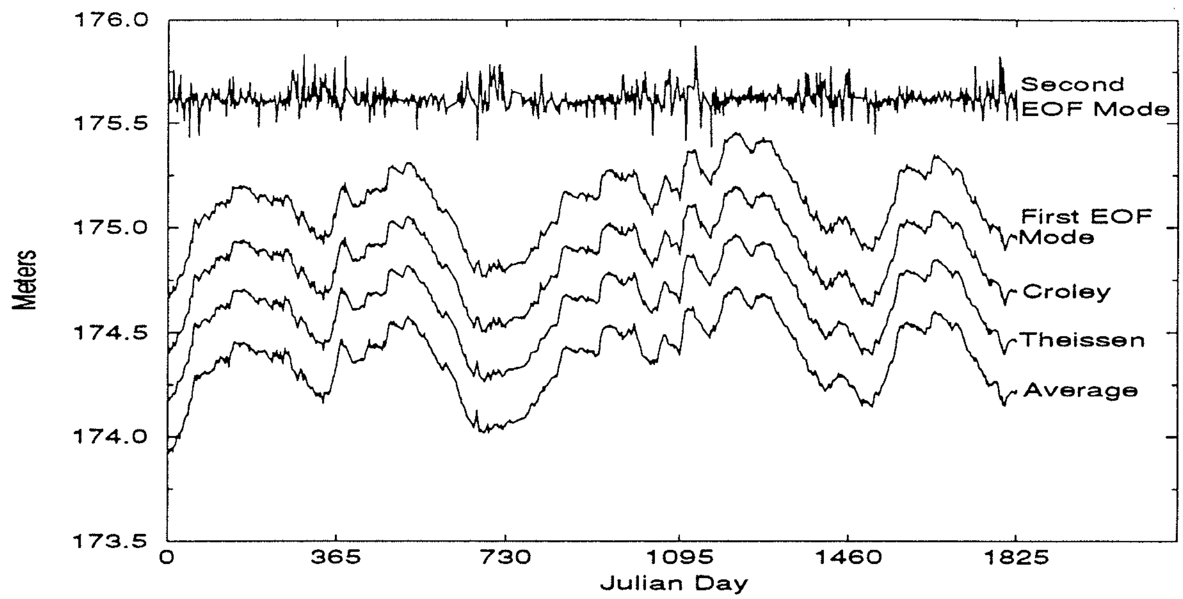


Figure 12. Mean lake levels (offset) for Lake Erie calculated for 2-day averaged water levels using uniform, Theissen, Croley, and EOF weights. Also shown is the second EOF mode.

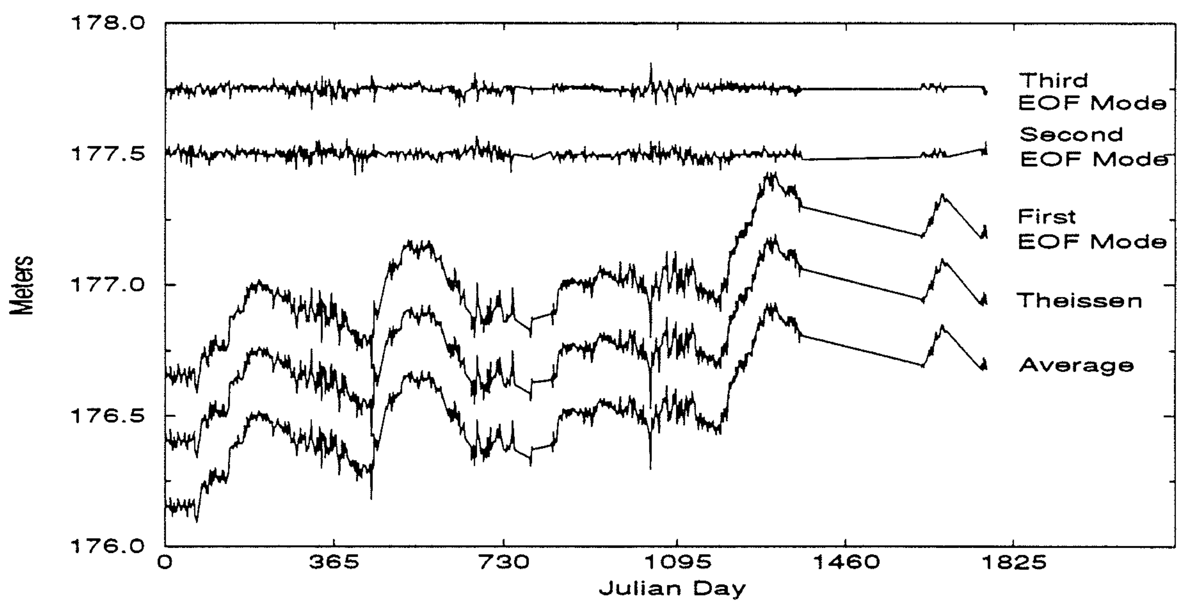


Figure 13. Mean lake levels (offset) for Lake Huron calculated for 2-day averaged water levels using uniform, Theissen, and EOF weights. Also shown are the second and third EOF modes.

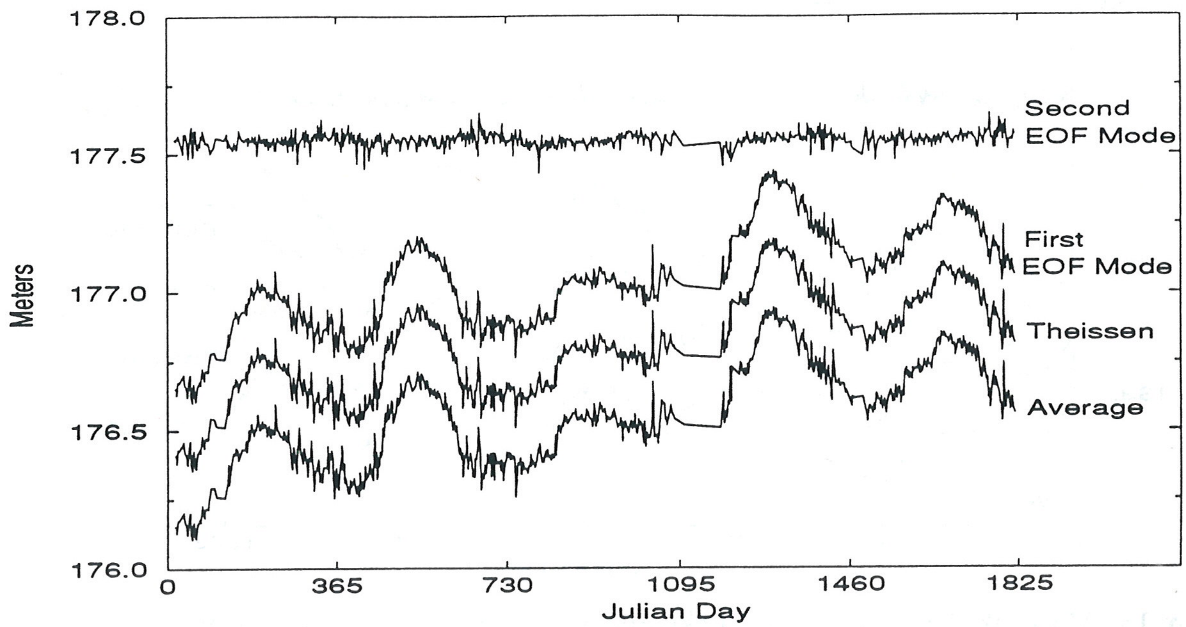


Figure 14. Mean lake levels (offset) for Lake Michigan calculated for 2-day averaged water levels using uniform, Theissen, and EOF weights. Also shown is the second EOF mode.

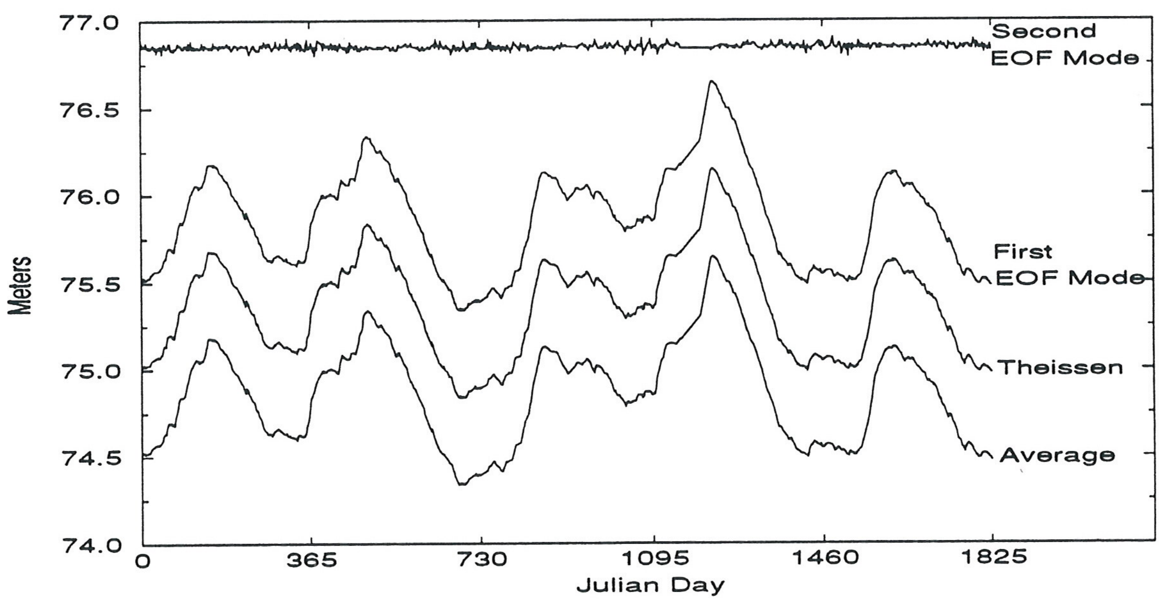


Figure 15. Mean lake levels (offset) for Lake Ontario calculated for 2-day averaged water levels using uniform, Theissen, and EOF weights. Also shown is the second EOF mode.

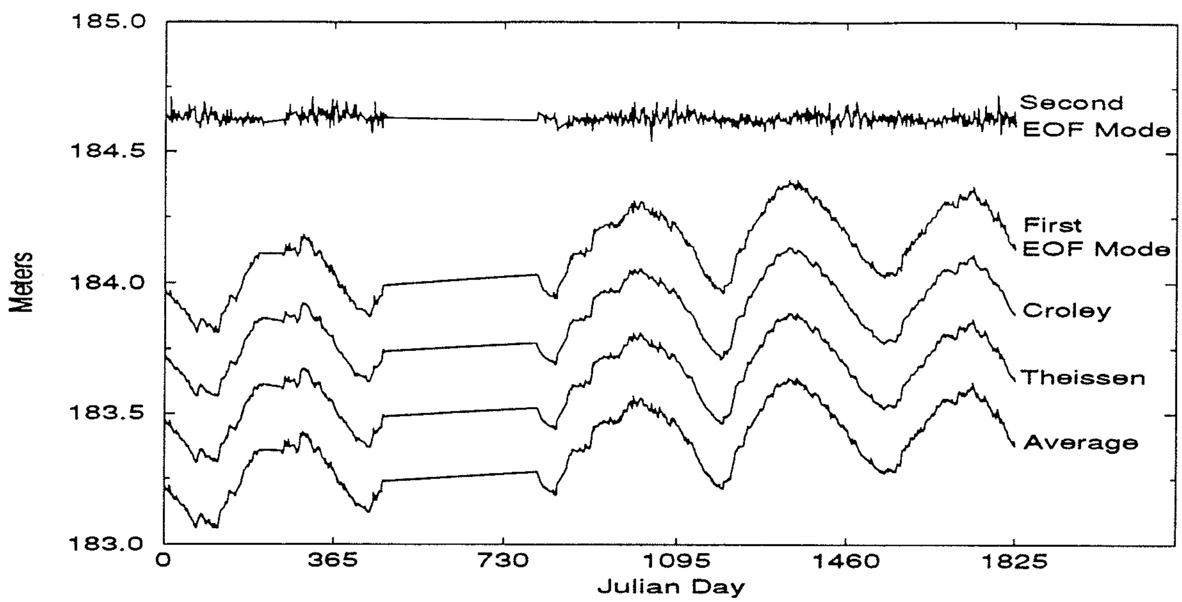
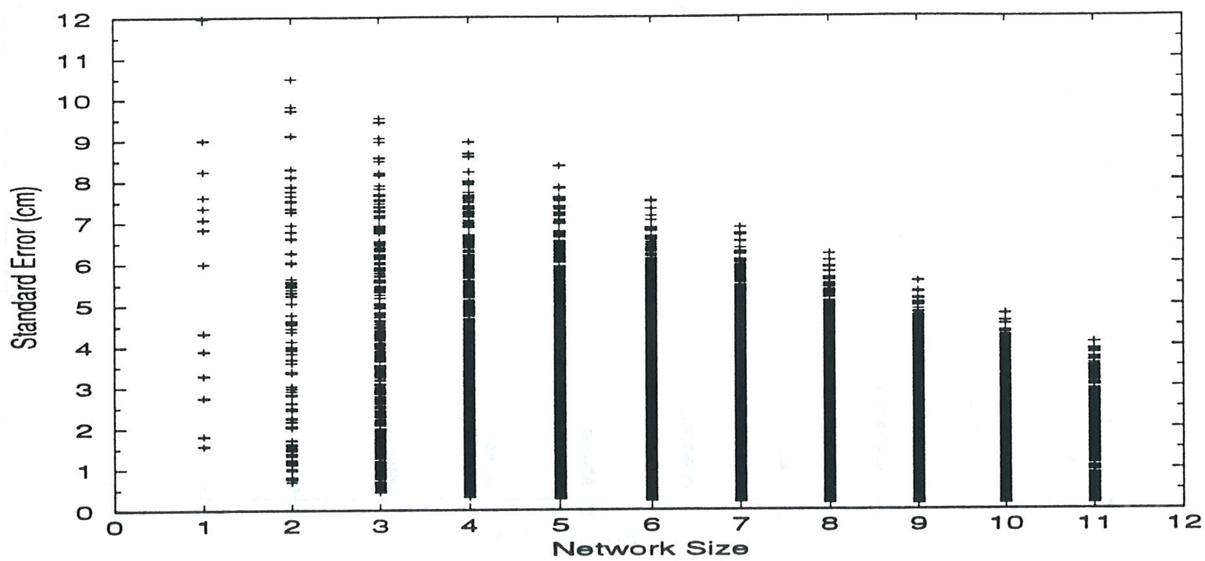
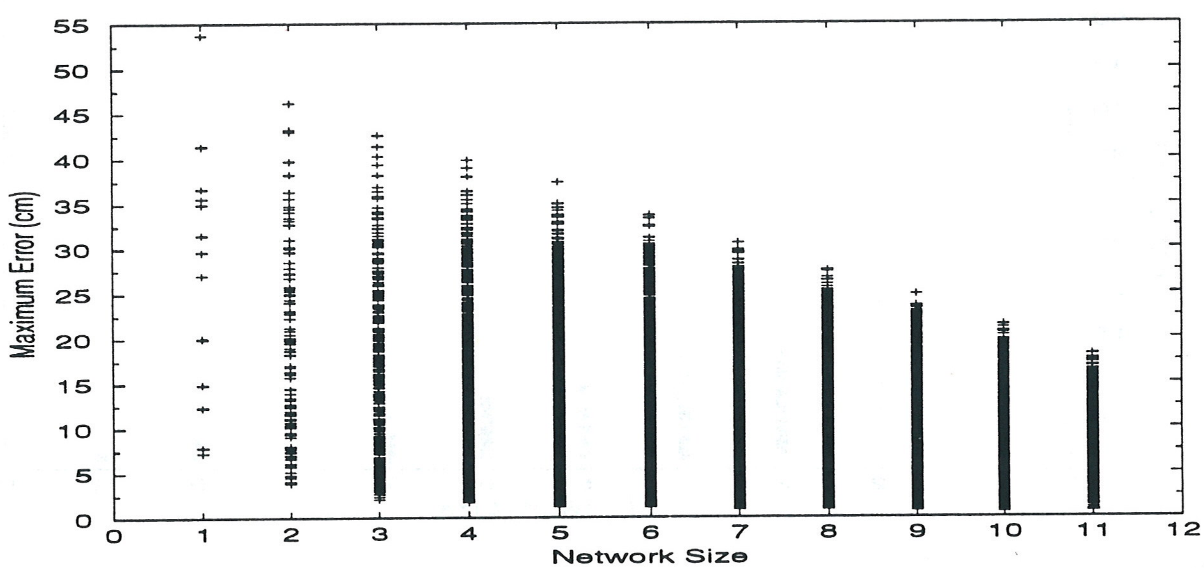


Figure 16. Mean lake levels (offset) for Lake Superior calculated for 2-day averaged water levels using uniform, Theissen, Croley, and EOF weights. Also shown is the second EOF mode.

