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A statistical assessment of the relationship of the El Nino/Southern Oscillation to Great Lakes water levels.

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A STATISTICAL ASSESSMENT OF THE RELATIONSHIP OF THE EL NINO / SOUTHERN OSCILLATION TO GREAT LAKES WATER LEVELS

By

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A Thesis Submitted
to the Faculty of Graduate Studies and Research
through the Department of Geography
in Partial fulfillment of the Requirements for
the Degree of Master of Arts at the
University of Windsor

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ABSTRACT

Water levels and basin data of the Laurentian Great Lakes were related to two major meteorological indices. Historical fluctuations have lead to suggestions that GLWL fluctuations are due to climate change and increased climatic variability of the local region. Related to climate change, increased frequency and intensity of the El Nino/Southern Oscillation (ENSO) phenomenon indicates that Lake level fluctuation may be related. This thesis considers the relationship between fluctuations of Great Lakes water levels and the El Nino/Southern Oscillation using data collected from 1950 to 1999. Water level data and net basin supply data collected monthly over this time span for Lakes Superior, Michigan-Huron, Erie and Ontario. The two major meteorological indices used to study water levels and basin data are the Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI) which, were statistically modeled using Box-Jenkins time series analysis. Time series analysis was used to determine how well each model could predict the historical patterns in the time series. Additionally, this thesis attempted to determine how well historical lake levels were described by the Multivariate ENSO Index (MEI), which is used to calculate ENSO parameters. Great Lakes net basin supply values (comprising net over-lake precipitation, evaporation, and runoff) were used to determine whether the ENSO phenomenon could be attributed to similar variations. The final analysis involved taking the information gained through time series analysis, and relating it to physical and systematic aspects of the Great Lakes water system.

Great Lakes water levels could indeed be satisfactorily characterized by the changes in ENSO events represented by the Multivariate ENSO Index. Using MEI as the independent regressor to water level data, statistical results are indicative of a system-wide swing of fluctuation, in regard to extreme weather patterns. It is apparent that ENSO events affect lake levels, despite the many other factors present within the Great Lakes system. With the peculiar lagged forms of the Multivariate ENSO Index when regressed with Lake level data, it appears that there is a temporal pattern present regarding ENSO events and Great Lakes Water Levels. Thus the present results suggest that with the introduction of an ENSO event, Lake levels are shifted most significantly after 3.5 years, with the exception of Lake Superior, which experiences modifications after 4.5 years. With regard to Lake net basin supply data, it was determined that when regressed against the Multivariate ENSO Index, a weak relationship between the two was apparent.

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I would like to extend the most sincere gratitude to my advisors Dr. P.D. Lavalle and Dr. V.C. Lakhan. Their insight, support, and guidance were pivotal to its success. Their influence and assistance have been constant mainstays throughout my graduate work, as well as my entire undergraduate career. For this, I am very appreciative. As well, thank you to Dr. J. Lovett-Doust for being a valuable and thoughtful external examiner. Thank you to all of my friends and family for their continual support throughout my university career.

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LIST OF ABBREVIATIONS

ACF	*Autocorrelation Function*
AIC	*Akaike Information Criterion*
AR	*Autoregressive*
ARMA	*Mixed Autoregressive Moving Average*
ARIMA	*Autoregressive Integrated Moving Average*
CDC	*Climate Diagnostic Centre*
COADS	*Comprehensive Ocean-Atmosphere Data Set*
ENSO	*El Nino/Southern Oscillation*
GLWL	*Great Lakes Water Levels*
MA	*Moving Average*
MEI	*Multivariate ENSO Index*
MEIQn	*Denotes the lagged value/quarter (n) of the MEI in statistical analysis.*
NBS	*Net Basin Supply*
PACF	*Partial Autocorrelation Function*
SBC	*Schwartz Bayesian Criterion*
SOI	*Southern Oscillation Index*
SST	*Sea-Surface Temperature*
LEWL	*Lake Erie Water Level*
LMHWL	*Lake Michigan-Huron Water Level*
LOWL	*Lake Ontario Water Level*
LSWL	*Lake Superior Water Level*

1.0 INTRODUCTION

Water is one of the most vital and precious natural resources on earth. The long but often difficult relationship between humankind and the coastal environment has lead to both lacustrine and terrestrial degradation, while the value of water has continually increased. Since the coastal zone is where land, water and air meet, coastal components are exceedingly complex, and must be treated accordingly. As a Resource Manager, it is considered necessary that any coastal environment be thoroughly studied, properly managed, and kept sustainable. Thus, the most important questions needing answers are considered interdisciplinary in nature, and surpass the definition of the problem and define the processes, which may magnify these problems over the long term.

The North American Great Lakes are a common resource to a great many people, bordering two nations. With increasing global environmental crises, the changes within a system such as the Great Lakes should be regarded with much care and much caution. In particular, lake level fluctuation, whether past, present, or future, have become more sensitive to various physical factors in which it is influenced. As a result, climatic influences are deemed most essential to Lake system productivity. With increased frequency and severity of the El Nino/Southern Oscillation (ENSO), the various impacts on Lake levels has become a paramount concern among researchers.

The Great Lakes-St. Lawrence River Basin is a huge, complex, interdependent system which has many varied, interacting components, most of which are exceedingly complex (Clamen, 1988). It is one of the world's largest freshwater resources, as well as one of the most extensively utilized. Fluctuation of Great Lakes Water Levels (GLWL) affects directly and indirectly, most of the 40 million people that live within the boundaries of the watershed (Environment Canada, 1999). It is the deviation of lake levels to extremes that cause profound impacts on the many uses the resource provides. As such, a study and examination of historical Great Lake water levels may enhance knowledge of the factors influencing the fluctuation. It will also promote necessary remedial and preventative measures, and determine how this valuable and extensive resource will be affected by future climate change and variability. The premise of this investigation is that sake levels will fluctuate in the future as they have in the past (Sanderson, 1993).

The historical fluctuation of lake levels may also be better understood with respect to factors that influence them. Consequently, these fluctuations have been of particular interest among researchers. Numerous studies have investigated the historical fluctuation of GLWL, while attempting to correlate them with some factor of climate variability. This vast and valuable natural resource is both unique and rare and thus demands continued research and investigation. Numerous studies, indicate the magnitude and significance of all that the Great Lakes system provides.

The purpose of this thesis is to investigate the statistical relationship between Great Lake water levels, and certain meteorological features of climate change such as precipitation, evaporation, runoff, temperature and so on. The El Nino/Southern Oscillation (ENSO) phenomenon is considered to be the largest factor involving an inter-annual time-scale, and climatic variability. This is the result of global ocean-atmosphere interactions which result in global climate teleconnections (Ji *et al.*, 1994). Consequently, increased effects of global warming factors suggest a return increase in the severity and frequency of ENSO events. The ENSO phenomena is believed to create short-term climatic changes to the atmosphere world-wide, creating alterations to factors such as rainfall, evaporation, runoff and temperatures. These are the main areas of concern for water level fluctuations within the Great Lakes. The two major indices used to measure ENSO are the Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI). These will be examined in this thesis, in relation to historical lake level data, and net basin supply values.

The practicality of this thesis is based on an improved understanding of Great Lake water level fluctuation and those factors believed to be responsible. Efforts to recognize and incorporate a global phenomenon, such as ENSO should strengthen existing theories due to its multi-faceted impacts on physical and societal process. Hence, this research is directed toward the usefulness of statistical fit, and applicability of the ENSO indices to describe GLWL. This thesis offers information facilitating responsible decision-making, and the possibility of reliable forecasting tools, to better understanding for coastal zone management of the Great Lakes region.

2.0 THE LAURENTIAN GREAT LAKES BASIN

2.1 Physical Aspects of the Great Lakes

The Great Lakes (see Figure 1 and Table 1) were formed by a series of geological processes approximately 11, 000 years ago, upon retreat of the glaciers at the end of the last ice age. They lie between the latitudes of 40□30' and 50□30' north and between the longitudes of approximately 75□20' and 93□10' west. Its basin is the largest freshwater system in the world, containing approximately 20% of the world's supply, while occupying an area of 770 000 km^2 (Craig and Kertland, 1998; Quinn *et al.*, 1997; Croley and Hunter, 1994; Sanderson, 1993).

The five major component are Lakes Superior, Huron, Michigan, Ontario, and Erie; all of which make up a natural series of storage reservoirs linked by connecting channels and straits (Lee, 1993); and are among the fifteen largest freshwater lakes in the world. Despite the myriad of statistics about the vast volume of water these lakes contain, the system is not a limitless supply of water, and is more reactive to stressors than many would think. This bounty of water is being used at an unprecedented rate, and this will likely increase with time.

The Great Lakes (see Figure 2) are bordered by the Canadian Province of Ontario, and eight US states (New York, Pennsylvania, Ohio, Michigan, Indiana, Illinois, Wisconsin and Minnesota). Donahue (1988) estimates that 20% of the entire U.S. population and 60% of the Canadian population reside along the Great Lakes Basin. The Great Lakes ecosystem provides fish and wildlife habitat, climate control, recreational opportunities, transportation routes, and water supply for drinking water, irrigation, and industrial uses (Vigmostadl *et al.*, 1988). As such, there is a large proportion of the population of both countries whose livelihoods, health and quality of life are influenced by the resource.

2.2 The Great Lakes System Flows

The Great Lakes basin extends approximately 1300km from the western edge of Lake Superior to the Moss-Saunders Power Dam on the St. Lawrence river. Lake Superior is the largest, deepest, coolest, and most-upstream lake in the system. It is approximately 563 km in length, has an average depth of 147 m, and has a total area of approximately 209 800 km^2 (GLERL, 1999). Its watershed is approximately 127 700 square kilometers which is considered small for a lake its size (GLERL, 1999). It is completely regulated, and has two interbasin diversions of water into the system. These diversions come from the Long Lac, and Ogoki Diversions.

Lake Superior has an average annual temperature of 4° C, which makes winters warmer and summers cooler (GLERL, 1999). In winter, temperatures near Superior can fall to about -35° C, while inland temperatures reach -43° C (GLERL, 1999). During most winters, Lake Superior is

TABLE 1

Physical Characteristics Of The Great Lakes

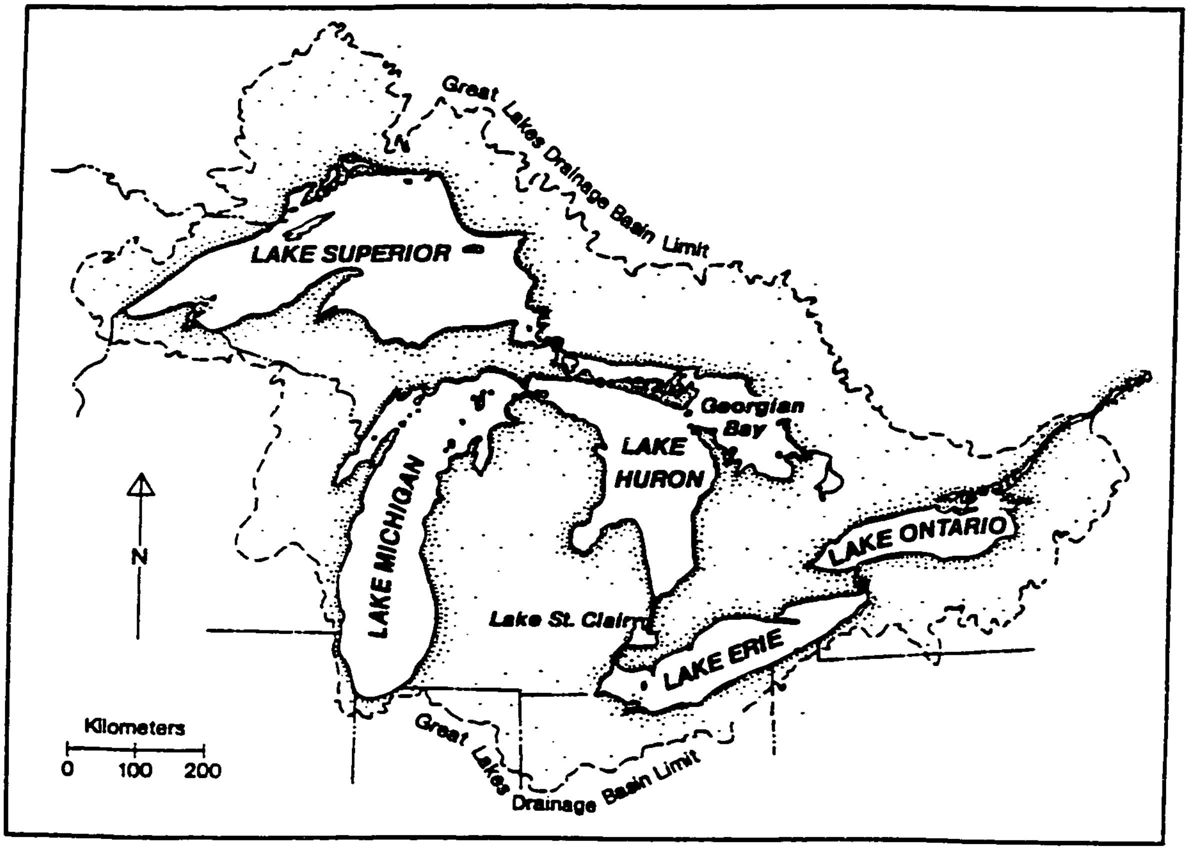
	Superior	Michigan	Huron	Erie	Ontario	Totals
Elevation (m)	183	176	176	173	74	
Length (km)	563	494	332	388	311	
Breadth (km)	257	190	245	92	85	
Average Depth (m)	147	85	59	19	86	
Maximum Depth (m)	406	282	229	64	244	
Volume (km^3)	12 100	4 920	3 540	484	1 640	22 684
Water Area (km^2)	82 100	57 800	59 600	25 700	18 960	244 160
Land Drainage Area (km^2)	127 700	118 000	134 100	78 000	64 030	521 830
Total Area (km^2)	209 800	175 800	193 700	103 700	82 900	765 900
Shoreline length (km)	4 385	2 633	6 157	1 402	1 146	17 017
Retention Time (yrs)	191	99	22	2.6	6	
Outlet	St Mary's River	Straits of Mackinaw	St Clair River	Niagara River/ Welland Canal	St Lawrence River	

Where:
Average depth and volume where measured at Low Water Datum
Land Drainage Area for Lake Huron includes St. Mary's River
Lake Erie includes the St. Clair-Detroit system
Lake Ontario includes the Niagara River
Shoreline Length values includes islands
Shoreline Length and Retention Time totals are greater than the sum of the shoreline length for the lakes because they include the connecting channels (excluding the St. Lawrence River).

Source: Great Lakes Environmental Research Laboratory (1999).
Http://www.coastwatch.glerl.noaa.gov/statistical/physical.html

FIGURE 1

The Laurentian Great Lakes and Drainage Basin



Source: Quinn (1992). Hydraulic Residence Times of the Great Lakes. Journal of Great Lakes Research; 18(1):22-2 covered with ice approximately 40 to 90 percent (Beranek, 1999). Open water is often found in the centre of the lake due to ice breakage and strong winds. Evaporation is greatest during the month of December (Mason, 1998).

The flow proceeds through various locks, down through St Mary's River into Lake Huron, where it is joined by water flowing from Lake Michigan (Croley, 1986). St Mary's River is situated at Lake Superior's southeast corner. It is a crooked 98 km channel of water separating Michigan's upper peninsula from the province of Ontario (Beranek, 1999). The St Mary's Rapids are situated only 26 km from the mouth of the river, and Lake Huron (Beranek, 1999).

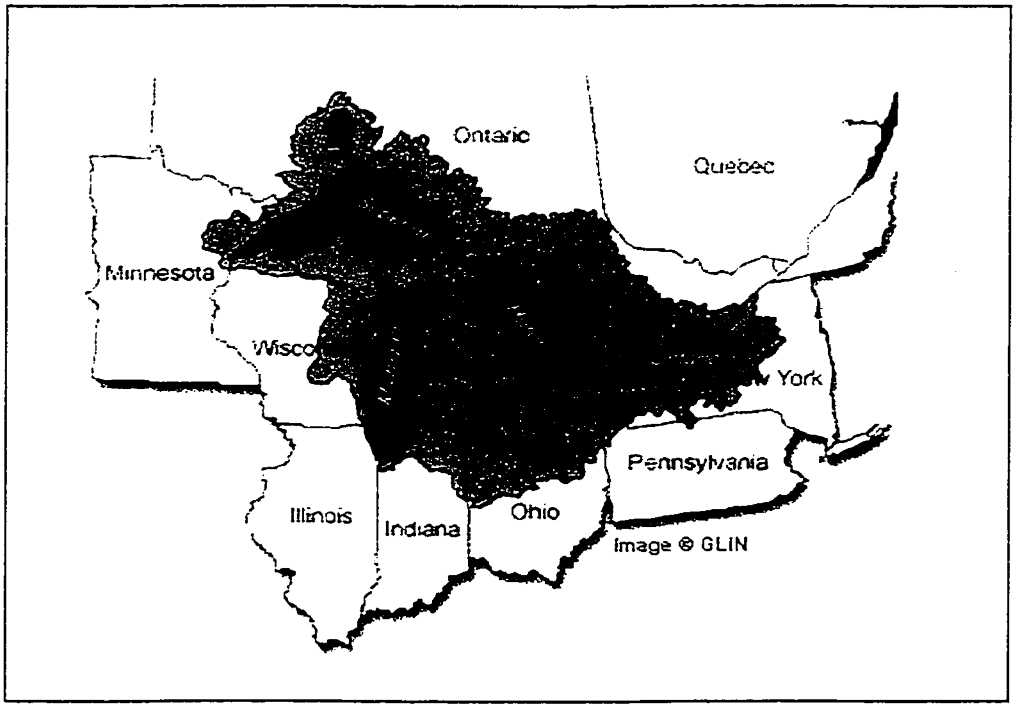
Water flows from this point into Lakes Michigan and Huron, which are commonly, considered a single lake, due to hydrologic and hydraulic similarities (Canadian Hydrographic Service, 1999; Hartmann, 1990). The key to this is the deep and immense straits of the Mackinaw river that allows for a close and interdependent relationship between the two lakes. According to Croley (1986), its vast surface area, (together- 117 400 km^2) provides a 'buffer to flow changes leaving the lake.' Additionally, because both lakes have the same elevation (176 km), many researchers deem them systematically similar (GLERL, 1999).

Lake Michigan has the second diversion, where water is diverted at Chicago to the Mississippi River Basin. The shape of Lake Michigan is long and narrow, (494 km by 190 km), and is considered a natural *cul-de-sac,* meaning that water entering the lake circulates slowly, and remains for a long time before it leaves the basin through the straits of Mackinaw (Farid *et al.*, 1997). It is important to note that only a relatively small amount of water flows out of the bottleneck at the strait between Michigan and Huron. Lake Michigan therefore, has a long retention time (Beranek, 1999). Lake Huron serves as a conveyor of water within the Great Lakes, as it carries water from the upper two lakes, to the rest of the system. Incidentally, Bishop (1990) states that water levels of Lake Michigan-Huron have substantially been influenced by various human-induced actions at the outlets of Lake Huron and the St Clair River.

These lakes discharge through the St Clair River, to shallow Lake St Clair, and then through the Detroit River system into Lake Erie. Lake St Clair has a surface area of 692 square kilometres, and has an average natural depth of approximately 6.5m (Beranek, 1999). The drop in elevation between the lakes, through their outlets, and Lake Erie is approximately 2.5m, which creates a 'backwater effect' among the Lakes (Beranek, 1999; Canadian Hydrographic Service, 1999; Hartmann, 1990; Croley 1986). The waterway between Lake Huron and Lake Erie is about 145 km long, and with the relatively small elevation difference, another seemingly large bottleneck occurs within the overall system (Beranek, 1999). This may mean that the potential amount of water that could flow within the system is quite large. However, the relatively small and narrow waterways between these lakes cause fewer and slower movement over a longer period of time. Levels of the lakes on both sides of the system usually result in corresponding levels of the St. Clair River, Lake St. Clair, and the Detroit River (Bishop, 1990; Canadian Hydrographic Service, 1999).

FIGURE 2

The Great Lakes: Surrounding Areas



Source: Environment Canada and US EPA. In: Great Lakes Information Network (2001). Http://www.great-lakes.net/lakes/

In turn, 95% of Lake Erie's total inflow comes via the Detroit River water from all of the "upper Lakes" in the system (Environment Canada and US EPA, 1995). Hostetler (1995) states that Lake Erie is especially influenced by the magnitude and phase of hydrological variations such as precipitation, evaporation and runoff. Because of its small size and shallow depth, it is quite vulnerable to lake level fluctuation. From Lake Erie, the water flows through its natural outlet, the Niagara River and Welland Diversion into Lake Ontario. The Welland Diversion bypasses Niagara Falls and is used for navigation and hydroelectric power. There are no major deviations in lake levels to upstream lakes due to water flowing through Niagara Falls. The difference in elevation between Lake Erie and Lake Ontario is approximately 99m (Canadian Hydrographic Service, 1999).

Lake Ontario is the lowest of the Great Lakes (74m in elevation) and its water flows through the St. Lawrence River into the Gulf of St. Lawrence and continues toward the ocean, over 1900km away. The difference in elevation between Lake Ontario and the St. Lawrence River is about 1.7m (Canadian Hydrographic Service, 1999). Lake Ontario is regulated whereby its outflows are controlled by the Moss-Saunders Power Dam located between Massena, New York and Cornwall, Ontario (Croley, 1986). Its canals do not serve as regulation, but a means for navigation through the bottlenecked channel. Lake Ontario is said to be strongly influenced by meteorological events, while water circulation is highly variable, being influenced by wind stress on surface waters, and hydraulic flows from discharging tributaries (Flint and Stevens, 1989). Flint and Stevens (1989) state that of all the Great Lakes, Lake Ontario has the largest ratio of watershed land area to lake surface area, suggesting a much larger relative drainage basin than the other lakes.

2.21 Great Lakes Connecting Channels

The connecting channels of the Great Lakes are St. Mary's River, the St. Clair River, Lake St. Clair, the Detroit River, the Niagara River, and the St. Lawrence River. These make up the system in which water flows from one lake to another (see Table 2). Considering the sizes of the lakes, these connecting channels are considered quite small (Mason, 1998). They are extremely important in water level management, as well as the most heavily used areas within the basin.

TABLE 2

Characteristics of the Great Lakes Connecting Channels

	ST.MARY'S RIVER	ST. CLAIR	DETROIT	NIAGARA	ST. LAWRENCE
LENGTH (KM)	121	63	41	58	150
ELEVATION DROP (M)	6.7	1.5	1.0	99.3	1.6
MEAN ANNUAL DISCHARGE (M^3/S)	2 100	5 097	5 210	5 692	7 739

Source: Mason (1998). Lake by Lake. State of the Great Lakes Report. Environment Canada. Http://www.on.ec.gc.ca/glimr/data/state-of-the-lakes/917

St. Mary's River drain's Lake Superior into Lake Huron, with a 6.7 metre drop in elevation between the two. According to Mason (1998), the river has several tributaries, however the water entering from these are only a small fraction of the water drainage from Lake Superior. The St. Clair River drains Lake Huron into Lake St. Clair. Its natural depth is actually quite shallow, however it has been dredged extensively to meet transportation needs. Here as well, the main water comes from Lake Huron than any other source. This river is characterized with a non-complex shoreline, fast current, and substantial artificial depth (Mason, 1998). The Detroit River connects Lake St. Clair to Lake Erie. Mason (1998) cites that 95% of the total river flow comes from the upper lakes. In addition, the Niagara River drains Lake Erie into Lake Ontario and drops in elevation by almost 100 metres along its course. Like the others, the large majority of water within the river comes mainly from the lake itself. Finally, the St. Lawrence River is the outlet of the Great Lakes system. It drains Lake Ontario to the Gulf of St. Lawrence on a course that extends 870 kilometers to the ocean.

2.3 Climatic Characteristics and their Controls

There is no question that climate change, and aspects of regional climate have the potential to affect the water levels of the Great Lakes. This would involve many factors, although climatic variables such as precipitation, evaporation, and runoff patterns, are of particular importance (Hartmann, 1990). Overall, the climate of Southern Ontario varies immensely especially due to the effects of the Great Lakes. Brown et al., (1980) states that the meteorological effect of the lakes is most pronounced along the shoreline, where the climate differs considerably from that in the uplands. Eichenlaub (1979) and Lee (1993) state at least four major controls that exert a marked influence over the climate of the Great Lakes area. These are 1) latitude; 2) air masses and atmospheric disturbances; 3) the continentality of the region (related to its position within the interior of North America); and 4) the modifying marine effects resulting from the presence of the Great Lakes. The following will describe these details as well as other pertinent components of climatic characteristics.