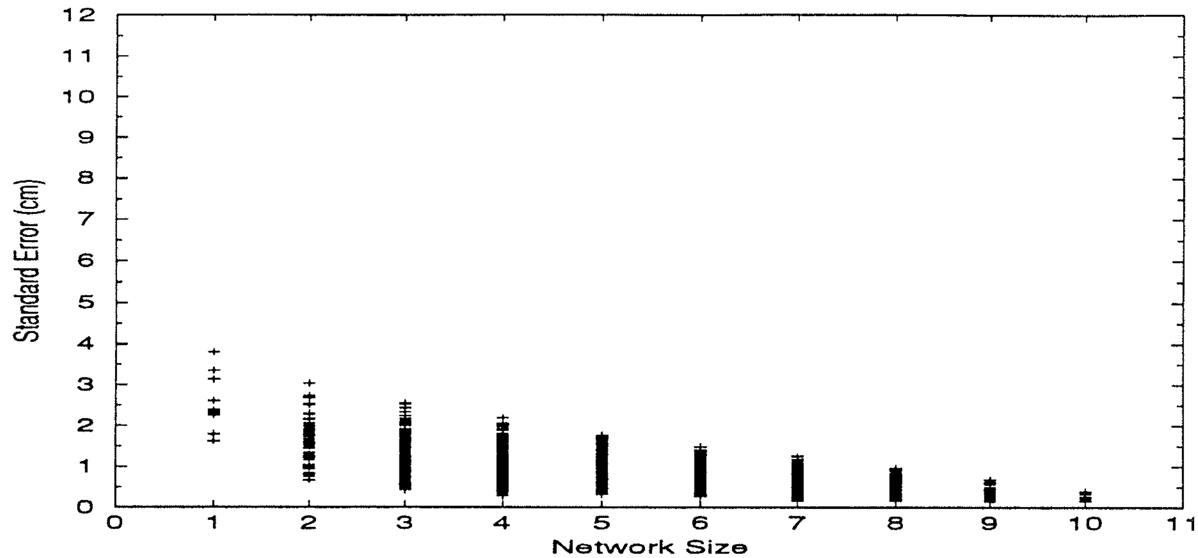


a)

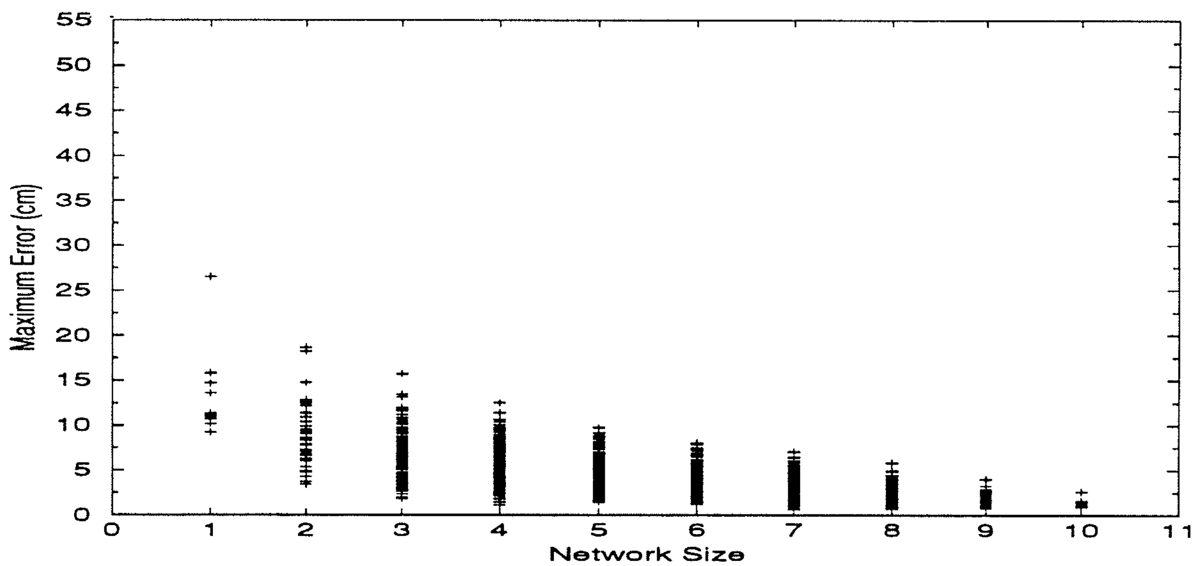


b)

Figure 17. a) Standard error and b) maximum error of subnetwork first EOF modes for Lake Erie 2-day averaged lake levels.

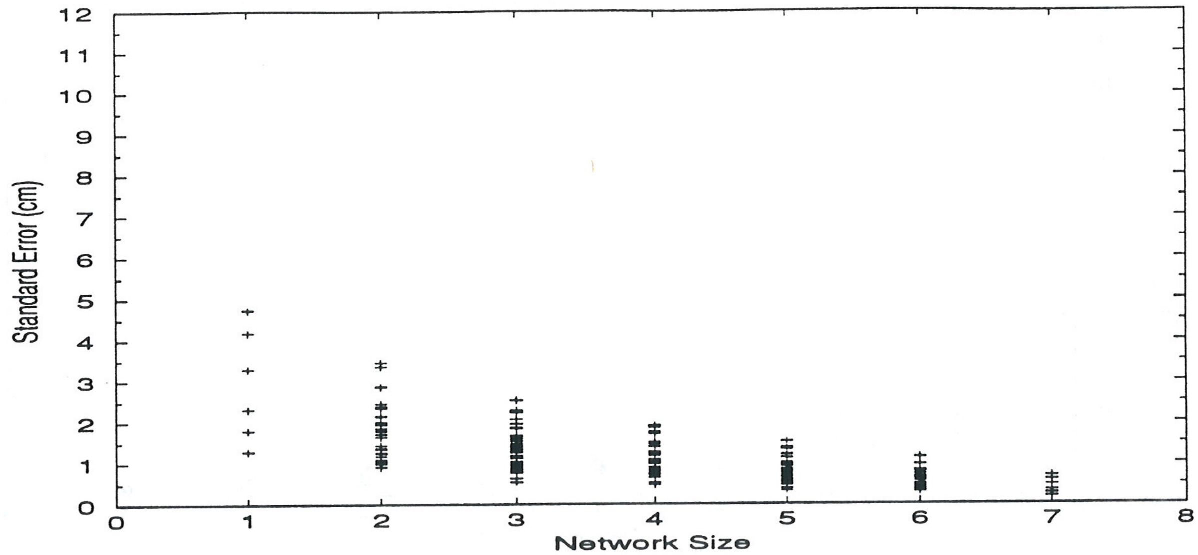


a)



b)

Figure 18. a) Standard error and b) maximum error of subnetwork first EOF modes for Lake Huron 2-day averaged lake levels.



a)

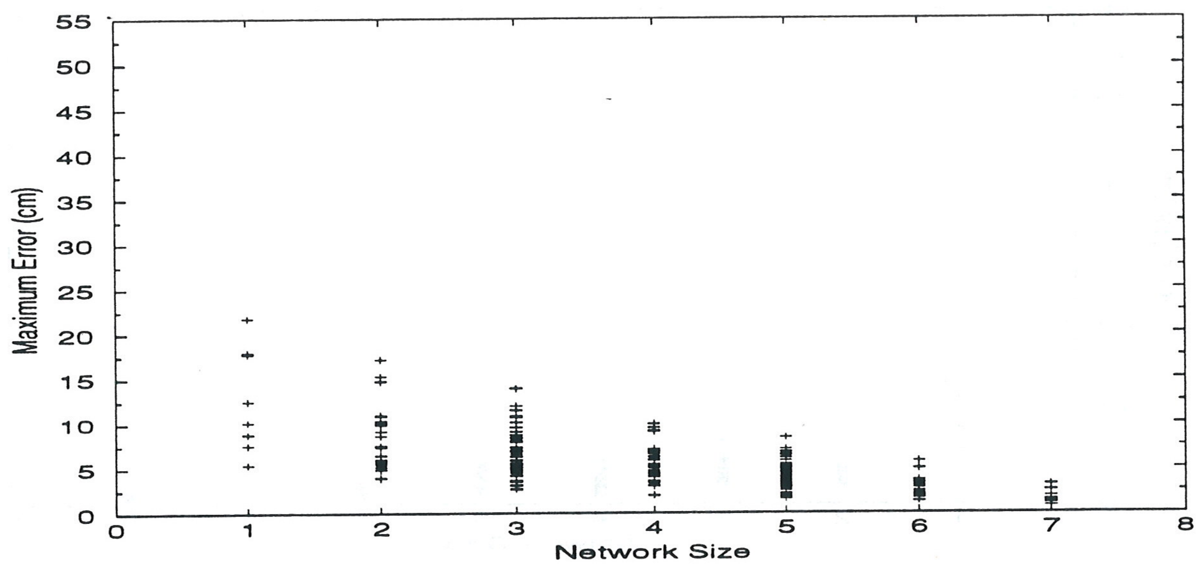
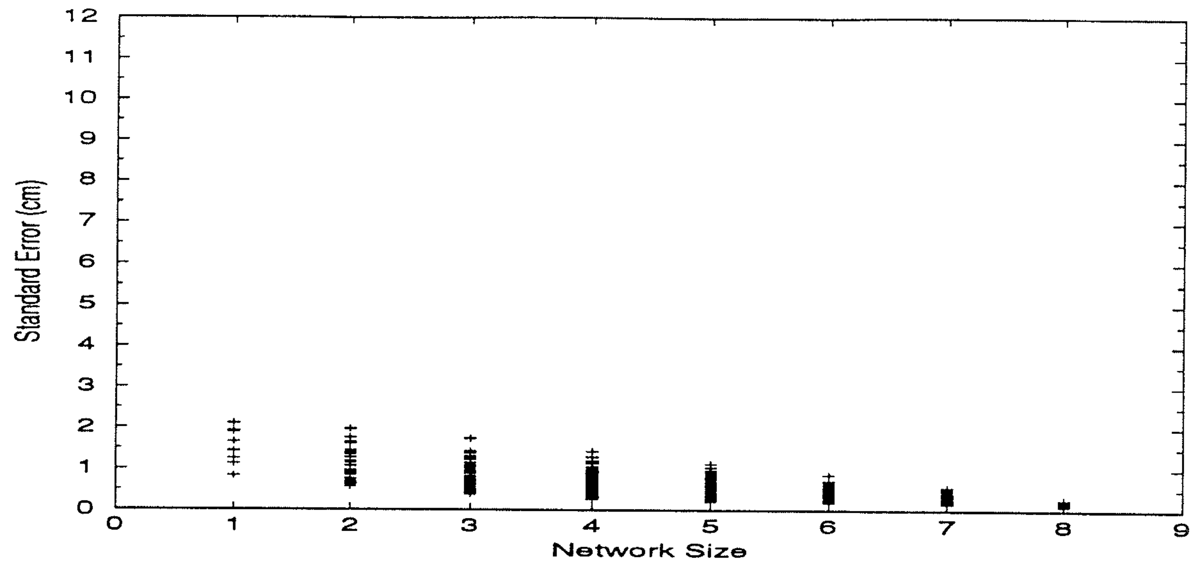
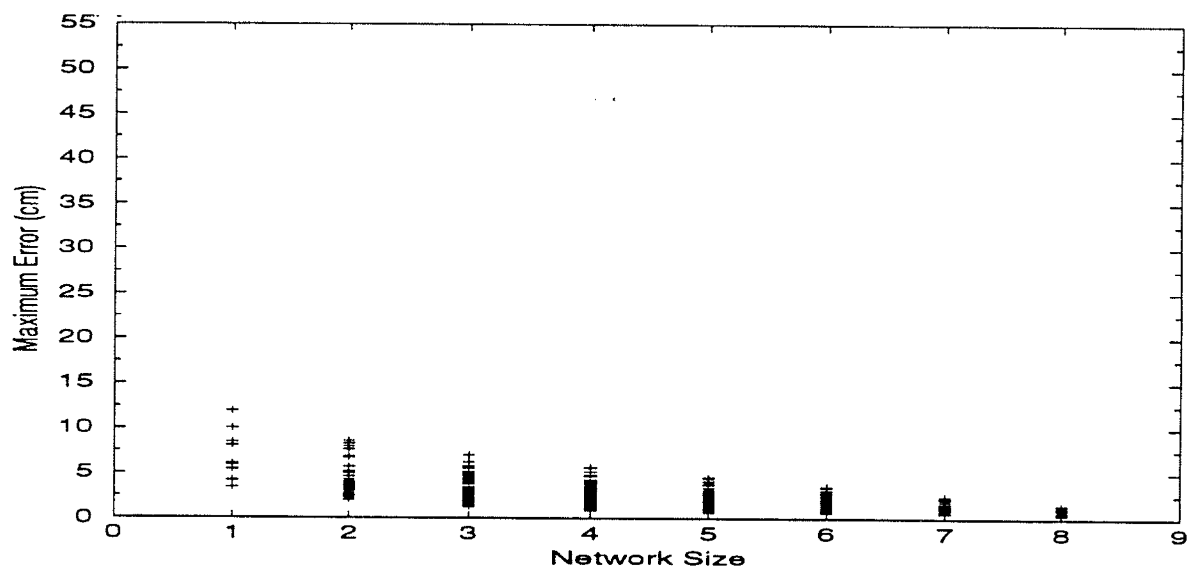


Figure 19. a) Standard error and b) maximum error of subnetwork first EOF modes for Lake Michigan 2-day averaged lake levels.