Controlling factors of climate indicate the effects of related components affecting the levels of the Great Lakes. Day-to-day weather is variable because much of the basin is located within the paths of several major storm tracks. Additionally, the climate of the Great Lake Basin may be simply characterized by a mix of continental and maritime climates (Eichenlaub, 1979). These factors induce the components affecting water levels. Factors such as precipitation, temperature, evaporation, atmospheric circulation patterns, lake circulation, and so on. Therefore, the unique climatic characteristic of the region under study must be presented in a descriptive and precise manner. The following will describe Great Lakes climatic characteristics, while later chapters will specifically focus on resulting factors that directly influence water levels.

2.31 Latitude and Situation

According to Eichenlaub (1979) latitude is the dominant control concerning climate, insuring that large differences in solar radiation will occur seasonally. This means that there is a marked contrast in energy received during the winter and summer months. These factors are essentially determined by the energy from the sun. The mid-latitude location effects seasonal and temperature variation, due to solar energy being three to four times greater in early summer than in early winter (Lee, 1993). The exact situation of the basin allows for a mix of air masses, storm tracks, variation in the prominence of four distinct seasons, and atmospheric circulation (Brown *et al.*, 1980). These effect the hydrologic cycle, seasonal variation, while comprising the main climatic traits of the region.

Situation of the region is an important factor in explaining and describing specific climate characteristics of the Great Lakes Region. For example, winter periods in most portions of the basin are quite cold and precipitous. The lack of relief or other barriers allow Arctic air masses, carrying extremely cold air masses to easily flow into the region. Lee (1993) states that the temperature may reach as low as -40□C. During winter seasons, the sustained cool temperature allows the build up of snow and ice over the lakes, and such storage of snow and ice on land and lake is responsible for lower lake levels during such periods.

2.32 Atmospheric Circulation Patterns

Weather systems, storm tracks and air masses continuously move across the Great Lakes region. These systems bring with them periods of heat, cold, rain or snow, sunshine or clouds. Brown *et al.* (1980) states that the strength and predominance of atmospheric patterns and various source-regions of air that allow for the variations in weather patterns and hence, the distinct properties of Great Lakes regional climate. The dominant air masses of the region are those originating from the Arctic, the northern oceans and the tropics, all of which bring distinctive types of weather (Brown *et al.*, 1980). Storms develop along 'weather fronts', or along the zone between two types of air masses.

Other factors responsible for the climate in the basin involve the large-scale general circulation of the atmosphere. The controlling factors of this are the polar jet stream and the semi-permanent high-pressure system located in the subtropical Atlantic (Lee, 1993). The polar jet stream is responsible for low-pressure storms that are conducive to precipitation. The subtropical high-pressure system is most intense during the summer, and brings with it large amounts of moisture from the Gulf of Mexico and the Atlantic Ocean. These may be considered the main sources of moisture/precipitation producing systems for this area. These systems also account for the high frequency of warm and humid days during the summer season especially over the southern portions of the basin (Lee, 1993).

Lee (1993) also contends that these systems are predominant and result in a very large range of variability concerning day-to-day weather.

ENSO events may be defined as the combination of ocean warming and the reversal of surface air pressure, at opposite ends of the tropical Pacific Ocean, that usually occur simultaneously (Ahrens, 1991). During ENSO events, air circulation at 5km high in the atmosphere is altered during El Nino and La Nina events. During El Nino winters, the jet stream over the North Pacific is likely to split on its approach to North America. Shabbar (1999) contends that a weaker branch would be diverted northward into the Northwest Territories while the lower subtropical branch (whose mean position is over the Pacific northwestern region of Canada) would be shifted several degrees latitude southwest. The southern Canadian region lies in between the two jets and receives milder, and drier than normal, winters (Shabbar, 1999). Shabbar *et al.*, (1997) and Shabbar and Khandekar (1996) have found that temperature and precipitation patterns over Canada respond to ENSO events which induce atmospheric agitation.

Peixoto and Oort (1992) found a very strong correlation between Sea Surface Temperatures (SST) anomalies in the eastern equatorial Pacific and that of the atmospheric temperature over the Northern Hemisphere. The correlation found is said to most strong when the atmospheric temperature lags the ocean temperature by four months (r=0.82). It was concluded that "since correlations with the mean Southern Hemisphere temperatures are very high, it is clear that a large part of the observed variability in the global atmosphere must be connected with ENSO events." Similar to that of Daly (1999), Peixoto and Oort found that atmospheric temperatures lag the SOI by approximately 8.5 months.

Meadows *et al.* (1997) related phenomena of high lake levels with significant changes in the nature of the Great Lakes basin cyclones. Support for this finding is provided by an apparent inter-decadal climate change reflected in a marked shift in track lines of extra tropical cyclones passing over the Great Lakes. This is paralleled by a decrease in lake levels and wave energies during different periods. Rohli et al. (1999), indicated important factors that define how local atmospheric anomalies affect the Great Lakes Basin. These are believed to affect local temperature regimes, as well as precipitation patterns.

2.33 Impact of Great Lakes on Regional Climate

The Great Lakes have a significant effect on their own regional climate. Accordingly, such knowledge allows for the ability to conventionally determine and devise a standard that would allow researchers to compare and base all other climatic differences or changes against. Brown *et al.* (1980) stated for example that heat provided by energy from the sun is transported to and from the Great

Lakes by the wind, and plays a dominant role in shaping the climate of Southern Ontario. For example, the temperature difference between the large water bodies and the landmasses, especially during different seasons, allow for alterations in climatic characteristics. The slow response of water temperature to seasonal changes in solar input has a significant effect on air temperatures at locations along the shoreline, strikingly different from places located away from the shore. In addition, Lee (1993) demonstrated that prevailing winds during the winter cause locations near the southeastern shores to be warmer than those at the same latitudes, while those in the summer near northeastern shores have cooler temperatures.

The term "lake effect" is a well-known climatic influence of the Great Lake region (Scott and Huff, 1996). Scott and Huff state that lake effects are most noticeable in precipitation and temperature, and vary with season, time of day, and lake size. As well, the lakes act as a large source of moisture to the lower atmosphere, allowing for changes in precipitation, temperature, and evaporation that would not normally exist without the presence of such a large lake system. The lake effect shows how Lake Superior has the greatest influence 'where up to 100% more precipitation falls downwind of the lake in winter compared to that expected without its presence.' Furthermore, in summer, all lakes cause a 10% to 20% downwind decrease in precipitation. Temperature aspects of the basin are altered in a manner where mean minimum temperatures are higher during all seasons; while producing a reduction in mean maximum temperatures during the spring and summer seasons (Scott and Huff, 1996).

The results of Scott and Huff (1996) suggest that lake-induced changes include cloud cover, which is greatest during the winter, and greatest immediately downwind of Lakes Superior and Michigan. During the summer, Lakes Huron and Michigan are said to induce a reduction of cloud cover by approximately 10%. Cloud cover may reduce the amount of sunshine, and indirectly, heat, by as much as 50% of the total possible (Eichenlaub, 1979). In winter, this is reduced by as much as 75% (Brown *et al.*, 1980). As such, the apparent lake effect on the surrounding area of the basin is a significant climatic effector, as well as a factor that influences lake levels

2.4 Resource Management Aspects

The inclusion of resource management aspects in any study concerning the Great Lakes is essential, considering its present and projected uses. The Great Lakes system is complex and requires meticulous research, regulation, and policy, for maintenance and protection. It must be addressed that the presence of several competing uses, often means having different ideas, plans, and goals for the future uses of the Great Lakes. Since a scenario such as this is usually accompanied by degradation of the resource, fastidious resource management, must be adapted. Although at present, there are several organizations attempting to keep the integrity of the system at an acceptable level, it is becoming an increasingly arduous task.

Therefore, in the course of comprehensive water planning, problems are identified, data are collected and analyzed, and projections are made. This provides a basis for integrating all of the functional components of comprehensive water management (Enger and Smith, 1993). The existing management strategies attempt to deal with the tremendous demand for use of the resource, while attempting to devise forecasting tools so that reliable long-term goals can be contrived, and eventually met. Over time, the Great Lake basin has seen approaches that comprise and are based on, net basin supplies, lake levels, and connecting channel flows that have been experienced over the first 75 years of this century (Hartmann, 1990). Projects include shore protection structures, hydropower production facilities and navigation locks, all of which have their own various impacts, both known and uncertain.

3.0 REVIEW OF THE LITERATURE

Researchers from various disciplines have long sought to determine the major causative factors of lake level fluctuation in the Great Lakes Basin. It has been suggested that fluctuation, at either a maximum or minimum, is a consequence to some degree or another, of local climate variability among many other components. Recent climate variability studies have focused on ENSO, thus developing indices to rate the severity and intensity of separate events over time. The Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI) have been used in various independent studies (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Assel, 1998; Wolter and Timlin, 1993 and 1998), while no one study has yet to resolve whether a particular index is more suitable. The following review includes past and recent research completed theoretically and empirically, from the field, to the laboratory.

3.1 History of Great Lakes Water Level (GLWL)

Water levels of the Great Lakes have historically fluctuated due to a variety of components. Many studies have attempted to define various factors that are responsible for influencing lake levels. The practicality of such studies, especially those concerned with coastal and water policy management, remains to be focused on extreme water level situations (Hartmann, 1990). Quinn (1999) has stated that there is great need for reliable lake level event frequency distributions because it is 'a critical component of any comprehensive strategy for coping with lake level fluctuations.' This becomes increasingly apparent when extreme fluctuation in lake levels occur more persistently than they have ever in history.

Great Lakes water levels have been continuously recorded since approximately 1860, with some of these records going back to about 1800 by sporadic and individual records. Bishop (1990) determined that historical records show that variation of lake levels did not fluctuate with any great significance. Likewise, Quinn *et al.* (1997) contended that despite the great concern and attention received by lake level variation, water levels change relatively slow due to 'large lake surface areas and constricted outlet channels, which integrate short-term climate fluctuations.' The recent fluctuation data are indicative of more recurrent and severe extreme levels. Figure 3 illustrates the standardized time series plots for the Great Lakes (1950-1999). Such research has led others to examine the cause of lake level fluctuation, and the grounds of its increased periodicity and rigor. It is suggested that climate change, global warming, and human alteration of the environment is the root and the generator of this phenomenon (Bruce, 1984; Hartmann, 1990; Sanderson, 1993; Croley, *et al.* 1996; Craig and Kertland, 1997; Assel, 1998; Quinn, 1998).

It has been determined that overall historical variability in annual lake levels is about 1.8m, while seasonal variability is approximately 20-40cm (Hartmann, 1990; Quinn *et al.* 1997; Angel, 1995). Although these values do not seem significant, many uses are dependent on water levels remaining at somewhat constant levels, and have become quite sensitive to even the smallest changes. This suggests that lake level sensitivity is increasing which may create potential coastal hazards. Croley (1986) has found through extensive and detailed research that precipitation and lake-levels are indeed correlated, and precipitation leads water levels by approximately one year. Therefore, it may be assumed that shifts in precipitation patterns will lead to corresponding shifts in lake levels. Other factors considered will determine the extent to which lake levels will fluctuate. Figure 3 illustrates Time Series Graphs of the Great Lakes (1950-1999).

Since the 1960's, it was considered that there have been comparatively high lake levels in place. This has been said to be attributed to a particular different climate regime from earlier times which has been portrayed with persistently high precipitation (Quinn *et al.*,1997; Hartmann, 1988; and Croley, 1986). Specifically, lake levels are said to be high in the 1950's, record lows in the early 1960's, with a consistently high precipitation regime from the late 1960's until the present time. This period is characterized by rapid and extreme shifts in lake levels. For example, record low lake levels in 1964 were directly replaced with high levels merely nine years later in 1973 (Croley, 1986). In fact, 1973 levels were so high that through the intervening period, record highs were set yet again on Lakes Superior, Michigan-Huron, and Erie. Hartmann (1988); Croley (1986), and Quinn (1986) identify this high precipitation pattern since about 1970.

Changnon and Changnon (1996) claim that sudden climate condition changes are responsible for the marked precipitation changes during the 1960's, 1970's, and 1980's (see also Hartmann, 1988; Croley, 1986; and Quinn, 1988). This is related to the extremely wet conditions experienced throughout the 1970-1994 period. Bishop (1990) identifies highs beginning in 1985 through to 1986. Lee and Noorkbakhsh (1992) studied GLWL forecasting during the years between 1982 and 1988.

It was found that, at the beginning of this period, the lakes were more or less at their average long-term levels. Sometime before 1985, the lakes experienced a steady rise and by 1985 and 1986, the lakes hit record highs. Hartmann (1988) states that this period was characterized with a 0.5m increase in long-term mean monthly lake levels. In fact, all lakes hit monthly record levels for at least one year except for Lake Ontario, which has different hydrological conditions on the basin, as well as regulation of its outflow (Lee and Noorkbakhsh, 1992). Abruptly by the end of

FIGURE 3

Standardized Time Series Plots of the Great Lakes 1950 - 1999

Figure 3.1
Lake Superior

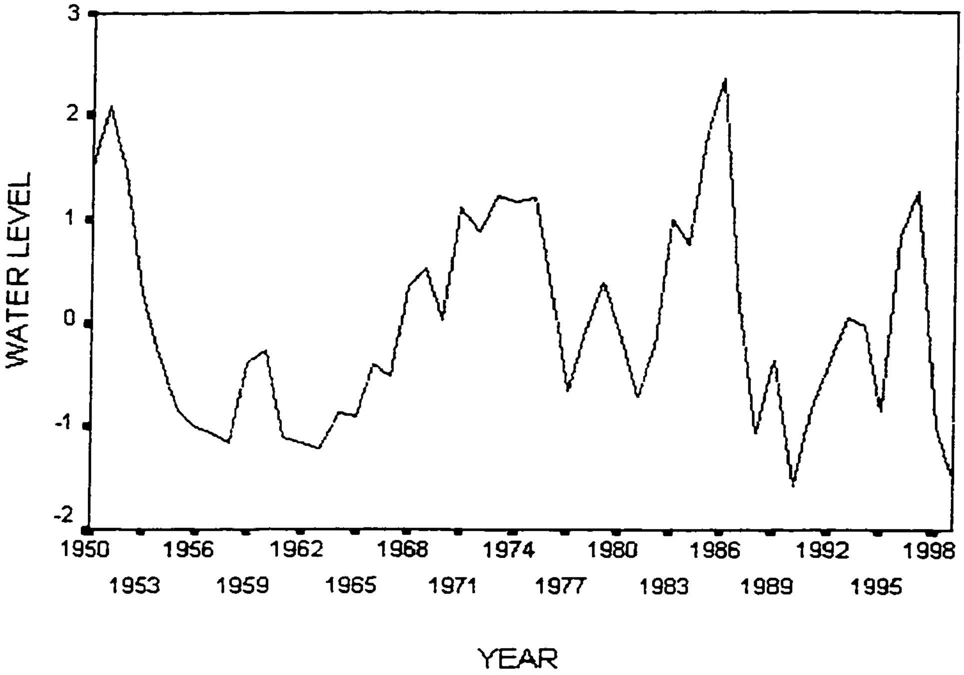


Figure 3.2
Lake Michigan-Huron

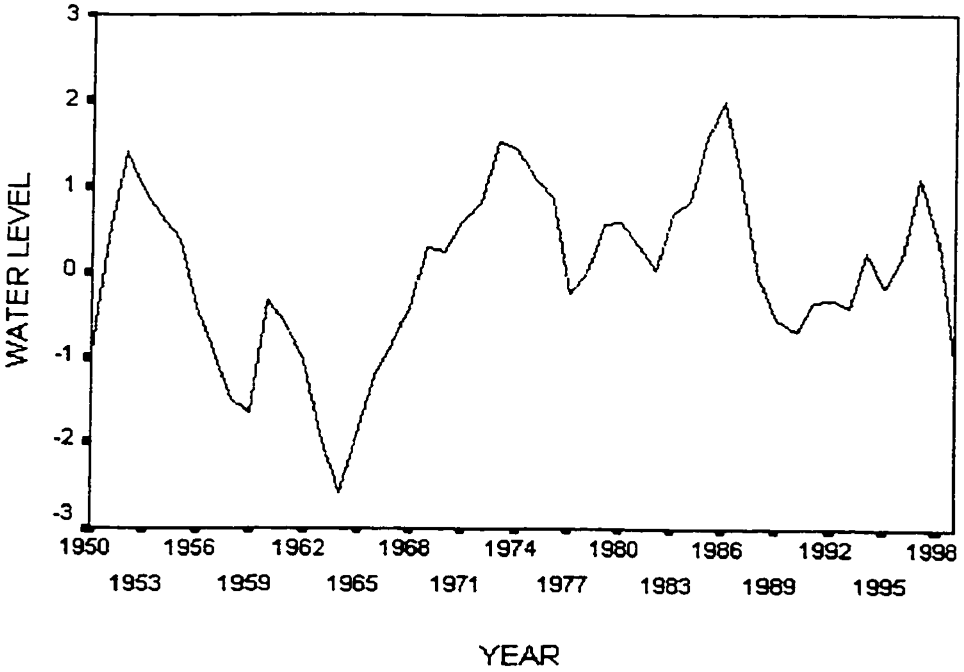


Figure 3.3
Lake Erie

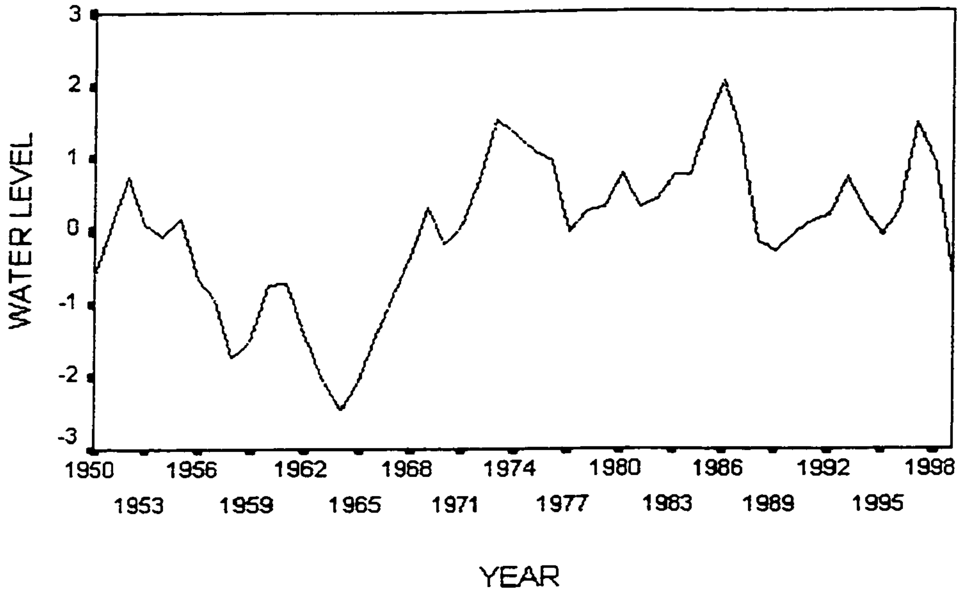
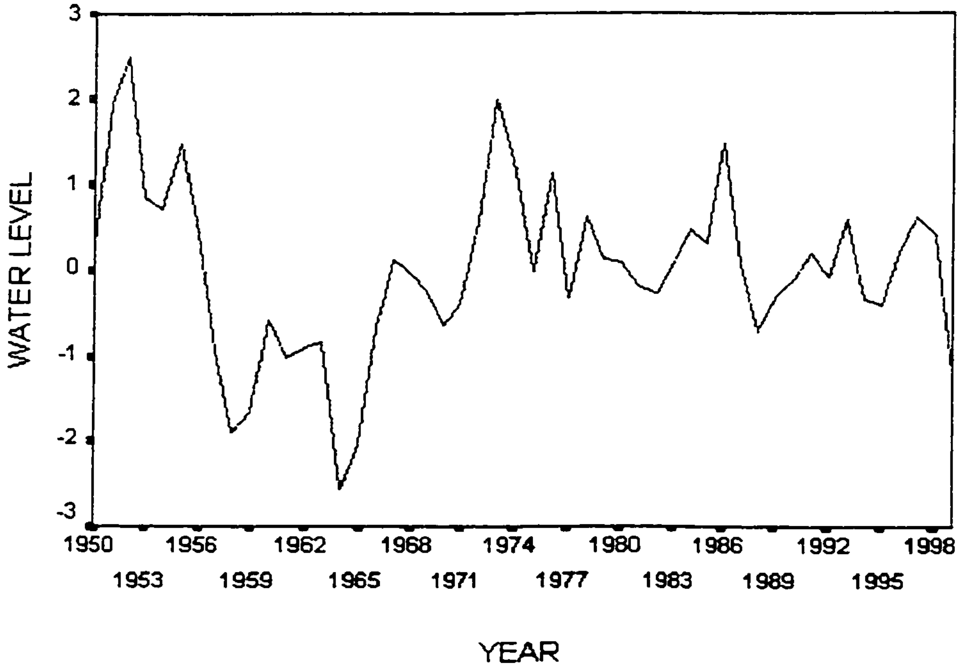


Figure 3.4
Lake Ontario



Source: Environment Canada (1999).

1986 and the beginning of 1987, low precipitation resulted in steadily decreasing lake levels. By the end of 1987, the lakes were for the most part below their long-term average levels.

3.2 Aspects of Water Level Fluctuation

In direct response to numerous and varied physical processes, water levels on the Great Lakes modulate on a wide range of time scales (Lee, 1993). The physical processes mentioned above include net basin supplies, inflows, outflows, and hydrologic variations. It is stated that variations occur over a very large time scale, of months in response to seasonal variations in supplies. In addition, diversity of temporal episodes may occur over several years in response to long-term climatic or atmospheric variation.

Water level fluctuations occur annually, seasonally, and over short-term periods. Annual levels of each lake may be superimposed within seasonal cycles. Variations may be understood as each lake undergoes annual cycles, as a result of a variety of climatic factors, while seasonal fluctuations occur with magnitudes depending on water supply and the local hydrologic cycle (Hartmann, 1990; Quinn, 1988; Croley, 1986). Extreme levels, or record highs or lows of the Great Lakes, are the result of mainly annual fluctuations, with a variability range of approximately 1.8m (Hartmann, 1990). Seasonal fluctuation in water levels may be logically defined as being at a minimum during winter periods (due to increased autumn and early winter evaporation from lake surfaces). As a result, spring and summer levels are usually increased due to increased snowmelt, spring precipitation and decreased evaporation; reaching a maximum in June (Croley, 1986).

Short-term precipitation patterns or variations involve storm surges and water set-up levels. This describes the build up of water on one side of a particular lake due to severe storms, high winds, and air pressure jumps due to the unique aspects of storm tracks and air masses that frequent the region (Quinn, 1988). Storm events cause a temporary redistribution of water in the lakes, as well as waves that create a short-term oscillation in the water surface (Lee, 1993). Short-term fluctuations are considered transitory and fleeting, and will not be included in this research problem. It must be noted however that these short-term fluctuations are significant because they describe the active area in which the Great Lakes are located. Here, cyclone passage due to the convergence of the westerly and southwesterly storm tracks are most active in late fall and early winter (Angel, 1995).

3.3 Factors Influencing Water Levels

The significance of studying the factors that influence GLWLs is critical considering the local climatic characteristics of the Great Lake basin, which are described in detail below. Hartmann (1988) puts this into perspective by stating that variations in GLWL are linked closely to the regional climate, and thus forecasts of lake levels are no better than the weather forecasts on which they are based.

Hence, it is imperative to strictly examine the factors involved in water level fluctuation. Assel (1999) confirms the notions of many others when he states that this region needs a manner in which to better define the linkages between regional and global climate, and to analyze the potential effects of ENSO events on Great Lakes monthly air temperature and precipitation, ice cover and water levels. As well, Sousounis (1998) states that studies of water level fluctuation have shown that the Great Lakes can respond relatively quickly to periods of varied but extreme precipitation, water supply and temperature conditions. The following will describe these factors as well as those that are related to the distinct study area.

3.31 Precipitation

Precipitation is indeed a major component of Great Lake water inflow. Over-lake precipitation is especially significant since over one-third of the Great Lakes basin (total land and water) area is lake surface (Canadian Hydrographic Service, 1999). Variations in hydrology are deemed effected by continental and regional shifts in atmospheric circulation that may persist for several years (Hostetler, 1996). Thus, it is believed that lakes fluctuate in size from 'storm-derived' increases in water inputs. Sanderson (1993) asserts that in order for GLWL to remain relatively constant the renewable portion must be re-supplied by nature. Thus, this renewable portion of the system must come in the form of precipitation (rain and snow). Precipitation may be considered here as rain and snow, minus the evaporation from lake surface, plus the run off from the land areas of the basin. This represents approximately 75cm on the surface of the Great Lakes annually (Sanderson, 1993).