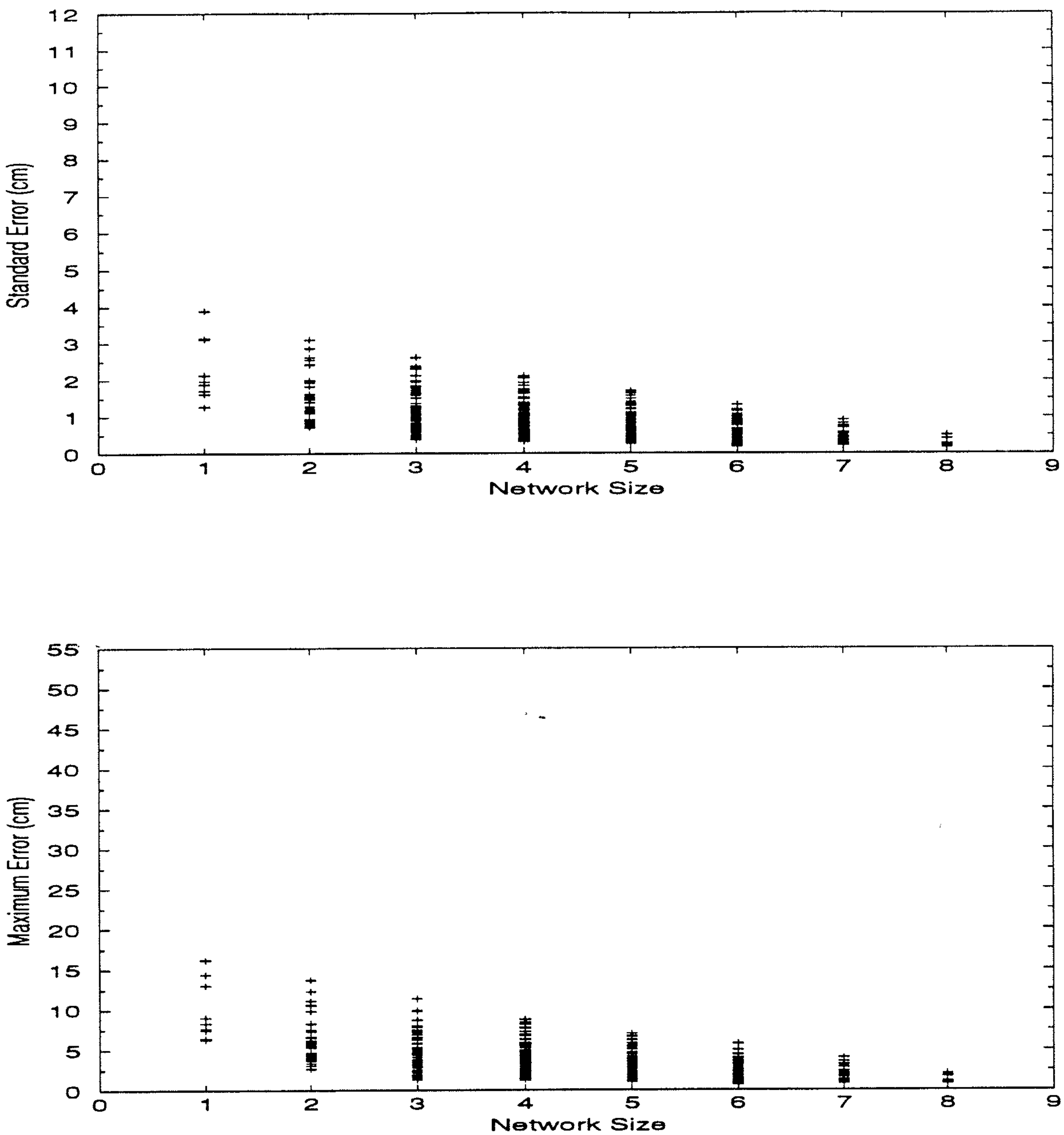


a)



b)

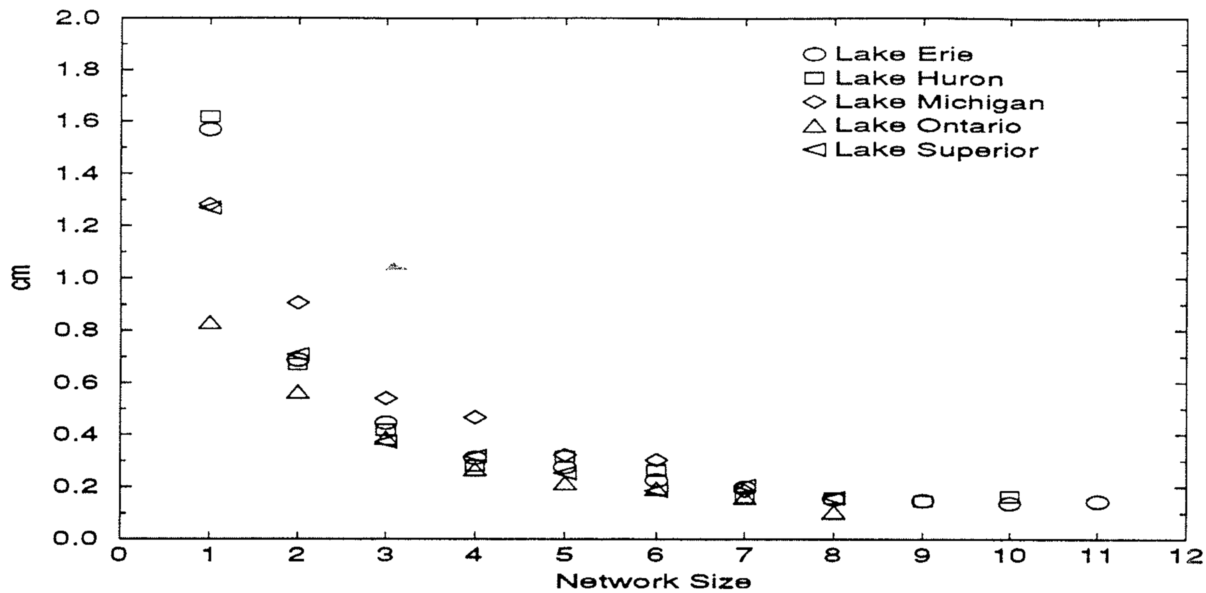
Figure 20. a) Standard error and b) maximum error of subnetwork first EOF modes for Lake Ontario 2-day averaged lake levels.



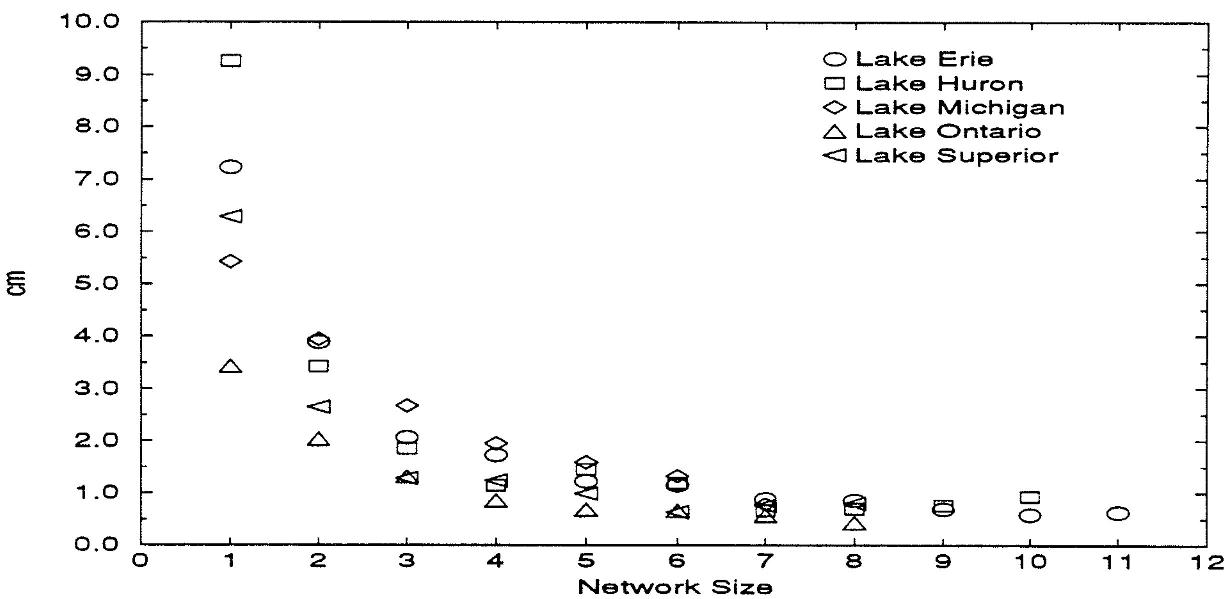
a)

b)

Figure 21. a) Standard error and b) maximum error of subnetwork first EOF modes for Lake Superior 2-day averaged lake levels.



a)



b)

Figure 22. Lowest first EOF mode a) standard error and b) maximum error for 2-day averaged lake levels.

5. ANALYSIS OF HOURLY DATA

5.1. MEAN LAKE LEVEL COMPARISONS

The four different methods of calculating mean lake levels from hourly data for 1990 are shown in Figures 23 to 27 (offset for comparison). The first EOF mode can be compared to the average, Theissen, and Croley (for Lakes Erie and Superior) methods. The second EOF modes representing lake surface tilt along the longer lake axis (plus the third EOF mode for Lake Huron) are also shown for comparison with the first EOF modes. All mean lake levels produce similar annual cycles with some high frequency differences during storms. As with the 2-day averaged data analyses in the previous section, Lakes Huron and Michigan mean lake levels have more high frequency variability. As before, the Theissen method gives a slightly smoother curve since stations near the middle of the lake are more heavily weighted than stations near the ends of the lake. If the Theissen method is assumed to produce the closest approximation to the mean lake level, then the resulting difference statistics relative to the Theissen method (standard error and maximum error) are shown in Table 3. Standard errors are less than 2 cm for all methods. Although none of the methods clearly stands out as the best overall, the EOF method has other desirable properties.

Table 3. Mean Lake Level Difference Statistics (cm) relative to the Theissen Method 1990 hourly data

	Method	Standard error	Maximum error
Lake Erie	Average	1.71	16.60
	Croley	1.48	15.00
	EOF	1.91	8.94
Lake Huron	Average	0.99	7.60
	EOF	1.60	11.95
Lake Michigan	Average	0.91	6.00
	EOF	1.21	5.02
Lake Ontario	Average	0.57	4.00
	EOF	0.70	3.44
Lake Superior	Average	0.75	4.50
	Croley	0.80	4.60
	EOF	1.01	4.04

5.2. MODAL ENERGY DISTRIBUTION

The EOF mode energy percentages for 1990 hourly data from the complete network for each lake are shown in Table 4. Compared to the 2-day averaged data, the percentage of energy is lower for the first mode and greater for the second mode. This is because the time averaging of the hourly data in the previous analyses reduced the amplitude of the lake surface tilt signal. The percentage of energy in the first mode ranges from 61.7% for Lake Erie to 98.0% for Lake Ontario. The amount of energy in the second mode, which is due to lake surface tilt along the longer axis of the lakes, ranges from 34.0% for Lake Erie to 1.1% for Lake Ontario. Lake surface tilt along the shorter axis is the third mode for Lakes Superior, Huron, and Ontario and the fourth mode for Lakes Michigan and Erie. The third mode of Lakes Michigan and Erie has the middle of the lake out of phase with the two ends. The third mode is comparable in energy to the second mode only for Lake Huron. These results are similar to the results obtained with 2-day averaged data.

Table 4. EOF Mode Energy Percentage (Hourly Data)

Mode	1	2	3	≥4
Superior	85.9	9.9	1.7	2.5
Michigan	87.7	7.4	1.4	3.5
Huron	87.6	6.0	3.7	2.7
Erie	61.7	34.0	1.6	2.7
Ontario	98.0	1.1	0.3	0.6

5.3. NETWORK SIZE

The consequences of using smaller network sizes to obtain both the first EOF mode and the second EOF mode were evaluated using hourly data for 1990. (In the previous section, using 2-day averaged data, only the first EOF mode errors were evaluated.) The error statistics in this case were calculated for the difference between the first mode of the complete network and of the subnetwork plus the difference between the second mode of the complete network and of the subnetwork. If the first two modes can be reproduced by a subnetwork, most of the water level variability in the lake is being measured. The error statistics are shown in Figures 28 to 32 for every possible subnetwork as a function of network size.

The errors for hourly data are greater than the errors for 2-day averaged data, since the lake surface tilt signal is stronger in the hourly data and now the error statistics for the first two EOF modes are being considered. Lake Erie has large ranges of errors for each network size due to its responsiveness to wind stress. Subnetworks with all stations near one end of the lake can have large errors (standard errors greater than 10 cm and maximum errors greater than 100 cm). However, more spatially balanced network configurations have small errors (standard errors less than 1 cm and maximum errors less than 10 cm). For the other lakes, the worst case networks have errors much smaller than the worst case networks of Lake Erie.

The lowest standard errors and the lowest maximum errors for each subnetwork size are shown in Figure 33. It can be seen that only small error reductions are obtained for networks greater than eight stations. It should be kept in mind that for each network size, a large number of other configurations will give only marginally greater errors.

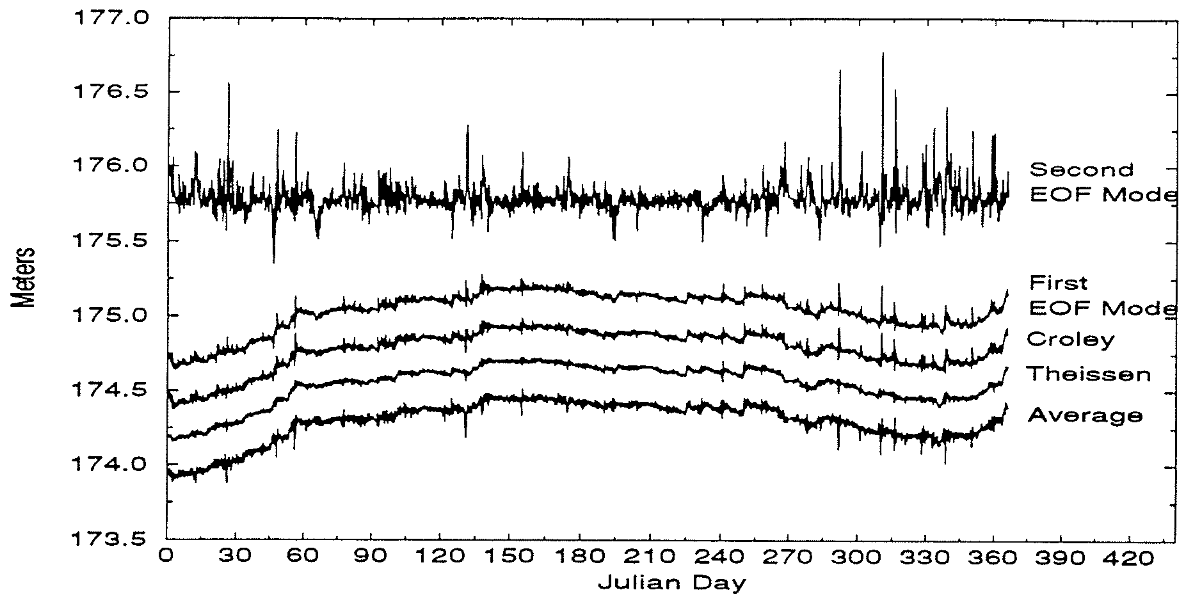


Figure 23. Mean lake levels (offset) for Lake Erie calculated for hourly water levels for 1990 using uniform, Theissen, Croley, and EOF weights. Also shown is the second EOF mode.