Croley (1986) states that other variables affecting inflow, besides precipitation, include inflow from upstream lakes, and diversions into the Lake. However, it is clearly stated and accepted, that it is precipitation that causes the major long-term variations in lake levels, and is the dominant and most important form of basin inflow. Again, Croley (1986) states that precipitation and lake levels are correlated, with precipitation leading lake levels by approximately one year. This points to a positive and interrelated relationship that the Great Lakes and precipitation have between each other. This may be because the lakes are an excellent source of atmospheric moisture, while being able to add or take away, significant amounts of heat from air masses which crosses them. Brown *et al.* (1980) state that, consequently, areas to the lee of the lakes experience more precipitation, as well as other factors such as clouds and moderate temperatures.

Shabbar *et al.* (1997) asserts that there is a significant relationship that exists between precipitation and the Southern Oscillation phenomenon. Both composite and correlation analyses indicate that regions of Southern Canada, including the Great Lakes region, are influenced by the Southern Oscillation, via precipitation pattern variations. Shabbar *et al* (1997) indicate an ongoing pattern of 'negative/positive precipitation patterns in these regions are common and indicative of this phenomenon during the first winter following the onset of El Nino/La Nina events'. Shabbar *et al* (1997) suggest that the correlations are so significant that it may be possible to correlate SOI values with observed precipitation patterns (over Southern Canada) thus, developing long-range forecasting techniques. This may be based on Canadian precipitation patterns and the occurrence and evolution of various phases of the Southern Oscillation.

3.32 Temperature

Air temperature affects lake level fluctuations in general since higher temperatures cause plants to use more water, resulting in higher evapo-transpiration rates, causing higher net rates of evaporation from the ground surface (Croley, 1986). This results in less runoff for the same amount of precipitation than would occur during a low temperature period, when there is less evaporation and transpiration.

The impact of ENSO on Canadian surface temperature is believed to be most strong during the winter season, disappearing by spring months. Shabbar and Khandekar (1996) have documented the two phases of ENSO (El Nino/La Nina) concerning the surface and lower tropospheric fields over Canada. Their study clearly shows that with the onset of an El Nino event, the corresponding, significant positive surface temperature anomalies spread eastward from the west coast of Canada to the Labrador coast from the late fall to early spring (November through May). Atmospheric circulation concerning this region results in a transition where accompanying temperatures in the lower troposphere vary. This tends to concentrate around the North American domain, and more specifically, the Great Lakes region during El Nino events. This results in a converse phenomenon where significant negative surface temperature anomalies spread south-eastward from the Yukon that extends into the upper Great Lakes region by the winter season following the onset of La Nina episodes.

Assel (1999) analysed seasonal temperature and precipitation records for El Nino, La Nina, and non-ENSO years for the time span of 1900-1990. The analysis showed that 'seasonal average temperatures are significantly cooler in the spring (La Nina onset year), summer, and fall (El Nino onset year), and late fall to winter (following the La Nina onset).' This corresponded to the additional findings that suggest that seasonal average temperatures are warmer for the late winter to early spring following the El Nino onset year. This is related to the seasonal average precipitation, which is significantly less from mid fall through winter following the onset of El Nino.

3.33 Evaporation

Evaporation from the Great Lakes represents a major loss to lake levels and must be considered an important factor. Evaporation is significant in the determination of lake levels because it has been found that levels are usually higher when evaporation rates are low, and vice-versa. Evaporation is at its highest when the differences between air and water temperature are greatest. This is due to being dependent on solar radiation, temperature differences between air mass and water, and on humidity and wind (Canadian Hydrographic Service, 1999). Thus evaporation from the lake surface is lower in winter and reaches a maximum in early fall. According to Croley (1986), there is an inverse relationship between evaporation and lake levels. Here, it is stated that as evaporation rates increase, lake levels tend to decrease. Croley (1986) studied such factors and determined that the highest lake levels occur in early summer when evaporation rates are low, and when snow and ice melt. In addition, there is a positive correlation between evaporation and temperature.

Evaporation rates for any of the Great Lakes varies in timing and magnitude. For example, Sousounis (1998) states that Lake Erie peaks in evaporation during October, while Lake Superior peaks in December. In relation, a shallow, warm lake, such as Lake Erie, experiences more evaporation than a deeper, colder lake, such as Lake Superior. The Canadian Hydrographic Service (1999) concluded that on average, the Great Lakes, annual evaporation is almost equivalent to average annual precipitation. This describes a strong relationship between evaporation, precipitation, and temperature that allows for the extreme levels the Great Lakes experience.

3.34 Runoff

Another factor that is involved in the determination of lake levels is the runoff of water from land, which flows into the lake. It is considered quite significant because it involves the region's hydrological cycle, while comprising a weighty part of the water supply. Correspondingly, runoff from the land areas peak in early spring and is at its minimum in the autumn (Sanderson, 1993). Approximately 10 to 150 km of land surface around the lakeshores is contributed to lake runoff through a series of complex rivers and streams (Canadian Hydrographic Service, 1999).

Runoff is most notable basin-wide during spring when snowmelt occurs, normally during late March through early June (Croley and Hunter, 1994). Net supplies of water are greatest in late spring due to melting, while they are at their lowest during early fall. Thus it may be stated that runoff is a factor of seasonality, where annual precipitation is rather more constant, but has seasonal features. It must be noted however, that runoff is usually directly related to precipitation and temperature. Runoff is often tabulated as precipitation rates per year, while temperature affects the length of time snow and ice remain on lake and land masses.

3.35 Great Lakes Circulation

According to Beletsky *et al.,* (1999), wind stress and surface heat powers long-term circulation or patterns in the Great Lakes. This is considered quite complex given the interplay between these two factors as well as underlying lake bathymetry. The results state that while some features of lake circulation appear stable, others tend to demonstrate significant interannual variability. Beletsky *et al.*, (1999) have deduced that summer circulation patterns are more complex than winter patterns due to the presence of 'baroclinic effects' in summer circulation, despite the fact that winter circulation currents are much stronger than that of summer circulation currents. Winter circulation is stated to be powered by wind-driven forces. Density-driven forces are negligible in winter because at this time, lakes lack significant surface heat.

Beletsky *et al.*, (1999), also concluded that circulation patterns show a tendency to be cyclonic in the larger Lakes (Lake Huron, Lake Superior, and Lake Michigan), especially in winter. Larger lakes are characterized by larger surface areas, and stronger lake-atmosphere temperature gradients (Beletsky *et al.*, 1999; Ullman *et. al.,* 1998). These factors are suggested to indicate the significance of 'lake-induced mesoscale vorticity in the wind field' (Beletsky, *et al.*, 1999). In summer, the circulation in Lake Ontario is somewhat cyclonic most likely due to density-driven currents. This is similar to cyclonic circulation in the larger Lakes (Michigan, Superior, and Huron) in the summer. The other smaller lake, Lake Erie, was anticyclonic in the summer, which is attributed to wind. Lake Erie and Ontario exhibit 'two-gyre' circulation patterns in winter, which are stated to be most likely due to somewhat uniform wind fields (Beletsky *et al.*, 1999).

A seiche is a free oscillation of water in a closed or semi-closed basin. It is frequently found in bays, lakes, and in almost any distinct basin of average size (Environment Canada, 1999). Seiches are usually induced by meteorological disturbances whereby the water surges back and forth. They are important when studying lake level fluctuation because they represent short-term lake level changes. The physical aspects of each lake determine how they are affected by, or conducive to seiche size, intensity, and frequency. The distinctive oscillation usually damps out by friction over a period of a few hours depending on the energy of the particular seiche. Lake Superior has very infrequent and weak seiches. According to Environment Canada (1999), seiches in this lake are typically less than 0.3m, while storm conditions may increase this to 0.6m. Seiche formation in Lakes Huron and Michigan is greatest at the extremities of the lakes. Bays are typically effected with the most intensity due to strong easterly winds found flowing across Georgian Bay. Lake Erie has very pronounced seiche activity because it is very shallow, and aligned with prevailing wind directions. Therefore, the perimeters of the lakes are subject to the greatest water level fluctuation. During storm conditions, the fluctuation has been found to be approximately 5m (Environment Canada, 1999). Finally, Lake Ontario has very little seiche activity because of its small area, deep waters, and symmetrical shape.

3.4 Net Basin Supply and Outflow

Net Basin Supply (NBS) is defined as direct rainfall plus runoff and net groundwater inflow, less lake evaporation associated with a lake basin (Boland, 1989). This not only includes over-lake dynamics, but also those that occur within the drainage systems as well. As a result, transient changes in NBS lead to changes seen in lake levels. Understanding the impacts of climate change on Great Lakes water resources includes those involved with its NBS. Sousounis (1998) stated concerns about extreme changes in NBS due to climate change, and stated that decreases for example, would result from lower land based runoff (from higher evapotranspiration and lake evaporation) during fall and early winter. This is illustrated in the following simpl-e equation:

$$NBS = P + R - E$$

Where: NBS denotes Net Basin Supply; P denotes precipitation; R denotes runoff; and E denotes evaporation (Quinn and Guerra, 1986).

The report by Sousounis (1998) outlined the importance of regional climate, especially weather extremes and inter annual variability. Extreme lows would result in lower lake levels, while the reduction in NBS would result in lower water levels as well. This is especially true when taking into consideration, the substantial variation in the hydrological cycle over each lake. Quinn and Guerra (1986) stated that the principal variables in Great Lake basin water supply are precipitation, runoff and evaporation. Water supply is added to through precipitation, and lost through evaporation, outflows and consumptive uses.

Lake outflows also vary as a function of lake levels. This means that the lakes on average rise in the spring due to runoff, and recede in late summer and early fall as runoff usually decreases (Sousounis, 1998). This seasonal variation is the result of melting ice and snow in the spring, which causes additional water into the system. As well, increased temperature and evaporation result in lower outflows since water levels are usually lower during this period. It must be noted however, that variation in lake levels are in part due to the gradual variation in lake outflows. This means that not all water entering the lake is immediately pushed through the system. There is an element of time involved which cause the fluctuation in lake levels. It is stated that the length of time required for noticeable changes in lake levels (and outflows) mainly depend on the intensity or strength of the weather, such as precipitation, and on associated temperatures.

TABLE 3

Ratios of Drainage Basin Area To Water Surface Area

LAKE SUPERIOR	1.6
LAKE MICHIGAN-HURON	2.1
LAKE ERIE	3.4
LAKE ONTARIO	3.0

Source: Environment Canada and the US Environmental Protection Agency (1995). In: The Great Lakes Information Network. Http://www.great-lakes.net/lakes/.

Other factors taken into consideration are drainage basin area, or catchment area (see Table 3 for drainage basin ratios for the lakes). This determines the potential amount of water a lake may receive through land runoff. The larger drainage basin, the greater the potential supply of land runoff. As well, another major factor is water flow from upstream lakes to downstream lakes. According to Farid *et al.* (1989), Lakes Superior and Michigan are not affected by this. However due to its orientation, Lake Huron receives 1.2 times as much water from Lakes Superior and Michigan than it receives from precipitation and runoff. The same study states that Lake Erie receives 3.6 times as much water from the upstream lakes while, Ontario, receives approximately 3.8 times as much. On the same note, Farid *et al.* (1997) continues with the importance of outflows which, are stated to be on average, higher than lake inflows. With this, it is put forward that in Lake Huron, its outflow into the St. Clair River is about 1.4 times as high as inflow from Lakes Michigan and Superior.

3.5 El Nino, La Nina, and the Southern Oscillation (ENSO)

Philander (1990) states that the coordinated El Nino/Southern Oscillation phenomenon (ENSO) is the strongest source of natural variability in the global climate system. El Nino was first called to attention in 1871 by Dr. Luis Carranza of Lima, who described a counter current flow moving north to south between the ports of Paita and Pacasmayo in Peru (Philander, 1990). This is evident along the west coast of South America, where the cool Peru current sweeps northward, and southerly winds promote upwelling of cold, nutrient-rich water that gives rise to an abundance in local marine populations (Ahrens, 1991). Thus, this natural pattern does not create very many local disturbances and no global disturbances. However, near the end of each calendar year, a warm, nutrient-poor moves southward replacing the cold, nutrient-rich surface water. Normally, this warming persists only a few weeks to a month or more, after which weather patterns return to normal (Ahrens, 1991).

A major El Nino event occurs when this warming lasts for many months to a year, with a more extensive warming pattern taking place. These are reported to occur in approximate intervals of 3 to 7 years (Daly, 1999; Ahrens, 1991; Philander, 1990). This fact may change with increased climate change, which is suggested to increase the severity and frequency of ENSO events. This may possibly explain why El Nino/Southern Oscillation events are not prominent in past records. Since the beginning of the data set used (1950-1999), there have been various strong to moderate ENSO events. These are 1951, 1953, 1957-58, 1963, 1965-66, 1969, 1972-73, 1982-83, 1986-87, 1991-92, 1994, and 1997-98 (Canadian Hydrograhic Service, 1999; Wolter and Timlin, 1993; Wolter and Timlin, 1998, Assel, 1998; Trenberth, 1990). The seven strongest ENSO events (according to the standard SOI) during this time period are as follows, 1957-58, 1965-66, 1972-73, 1982-83, 1986-87, 1991-92, and 1997-98 (CDC, 1999).

El Nino/Southern Oscillation (ENSO) considers both the oceanic and the atmospheric changes in the Pacific Ocean region. More specifically, Southern Oscillation may be described as a 'see saw' in atmospheric mass involving exchanges of air between eastern and western hemispheres (Rohli *et al.*, 1999; Kane, 1997; Bunkers and Miller, 1996, and Glantz *et al.*, 1991; Trenberth, 1990). Consequently, because of its characteristic inter-annual variations in weather and climate, it is considered a reliable indicator of prominent anomalies. As well, it is no longer considered merely a regional phenomenon, but one that is appreciated as global, affecting many regions of the world, with various implications.

Research completed on how ENSO affects various regions of the globe include Daly (1999); Assel (1998); Kane (1997); Bunkers and Miller, (1996); Guetter and Goergakakos (1995); Glantz *et al.*, 1991; Trenberth (1990) and Wolter (1987). This suggests that investigation of the processes of global climate systems and variability, will allow more precise research concerning inter-annual time-scales. Daly (1999) and Peixoto and Oort (1992) both have found through similar research that atmospheric anomalies, both positive and negative, are correlated to the global temperature of the lower troposphere. In addition, there was found a strong correlation between SST anomalies and atmospheric temperature. Both studies claim that ENSO events are overwhelmingly responsible for the observed variability in global temperature, atmospheric circulation, and SSTs.

As one investigates the significance of Great Lake levels, the dynamics of the atmosphere must be considered to fully understand the essential processes involved in ENSO. The most broad impact on circulation variability and associated climatic anomalies worldwide is the atmospheric response to the oceanic El Nino phenomenon, the Southern Oscillation. Rohli *et al.* (1999) stated that air masses of both Arctic and tropical source regions exert dominance over the Great Lakes basin during various months, but for any given month of the year the degree of influence of both air mass types varies interanually. As a result, it is stated that regional-scale circulation patterns are the most direct cause of the degree of influence of air masses. Variables stated to be effected are considered to be surface components, because it is atmospheric circulation that forms the main link between regional changes in wind, temperature, precipitation, and other climatic variables (Trenberth, 1990).

The Indices

Research concerning ENSO has developed a number of measures that attempt to monitor the phenomenon using numerous variables. In order to strive for a better manner to understand and represent the ENSO phenomenon, the present research critically examines two general indices, to observe how well they predict the natural system of coastal phenomenon.

3.51 The Southern Oscillation Index (SOI)

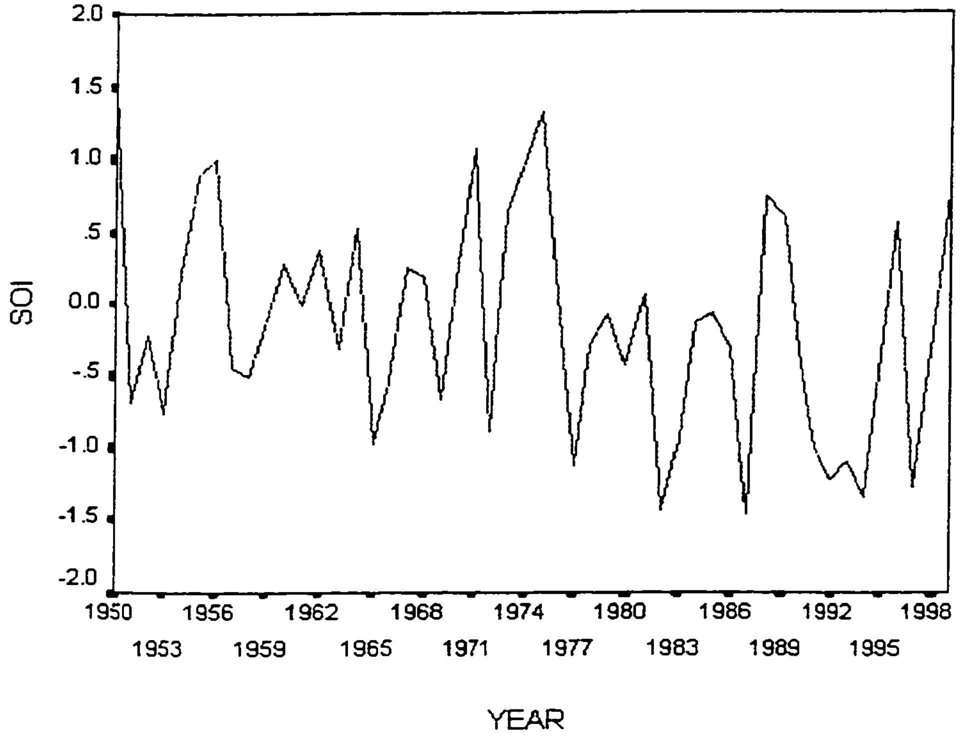
Sir Gilbert Walker first described the Southern Oscillation, and devised an index that eventually became known as the Southern Oscillation Index. According to Kyle (1999) the manner in which to form the SOI, requires the annual cycle of pressure at each station and removing by forming anomalies, or differences, from the long-term monthly averages. Monthly values are then normalized by the appropriate monthly standard deviations, then the difference Tahiti minus those from Darwin, Australia is taken. Research completed using or studying the Southern Oscillation Index include: Troup (1965); Wolter and Timlin (1998); Kane (1997); Bunkers and Miller (1996); Shabbar and Khandekar (1996); Guetter and Georgakakos, (1995); and Wang (1995). These studies attempted correlation analysis between the SOI and climate patterns are related phenomena.

Kyle (1999) states that the Southern Oscillation involves a negative correlation between pressure over Indonesia and pressure over the southeastern Pacific. When the southern oscillation is coupled with warming of the ocean off western South America, a resulting El Nino/Southern Oscillation event can effect weather patterns across the globe. The Southern Oscillation Index (SOI) is defined as the difference between sea level pressures at Tahiti and Darwin, Australia (Glantz *et al.*, 1991; Daly, 1999). The difference between the two can be used to generate an "index" number, indicating warm and cold events with sustained low negative values and high positive values respectively. This index is commonly used due to its efficiency and reliability concerning the defining and understanding of the long-term variability and influence of this oceanic and atmospheric phenomenon. Figure 4 shows graph of the Southern Oscillation Index from 1950-1999.

FIGURE 4

The Southern Oscillation Index 1950 – 1999

Standardized Values (Z Scores)



Source: Jones (1999).

3.52 The Multivariate ENSO Index (MEI)

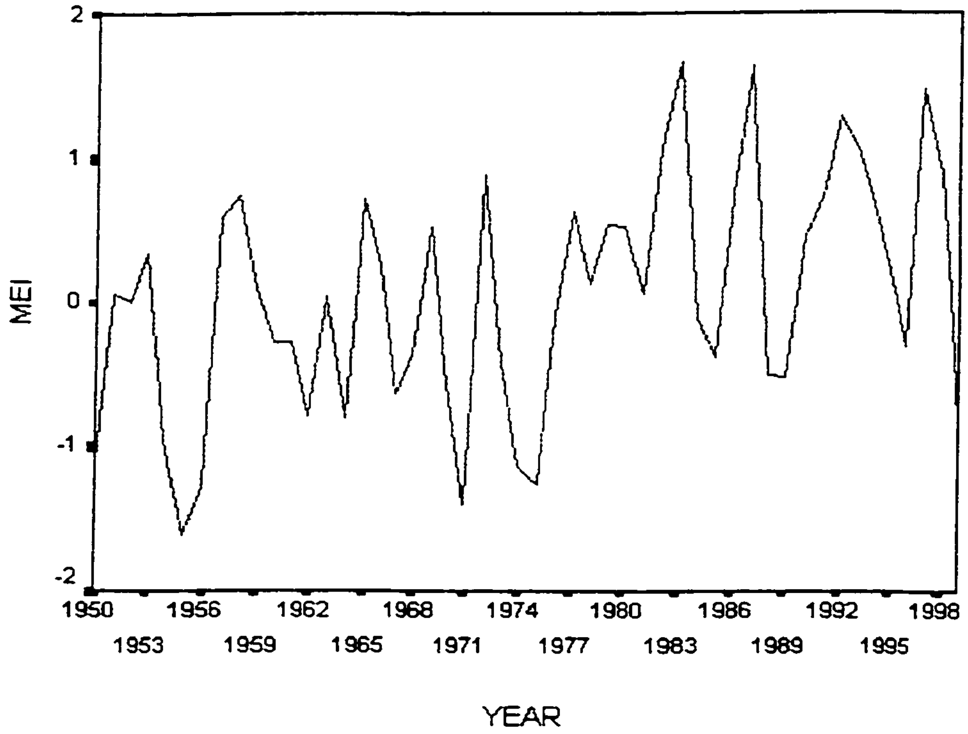
The Multivariate ENSO Index (MEI) is a method used to monitor and study the coupled oceanic-atmospheric character of ENSO, by basing its values on the principal variables observed over the tropical Pacific (Wolter, 1999a). Wolter (1999a) defined MEI as a weighted average of the 6 major features that approximate ENSO characteristics. These variables are sea-level pressure, sea surface temperature (SST), surface air temperature, the east-west and north-south components of the surface wind, and total amount of cloudiness. The values for the parameters are collected over the tropical Pacific. Figure 5 illustrates the MEI index calculated during the years 1950 – 1999. These values are in standard score format to serve as a dimensionless criterion when undergoing analysis. The MEI values are a result of principle component analysis, which derive the standard scores out of a huge variable bank.

The Multivariate ENSO Index attempts to approximate the coupled oceanic-atmospheric character of ENSO through the incorporation of six variables mentioned above. The region comprises the entire tropical Pacific basin. It is believed that because the variables are in large scale pattern forms, rather than point measurements, the variables can be used in relation to each other to obtain a more comprehensive measure of ENSO related interactions (Wolter, 1999b). Research using the MEI include Wolter (1999a and b); Assel (1998); Wolter and Timlin (1998); and Wolter (1987). These comprise research concerning the feasibility of the index, and how well they relate to climatic phenomena of the Great Lakes. More specifically, these studies related climate phenomena to the Multivariate ENSO Index.

FIGURE 5

The Multivariate ENSO Index 1950 – 1999

Standardized Values (Z Scores)



Source: Wolter (1999a).

Wolter (1999a) considers it a superior index describing ENSO events because it is said to be less vulnerable to occasional glitches in the monthly update cycles due to the efficiency of variable description. This is coupled with the incorporation of several ENSO variables (stated above) which are said to make this index more descriptive, therefore more reliable and efficient. This is stated in reference to the general monitoring of the ENSO phenomenon, whereas other ENSO indices might serve as well, depending on the nature of the research being employed.

4.0 CONCEPTUAL BASIS OF THE STUDY

An *a priori* model is a provisional mental construct used to portray some aspect of the real world under study, while demonstrating meaningful aspects of theory. In order to define a problem, it is required to fashion a manner in which to investigate the theoretical background, the previous research accomplished, while attempting to resolve and determine possible explanations to the present query. Figure 6 illustrates the *a priori* model developed for this thesis which is based on the recorded historical data (1950-1999) of Great Lakes water levels, and previous investigations plus a statistical model incorporating temporal and spatial behaviour.