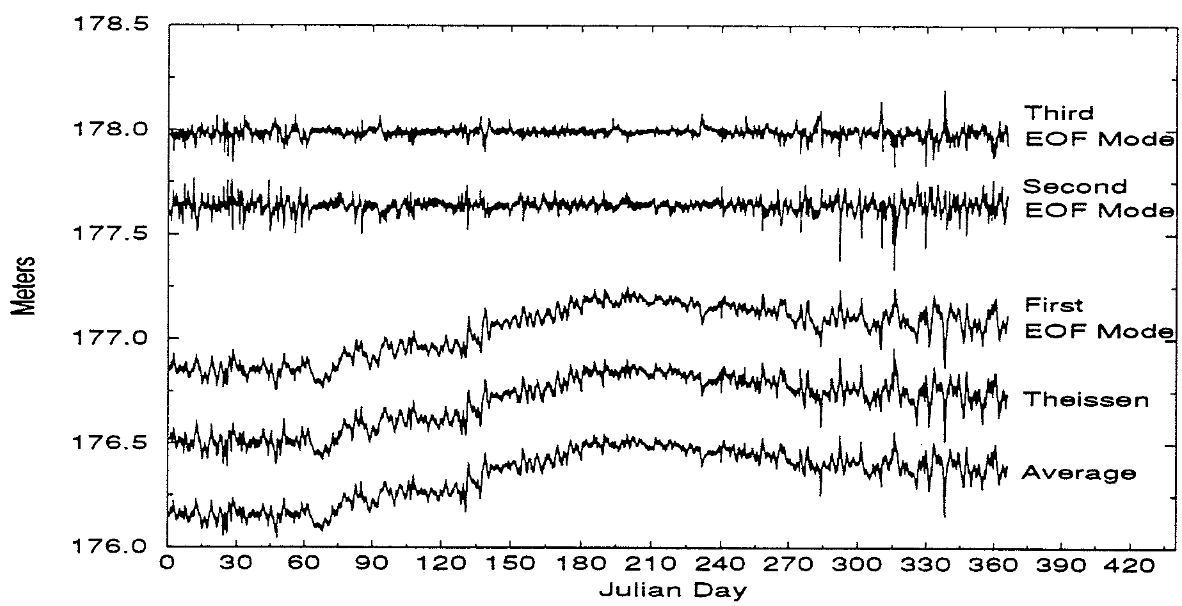


Figure 24. Mean lake levels (offset) for Lake Huron calculated for hourly water levels for 1990 using uniform, Theissen, and EOF weights. Also shown are the second and third EOF mode.

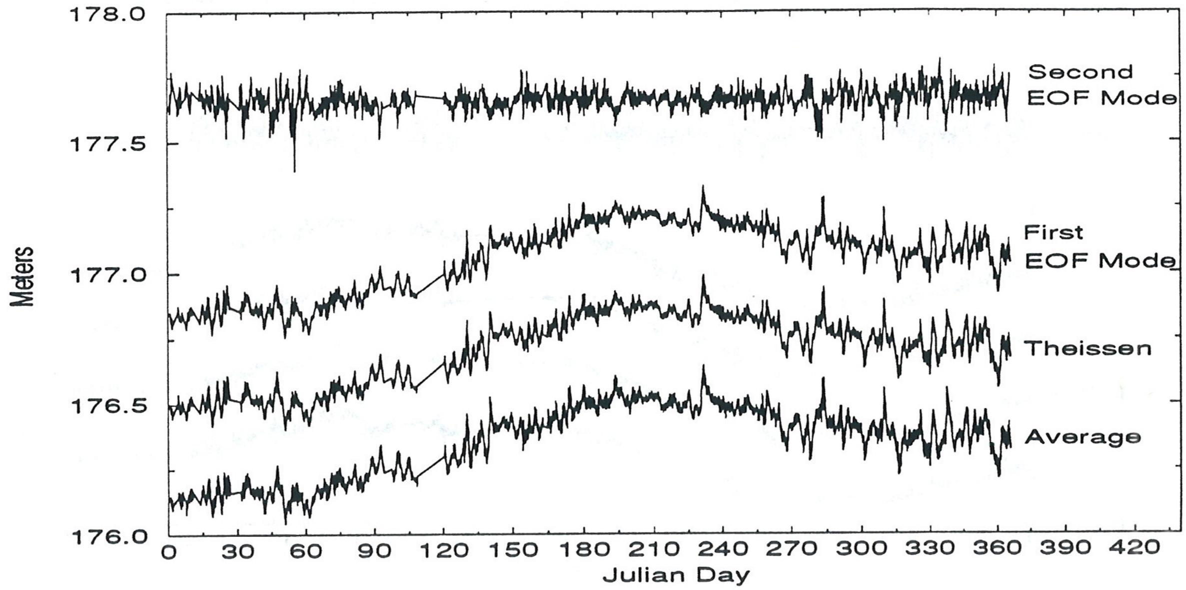


Figure 25. Mean lake levels (offset) for Lake Michigan calculated for hourly water levels for 1990 using uniform, Theissen, and EOF weights. Also shown is the second EOF mode.

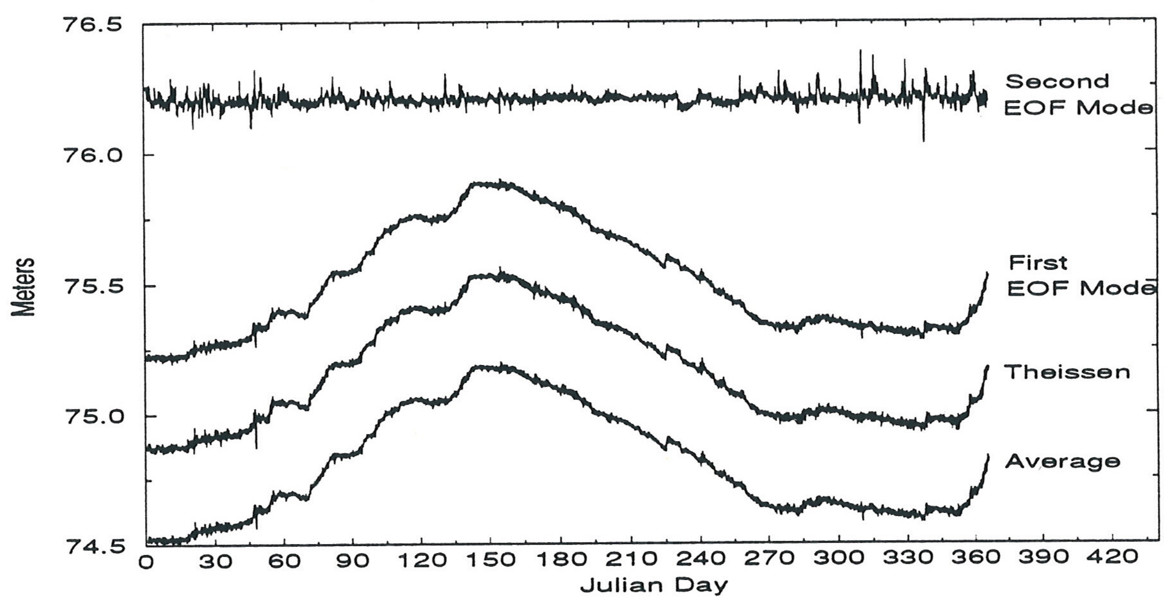


Figure 26. Mean lake levels (offset) for Lake Ontario calculated for hourly water levels for 1990 using uniform, Theissen, and EOF weights. Also shown is the second EOF mode.

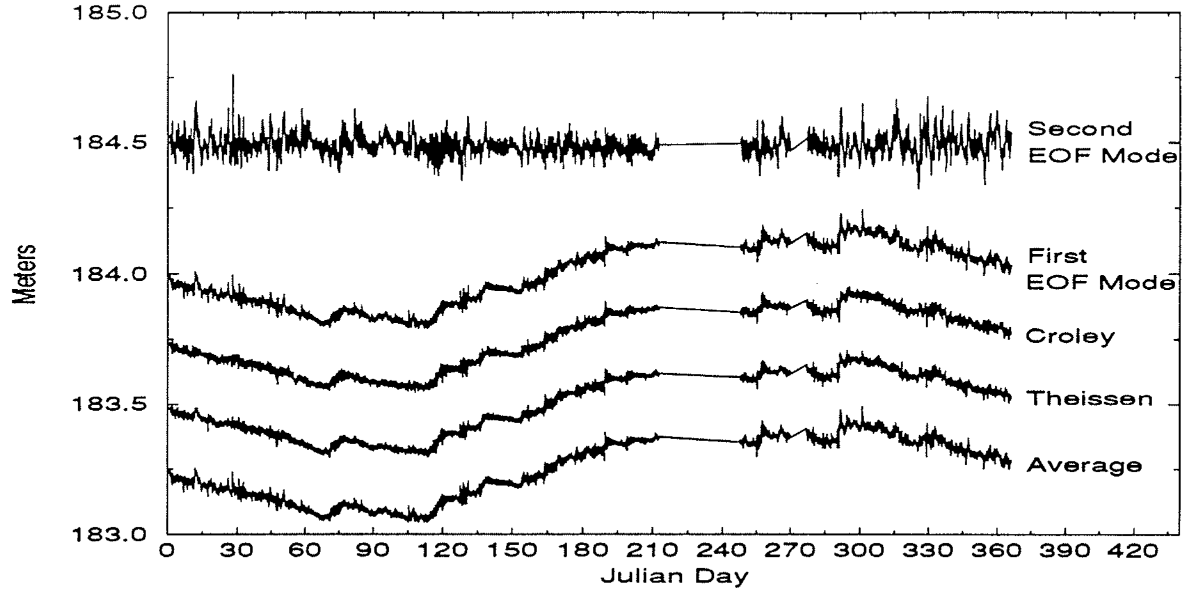
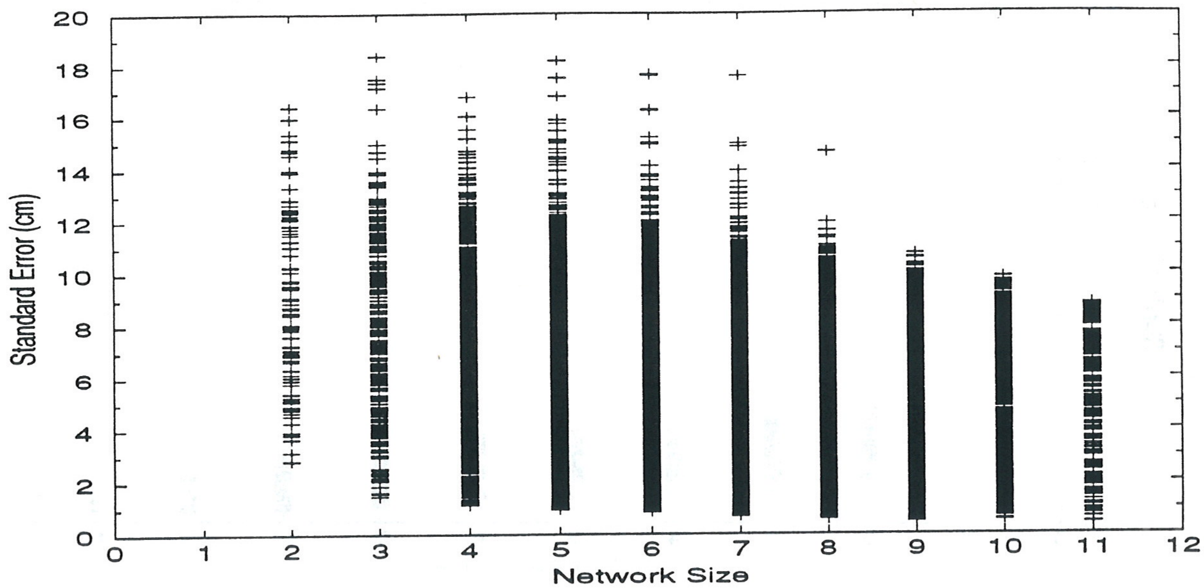
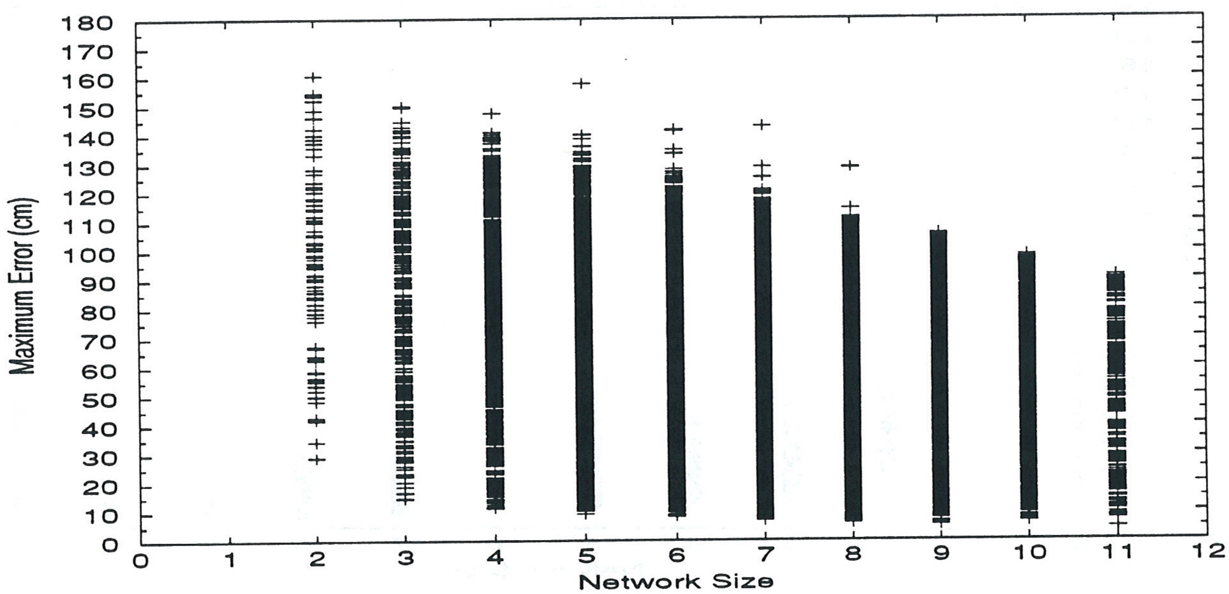


Figure 27. Mean lake levels (offset) for Lake Superior calculated for hourly water levels for 1990 using uniform, Theissen, Croley, and EOF weights. Also shown is the second EOF mode.