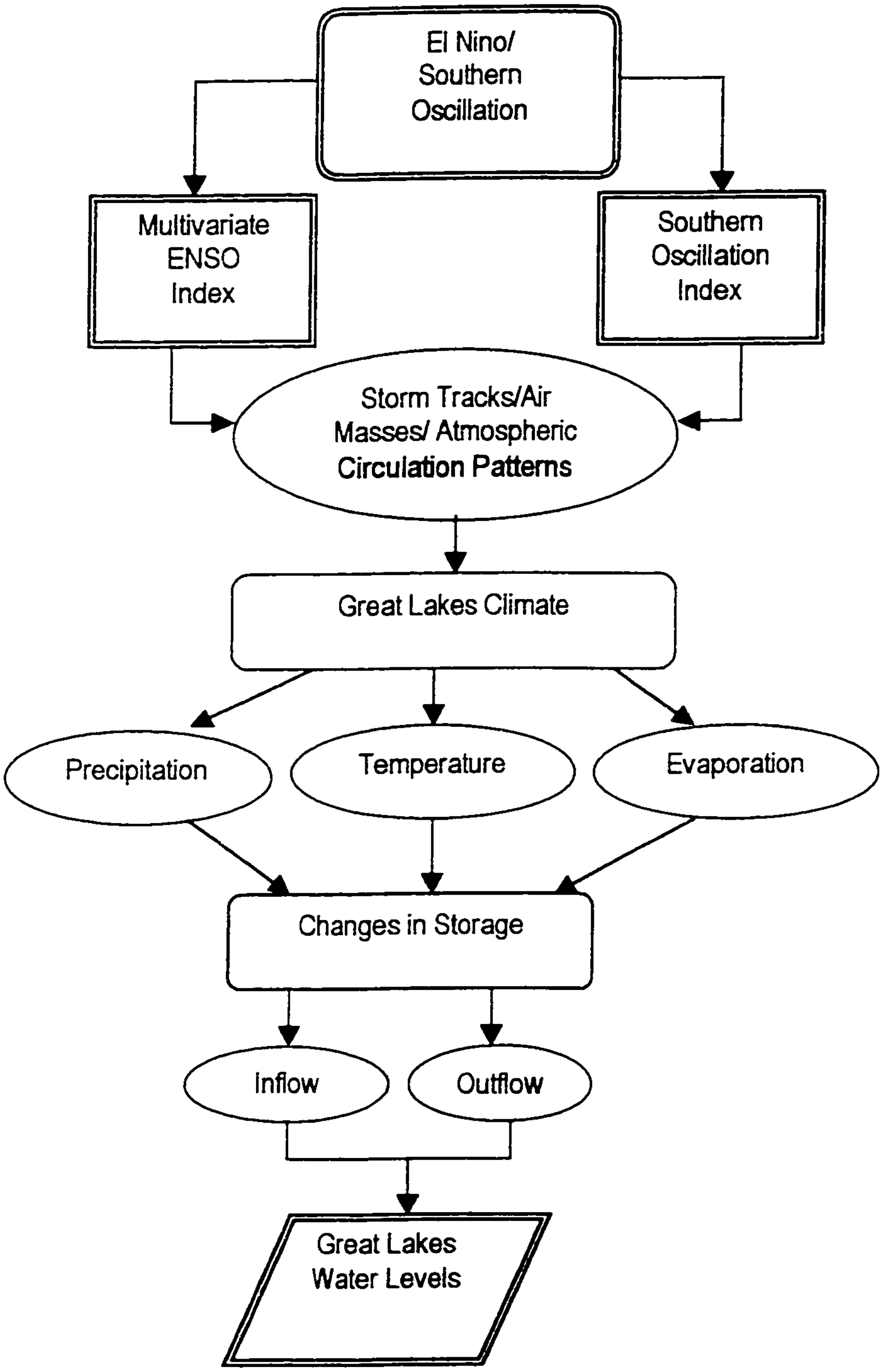
A common group of factors has been identified through the inquiries of many others that have accomplished successful and meaningful research concerning lake level and climate variability. However, a scientific investigation to obtain a deeper analytical understanding of the precise mechanisms affecting lake level extremes remains to be uncovered. As such, researchers continue their quest for higher levels of explanation. Previous work has indicated that there exists a multitude of various components that are in some degree or another, factors affecting Great Lakes water levels (Assel, 1998; Quinn, 1998; Gabriel *et al.*, 1997; Meadows *et al.*, 1997; Lee, 1993; Sanderson, 1993; Bishop, 1990; Hartmann, 1990; Croley, 1986; Quinn and Guerra, 1986; Bruce, 1984).

Amongst these and many others, it is suggested that climate variability is the dominant element explaining fluctuation, and thus, will be the focus of this thesis. Examination and review of the pertinent literature suggests that climatic variability has been augmented by El Nino/Southern Oscillation events, while owing some responsibility to significant fluctuations in GLWL. The relation between Great Lakes Water Levels and the El Nino / Southern Oscillation have been examined by many researchers in the past and have discovered positive correlations (Assel, 1999; Assel, 1998; Quinn, 1998; Croley et al., 1996; Hostetler, 1996; Stakhiv, 1996; Hartmann, 1990). Thus, the essence of this thesis lies in the determination of how El Nino / SouthernOscillation events affect Great Lakes Water Levels through further examination of two indices that portray it. The indices examined are the Southern Oscillation Index and the Multivariate ENSO Index.

The a prior model that will be employed for the purpose of this investigation suggests that a reasonable explanation should be found concerning the ENSO indices, and how they correlate with short-term water level fluctuation in each of the five Great Lakes. A systematic response study will also be explored. More specifically, both the Southern Oscillation Index and the Multivariate ENSO Index

FIGURE 6

A Priori Model



Source: Author, 2000.

represent different aspects of ENSO mechanisms and thus, may describe Great Lake water levels in distinct fashions. Kite (1989, 1991) stated that climate-related time series should, through statistical analysis, have valid physical explanations for the components utilized. It is the purpose of this thesis to determine better understanding of GLWL fluctuation with the index that describes lake levels with the utmost fit, applicability, and usefulness.

In summary it is found:

a) The quest for reliable information concerning GLWL fluctuation is a worthwhile endeavor, and should be examined so that efficient indicators and prediction tools can be developed.

b) ENSO events may be statistically correlated to GLWL fluctuation, although all mechanisms and aspects involved are not completely understood.

c) Factors affected by ENSO, and in turn effect GLWL are those such as air/storm tracks, atmospheric circulation, precipitation, temperature, evaporation, and runoff.

d) The MEI and the SOI are two of the most common ENSO indicators and may be most useful in determining a relationship between ENSO and GLWL.

e) The situation and system of the Great Lakes to local air masses and storm tracks may reveal different temporal and spatial behaviour, thus using different statistical means to portray them.

f) Time series analysis may provide description and explanation of GLWL fluctuation and the extent if any, that ENSO may be involved. If possible, one of the indicators may serve the study most efficiently, and better explain the connection between ENSO and GLWL.

4.1 Hypotheses

In essence, both phases of ENSO affect climate and its variability, and thus, the related components of local Great Lakes basin climatic characteristics. Meteorological factors such as precipitation, evaporation, temperature, general atmospheric circulation and so on, are in some way altered from their normal range of variability in a manner that is hindered or enhanced. In other words, there is a resulting change in the inflow and outflow rates within the basin. Hence these components are suggested by many researchers to be responsible for the extreme fluctuations of Great Lakes water levels.

Although the Great Lakes behave and react as a system, each will react to atmospheric/climate variability distinctly. It is not sufficient to render all lakes to one specific time series model, since each will behave according to various factors such as size, depth, orientation, local climate phenomena, and so on. This includes of course, the effects received from the other lakes. The following hypotheses are loosely based on the assumption that lake level fluctuation is function of a collective system, as well as what characterizes the individual lake. Appendix III defines the statistical terminology.

Thus, it is hypothesized:

Hypothesis #1

Lake Superior, being the western-most lake, often receives the driest part of climate patterns (Croley *et al.*, 1995; and Quinn *et al.*, 1997). Lakes Michigan-Huron are situated perpendicular to the storm tracks, thus are less exposed, and are therefore more sensitive to short term memory shocks in the first year and less sensitive to the second order autoregressive term. Statistically, this means that instead of a long memory process being present, the effects of the second shock are muted to a moving average process. This means that Lakes Superior and Michigan-Huron (through water level fluctuation) will encounter responses to ENSO induced climate changes, although the response will be eventually damped out over a finite period of time. This is what characterizes the nature of an ARMA (1,0,1) process.

Thus, it is hypothesized that Lakes Superior and Michigan-Huron will exhibit a response to ENSO in that the effect of the lag 2 random shock exposure to the passage of weather systems is dampened. This may be due to their large sizes and orientation. Thus it is hypothesized that an ARMA (1,0,1) process may be present in the systems characterizing Lake Superior and Michigan-Huron. The ARMA (1,0,1) process is represented by the following equation.

$$Y_t = \Phi_1 Y_{t-1} \pm \epsilon \pm \theta_1 Z_{t-1}$$

Where Y_t denotes the forecasting function, Φ denotes the AR (Autoregressive Model), θ denotes the MA (Moving Average Model) and ϵ denotes the error (Chatfield, 1985).

Hypothesis #2

Since Lake Erie's long axis is oriented in a northeast-southeast direction (oblique), and due to its relatively small size and shallow nature, neither an ARMA or AR(2) process may describe the data. As well, the effects of the random shock (or ENSO induced climate changes) at lag t-2 may be damped out or absent (Lavalle *et al.*, 1999). It is hypothesized then that this should yield a simple AR(1) model.

$$Y_t = \Phi_1 Y_{t-1} \pm \epsilon$$

As above, Y_t denotes the forecasting function, Φ denotes the AR (Autoregressive Model), and ϵ denotes the error. Here, the Y_{t-2} (or longer response to the shock) may be considered non-significant. This may be due to its constricted outlet. It is constrained by the Welland Canal, Niagara Falls etc. at a 30 degree angle. Lavalle *et al.*, (1999) found that Lake Erie modeling contained first-order autoregression with semester data (semi-annual), thus suggesting that with quarterly data, the results should be similar.

Hypothesis #3

Since Lake Ontario has its long axis oriented in an east-west direction, it should be partially prone to the effects weather systems. This would lengthen its exposure to ENSO induced climate changes and therefore approximate an AR (2) model. The effects of ENSO induced climate changes would be strongly felt due to its small size and deep nature which makes it capable of thermal heat storage, effecting evaporation rates (Quinn *et al.*, 1997). This means that the lake level fluctuation will be affected significantly in the sense of a prolonged time interval. Therefore, it is hypothesized that Lake Ontario water level behaviour may be characterized by a second order AR (2) process according to the equation:

$$Y_t = \Phi_1 Y_{t-1} \pm \Phi_2 Y_{t-2} \pm \epsilon$$

Where Y_t denotes the forecasting function, Φ denotes the AR (Auto Regressive Model), and ϵ denotes the error, and on the condition, that the data is not seasonalized (Troup 1965; Chatfield, 1985). All data has already been deseasonalized in the standardization process. An AR (2) model will exhibit a 'memory' in the sense that each value is correlated with all the preceding values. Thus, each shock or disturbance to the system will have a diminishing effect on all the subsequent time-periods. An AR (2) model describes a pseudo-oscillatory process generated by long-term memory random shocks at lag 1 and lag 2.

Hypothesis #4

Since MEI is an indicator of the ENSO phenomena, which affects climatic variables basin-wide, Lake NBS should be a function of ENSO events. Since water levels change slowly due to the large lake surface areas and constricted outlet channels, (Hartmann, 1988; Quinn *et al.*, 1997; Mason, 1998) they combine short-term climate fluctuations. Thus it is hypothesized that Lake NBS should approximate a model where a random shock associated with ENSO at lag t-2 may be absent, or dampened. Thus, Lake NBS models should approximate a weak AR(1) model.

One would expect to find a weak AR model with lower lags since the ENSO phenomena would generate changes in local climate variability for each of the lakes. As well, this hypothesized weak relationship with the MEI may be due to the fact that MEI may be merely a trigger, dissipating by the time the effects reach this region. Thus, each shock or disturbance to the system will have a diminishing effect on all ensuing time periods. This should be present in the NBS data for all lakes, and correlate with the findings concerning ENSO and water levels.

5.0 METHODOLOGY

The following will define the variables under investigation, and outline how they will be employed.

5.1 Data: Acquisition and Characteristics

The monthly Great Lake water level data used in this thesis have been provided by Environment Canada (1999). These data are comprised of monthly values between the years of 1950 to 1999. Earlier data exists for both the Southern Oscillation Index and Great Lakes Water Levels, but precise and reliable Multivariate ENSO Index data is not available prior to 1950. For consistency, the base year was set at 1950, allowing for a strong 50-year inquiry.

The Multivariate ENSO Index values were taken from Klaus Wolter (1999b) through the NOAA-CIRES Climate Diagnostic Center. The Multivariate ENSO Index values are bimonthly (Dec/Jan....Nov/Dec), and span the years of 1950 – 1999. All values have already been normalized for each season so that there is an average of zero and a standard deviation of one (Wolter, 1999a). It is computed monthly, based on two preceding calendar months. Negative MEI values indicate cooling, or La Nina events. Correspondingly, positive MEI values indicate warming, or El Nino events.

Values of the Southern Oscillation Index (SOI) were taken from the Climatic Research Unit (Jones, 1999). For the purpose of this thesis, SOI may be defined as the sea-level air pressure difference between stations at Tahiti and Darwin, Australia divided by standard deviation of these differences. This SOI formulation follows that of Troup (1965). The monthly data have been standardized to remove different units of measurement among the variables. Net Basin Supply (NBS) data (monthly approximations of precipitation plus runoff minus evaporation for each lake) were provided by Rob Caldwell (2000) of the Department of Fisheries and Oceans at Environment Canada. The data used were monthly values for the years spanning 1950 to 1999. NBS data involve total water values comprising of precipitation, runoff, and net ground water inflow, minus evaporation. Although NBS is not involved in the hypotheses, it was used to provide a foundation in which to base the changes in lake levels. Net Basin Supply data for each lake were examined and used as a regressor against the ENSO indices to determine whether the statistics found among the same lakes were comparable, thus providing more supportive results.

5.2 Data Analysis

The original monthly values were compiled into quarters, comprising three-month intervals, specifically: December to February; March to May; June to August; and September to November. Quarterly data were generated because an ENSO event is approximately 4 to 8 months long, and monthly data is thought to disperse or mask any real affects of ENSO factors (Lavalle *et al.*, 1999). An ENSO event usually consists of a long sequence whose cumulative effect acts as a random shock that alters weather patterns (Lavalle *et al.*, 1999). Therefore, in order to view the effects of ENSO induced-climatic triggers on lake levels, quarterly data will be used to best provide a snapshot of historical fluctuation.

To compare the sequential dynamics of GLWL with both the SOI and the MEI, the data were standardized to remove the effects of the different units of measurement in the variable set, as well as seasonal effects of the Great Lakes variables (Lavalle *et al.*, 1999). In order to convert each variable into a dimensionless criterion, the data were transformed into standard scores (z) using the following formula:

$$z = X - \mu / \sigma$$

Here, X is a variate score, μ is the data mean, and σ is the standard deviation (Lavalle *et al.*, 1999).

The initial step taken to analyze the data was to create correlograms, or autocorrelation function (ACF) and partial autocorrelation function (PACF) diagrams to examine initial observations against time. This includes studying important features such as trend, seasonality, discontinuities, and outliers. Each data set was identified with a particular (AR), and/or (MA), process.

After examining lake level time series plots, it was determined that the data sets should be split. This means that in most cases the series are characterized with an abrupt change in trend from one varying range of values, which differ from the preceding values. This was executed with the SPSS statistical software, which modeled the data, and served to prepare the variables for statistical analysis. Therefore, case number 91 or year 1972 (second quarter) was chosen because it seems to intervene at a peak El Nino/Southern Oscillation event, and separates two distinct averages found within all of the series.

This allowed for the acceptance of Box-Jenkins properties which define an approach to time series analysis. These properties are outlined in Chatfield (1985) and concern the following in the data series being used;

a) There should be no systematic change, or trend in mean.
b) There should be no systematic change in variance.
c) There should be no deterministic periodic variations.
d) The autocorrelation function is dependent on the lag interval and not the starting position of the series.

In order to ensure sound statistical results, the following steps were taken to analyze the data, and test the hypotheses. Once the ACF and PACF correlograms were constructed and examined, the data were fit to either an autoregressive model, moving averages model, or a combination of the two. SPSS statistical software was used to fit the models. The residuals from the fitted models were tested for serial autocorrelation on the correlograms. This estimation and diagnosis of the most acceptable model was completed to determine the models' goodness-of-fit.

The hypotheses were further examined by using the MEI as an independent regressor to more fully understand the effects of ENSO induced changes and the corresponding responses to lake level fluctuation. These results and discussion are included with each hypothesis. Once this was complete, the data sets were analyzed using time series analysis. This was done by constructing models based on the processes identified during the previous stage (SPSS, 1994).

The Multivariate ENSO Index was found to be the best descriptor according to the results of the model fitting (see Figures 8-11, and Tables 4 and 5) and was used as the regressor to each lake's NBS, data and the lake level data, to determine how well the index fit the other models. The statistical significance and strength of various parameters were identified as well during this stage of data analysis. Estimation and diagnosis of the most acceptable and efficient models have been completed through examination of residuals. The parameters that are said to affect water levels include precipitation, evaporation, runoff and temperature. These are said to be modified by the presence of an ENSO event. Lake level data and lake Net Basin Supply data were examined for statistical significance using the best fit between the SOI and the MEI, to determine any correlation between atmospheric changes induced by the ENSO influence. This is presented below.

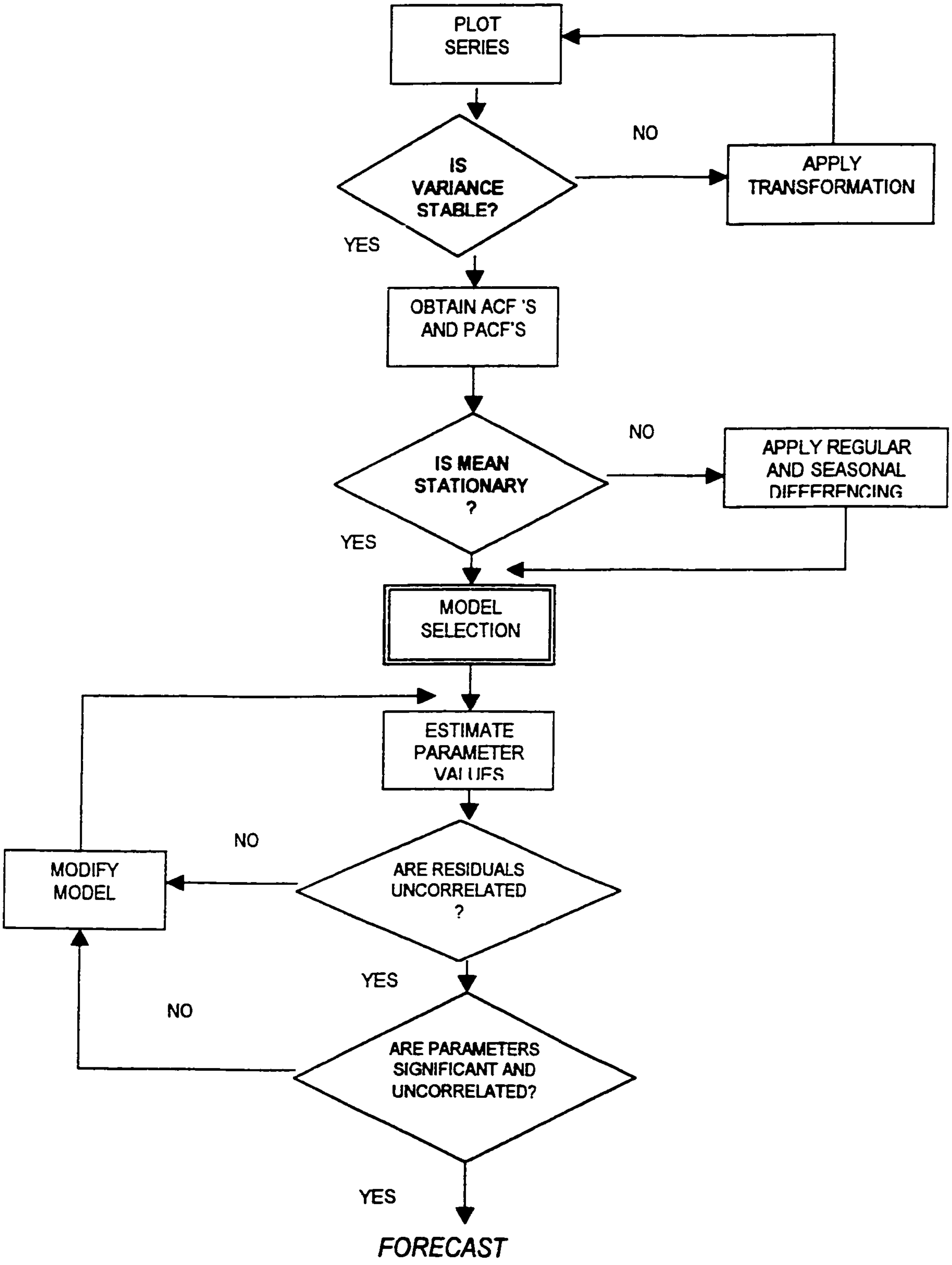
5.3 Aspects of Time Series Analysis

Time series analysis is used because it is mainly concerned with decomposing a series into a trend. Trends may be defined in many ways including seasonal effects, cyclic changes and other irregular fluctuations (Chatfield, 1985). Therefore, within the Great Lakes study region, one may suspect to find trends due to a variety of conditions including climatic change, stochastic processes, and extreme variability. Therefore, time series analysis may be used as a manner of estimating the probability of observing enhanced forms of predicted and recorded lake levels (Kite, 1991). Kite (1991) contends that the trend component of a time series is generally associated with changes in the structure of the time series caused by cumulative natural or man-made phenomena.

In order to examine the proposed statistical correlation amongst lake levels, the Autoregressive Integrated Moving Average (ARIMA) modeling procedure was used. ARIMA models are, in theory, the most general class of models for forecasting a time series, which may be stationarized by transformations such as differencing and logging (Chatfield, 1985). More specifically, lags of the forecast errors are called 'moving average' terms, and a time series which

FIGURE 7

Box-Jenkins Modeling Approach



Source: Arsham (2000). Time Series and Forecasting Techniques. Http://www.ubmail.ubalt.edu needs to be differenced to be made stationary is said to be an integrated version of a stationary series. The Box-Jenkins approach was used because it portrays Univariate ARIMA analysis by evaluating time series data by extracting the predictable movements from the data set. Figure 7 illustrates the steps taken in time series analysis, which are described in Box-Jenkins procedures. This is the most efficient method because it identifies which filters are most appropriate for the series being analyzed (Chatfield, 1985).

Chatfield (1985) identifies three linear filters used in this method and are the autoregressive, the integration, and the moving average filter. In an autoregressive process, each value in a series is a linear function of the preceding value or values. The order of the autoregressive process indicates how many preceding values are used. In a moving average process, the each value is determined by the average of the current disturbance and one or more previous disturbances. The integrated term in time series analysis may indicate differencing to smooth the data, or to make it stationary.

Time series is best employed in such research because it possesses the distinguished feature of taking into account that successive observations are usually not independent (Chatfield, 1985). Therefore, the analysis takes into account the time order of observations. If it is found that the time series can be predicted exactly from using past observations, the series may be stated as deterministic. However, very few series conform to this, especially those that represent natural phenomenon and natural variability. Consequently, the time series will be stated as stochastic if the future is only partly determined by past observations. The collection of GLWL data, and its correlation with ENSO indices, cannot realistically, be completely explained, which means that future values will have a probability distribution which is conditioned by a knowledge of past values (Chatfield, 1985).

5.4 Modeling of the Southern Oscillation Index and the Multivariate ENSO Index

In order to determine the extent of the effects of ENSO on Great Lakes Water Levels, an index must be selected, which is believed to represent the nature of ENSO (temporal behaviour) optimally. This thesis modeled both the Southern Oscillation Index and the Multivariate ENSO Index and found that the latter would serve this thesis more efficiently due to the statistical results (see Figures 8 to 11; and Tables 5 and 6 at the end of this section).