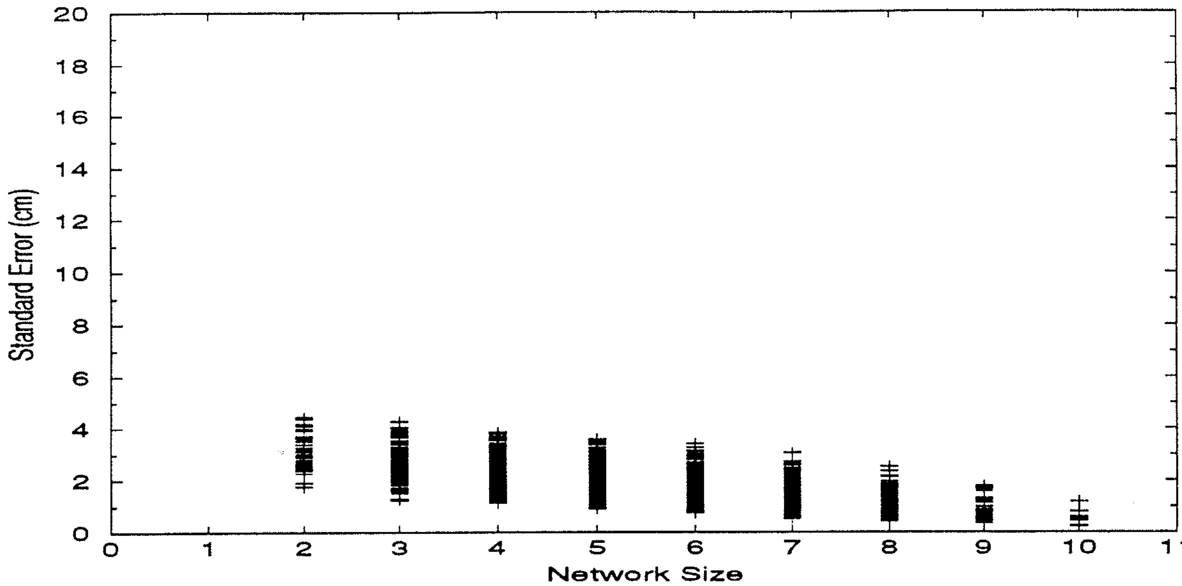


a)

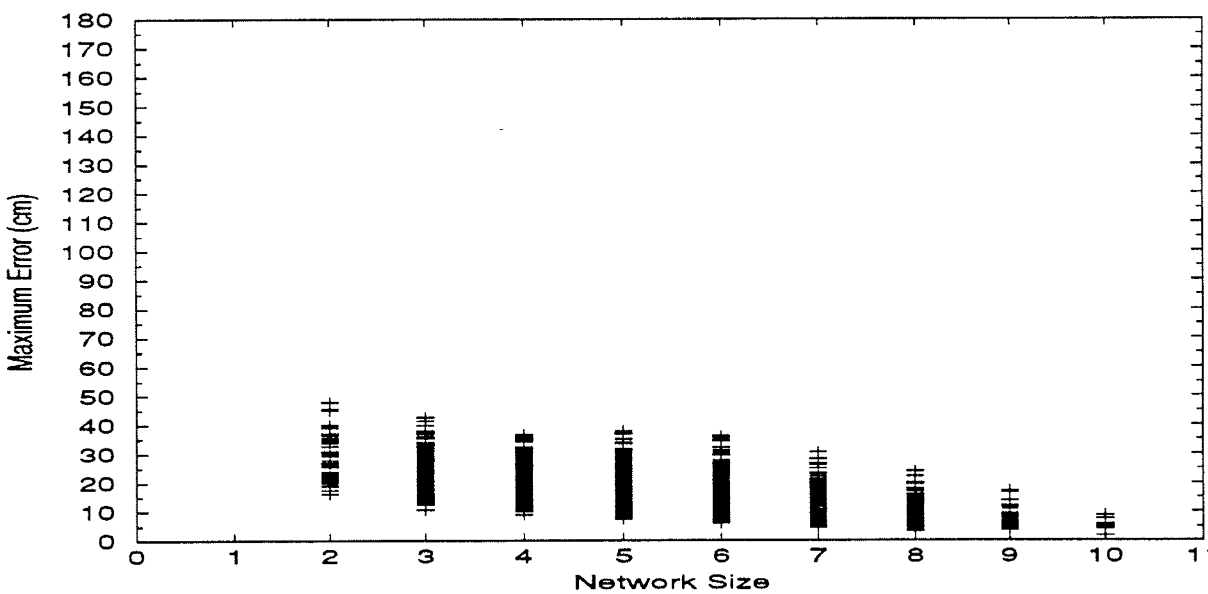


b)

Figure 28. a) Standard error and b) maximum error of subnetwork first and second EOF modes for Lake Erie hourly water levels.

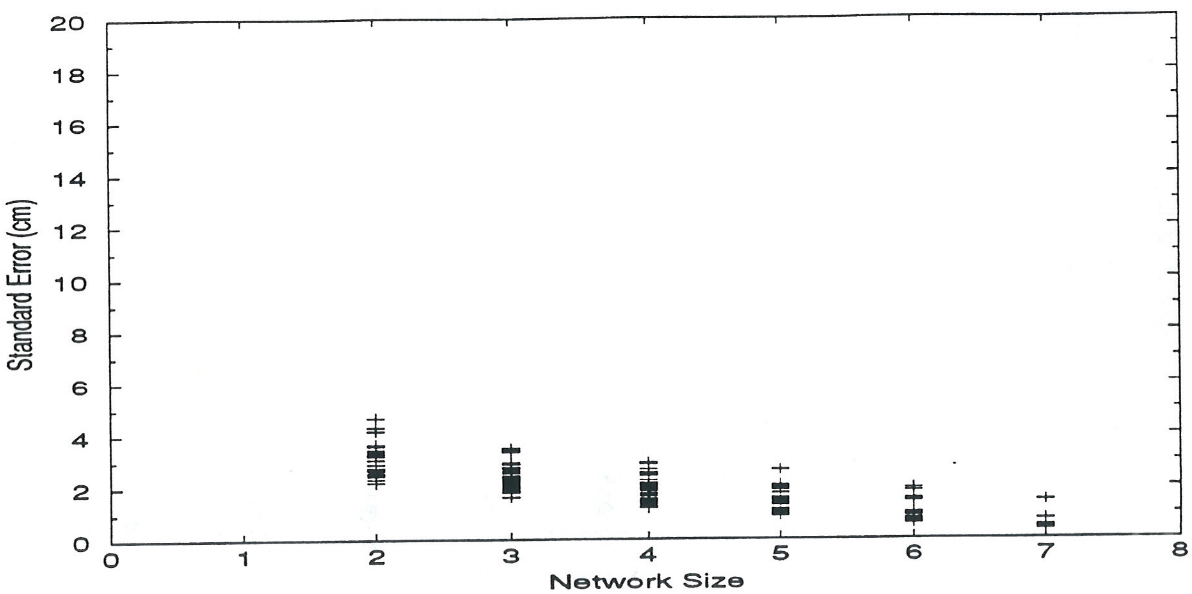


a)

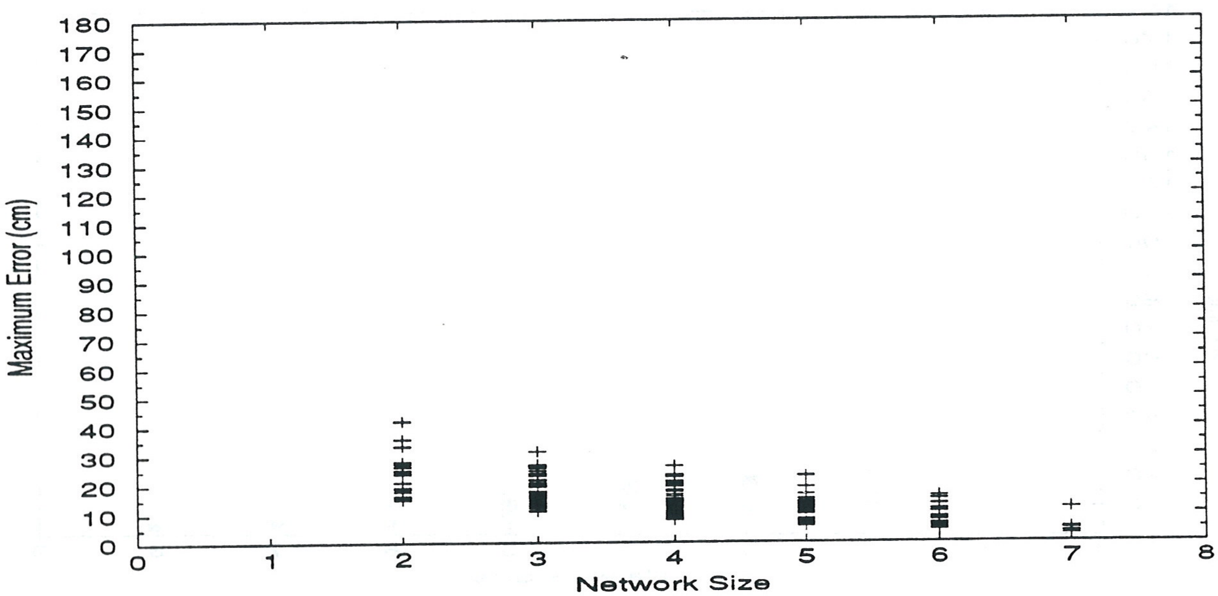


b)

Figure 29. a) Standard error and b) maximum error of subnetwork first and second EOF modes for Lake Huron hourly water levels.

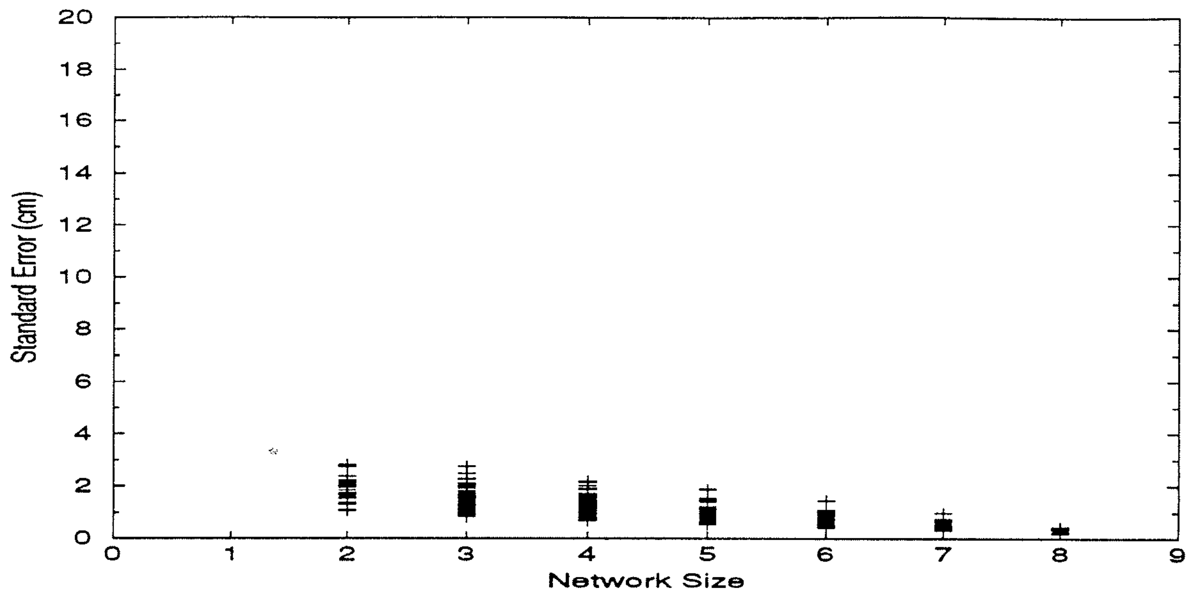


a)

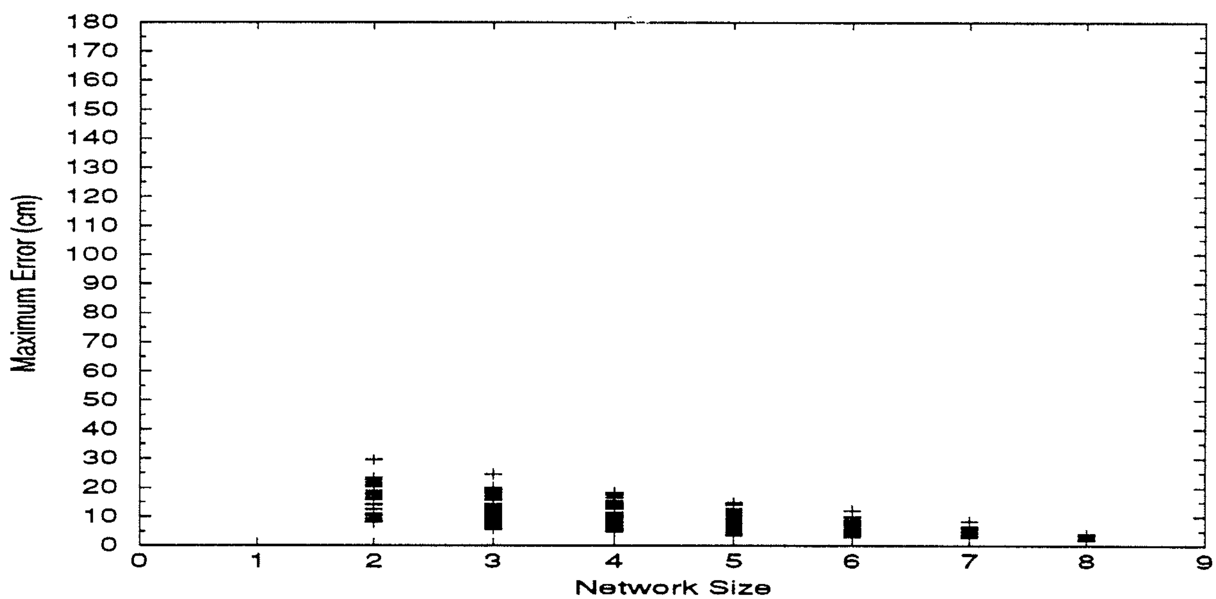


b)

Figure 30. a) Standard error and b) maximum error of subnetwork first and second EOF modes for Lake Michigan hourly water levels.

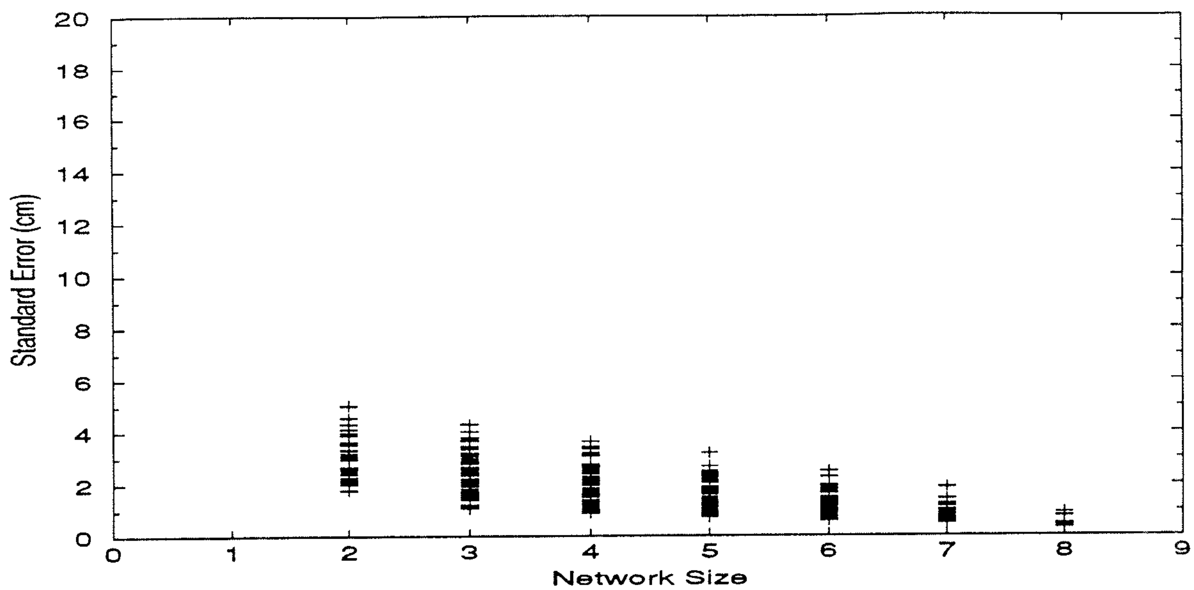


a)

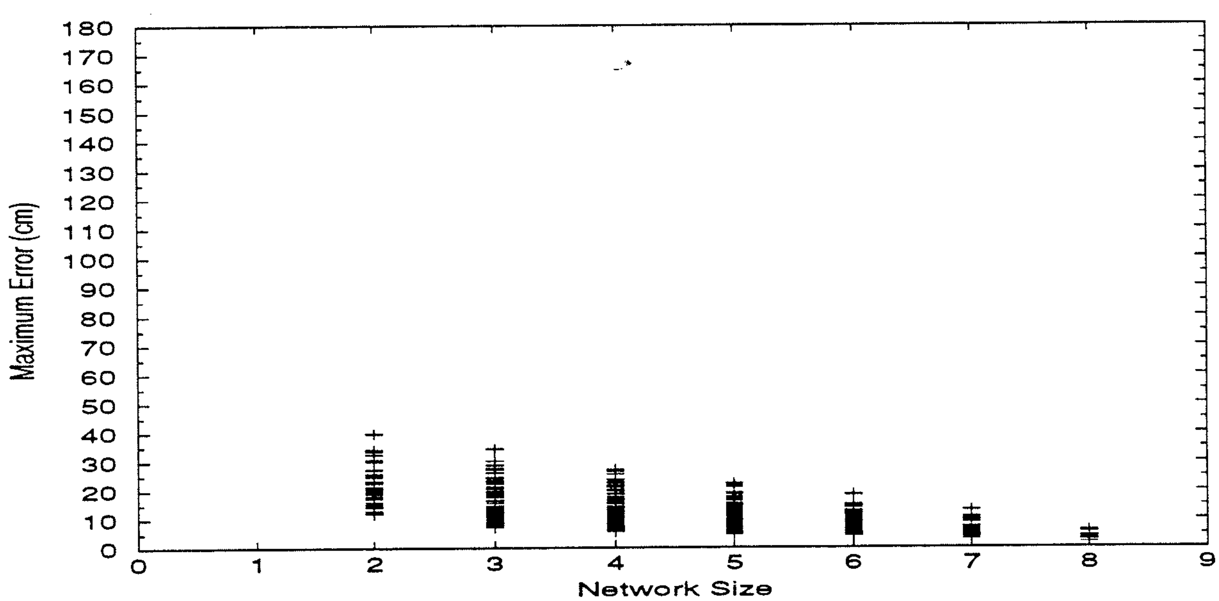


b)

Figure 31. a) Standard error and b) maximum error of subnetwork first and second EOF modes for Lake Ontario hourly water levels.

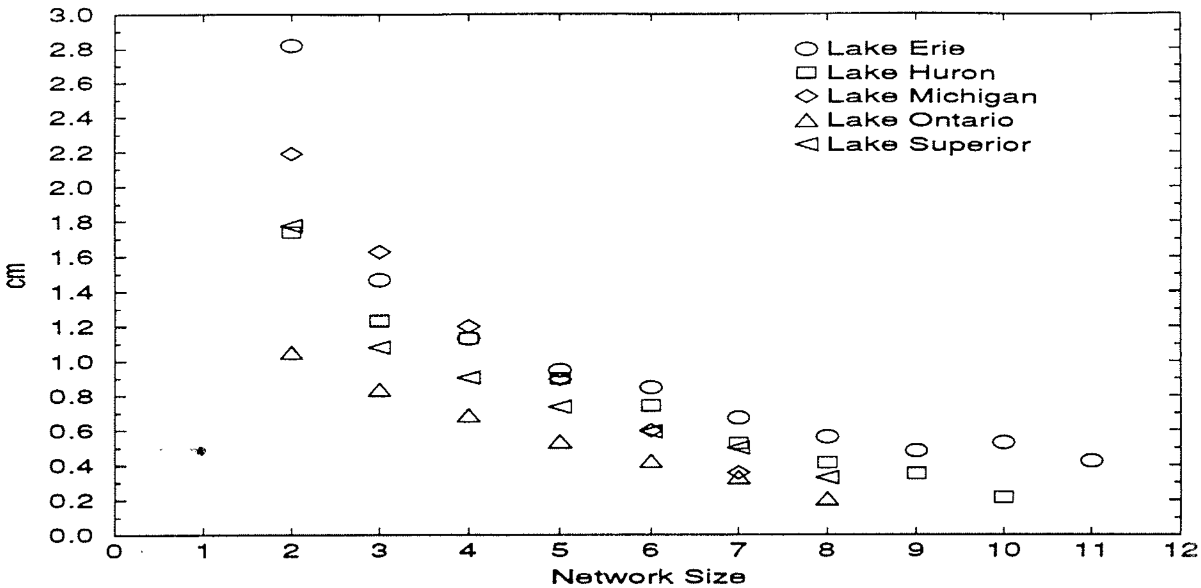


a)

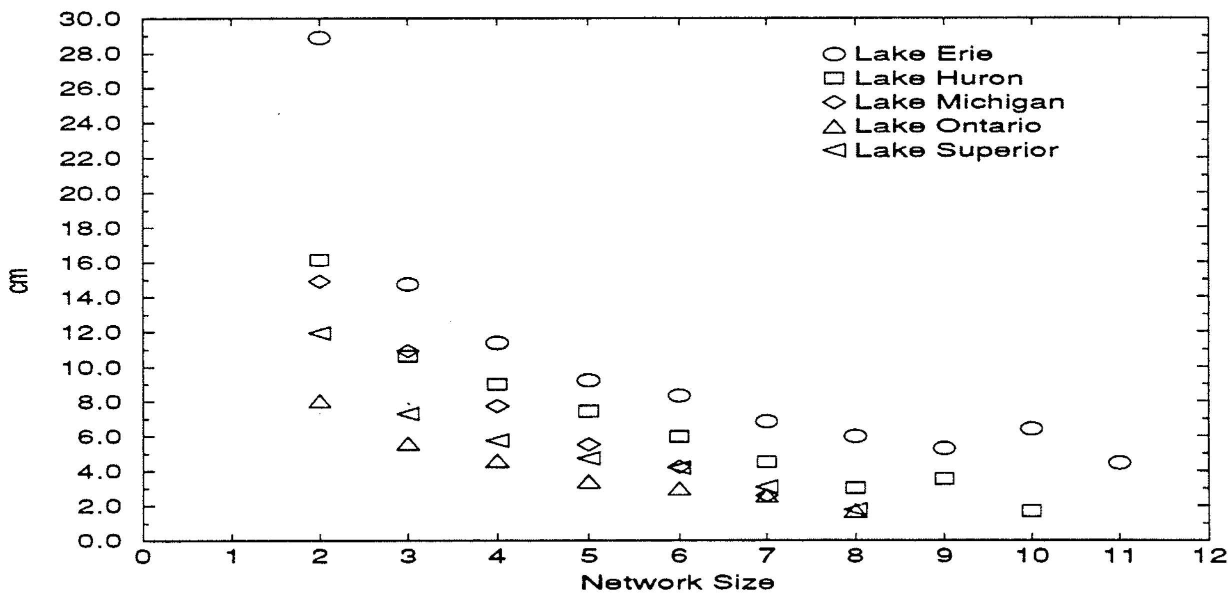


b)

Figure 32. a) Standard error and b) maximum error of subnetwork first and second EOF modes for Lake Superior hourly water levels.



a)



b)

Figure 33. Lowest first and second EOF mode a) standard error and b) maximum error for hourly water levels.

6. DISCUSSION

6.1. CORRELATIONS BETWEEN STATIONS

The cross correlation matrix formed in solving for EOF modes with hourly data shows how closely the signals at any two stations resemble each other. A correlation coefficient of 1.0 indicates complete correlation; 0.0 indicates no correlation; and -1.0 indicates complete correlation but 180 degrees out of phase. In Figures 34 to 37, station pairs for Lakes Erie, Huron, Michigan, and Superior with correlation coefficients greater than 0.90 are connected. For Lake Ontario, all stations are correlated with each other at a level greater than 0.95, so only correlation coefficients greater than 0.99 are shown (Figure 38). It can be seen that two stations that are close together generally have extremely high correlation coefficients.

The high correlations between nearby stations makes it natural to consider how large an error would result if the hourly water levels at one station were used as a direct substitute for hourly water levels at another station. Then, if a station is to be removed, data from a substitute station with a statistical error range can be used to estimate water level at the removed station. Statistics for the differences between pairs of stations were examined and for each station, the best substitute station was chosen based on the least standard error. The mean error, standard error, and maximum error for each substitute station are shown in Table A in the Appendix. The mean error may be attributed to long-term tectonic movement and/or gauge offset errors. Standard errors range from 1.7 cm for the Gros Cap - Port Iroquois pair on Lake Superior to 11.0 cm for the Green Bay - Sturgeon Bay pair on Lake Michigan. Maximum errors range from 12 cm for the Cape Vincent - Kingston pair on Lake Ontario to 90 cm for the Essexville - Lakeport pair on Lake Huron.

6.2. RECONSTRUCTION OF TIME SERIES AT INDIVIDUAL STATIONS

Since most of the hourly water level variance at any station on the Great Lakes is a linear combination of the first EOF mode and the second EOF mode (and the third EOF mode for Lake Huron), it should be possible to reconstruct most of the signal at any station based on EOF modes derived from subnetworks not containing that station. As an example, the best four, six, and eight station networks listed in Table B in the Appendix were used to obtain first and second EOF modes (and the third EOF mode for Lake Huron). The modes were scaled using eigenvectors obtained in EOF analyses of the complete networks to approximate the time series at stations not in the subnetworks. (For example, the water levels at Port Colborne, Erie, Cleveland, and Kingsville were used to reconstruct the time series at the rest of the Lake Erie stations.)

The error statistics for the difference between the reconstructed time series and the observed time series are shown in Table 5 for each of the subnetworks. In many cases, smaller standard errors were obtained for the reconstructed signals than for a single station substitution. However for other stations (marked in italics), substituting one single station resulted in a smaller standard error than attempting to reconstruct the signal from the EOF modes (compare Table 5 with Table A of the Appendix). This is true for station pairs close together which are highly correlated.

Table 5. Reconstructed Time Series Error Statistics (cm)

		4-Station Network		6-Station Network		8-Station Network	
Lake	Station	Standard Error	Maximum Error	Standard Error	Maximum Error	Standard Error	Maximum Error
Erie	Buffalo	*4.4*	*57*				
	Sturgeon Point	*2.9*	*38*	*2.7*	*35*		
	Port Colborne			*2.9*	*35*	2.6	31
	Port Dover	3.4	40				
	Erie					3.5	37
	Port Stanley	5.1	46	5.1	45		
	Fairport	3.7	51				
	Erieau	3.3	33	3.4	32		
	Cleveland			*4.3*	*74*	*4.8*	*81*
	Marblehead	4.1	48				
	Kingsville					3.1	34
	Bar Point	*5.7*	*88*	*5.7*	*77*		
Huron	Mackinaw	*4.2*	*38*				
	De Tour	2.0	16			1.9	13
	Thessalon			*2.6*	*21*		
	Little Current	4.3	35				
	Parry Sound	*4.0*	*36*	3.2	25	2.8	27
	Collingwood	*4.3*	*40*				
	Tobermory			2.3	19		
	Harrisville	2.8	33	3.0	36		
	Harbor Beach			2.9	29	2.5	26
	Lakeport	4.2	41				
Michigan	Port Inland	4.2	25				
	Sturgeon Bay	3.4	18	3.1	21		
	Milwaukee	4.2	34				
	Holland	4.0	33	3.7	34		
Ontario	Kingston	*1.8*	*15*	*2.1*	*16*		
	Oswego	2.9	25				
	Rochester			2.5	19		
	Cobourg	3.0	29				
	Olcott	*2.2*	*12*			1.9	11
	Port Weller	1.7	10	1.5	9		
Superior	Gros Cap			*2.7*	*22*		

Table 5. Reconstructed Time Series Error Statistics (cm)

Lake	Station	4-Station Network		6-Station Network		8-Station Network	
		Standard Error	Maximum Error	Standard Error	Maximum Error	Standard Error	Maximum Error
	Point Iroquois	*2.4*	*21*				
	Michipicoten	3.8	28				
	Rossport					3.3	15
	Thunder Bay	3.6	23				
	Ontonagon	2.6	16	2.5	13		
	Grand Marais	3.1	27	2.8	28		

6.3. LAKE HURON - LAKE MICHIGAN SYSTEM

It has been noted that the higher frequency variability (1-5 day periods) of the Lake Huron and Lake Michigan mean lake levels is greater than those of the other three lakes. This is because the two lakes are connected at the Straits of Mackinac and water can be transferred back and forth between the lakes by meteorological forcing. Since the two lakes have nearly identical surface areas, if the mean lake levels of the two lakes are averaged, the effect of the transfer of water between lakes should be eliminated. The first EOF modes of the 2-day averaged data for Lakes Huron and Michigan are shown in Figure 39 together with their mean (offset for comparison). The mean of the two lake levels is a much smoother time series, similar to the mean lake levels of the other lakes. The mean of the hourly first EOF modes for Lakes Huron and Michigan (Figure 40) also shows a significant reduction in higher frequency energy compared to the first EOF mode for each individual lake. Therefore, calculation of the mean of the Lake Huron and Lake Michigan first EOF modes is necessary to eliminate the meteorological forcing effects.

6.4. STRATEGY FOR EVALUATING NETWORK SIZE REDUCTIONS

The results of this investigation can provide guidelines for evaluating the effects of network size reductions. First, a desired level of accuracy should be chosen for one or more lake level statistics, based on users requirements. Standard errors and maximum errors could be specified for 2-day averaged mean lake levels. Standard errors and maximum errors could also be specified for hourly mean lake levels and lake level tilts and/or the total signal at any particular station that may be eliminated.

Then, an examination of Figures 22 and 33 can give an idea of the minimum network size that would be needed for each lake to produce the desired accuracy. Figure 22 shows subnetwork errors for the first EOF mode for 2-day averaged data; Figure 33 shows subnetwork errors for the first and second EOF modes for hourly data. The larger the acceptable error, the smaller the network can be. Once the reduced network size is decided, the lowest error subnetwork can be chosen as the new network. However, there will be many other combinations which will be almost as good as the lowest error subnetwork, so other considerations can be taken into account in deciding which stations could be removed.

The maps in Figures 34 to 38 showing the highest correlation coefficients between stations are helpful in identifying station pairs that give almost identical water level information. This often occurs where a U. S. and Canadian station are located very close together (e.g. Fermi and Bar Point, Buffalo Harbor and Port Colborne, De Tour Village and Thessalon, Point Iroquois and Gros Cap, Olcott and Port Weller, Cape Vincent and Kingston). Other stations that have high correlation coefficients with more than one nearby stations could also be considered duplicative (e.g. Sturgeon Point, Kingsville, Parry Sound, or any station on Lake Ontario). When a smaller network has been chosen, an EOF analysis can be carried out and the resulting modes can be compared with the EOF modes from the full network to see if the desired accuracy levels have been met.