Since the Multivariate ENSO Index uses more information to characterize El Nino/Southern Oscillation (ENSO) events than the Southern Oscillation Index (SOI), it should be more useful in correlating the flow variables describing Great Lakes hydrology with El Nino/Southern Oscillation influences. The modeling was designed to isolate either the SOI or the MEI, by examination of statistical results indicating the most parsimonious model, and then using this to approximate Great Lakes Water Levels and net basin supply values. When attempting to model the SOI and MEI time series, it was found that a simple model could not fit either. By simple, we expect the time series to have as few parameters as possible and a large number of degrees of freedom among all models that fit the data (Chatfield, 1985). Cross-correlation analysis suggested that the difficulty may be due to an apparent interval in lag time. Although many models appeared to be statistically significant, the autocorrelation function indicated otherwise, with clear autocorrelation among the residuals. As a result, it was tested whether lagged forms of the two indices would fair better outcomes. The results for the modeling of the SOI and the MEI are located at the end of this section.

The SOI was found to be best fitted by an ARIMA (1,1,0) process, with SOI lagged at 3 and 5. The first-order autoregression model is characterized by differencing because the index reflects the cumulative monthly effect of the factors that trigger it. The integrated concept of this model characterizes an AR model of a differenced series. When modeled, the MEI was lagged at 2 and 3, with an ARMA (1,0,1) process. As in many natural phenomena, there is a random or stochastic element, which defines much of the behaviour seen in the two indices. The lagged values, may indicate the random and oscillatory nature of the factors triggering the various monthly values of SOI and MEI. As such, the model represents a manner of time delay within the series, resulting in cycles within the cycle.

The SOI model was significant at a level of 0.05, with all T-ratios significant. The R value of 0.68 indicates a strong relationship with approximately 46% of the variation in the SOI explained by the lagged values of itself. All Box-Ljung statistics were insignificant at 0.05, while no meaningful autocorrelation existed among the residuals. This is supported by the Durbin Watson statistic of 1.758 (see Figures 10, 11, and Table 5 for statistical results).

As with the SOI, the MEI model was fit to a sufficient model. It was found that an ARMA (1,0,1) with lagged values of MEI at 2 and 3, served to fit the series. The model was significant at a level of 0.05, with all T-ratios significant. The R value of 0.86 indicates a strong relationship with approximately 74% of the variation in the MEI explained by the lagged values of itself. The Box-Ljung statistics were insignificant at 0.05, while no meaningful autocorrelation existed among the residuals. This is supported by the Durbin Watson statistic of 1.981 (see Figures 8, 9, and Table 4 for statistical results).

The MEI was chosen due to the variety of statistical results such as a higher R value which, is statistically stronger, as well as the higher R Square value (74%, as opposed to 46%). In addition, residual variance and standard error values were all significantly lower in the model that approximated the MEI time series (see Table 4). Residual autocorrelations on the ACF plot were significantly higher, concerning the Box-Ljung statistic (see Figure 9). This is concurred with one of the residual lags of the

SOI model being slightly autocorrelated (although still statistically significant), whereas this is absent in that of the MEI model. AIC and SBC indicators were substantially lower, while all T-Ratios were substantially higher than that of the SOI model. Therefore, although both models were not ideally simple, it is still acceptable to embrace the MEI data set, as the series to be used for the examination of lake Level fluctuation, and net basin supplies of the Great Lakes.

For our purposes, the lagging of the indices may represent important aspects of historical patterns within the data set. For instance, because the lag can represent the cumulative effect of ENSO, and one lag is equal to three months, then the lag aspect of both SOI and MEI, may be due to pivotal periods within the time series. Not all values within the time series are those that are associated with ENSO events. The lag values may represent trigger periods, where both SOI and MEI must be lagged at particular intervals to thoroughly portray the characteristics of each data set. For example, the MEI was lagged at the 2nd and 3rd quarters, highlighting possible forcing mechanisms throughout the months of April, May and June. The SOI was lagged at the 3rd and 5th quarters, suggesting that spring and the following winter periods are most meaningful. The ARMA nature of the MEI suggests that disturbances within the series may be characterized with a memory, and one where the disturbances are damped out, and ceases to exist. The AR (1) nature of the SOI model may depict a resilience of the disturbances, one where memory continues to exist.

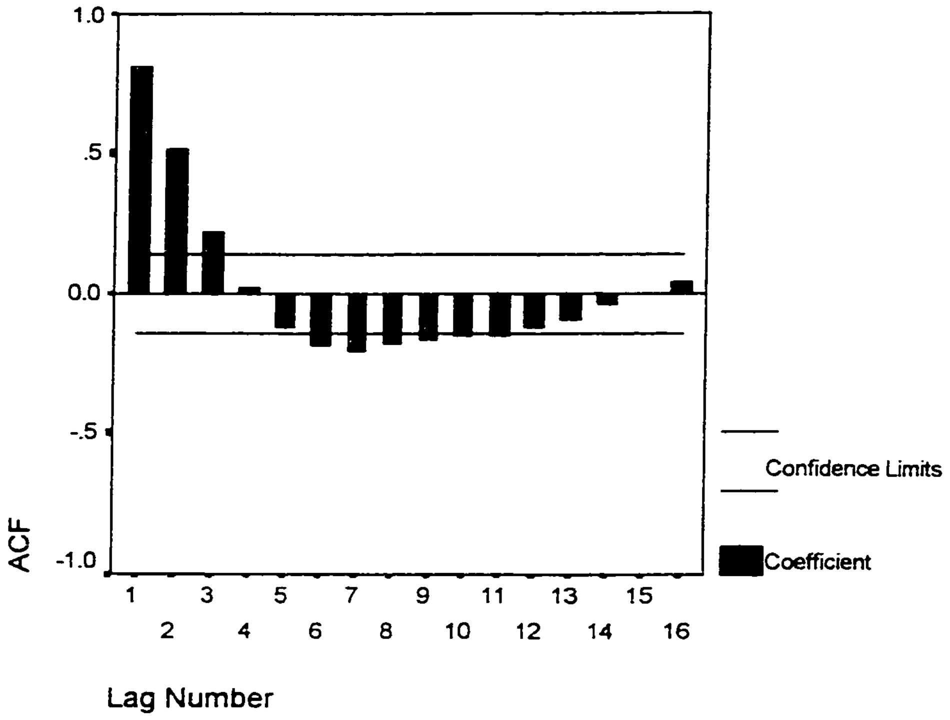
Due to the nature of both of the index models, semester series (semi-annual data) of both the SOI and MEI were run to determine whether simple models were available, and if they corroborated the findings using quarterly data. The semester series did indeed allow for more simple measures of fitting models for both the SOI and MEI. As well, the MEI was found to have the superior model fit, showing strong statistical results (see Appendix 1). The MEI series was fit to an AR model (2,0,0), with statistically sound results, and an R value of .681, R Square of .463, and no significant autocorrelation among the residuals. The SOI series was fit to an AR model (1,0,0), with an R value of .491, and an R Square value of .241. All statistical results associated with the model were significant as well. The MEI model validated preferred results in the R value, R Square value, Durbin Watson statistic, the AIC, and residual variances. The ACF of the modeled series favored the MEI model due to higher Box-Ljung statistics. See Appendix 1 for the statistical results for the semester data.

In addition, the series of both SOI and MEI were converted to yearly averages to determine whether a model could be fit with more simplicity. Both series fit an MA model with the SOI having to be differenced. Quick examination of the results displayed that the parsimonious model was that which was fit to the MEI. Autoregressive models did not fit either series probably due to the fact that they were averages. This means that the moving average characteristic is one that merely smoothes fluctuations and distortions in the data, while providing a meaningful representation of underlying trends and cycles. In this case, each value in the series is a weighted average of the most recent random disturbance. Here, a random disturbance affects the system for a finite number of periods (the moving average order), and then ceases to affect it (SPSS Inc., 1988).

It may be accepted that a satisfactory ENSO index may be confidently taken to use with the lake Level data and net basin supply, to determine the theoretical questions posed. This in no way deems the SOI unacceptable, but merely excludes it for the purpose of simplicity and precision related to this thesis. Therefore, the MEI was used in what follows, to determine whether there is a relation between it, and Great Lakes water levels, and net basin supplies.

FIGURE 8

A: THE MEI AUTOCORRELATION FUNCTION



B: THE MEI PARTIAL AUTOCORRELATION FUNCTION

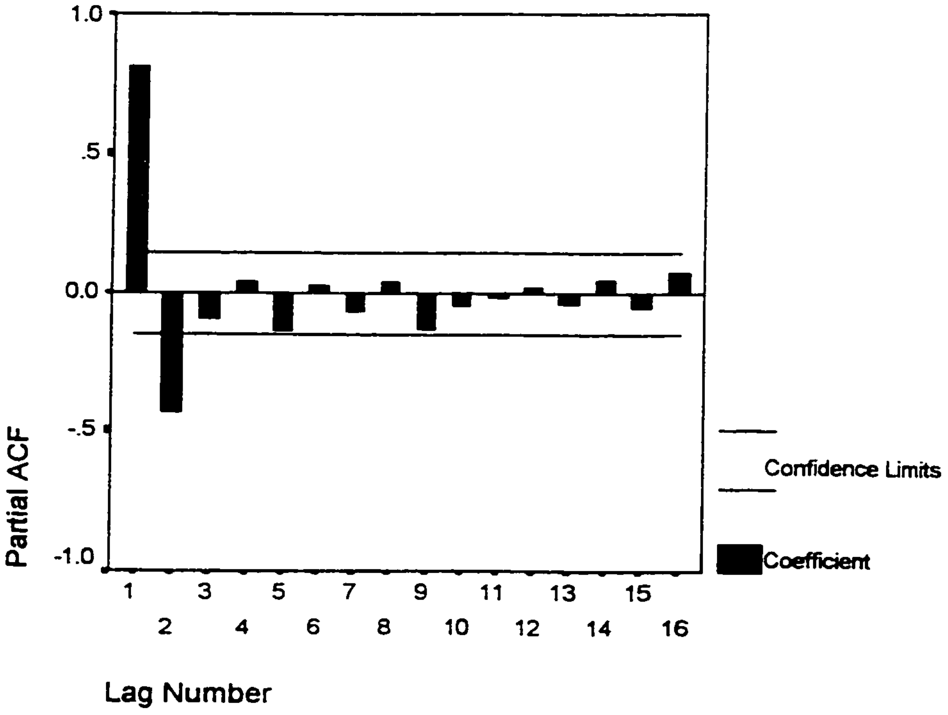


TABLE 4

MEI ARMA MODEL (1,0,1) Statistical Results

FINAL PARAMETERS:

Number of residuals	187
Standard error	.47463494
Log likelihood	-125.31903
AIC	258.63806
SBC	271.56249

ANALYSIS OF VARIANCE:

	DF	ADJ.SUM OF SQ.	RESIDUAL VARIANCE
RESIDUALS	183	41.826	0.225

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.28440825	.08239416	3.451801	.00
MA1	-.93958275	.04399277	-21.357664	.00
MEIQ2	.64646560	.04901116	13.190170	.00
MEIQ3	-.31503594	.04896846	-6.433445	.00

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R .861
R SQUARE .741
DURBIN WATSON 1.981
SIG .00

FIGURE 9

MEI AUTOCORRELATION FUNCTION
ARMA (1,0,1) RESIDUALS

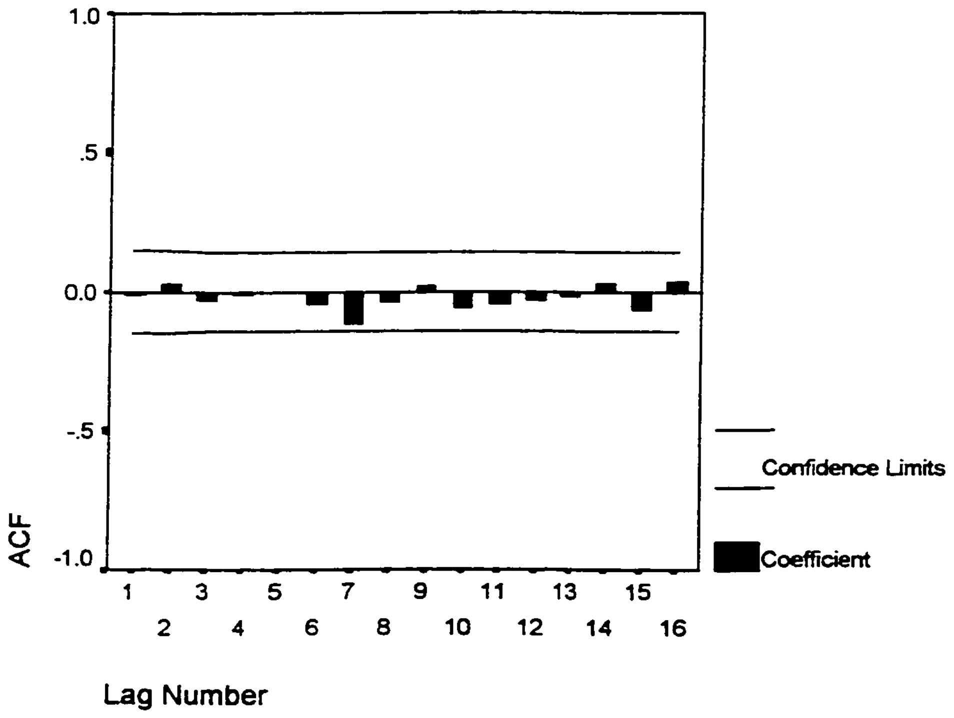
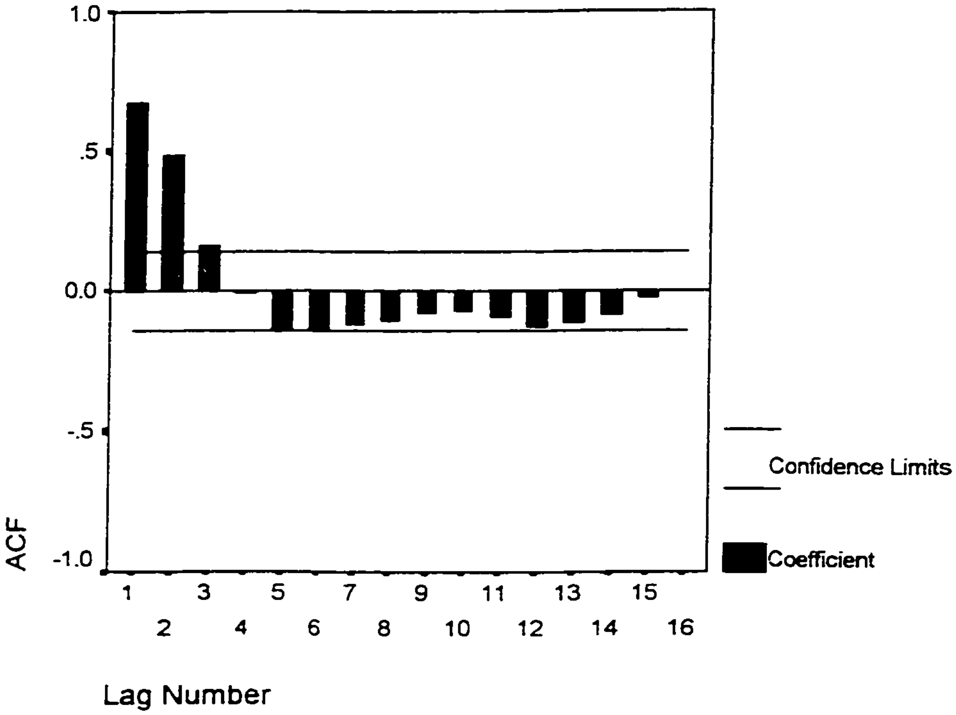


FIGURE 10

A: THE SOI AUTOCORRELATION FUNCTION



B: THE SOI PARTIAL AUTOCORRELATION FUNCTION

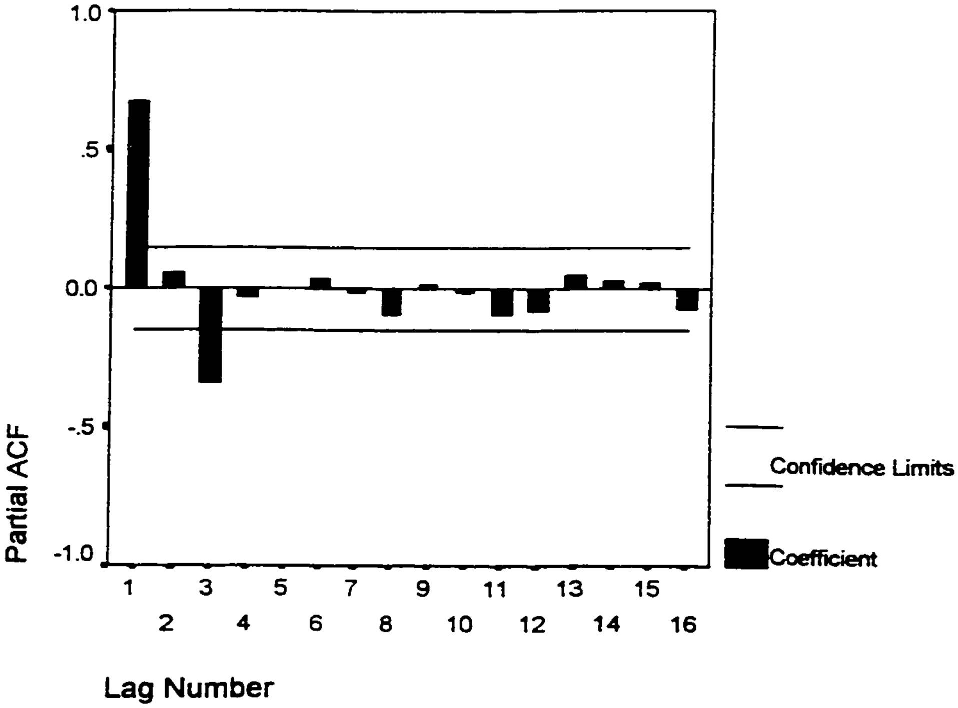


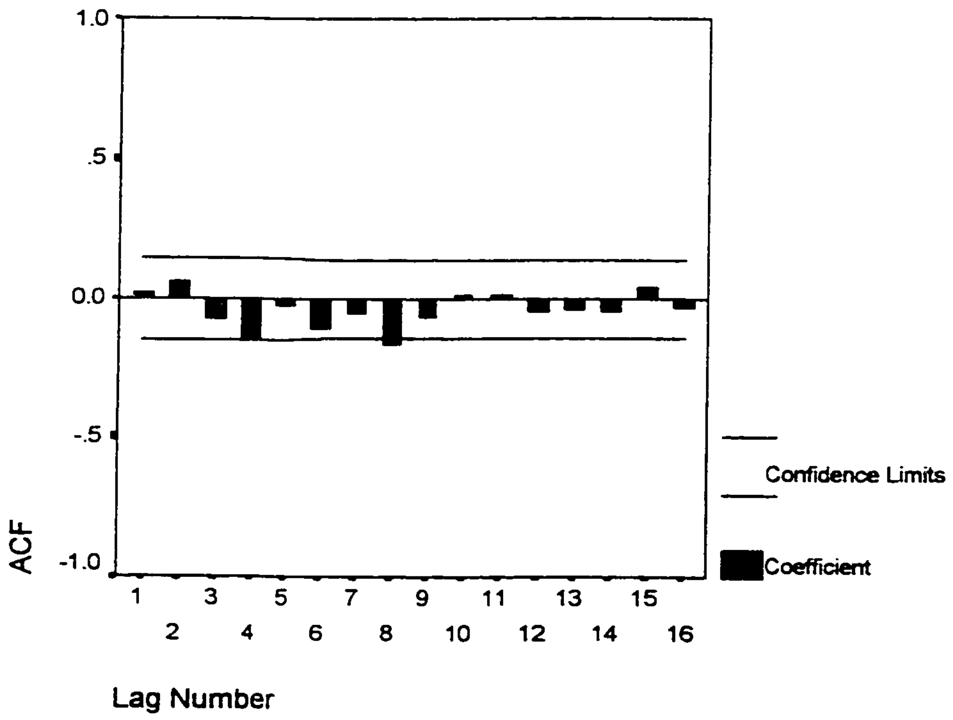
TABLE 5

SOI AR (1,1,0) MODEL Statistical Results

```
FINAL PARAMETERS:                        ANALYSIS OF VARIANCE:
Number of residuals  184                              DF    SUM OF SQUARES    RESIDUAL VARIANCE
Standard error      .72170317            RESIDUALS    181       94.311              0.521
Log likelihood     -199.60888
AIC                 405.21776
SBC                 414.86257

VARIABLES IN THE MODEL:
              B            SEB          T-RATIO     APPROX. PROB.

AR1     -.25916595    .07307048    -3.5467940      .00
SOIZ3   -.18224820    .07083159    -2.5729790      .01
SOIZ5   -.19113608    .07072550    -2.7025059      .00

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R    .681
R SQUARE    0.464
DURBIN WATSON    1.758
DF    183
SIG    .00
```

FIGURE 11

THE SOI AUTOCORRELATION FUNCTION
AR MODEL (1,1,0) RESIDUALS



6.0 STATISTICAL RESULTS

6.1 Statistical Results

Correlograms of the autocorrelation functions linking lag intervals and autocorrelation values were produced. These were studied to help to determine possible processes for model fitting. Once modeling was accomplished, it was found that Lake Superior characterized an ARMA process (see Figure 12); Lake Michigan-Huron characterized an ARMA process (see Figure 14); Lake Erie displayed an AR process (see Figure 18); Lake Ontario displayed an AR process (see Figure21); and both MEI and SOI displayed an AR process (see Figure 8 and 10, respectively). With these results, the next step was to run and evaluate various models using the initial observations. These are evaluated below. See Table 6 for a display of the statistical results and Appendix III for Statistical Definitions.

TABLE 6

Statistical Results and Fitted Models

Lake	Model	MEI Model	NBS Model
Superior	ARMA (1,0,1)	ARMA (1,0,1) MEI lagged by 18 quarters	ARMA (1,0,1) MEI laged by16 qyarters
Michigan-Huron	ARMA (1,0,1)	ARMA (1,0,1) MEI lagged by 14 quarters	*
Erie	AR (1,0,0)	AR (1,0,0) MEI lagged by14 quarters	AR (1,0,0) MEI lagged by 8 quarters
Ontario	AR (2,0,0)	AR (2,0,0) MEI lagged by14 quarters	AR (1,0,0) MEI lagged at 3 quarters

* No model fit applicable.

6.2 Assessment of Hypothesis #1

The first hypothesis states that Lakes Superior and Michigan-Huron may exhibit a response to ENSO in that the effect of the lag 2 random shock exposure to the passage of weather systems is dampened. Therefore, it is not expected that the effects of ENSO induced climatic changes should not alter they systems of Lake Superior and Michigan-Huron for a lengthy time interval. This means that a pseudo-cycle is thought to exist where a disturbance to the system will exist within a particular time interval without creating lasting affects within the system. A pseudo-cycle suggests that in all likelihood, a complete cycle does not exist in this case, the climatic factors being affected by ENSO change from their norm due to atmospheric alterations (to precipitation, evaporation, runoff and temperature) and create a resulting change in lake levels. The ARMA process suggests that ENSO creates random shock(s) which occur in the same lag interval.

Thus, it was tested that an ARMA (1,0,1) process would be sufficient to model the Lakes Superior and Michigan-Huron in regard to how they fluctuate with climatic variability such as ENSO events. It was suggested that those Great Lakes with their long axes oriented in a north-south direction (Michigan-Huron) may exhibit a different response to ENSO induced effects. Correspondingly, Lake Superior being the western-most lake and the largest, would also exhibit ARMA characteristics. It was hypothesized that an ARMA (1,0,1) process was involved due to the fact that Lakes Michigan and Huron are situated perpendicular to storm tracks and are therefore more sensitive to short memory shocks in the first year and less sensitive to the second order autoregressive term. It was proposed that instead of a second long memory process being present, the effects of the second shock were muted to an MA process due to the shortened exposure to storm tracks.

Lake Superior was found to be influenced by an autoregressive process given the results of the autocorrelation function (ACF) correlogram (see Figure 12) which, decayed exponentially. This supports the process fit with Lake Michigan-Huron water levels as well. Next, Lake Superior water levels (LSWL) were fit to an ARMA (1,0,1) model (see Figures 12, 13, and Table 7). The autocorrelation function of the residuals illustrates no significant autocorrelations. The probabilities associated with the Box-Ljung Q statistics are all well over the .05 significance level, indicating no autocorrelation among the residuals. The model significance parameter was .00 for both the AR and MA terms respectively.

Lake Michigan-Huron water levels were parsimoniously fit to an ARMA (1,0,1) (see Figures 14, 15, and Table 8). The ACF plot indicated no significant autocorrelation among the residuals, with the Box-Ljung statistics all well above the 0.05 level. The B coefficients were statistically significant at an alpha of 0.05, and the approximate probability at 0.00, respectively.

Since both Lakes Superior and Michigan-Huron exhibited an ARMA process, both were tested against the independent regressor MEI to determine how well a model could be fit. When Lake Superior water levels were regressed with MEI (lag 18/4.5 years), an ARMA (1,0,1) model best fit the series, in a significant and strong manner (see Figure 16 and Table 9). The autoregressive parameter is 0.82, while the moving average parameter is –0.37. The MEIQ18 coefficient is approximately –0.16 the approximate probabilities were 0.00, 0.00, and 0.10 respectively, at an alpha of 0.05. The R value of 0.89 denotes a strong relationship, while the R Square value suggests that approximately 81% of the variance of LSWL, over time, is accounted for by the model. The residuals on the correlograms showed no signs of autocorrelation, as illustrated by the non-significant Box-Ljung statistics (see Figure 16).

When Lake Michigan-Huron was regressed using MEI as the independent regressor, it was found that there existed a strong and significant relationship was observed here too, when applied to ARMA processes (see Figure 17 and Table 10). With MEI regressed 14 quarters (3.5 years), the AR coefficient was 0.95, the MA coefficient was –0.42, the lagged form of MEI value was set at 0.6. All T-ratio values were significant at a level of 0.05. The R value of 0.95 denotes a strong relationship, while the R Square indicated that 95% of the variation in the model was accounted for. The plot of the residuals (see Figure 17) show no significant autocorrelation, and all of the Box-Ljung values are insignificant at a level of 0.05.

The weak AR(1) component suggests that each shock or disturbance to the system has a diminishing effect on all subsequent time periods (SPSS Inc., 1988). The MA(1) process within the system has a dampening effect whereby the shock depicted is abrupt and has a short memory. Since both Lakes Superior and Michigan-Huron most efficiently fit an ARMA model, being both strong and statistically significant, the hypothesis may be accepted. Therefore, the two uppermost, and largest lakes are typified with abrupt shocks without any meaningful long-term memory being present.

Assessment of Hypothesis #2

In regard to Lake Erie, it was proposed that since its long axis is oriented in an northeast-southeast direction, and due to its relatively small size and shallow nature, neither an ARMA nor AR(2) process may describe the data, and the effects of the random shock at Y_{t-2} may be damped out or absent. Thus, it was hypothesized that an AR(1) model may sufficiently describe the underlying processes. It was found that Lake Erie did indeed exhibit a first-order autoregressive model (see Figures 18, 19, and Table 11). The correlogram in Figure 18 illustrates the nature of an autoregressive process, which requires the interdependence of lags, on the previous values. This is shown through the decay of lags over time. Figure 19 and Table 11 refer to the statistical results generated with the MEI as the independent regressor.

The autoregressive parameter (B) of 0.94 is significant at an alpha of 0.05, and an approximate probability of 0.00, respectively (see Table 11). Because this value is quite near to the value of 1.0 (limit of stationarity), it may be stated that the differences between lake levels from one observation to the next should be distributed as white noise or stochastic factors (SPSS Inc., 1994). The autocorrelation function illustrates that the residuals have no significant autocorrelation and appear to be randomly distributed. The Box-Ljung Q statistics are all well above the 0.05 level.

FIGURE 12

A: LAKE SUPERIOR WATER LEVEL AUTOCORRELATION FUNCTION

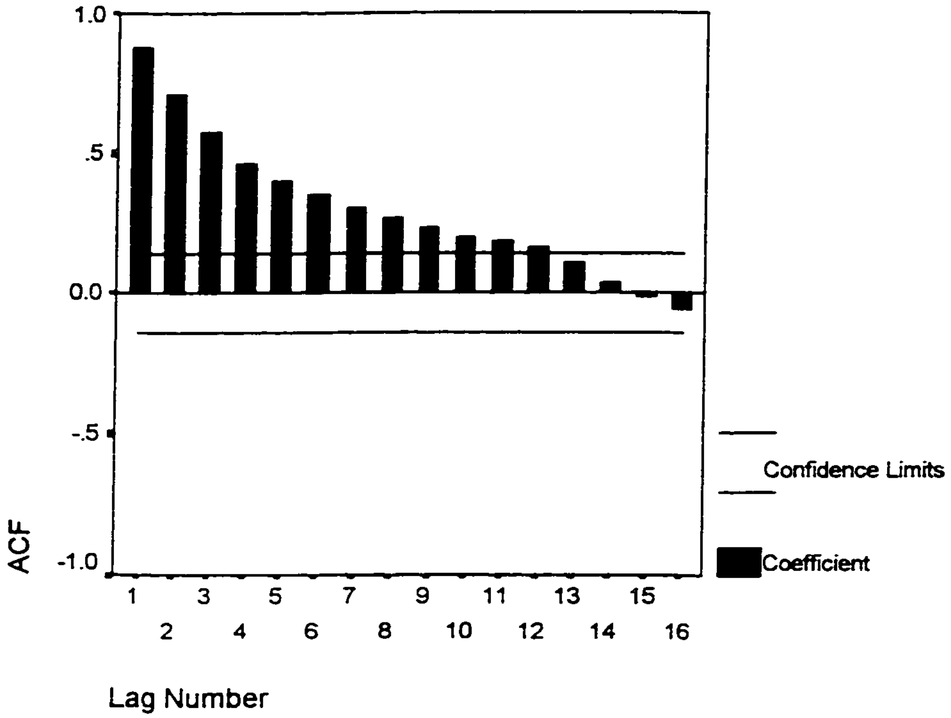


TABLE 7

LAKE SUPERIOR WATER LEVELS ARMA MODEL (1,0,1)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.449940
Log likelihood	-121.21078
AIC	246.42156
SBC	252.97779

ANALYSIS OF VARIANCE:

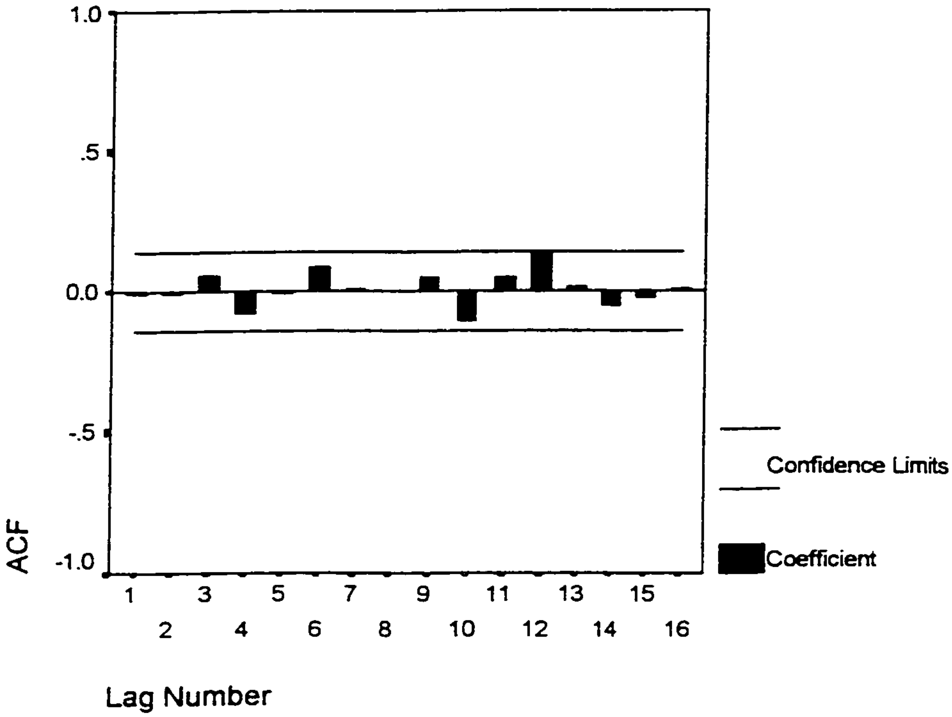
	DF	Adj. Sum of Squares	Residual Variance
Residuals	194	39.53	.2019

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.80703833	.04768684	16.923711	.00
MA1	-.37893084	.07344970	-5.159052	.00

FIGURE 13

**A: LAKE SUPERIOR WATER LEVEL ARMA MODEL (1,0,1)
AUTOCORRELATION FUNCTION ERROR**



**B: LAKE SUPERIOR WATER LEVEL ARMA MODEL (1,0,1)
PARTIAL AUTOCORRELATION FUNCTION ERROR**

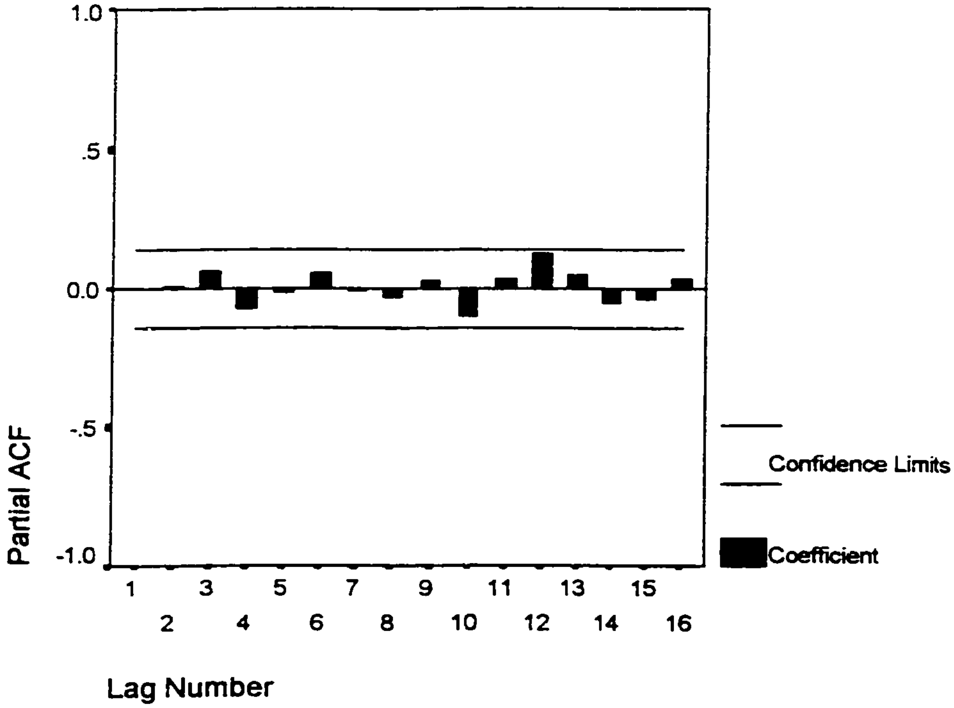


FIGURE 14
LAKE MICHIGAN-HURON WATER LEVEL AUTOCORRELATION FUNCTION

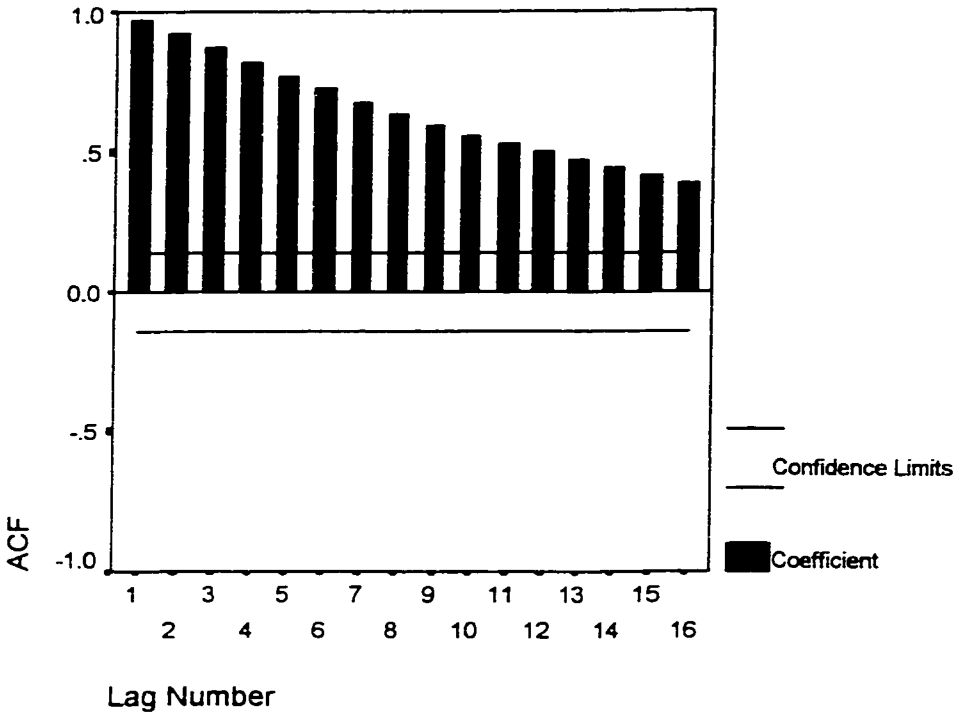


TABLE 8

LAKE MICHIGAN-HURON ARMA MODEL (1,0,1)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.29170597
Log likelihood	-37.34913
AIC	78.69826
SBC	85.254489

ANALYSIS OF VARIANCE:

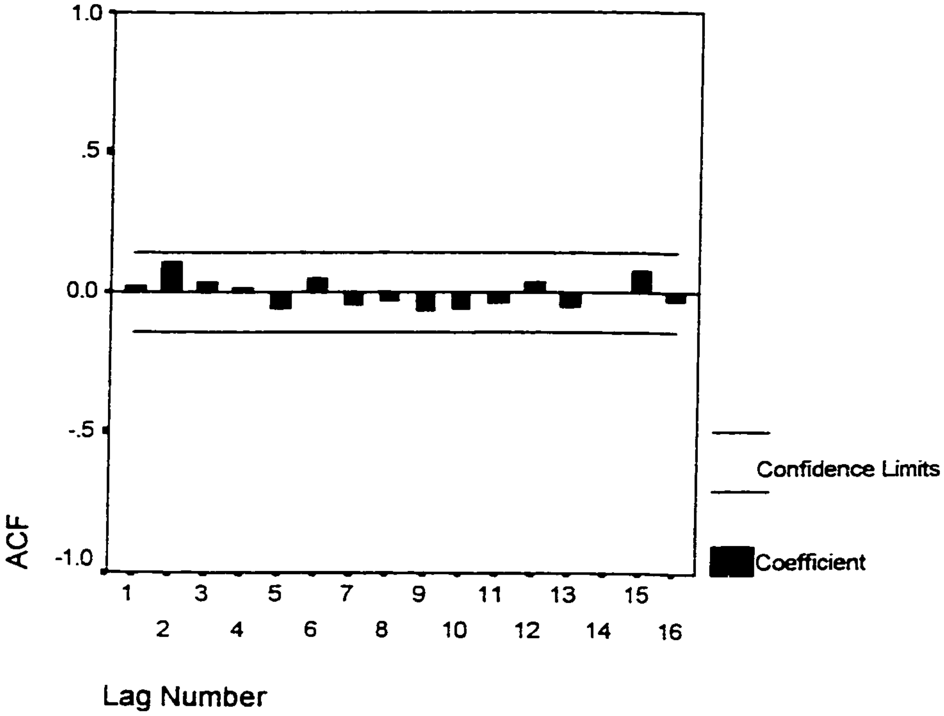
	DF	Adj. Sum of Squares	Residual Variance
Residuals	194	16.799	.0851

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.96224265	.01860712	51.713690	.00
MA1	-.39953884	.06654729	-6.003833	.00

FIGURE 15

A: LAKE MICHIGAN-HURON WATER LEVEL ARMA MODEL (1,0,1)
AUTOCORRELATION FUNCTION ERROR



B: LAKE MICHIGAN-HURON WATER LEVEL ARMA MODEL (1,0,1)
PARTIAL AUTOCORRELATION FUNCTION ERROR

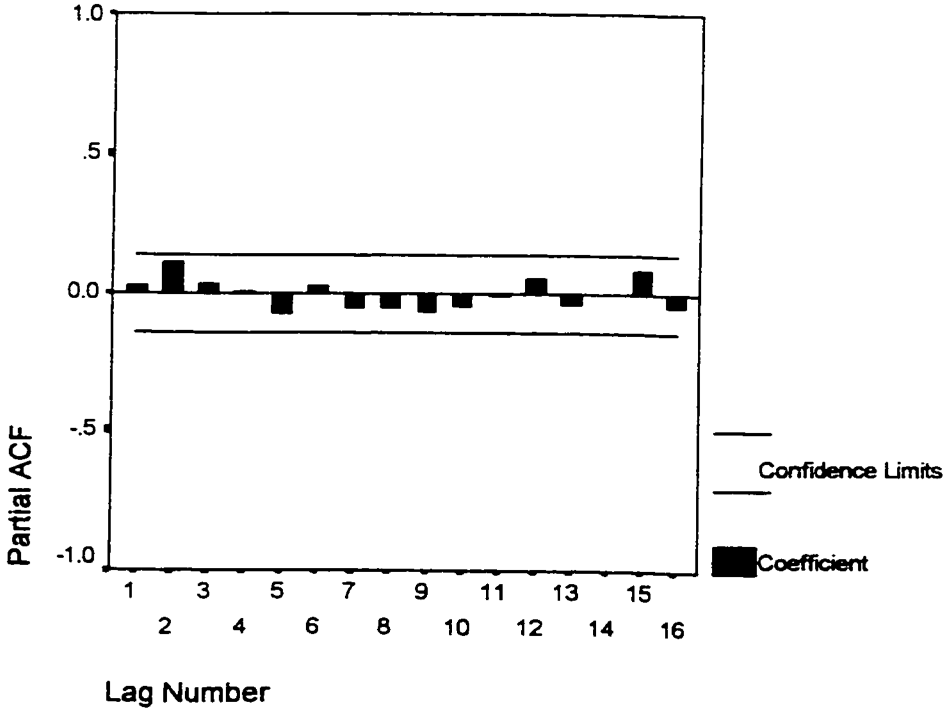


TABLE 9

LAKE SUPERIOR WATER LEVEL AND THE MEI MODEL

VARIABLE: LAKE SUPERIOR WATER LEVELS) ARMA MODEL (1,0,1) REGRESSOR: MEI AT LAG 18 (MEIQ18)

FINAL PARAMETERS:

Number of residuals	195
Standard error	.44295
Log likelihood	-117.2782
AIC	240.55641
SBC	250.37541

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	192	38.014	.1962

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.81537384	.04714991	17.293223	.00
MA1	-.36800801	.07411312	-4.965491	.00
MEIQ1	-.15864176	.06113066	-2.595126	.02

MODEL SUMMARY

CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R	.899
R SQUARE	.808
DURBIN WATSON	2.027
DF	180
SIG	.00

FIGURE 16

LAKE SUPERIOR WATER LEVEL AND MEIQ18 ARMA MODEL (1,0,1)

AUTOCORRELATION FUNCTION ERROR

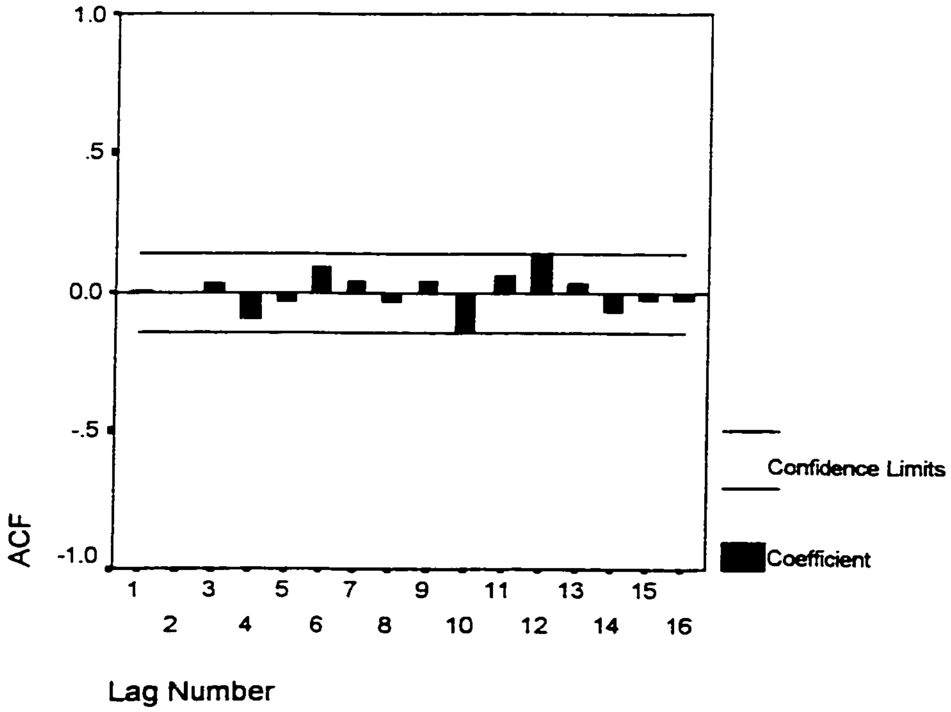


TABLE 10

LAKE MICHIGAN-HURON WATER LEVEL AND THE MEI MODEL
VARIABLE: LAKE MICHIGAN-HURON WATER LEVEL ARMA MODEL (1,0,1) REGRESSOR: MEI AT LAG 14

FINAL PARAMETERS:

Number of residuals	182
Standard error	.20989547
Log likelihood	25.765128
AIC	-45.530255
SBC	-35.918235

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	179	8.028	.0440

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.95299769	.02193005	43.456255	.00
MA1	-.42101140	.06945568	-6.061584	.00
MEIQ14	.06045971	.02960646	2.042112	.04

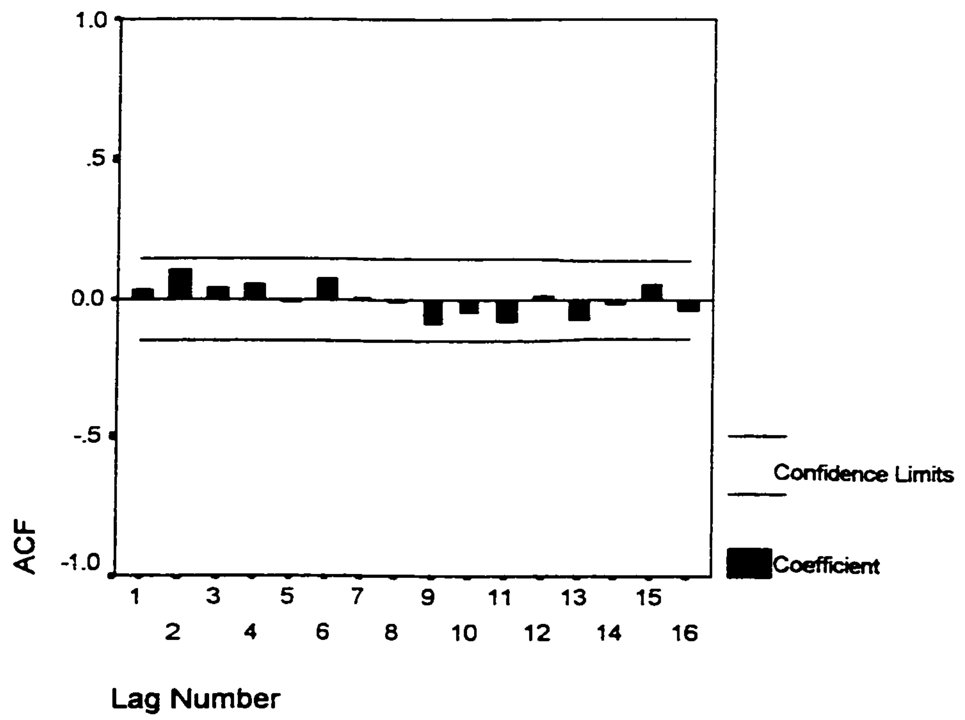
MODEL SUMMARY

CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R	0.974
R SQUARE	.95
DURBIN WATSON	1.797
DF	181
SIG	.00

FIGURE 17

LAKE MICHIGAN-HURON WATER LEVEl AND MEIQ 14 ARMA MODEL (1,0,1)
AUTOCORRELATION FUNCTION ERROR



Therefore, it may be stated that the Box-Ljung statistic for the ACF is not statistically significant at any lag. This suggests that the Lake Erie modeling is a first-order autoregressive process. Consequently, the initial shock or triggering effects of ENSO has a diminishing effect on the subsequent time series. Higher-order autoregressive parameters and the ARMA process could not sufficiently describe the model.