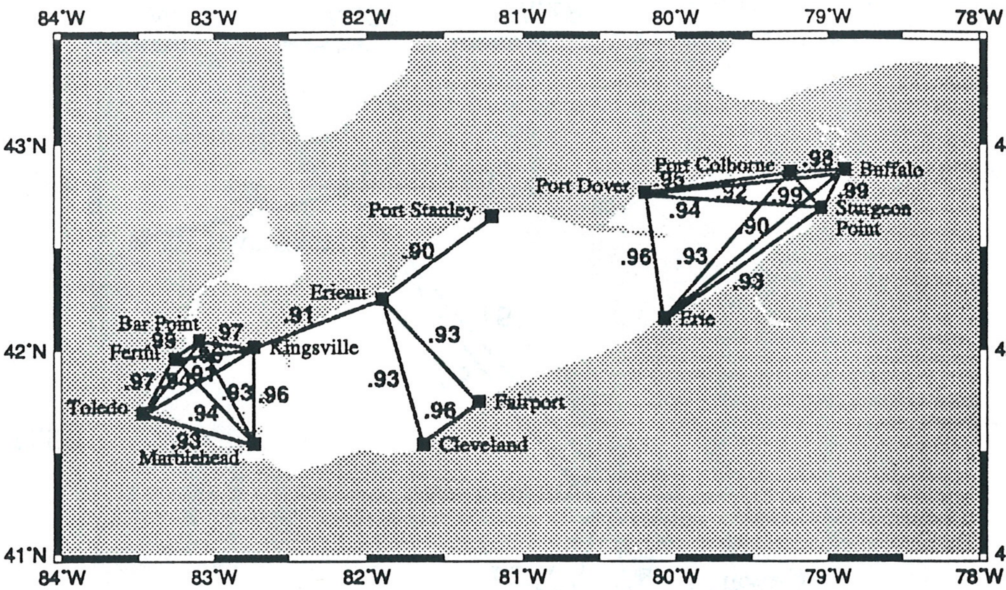


Figure 34. Correlation coefficents greater than 0.90 for Lake Erie 1990 hourly water levels.

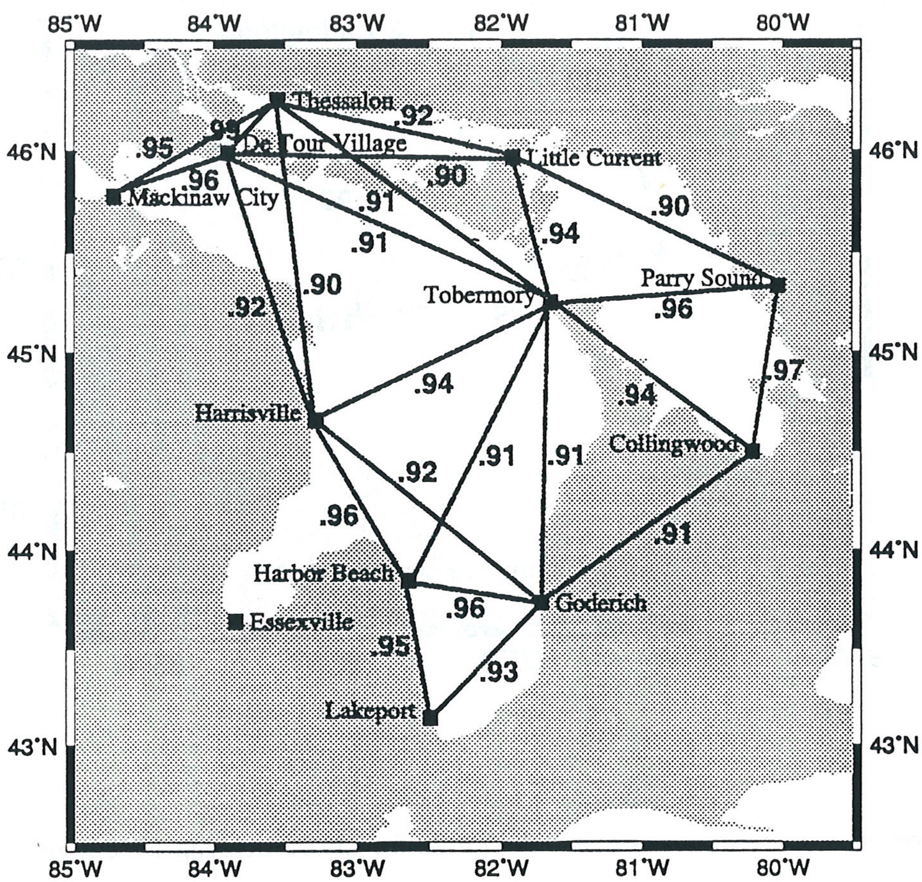


Figure 35. Correlation coefficients greater than 0.90 for Lake Huron 1990 hourly water levels.

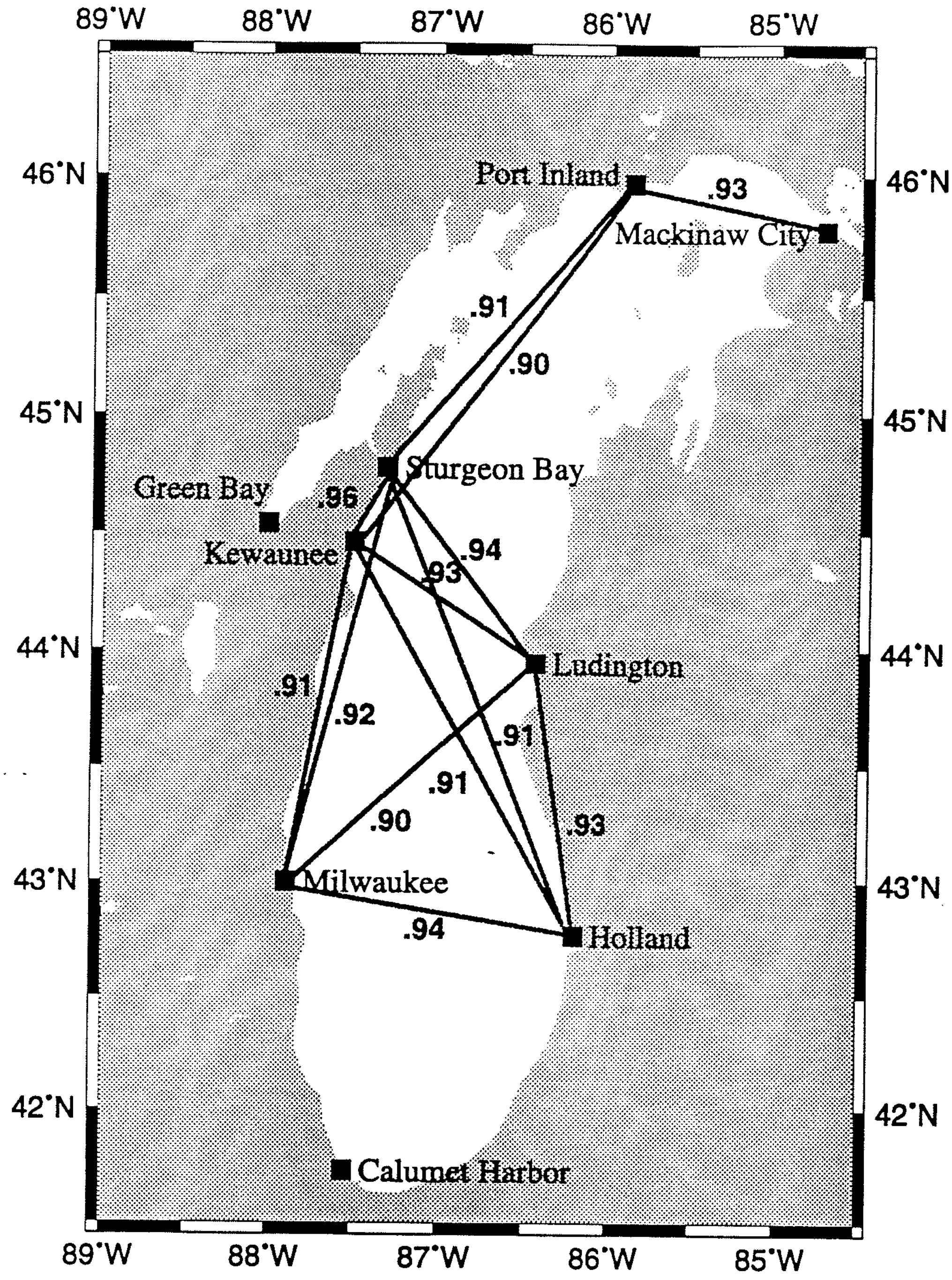


Figure 36. Correlation coefficients greater than 0.90 for Lake Michigan 1990 hourly water levels.

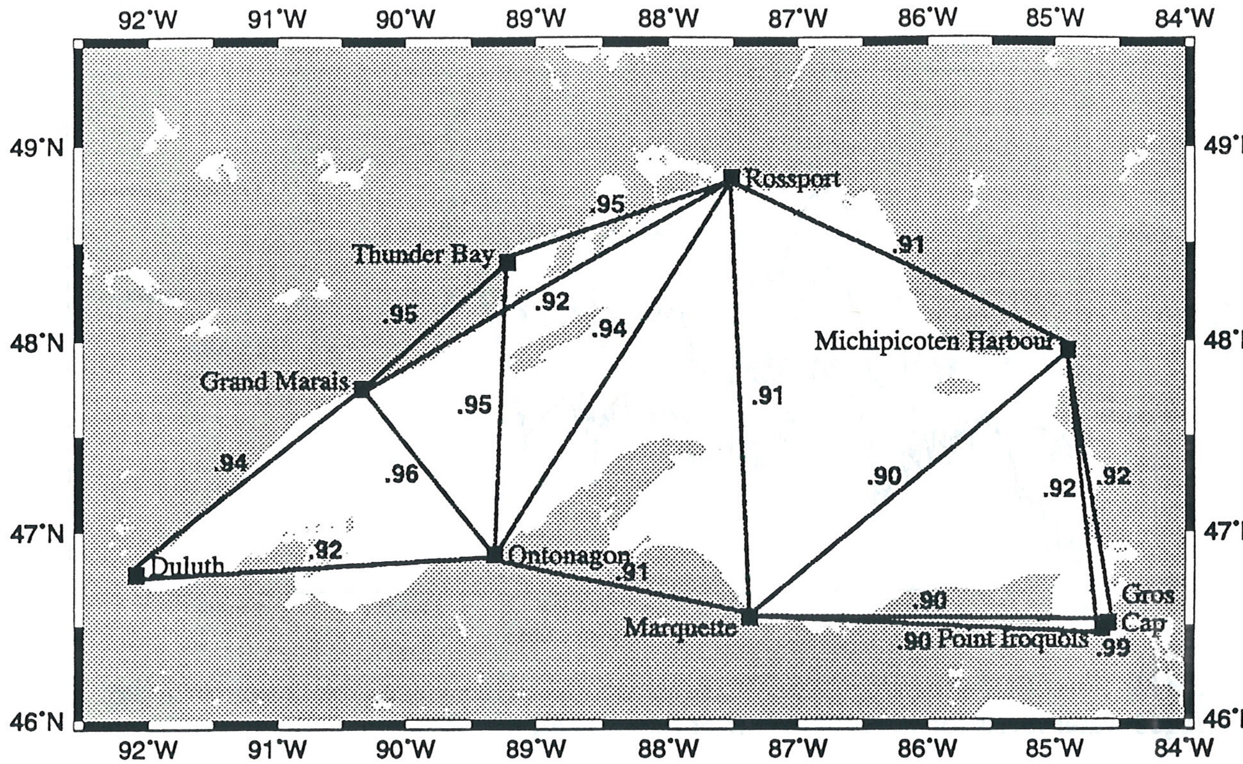


Figure 37. Correlation coefficients greater than 0.90 for Lake Superior 1990 hourly water levels.

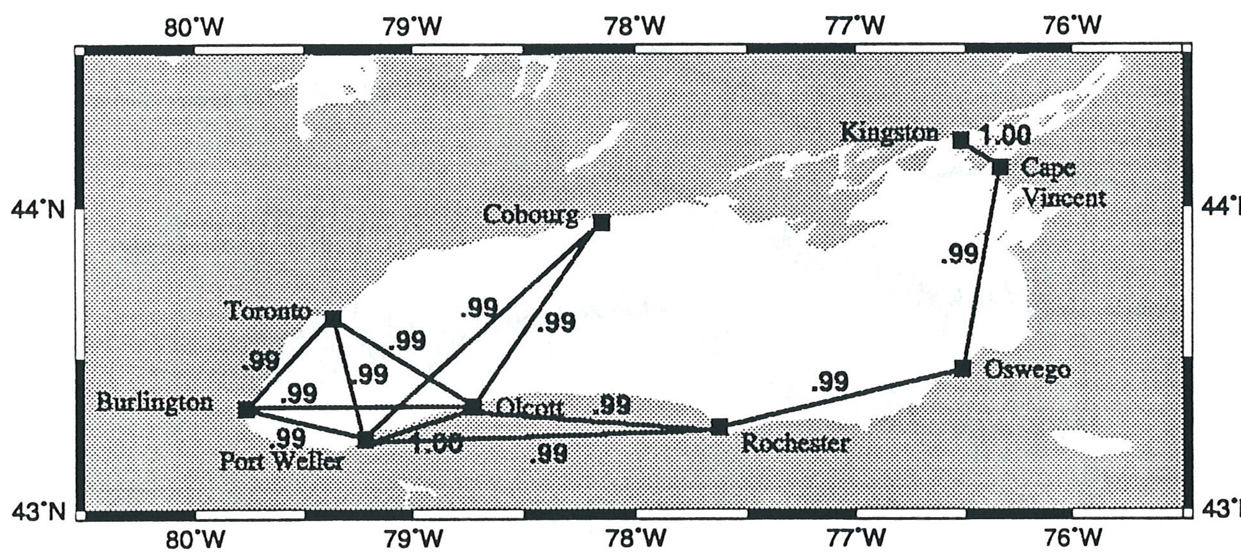


Figure 38. Correlation coefficients greater than 0.99 for Lake Ontario 1990 hourly water levels.

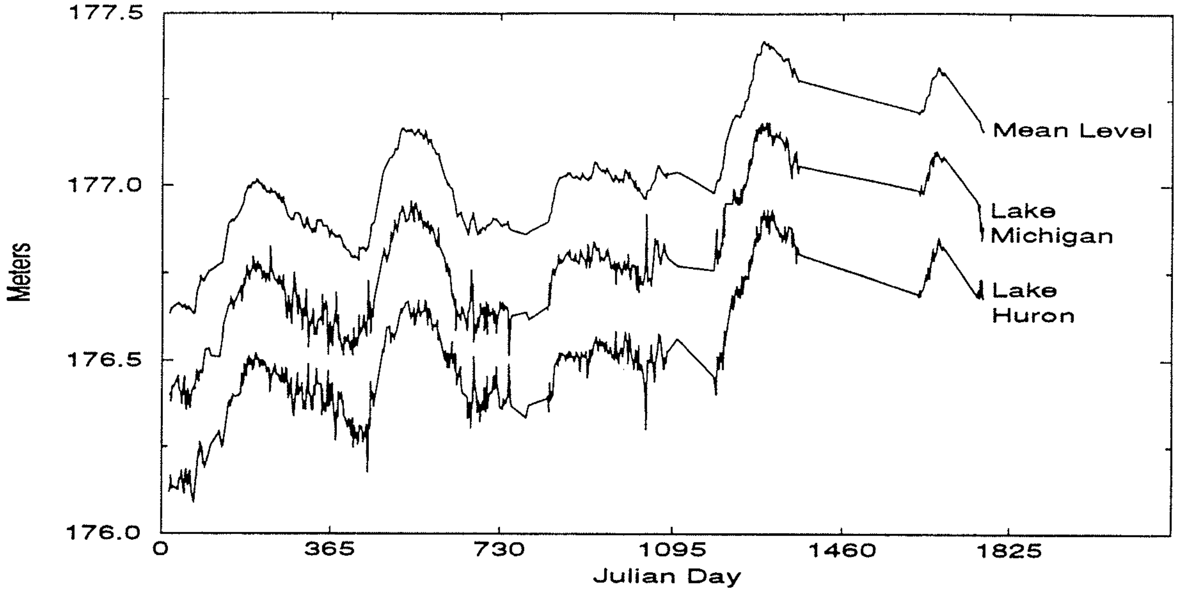


Figure 39. First EOF modes for Lake Michigan and Lake Huron and their mean for 2-day averaged water levels for 1990-1994 (offset for comparison).

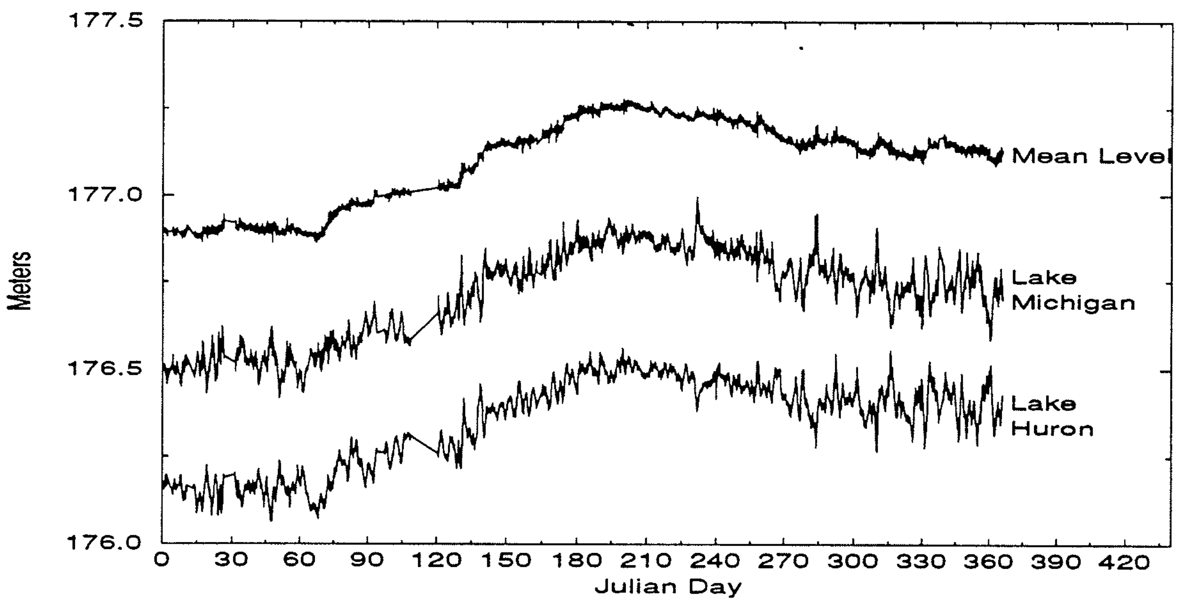


Figure 40. First EOF modes for Lake Michigan and Lake Huron and their mean for hourly water levels for 1990 (offset for comparison).

7. CONCLUSION

The goal of this investigation was to quantify the reduction in mean lake level accuracy that would occur if the number of gauges presently in place on the Great Lakes were to be reduced. Five years of water level data (1990-1994) from 52 stations on the Great Lakes were used in the analyses of network configurations. First, the calculation of the mean lake level using 2-day averaged data for each lake was examined. This statistic is required by the Corps of Engineers for the regulation of lake levels. An empirical orthogonal function analysis for each lake showed that 90.2% to 99.7% of the energy was in the first mode corresponding to the mean lake level. The first EOF mode obtained with smaller network configurations was then compared with the first EOF mode from the complete network. The difference statistics indicate the accuracy of each subnetwork. The lowest standard errors and lowest maximum errors decrease with increasing subnetwork size up to a seven station network with a standard error below 0.2 cm and a maximum error below 1 cm.

Next, the EOF analysis was repeated for hourly data for 1990. Without the time averaging of the data, the first mode (corresponding to mean lake level) had a smaller percentage of the total energy (61.7% to 98.0%). The second mode (corresponding to lake surface tilt along the longer axis of each lake) had a larger percentage of the energy (1.1% to 34.0%). The EOF analysis was then carried out for every possible subnetwork, and the difference statistics for both the first and the second mode were examined. The lowest standard errors and lowest maximum errors decreased with increasing network size up to an eight station network with a standard error below 0.7 cm and a maximum error below 7 cm.

If a station is dropped from the network, it is possible to obtain an approximation of the signal at that location using other stations still in the network. This can be done by using the other stations to calculate the time series for the first and second EOF modes and then scaling them for the station not in the reduced network. Alternatively, the high correlation coefficients between stations that are close together suggest simply substituting the time series of the nearest station. As an example, the four, six, and eight station subnetworks with the lowest standard error were used to approximate stations not in the subnetworks. In some cases, reconstructing the signal gave a better approximation while in other cases, substituting the nearest station gave a better approximation.

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APPENDIX

Table A. Best Substitute Station Error Statistics (cm)

	Station	Substitute	Mean Error	Standard Error	Maximum Error
Lake Erie	Buffalo	Sturgeon Point	0.8	3.4	39
	Sturgeon Point	Port Colborne	-1.1	2.6	30
	Port Colborne	Sturgeon Point	1.1	2.6	30
	Port Dover	Erie	-1.3	4.1	35
	Erie	Port Dover	1.3	4.1	35
	Port Stanley	Erieau	1.7	6.3	58
	Fairport	Cleveland	2.0	4.2	46
	Erieau	Fairport	-2.0	5.2	69
	Cleveland	Fairport	-2.0	4.2	46
	Marblehead	Kingsville	-1.1	5.3	57
	Kingsville	Bar Point	0.5	4.9	44
	Bar Point	Fermi	0.6	3.5	45
	Fermi	Bar Point	-0.6	3.5	45
	Toledo	Fermi	-0.4	6.9	77
Lake Huron	Mackinaw City	De Tour	0.2	3.5	30
	De Tour	Thessalon	-0.3	2.1	17
	Thessalon	De Tour	0.3	2.1	17
	Little Current	Tobermory	-2.5	4.9	43
	Parry Sound	Collingwood	-0.7	3.5	30
	Collingwood	Parry Sound	0.7	3.5	30
	Tobermory	Parry Sound	2.9	4.1	36
	Harrisville	Harbor Beach	-0.6	3.9	32
	Essexville	Lakeport	-1.0	10.0	90
	Harbor Beach	Harrisville	0.6	3.9	32
	Goderich	Harbor Beach	0.2	3.9	33
	Lakeport	Harbor Beach	0.2	4.6	47
Lake Michigan	Mackinaw City	Port Inland	0.3	5.0	27

Table A. Best Substitute Station Error Statistics (cm)

	Station	Substitute	Mean Error	Standard Error	Maximum Error
	Port Inland	Mackinaw City	-0.3	5.0	27
	Green Bay	Sturgeon Bay	0.7	11.0	73
	Sturgeon Bay	Kewaunee	0.2	4.0	27
	Kewaunee	Sturgeon Bay	-0.2	4.0	27
	Ludington	Sturgeon Bay	1.0	4.6	26
	Milwaukee	Holland	-0.2	4.6	49
	Holland	Milwaukee	0.2	4.6	49
	Calumet Harbor	Milwaukee	-0.1	7.0	49
Lake Ontario	Cape Vincent	Kingston	-1.0	1.7	12
	Kingston	Cape Vincent	1.0	1.7	12
	Oswego	Rochester	0.5	3.5	30
	Rochester	Olcott	-0.3	3.2	21
	Cobourg	Port Weller	-0.9	3.2	33
	Olcott	Port Weller	-0.3	2.1	15
	Toronto	Port Weller	0.0	2.5	16
	Port Weller	Olcott	0.3	2.1	15
	Burlington	Port Weller	-0.4	2.6	20
Lake Superior	Gros Cap	Point Iroquois	-1.0	1.7	14
	Point Iroquois	Gros Cap	1.0	1.7	14
	Michipicoten	Rossport	1.0	5.2	30
	Marquette	Ontonagon	0.4	5.0	27
	Rossport	Thunder Bay	-1.3	3.7	20
	Thunder Bay	Rossport	1.3	3.7	20
	Ontonagon	Grand Marais	-0.5	3.5	23
	Grand Marais	Ontonagon	0.5	3.5	23
	Duluth	Grand Marais	-0.7	4.7	30

Table B. Lowest Standard Error Subnetwork Configurations

	4-Station Network	6-Station Network	8-Station Network	
Lake Erie	Port Colborne	Buffalo Harbor	Buffalo Harbor	Fairport
	Erie	Port Dover	Sturgeon Point	Erieau
	Cleveland	Erie	Port Dover	Marblehead
	Kingsville	Fairport	Port Stanley	Bar Point
		Marblehead		
		Kingsville		
Lake Huron	Thessalon	Mackinaw City	Mackinaw City	Tobermory
	Tobermory	De Tour Village	Thessalon	Harrisville
	Harbor Beach	Little Current	Little Current	Goderich
	Goderich	Collingwood	Collingwood	Lakeport
		Goderich		
		Lakeport		
Lake Michigan	Mackinaw City	Mackinaw City		
	Kewaunee	Port Inland		
	Ludington	Kewaunee		
	Calumet Harbor	Ludington		
		Milwaukee		
		Calumet Harbor		
Lake Ontario	Cape Vincent	Cape Vincent	Cape Vincent	Cobourg
	Rochester	Oswego	Kingston	Toronto
	Toronto	Cobourg	Oswego	Port Weller
	Burlington	Olcott	Rochester	Burlington
		Toronto		
		Burlington		
Lake Superior	Gros Cap	Port Iroquois	Gros Cap	Thunder Bay
	Marquette	Michipicoten	Port Iroquois	Ontonagon
	Rossport	Marquette	Michipicoten	Grand Marais
	Duluth	Rossport	Marquette	Duluth
		Thunder Bay		
		Duluth		

NWLON GREAT LAKES SIZING STUDY

Prepared by

The Oceanographic Products and Services Division
National Ocean Service
National Oceanic and Atmospheric Administration

APPENDIX D

(Source http://www.cciw.ca/glimr/data/board-control/niagara.html)

The International Niagara Board of Control

International Cooperation on the Niagara River

The Boundary Waters Treaty of 1909 requires that the United States and Canada, together, approve projects that affect the levels and flows of waters along their common boundary. Water diversions in the Niagara River for hydroelectric power projects in both countries were approved by the 1950 Niagara Treaty. Water diverted from the river above Niagara Falls is returned to the river below the Falls. The 1950 Niagara Treaty specifies the minimum amount of water that must flow over the Falls at different times.

The International Joint Commission

The 1909 Boundary Waters Treaty also created the **International Joint Commission** to help prevent and resolve disputes over the use of waters along the boundary between Canada and the United States. The Commission was asked to help implement the 1950 Niagara Treaty by overseeing the design, construction and operation of works in the Niagara River that control the level of the Chippawa-Grass Island Pool. The Commission also oversees the annual installation of an ice boom that is designed to reduce ice jams in the Niagara River. The Commission requires that these activities meet certain conditions to ensure that interests in both countries are protected.

The International Niagara Board of Control

The **International Niagara Board of Control** was established by the Commission in 1953 to provide advice on matters related to the Commission's responsibilities for water levels and flows in the Niagara River. The Board's main duties are to oversee water levels regulation in the Chippawa-Grass Island Pool and installation of the Lake Erie-Niagara River Ice Boom. The Board also collaborates with the International Niagara Committee, a body created by the 1950 Niagara Treaty to determine the amount of water available for the Falls and power generation.

The Board meets at least twice a year and provides semi-annual progress reports to the Commission. The Board also produces an annual report on the operation of the Lake Erie-Niagara River Ice Boom and holds an annual public meeting to provide information and receive input from all interested persons.

Regulation of the Chippawa-Grass Island Pool

Various international studies have examined factors affecting the scenic beauty of Niagara Falls and the Niagara River. Remedial works, first suggested in 1929, were constructed in the 1950s to enhance scenic beauty, provide for the most beneficial use of the river's waters and maintain the minimum flows over the Falls required by the 1950 Niagara Treaty. The remedial works consist of the International Niagara Control Works, which controls water levels in the Chippawa-Grass Island Pool, and excavation and fill on both flanks of Horseshoe Falls. The excavation and fill provide for a more even and unbroken flow across Horseshoe Falls.

The International Niagara Control Works is a structure extending about 0.8 kilometre (0.5 mile) into the river from the Canadian shore at the downstream end of the Chippawa-Grass Island Pool. Its 18 sluice gates allow for precise changes in the flow over the Falls and adjustments to the water level in the Chippawa-Grass Island Pool, where water is diverted for hydroelectric power production.

The Board monitors operation of the control works by the power entities, Ontario Hydro and the New York Power Authority, under a Commission directive. To lessen the adverse effects from high or low water levels, the power entities are required to maintain the long-term average level of the Chippawa-Grass Island Pool within certain tolerances. Under abnormal flow or ice conditions, these tolerances may be suspended and a somewhat wider range of levels is permitted. Operation of this structure does not change the total flow of the Niagara River and has no measurable effect on Lake Erie water levels.

The ability to change water levels near Niagara Falls by adjusting gate settings and altering plant diversions has, on numerous occasions, assisted in river rescue operations to save people from going over the Falls.

Lake Erie-Niagara River Ice Boom
In 1964 the Commission approved an application by the power entities to install a floating ice boom in Lake Erie near the entrance to the Niagara River. The purpose of the ice boom is to reduce the frequency and duration of heavy ice runs into the river. Ice runs may cause ice jams that can damage shoreline property and significantly reduce power diversions. The ice boom speeds formation of and stabilizes the natural ice arch near the head of the Niagara River every winter. The boom is owned, operated and maintained by the power entities.

When in position, the 2,700-metre (8,000-foot) ice boom is located approximately three kilometres (two miles) upstream of the Peace Bridge and spans the outlet of Lake Erie. The floating sections of the boom are installed each winter when the water temperature at the Buffalo water intake reaches four degrees Celsius (39 degrees Fahrenheit). All floating sections of the ice boom are opened by April one, unless ice cover surveys on or about that date show there is more than 650 square kilometres (250 square miles) of ice remaining in the eastern end of the lake. If that is the case, the ice boom opening may be delayed.

Membership
The International Niagara Board of Control is appointed by the International Joint Commission and consists of four members, two each from the United States and Canada. Members serve in their personal and professional capacities and not as representatives of their home organizations. The members for the U.S Section are from the U.S. Army Corps of Engineers and the Federal Energy Regulatory Commission. The members for the Canadian Section are from Environment Canada and the Ontario Ministry of Natural Resources.

The Board is supported in its role by the International Niagara Working Committee. The Working Committee is made up of members from federal and provincial agencies, the New York Power Authority and Ontario Hydro.

More Information

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