Using MEI, Lake Erie was found to exhibit a first-order autoregressive process with MEI at lag 14. This was determined through cross-correlation, as well as numerous modeling attempts. This model was the most parsimonious, with an AR coefficient of 0.94, and the MEIQ14 (3.5 years) coefficient being 0.13. The approximate probabilities were 0.00 at a significance level of 0.05. The T-ratios were all above the critical levels (see Table 12). The R value of 0.95 represents a strong relationship, while the R Square value of 0.89 indicates that approximately 90% of the variance in the model is accounted for by the MEI. The ACF plot for this model shows that the residual series are all well over the value of 0.05, and there seems to be no autocorrelation present (see Figure 20). The result of this model indicates that with MEI lagged by 14 (3.5 years), the series is described most efficiently. Fluctuations in Lake Erie water levels are characterized with an initial shock or disturbance, that is after an approximate time period of 3.5 years, the relationship between Lake Erie water levels and the effects of ENSO become significant. It is important to note that there exists "feedback" or memory within the series, which can be expressed as an autoregressive function of theprevious value of the series, and a random disturbance. Accordingly, the hypothesis stating that Lake Erie would approximate a first-order autoregressive process (AR 1) may be accepted.

6.3 Assessment of Hypothesis #3

It was hypothesized that since Lake Ontario has its long axis oriented in an east-west direction, it should be prone particularly to the effects of the passage of weather systems. This would lengthen its exposure to ENSO induced climate changes and approximate a second-order autoregressive model. The AR(2) statistical summary indicated that this model was best fit to Lake Ontario with an AR(2) coefficient of –0.25 (see Table 13). The first-order coefficient is 0.94. The choice of the second-order autoregressive model was chosen because the AIC values were lowest with this model, and the Box-Ljung and probability values of the residuals were highest. The T-ratio values are significant at a value of –3.53, with an approximate probability of 0.00 at a significance level of 0.05. With this, the hypothesis that Lake Ontario may be characterized by a second-order autoregressive process may be accepted (see Figures 22, 23, and Table 14).

FIGURE 18

LAKE ERIE WATER LEVEL AUTOCORRELATION FUNCTION

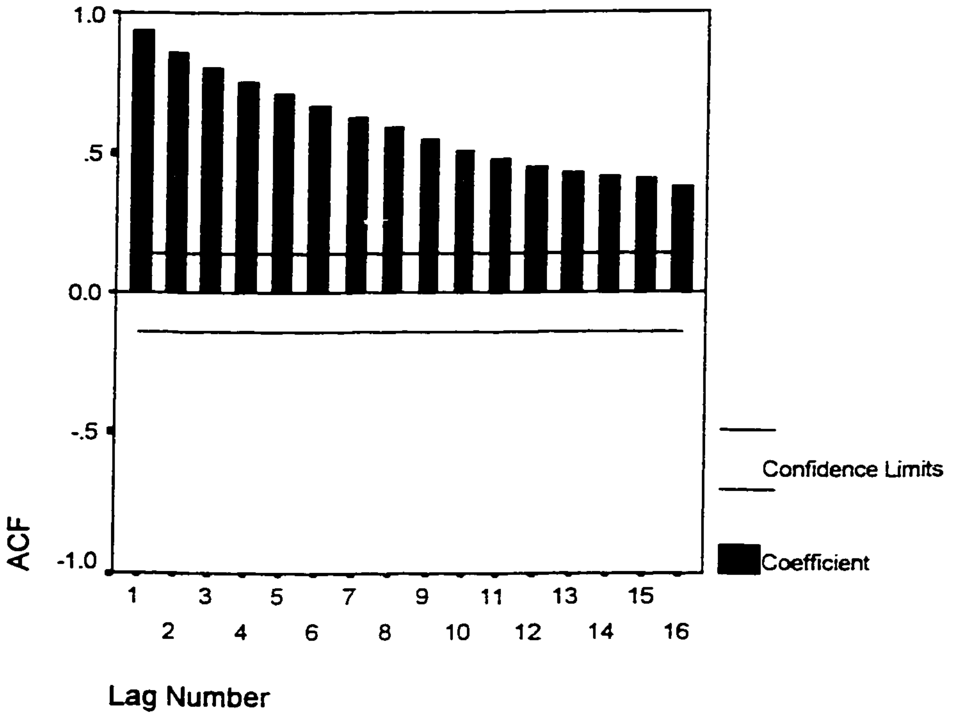


TABLE 11

LAKE ERIE WATER LEVEL AR MODEL (1,0,0)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.33431217
Log likelihood	-63.921837
AIC	129.84367
SBC	133.12179

ANALYSIS OF VARIANCE:

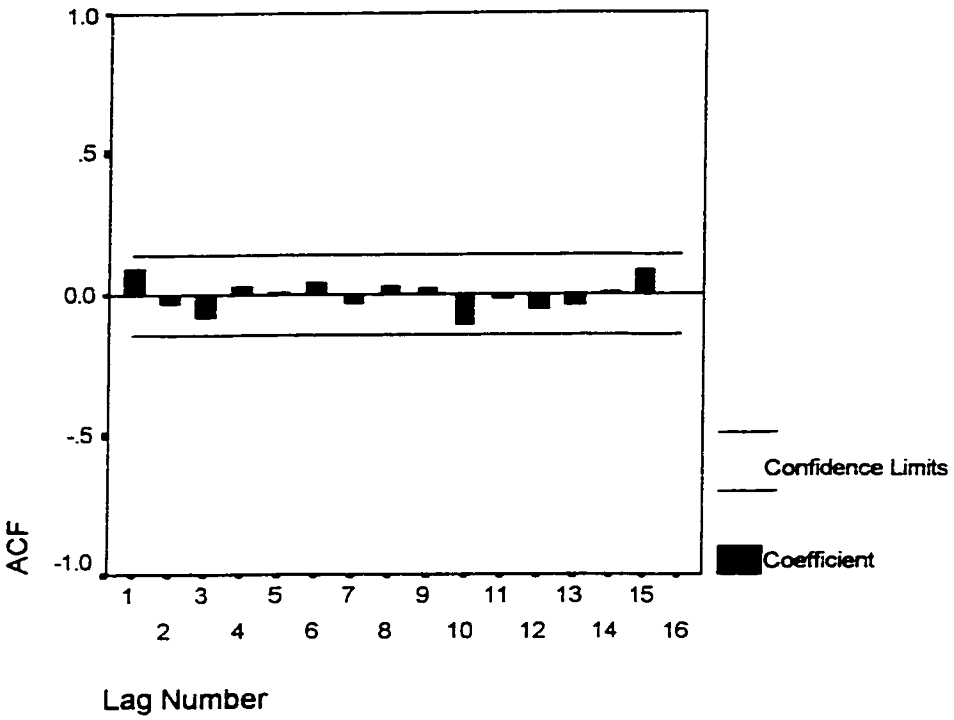
	DF	Adj. Sum of Squares	Residual Variance
Residuals	195	22.032	.112

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.93843071	.02374218	39.525889	.00

FIGURE 19

**A: LAKE ERIE WATER LEVEL AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR**



**B: LAKE ERIE WATER LEVEL AR MODEL (1,0,0)
PARTIAL AUTOCORRELATION FUNCTION ERROR**

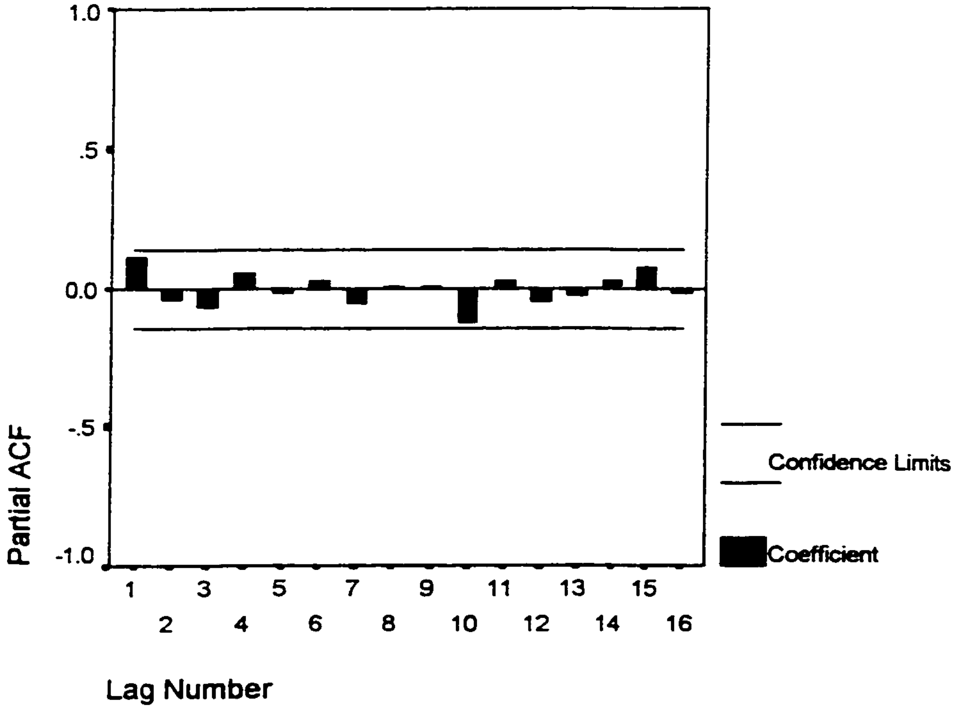


TABLE 12

LAKE ERIE WATER LEVEL AND THE MEI MODEL
VARIABLE: LAKE ERIE WATER LEVEL AR MODEL (1,0,0) REGRESSOR: MEI AT LAG14 (MEIQ14)

FINAL PARAMETERS:

Number of residuals	182
Standard error	.32752223
Log likelihood	-55.178441
AIC	114.35688
SBC	120.7649

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	180	19.540	.107

VARIABLES IN THE MODEL:

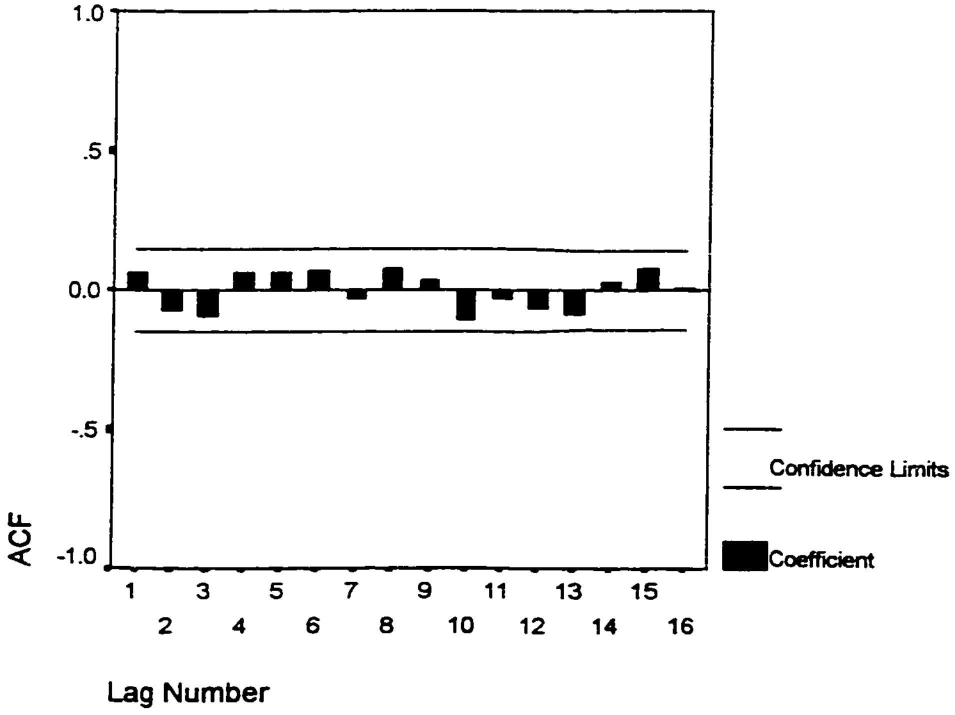
	B	SEB	T-RATIO	APPROX. PROB.
AR1	.94123171	.02404271	39.148324	.00
MEIQ14	.12932143	.04407872	2.933874	.00

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R .95
R SQUARE .89
DURBIN WATSON 1.81
DF 181
SIG .00

FIGURE 20

LAKE ERIE WATER LEVEL AND MEIQ14 AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR



Further, with MEI lagged 14 quarters, and used as an independent regressor against Lake Ontario water levels, a significant and strong relationship was shown to exist. The autoregressive coefficients were significant at an approximate probability of 0.00, 0.00 and 0.05 respectively (see Table 14). The R value was strong at 0.73, while the R Square value indicated that the model accounted for approximately 53% of the explained variation in Lake Ontario water levels. The residuals generated from this model showed no signs of autocorrelation, with non-significant Box-Ljung statistical values (see Figure 23). Lake Ontario may be characterized by an AR (2) process because it is prone to the effects of weather systems at a greater rate than the other lakes. Here, the shocks to the system would be felt from the first two lags, maintaining memory throughout the series. Consequently, since Lake Ontario water levels adequately fit a second-order autoregressive process, the hypothesis may be accepted due to the statistically significant results.

Assessment of Hypothesis #4

Net basin supply data for each lake were tested in order to gain a more complete view of lake level fluctuation in the midst of an ENSO event. Examination of the results showed that for each Lake NBS time series, the effects of the random shock to the system are being felt well after the incipient trigger. As seen on the model results, and the correlograms of the residuals, there are no significant autocorrelations, and all values associated with the Box-Ljung Q statistics are well above the 0.05 value. This suggests a weak first-order autoregressive process exists within each of the Lakes net basin supplies. Furthermore, all T-ratio values were significantly larger than the critical value of approximately 1.658, with the approximate probabilities at no larger than 0.01. See statistical results at the end of this section. Once the net basin supply variables were appropriately modeled, the variables were tested with the MEI index to determine a temporal fit. The results show that only Lakes Erie and Ontario approximate an AR (1) model, while Lake Superior fit an ARMA (1,0,1) and Michigan-Huron failed to meet the requirements that fit any model, altogether. The results are described in detail below.

Lake Superior Net Basin Supply and MEI

The relationship between the MEI (the independent regressor) and Lake Superior net basin supply was found to fit an ARMA (1,0,1) model with a lagged MEI value of 16. This represents the best-fit model, although statistically weak. All coefficients and parameters are statistically significant at an approximate probability of 0.00 respectively. As well, the T-ratios for each variable were acceptable. The first-order autoregressive coefficient of 0.89 suggests a strong

FIGURE 21

LAKE ONTARIO AUTOCORRELATION FUNCTION

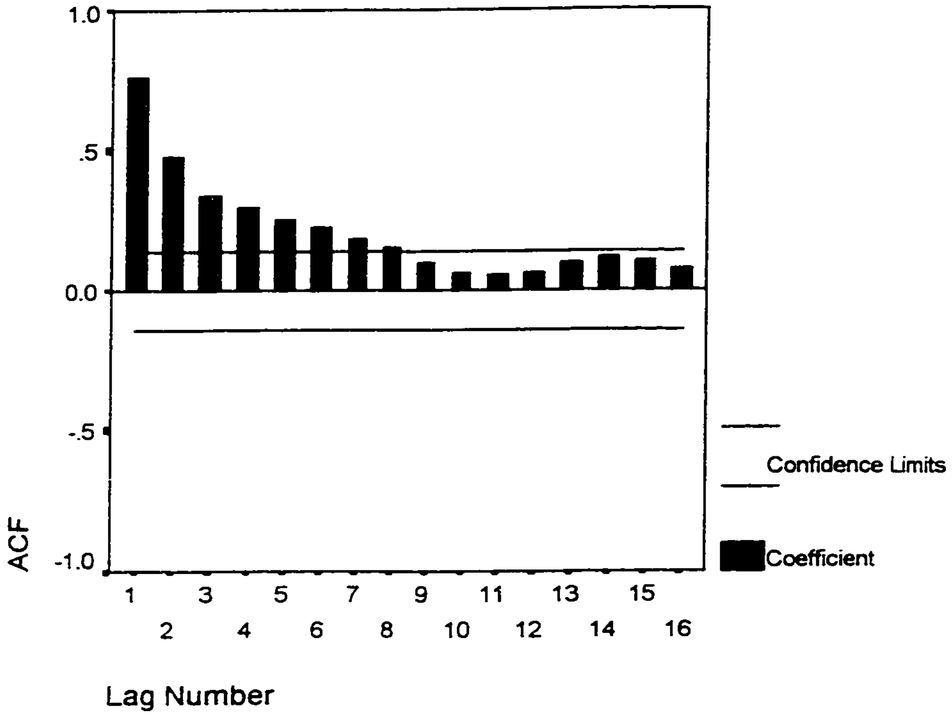


TABLE 13

LAKE ONTARIO WATER LEVEL AR(2) MODEL

FINAL PARAMETERS:

Number of residuals	196
Standard error	.63419093
Log likelihood	-188.33228
AIC	380.66456
SBC	380.22079

ANALYSIS OF VARIANCE:

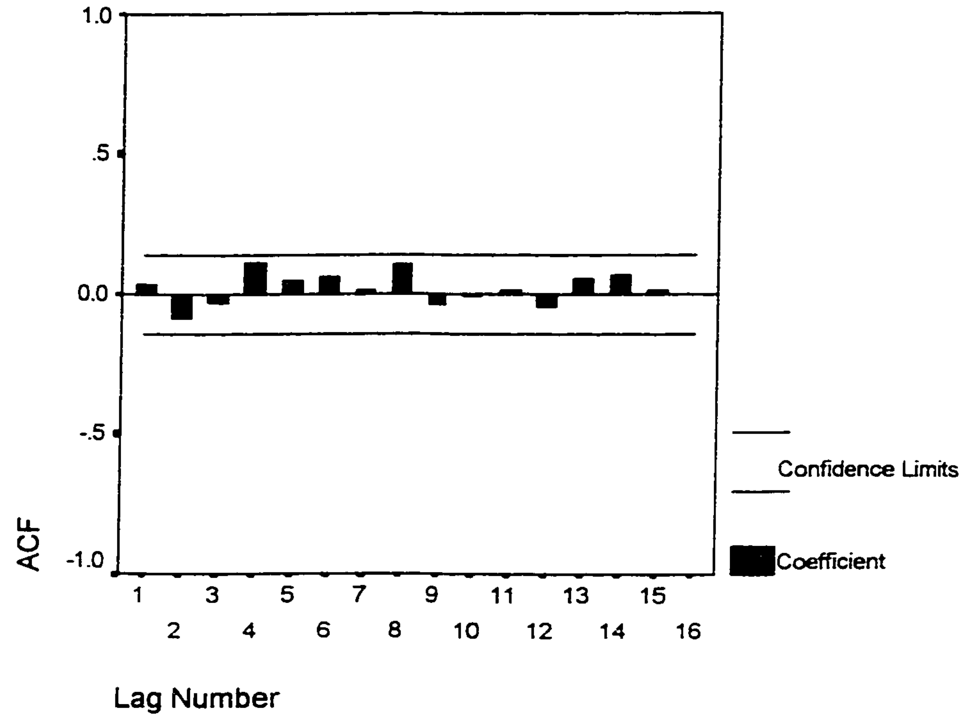
	DF	Adj. Sum of Squares	Residual Variance
Residuals	194	78.412	.4021

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.94165201	.07095801	13.270553	.00
AR2	-.25021064	.07098037	-3.525068	.00

FIGURE 22

**A: LAKE ONTARIO WATER LEVEL AR (2) MODEL (2,0,0)
AUTOCORRELATON FUNCTION ERROR**



**B: LAKE ONTARIO WATER LEVEL AR (2) MODEL (2,0,0)
PARTIAL AUTOCORRELATION FUNCTION ERROR**

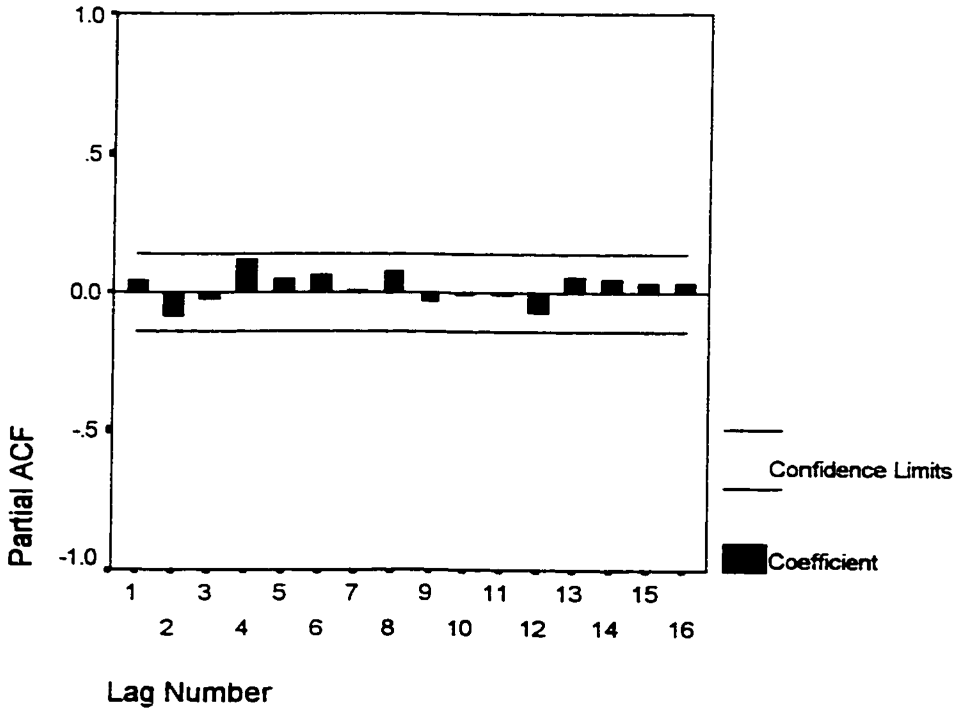


TABLE 14

LAKE ONTARIO WATER LEVEL AND THE MEI MODEL
VARIABLE: LAKE ONTARIO WATER LEVEL AR(2) MODEL (2,0,0) REGRESSOR: MEI AT LAG14 (MEIQ14)

FINAL PARAMETERS:

Number of residuals	182
Standard error	.6356108
Log likelihood	-174.66131
AIC	355.32261
SBC	364.93463

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	179	72.632	.4040

VARIABLES IN THE MODEL:

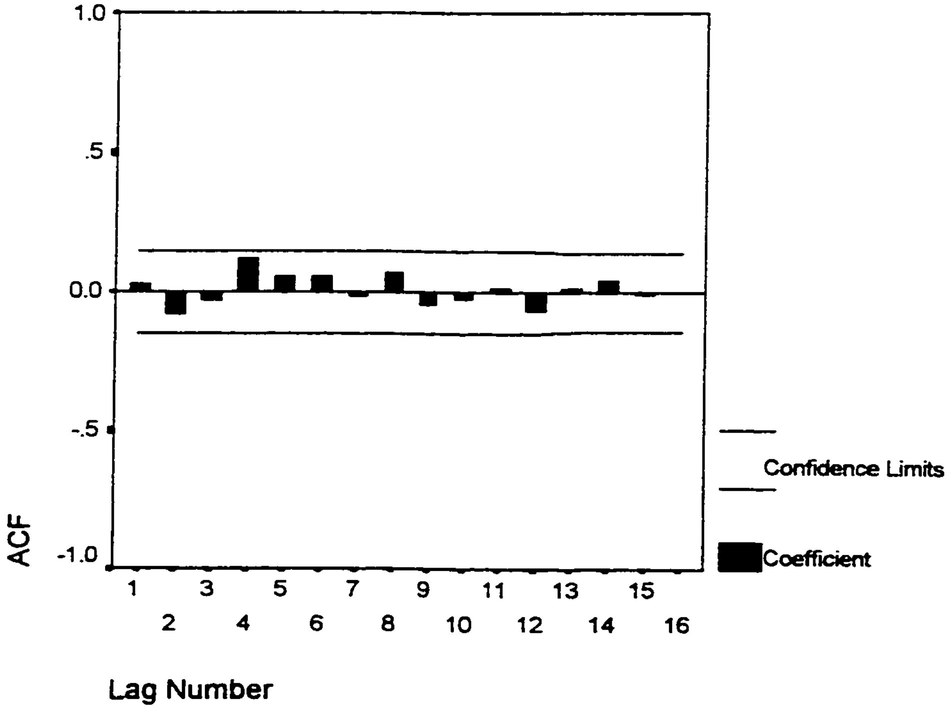
	B	SEB	T-RATIO	APPROX. PROB.
AR1	.87121697	.07375474	11.812353	.00
AR2	-.25073135	.07374209	-3.400112	.00
MEIQ14	.17792599	.09179497	1.938298	.05

MODEL SUMMARY
CORRELATION BETWEEN THE DEPENDENT VARIABLE AND MODEL FIT

R	.728
R SQUARE	.529
DURBIN WATSON	1.894
DF	181
SIG	.00

FIGURE 23

**LAKE ONTARIO WATER LEVEL AND MEIQ14 AR2 MODEL (2,0,0)
AUTOCORRELATION FUNCTION ERROR**



process exists between Lake Superior NBS and the MEI. The moving average parameter is 0.81 indicating points in the series where Lake NBS values fluctuate at random intervals in a more abrupt and brief manner. This is reinforced with the observation that only 6% of the variations within the series accountable within the model (R Square parameter). The R value of 0.26 indicates a weak relationship at a significance value of .00. This may be indicative of the size of the lake and its corresponding drainage basin. The net basin supply for Lake Superior may act on random intervals rather than anticipated cycles. The lagged MEI value of 16 suggests a four-year, weak relationship exists between Lake Superior NBS and MEI. Thus, the relationship is weak, although statistically significant (see Figures 24 and 25; Tables 15 and 16), characterized by both long memory and short random shocks (or damped oscillations). The plots of the residuals indicate a significant result with all Box-Ljung values being well over the 0.05 level, and characterized with no significant autocorrelations (see Figures 24 and 25; Tables 15 and 16).

Lake Michigan-Huron Net Basin Supply and MEI

The modeling of Lake Michigan-Huron NBS with MEI as the independent regressor resulted in a complete inability to parsimoniously fit the variables. It was found that despite initial success, either the residuals were autocorrelated or the statistical results were in no manner significant or acceptable. Possible explanations for this will be discussed in the following chapter.

Lake Erie Net Basin Supply and MEI

When Lake Erie NBS data was put into an AR model with lagged values of MEI as an independent regressor, an AR (1,0,0) process with 8 lags (2 years), was found to produced significant, although weak results (see Tables 18 and 19). The autoregressive coefficient is 0.172, at an approximate probability of 0.01 at an alpha of 0.05. The T-ratio statistic were both at acceptable values. The plot of the models errors indicate no autocorrelation among the residuals, which are indicative of the insignificant Box-Ljung statistics. The model is considered weak with an R value of 0.232, which was expected, while approximately 5% of the variation in Lake Erie Net Basin Supply was accounted for within the model (see Figures 30 and 31).

Lake Ontario Net Basin Supply and MEI

Lake Ontario NBS modeled with MEI as the independent regressor, resulted in a significant but weak relationship as well (see Figures 32 and 33; Tables 20 and 21)). The best-fit model was that of a first-order autoregressive process with MEI lagged at the third quarter (0.75 years/ lag beginning: September). With an autoreggressive coefficient of 0.25, at alpha 0.05, the approximate probability was about 0.01. There were no significant autocorrelation among the residuals, and all Box-Ljung values were non-significant at values well above the 0.05 level. The R value of 0.324 indicates a weak relationship, with approximately 10% of the variation of Lake Erie NBS being accounted for by the model.

In conclusion, it was found that each lake level time series fit a weak AR model (1,0,0). However, when fitted to models associated with the MEI as the independent regressor, it was found that only Lakes Ontario and Erie fit the first-order autoregressive model. Lake Superior fit an ARMA (1,0,1) model; while Lake Michigan-Huron could not parsimoniously fit a model with MEI. Thus, although the original correlograms of Lake NBS indicate a first-order autoregressive process, they do not follow this pattern associated with the MEI representing ENSO events. The hypothesis stating that Lake NBS should approximate an autoregressive model where a random shock associated with ENSO at lag t-1 must be rejected. Of course, this is with the exception of the smaller and southern lakes within the system (Erie and Ontario).

FIGURE 24

LAKE SUPERIOR NET BASIN SUPPLY AUTOCORRELATION FUNCTION

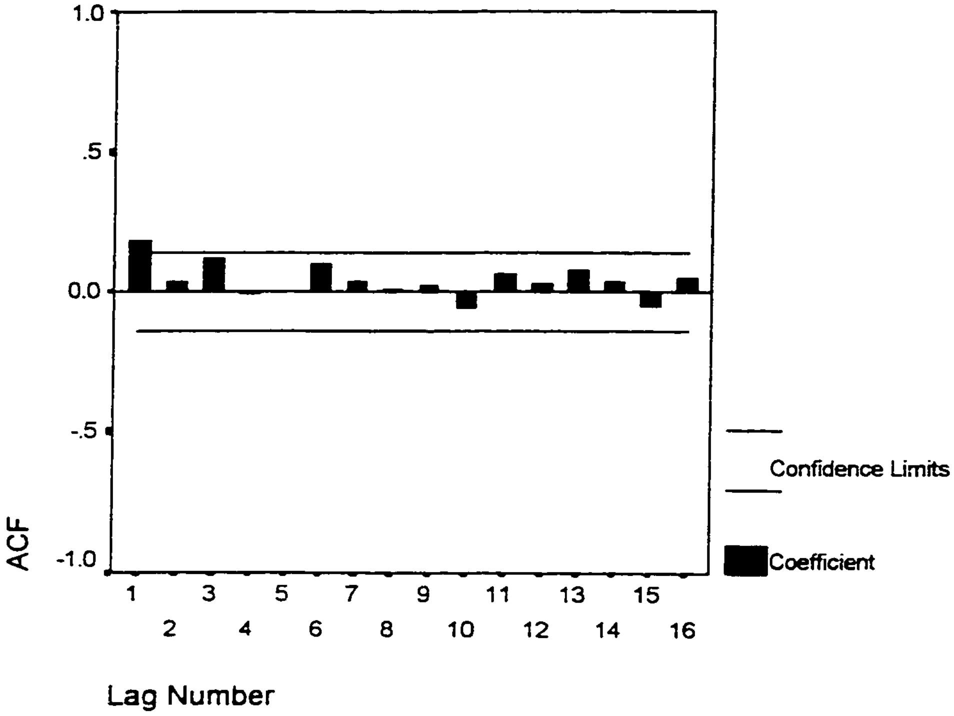


TABLE 15

LAKE SUPERIOR NET BASIN SUPPLY
AR MODEL (1,0,0)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.97267946
Log likelihood	-272.19328
AIC	546.39256
SBC	549.67067

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	195	184.51	.946

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.19709115	.07024231	2.8058750	.00

FIGURE 25

LAKE SUPERIOR NET BASIN SUPPLY AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR

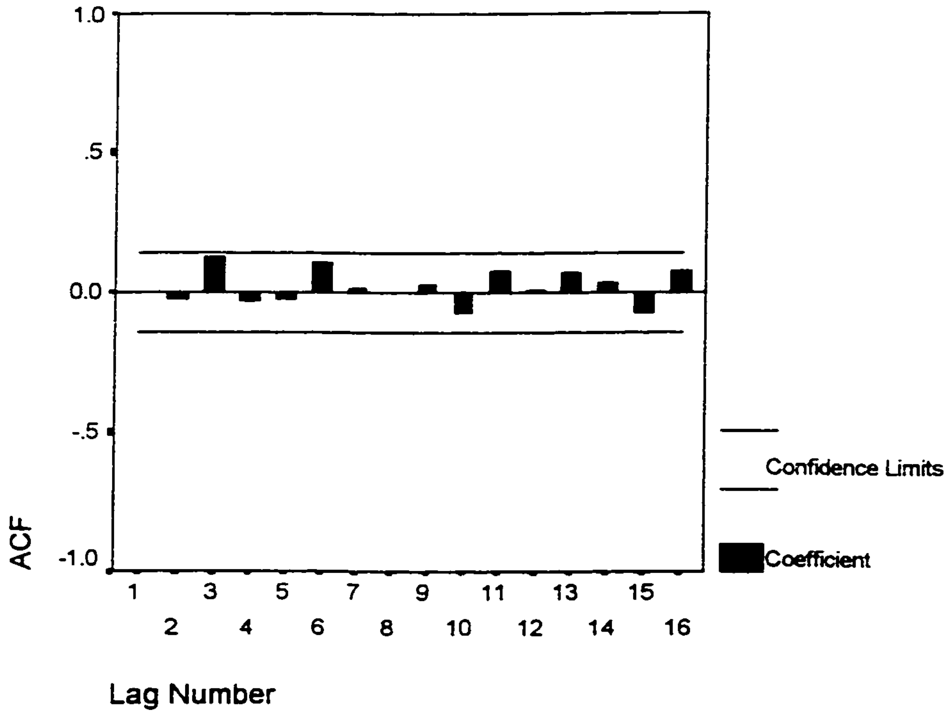


TABLE 16

LAKE SUPERIOR NET BASIN SUPPLY AND THE MEI MODEL
VARIABLE: LAKE SUPERIOR NBS MODEL ARMA (1,0,1) REGRESSOR: MEI AT LAG 16 (MEIQ16)

FINAL PARAMETERS:

Number of residuals	174
Standard error	.94020902
Log likelihood	-234.70778
AIC	475.41556
SBC	484.89272

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	171	151.23	.8839

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.88700773	.13160154	6.7401016	.00
MA1	.80758807	.16662045	4.8468724	.00
MEIQ16	-.24020540	.07930259	-3.0289730	.00

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R	.257
R SQUARE	0.06
DURBIN WATSON	1.913
DF	173
SIG	.00

FIGURE 26

LAKE SUPERIOR NBS AND MEIQ 16 ARMA MODEL(1,0,1) AUTOCORRELATION FUNCTION ERROR

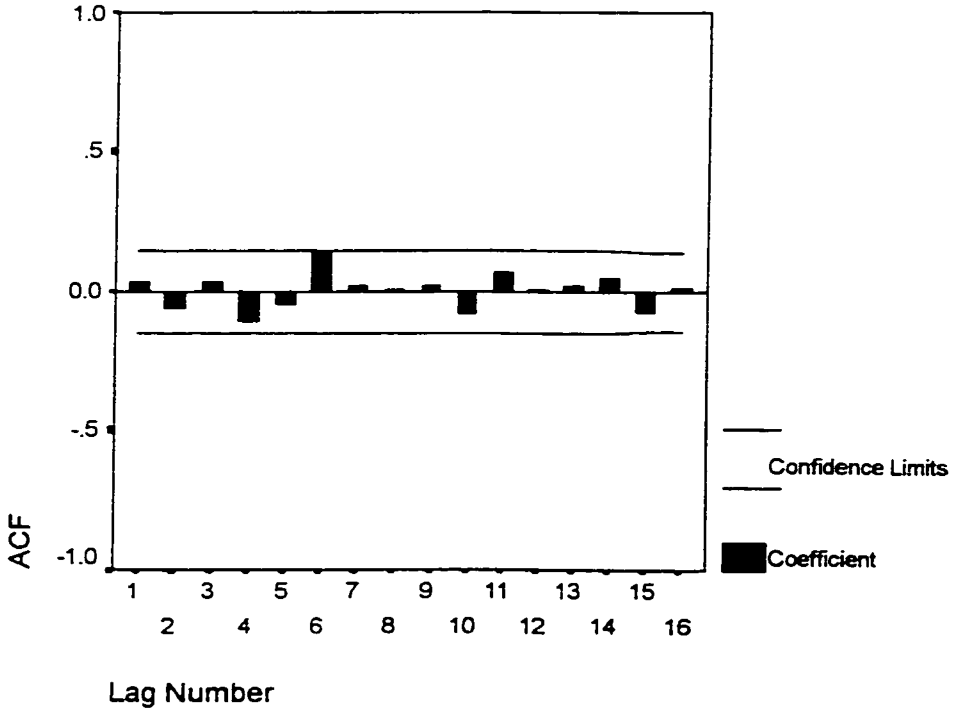


FIGURE 27

LAKE MICHIGAN-HURON NET BASIN SUPPLY AUTOCORRELATION FUNCTION

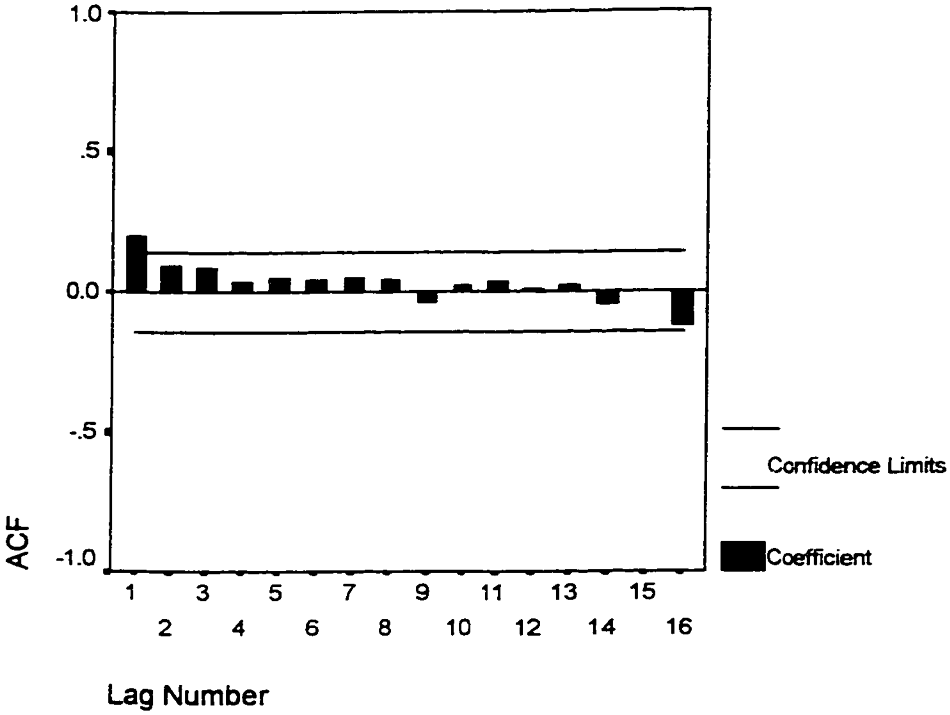


TABLE 17

LAKE MICHIGAN-HURON NET BASIN SUPPLY
AR MODEL (1,0,0)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.99152322
Log likelihood	-275.97148
AIC	553.94296
SBC	557.22108

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	195	1191.763	.983

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.23420199	.06992198	3.3494761	.00

FIGURE 28

LAKE MICHIGAN-HURON NBS AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR

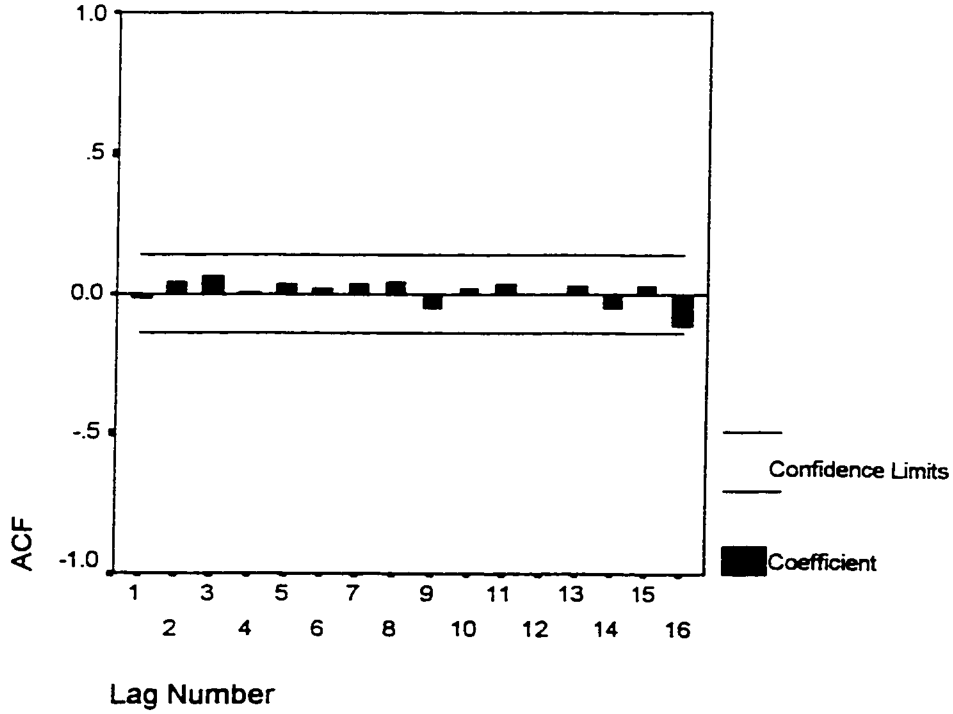


FIGURE 29

LAKE ERIE NET BASIN SUPPLY AUTOCORRELATION FUNCTION

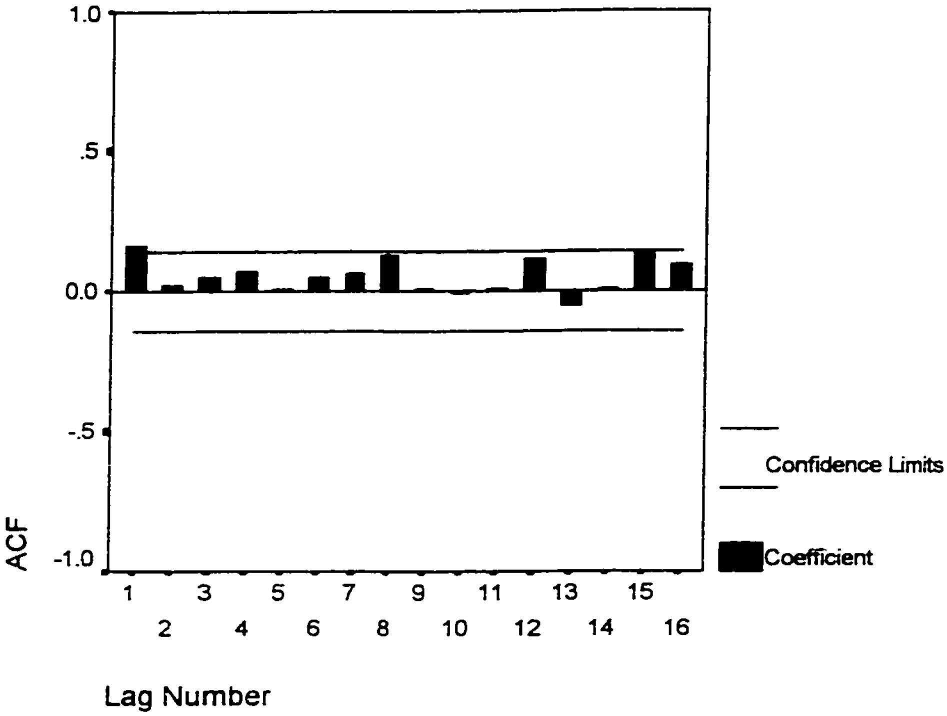


TABLE 18

LAKE ERIE NET BASIN SUPPLY AR MODEL (1,0,0)

FINAL PARAMETERS:

Number of residuals	196
Standard error	1.0034472
Log likelihood	-278.30303
AIC	558.60605
SBC	561.88417

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	195	196.380	1.1006

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.18115474	.07061642	2.5653348	.01

FIGURE 30

LAKE ERIE NBS AR MODEL (1,0,0) AUTOCORRELATION FUNCTION ERROR

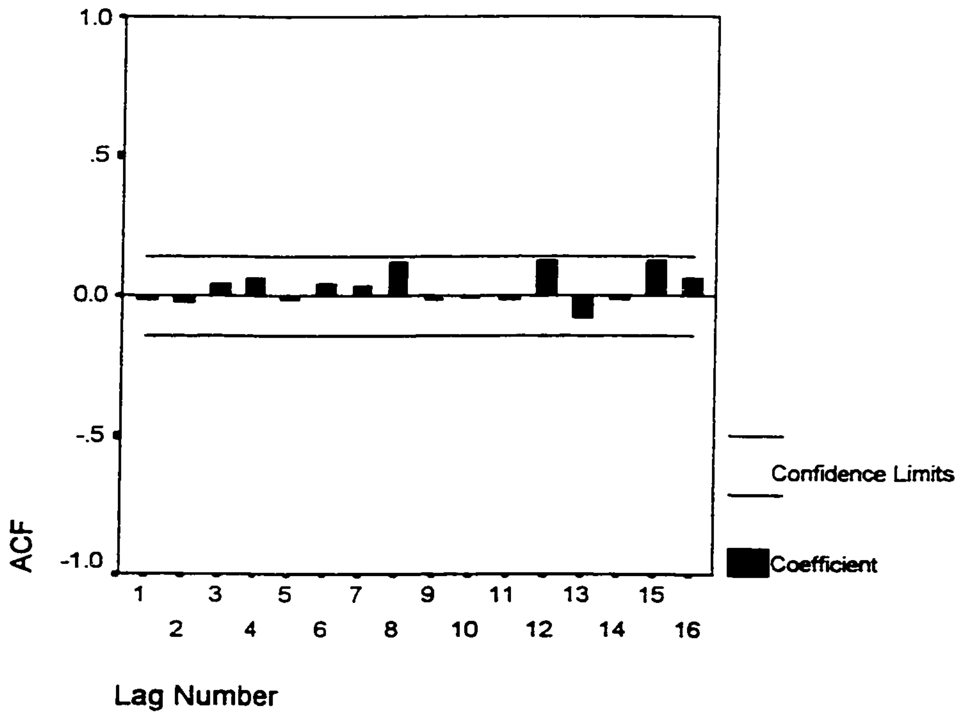


TABLE 19

LAKE ERIE NET BASIN SUPPLY AND THE MEI MODEL
VARIABLE: LAKE ERIE NBS MODEL AR (1,0,0) REGRESSOR: MEI AT LAG 8 (MEIQ8)

FINAL PARAMETERS:

Number of residuals	188
Standard error	.97672904
Log likelihood	-261.34862
AIC	526.69724
SBC	533.17012

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	186	177.472	.954

VARIABLES IN THE MODEL

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.17183444	.07225792	2.3780705	.01
MEIQ8	-.19839581	.08800778	-2.2542984	.02

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R .232
R SQUARE .054
DURBIN WATSON 1.993
DF 187
SIG .00

FIGURE 31

LAKE ERIE NBS AND MEIQ8 AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR

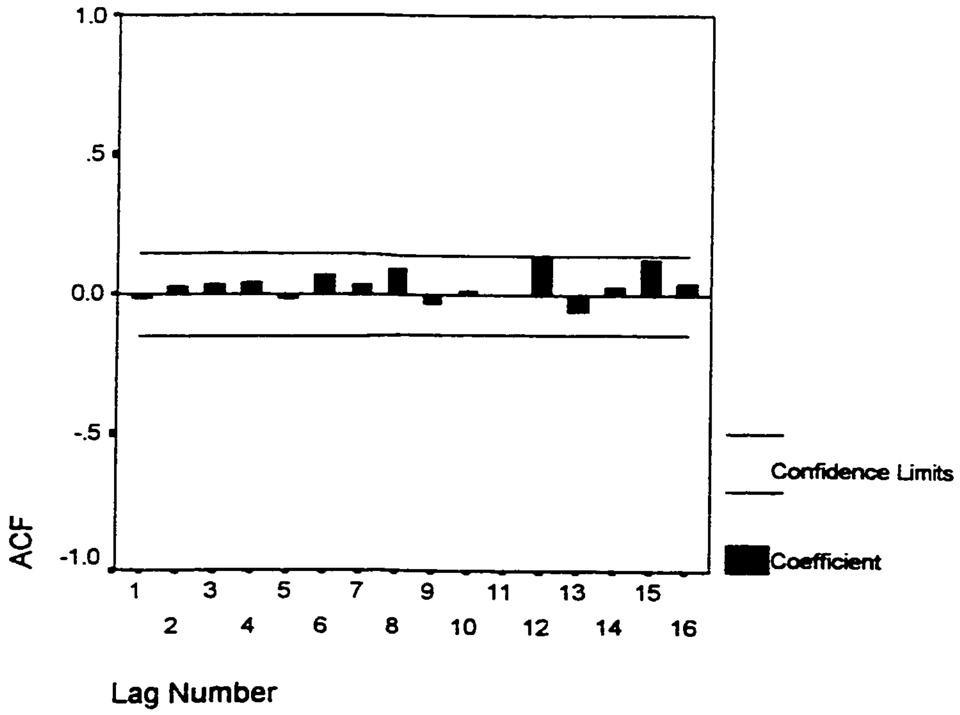


FIGURE 32

LAKE ONTARIO NBS AUTOCORRELATION FUNCTION

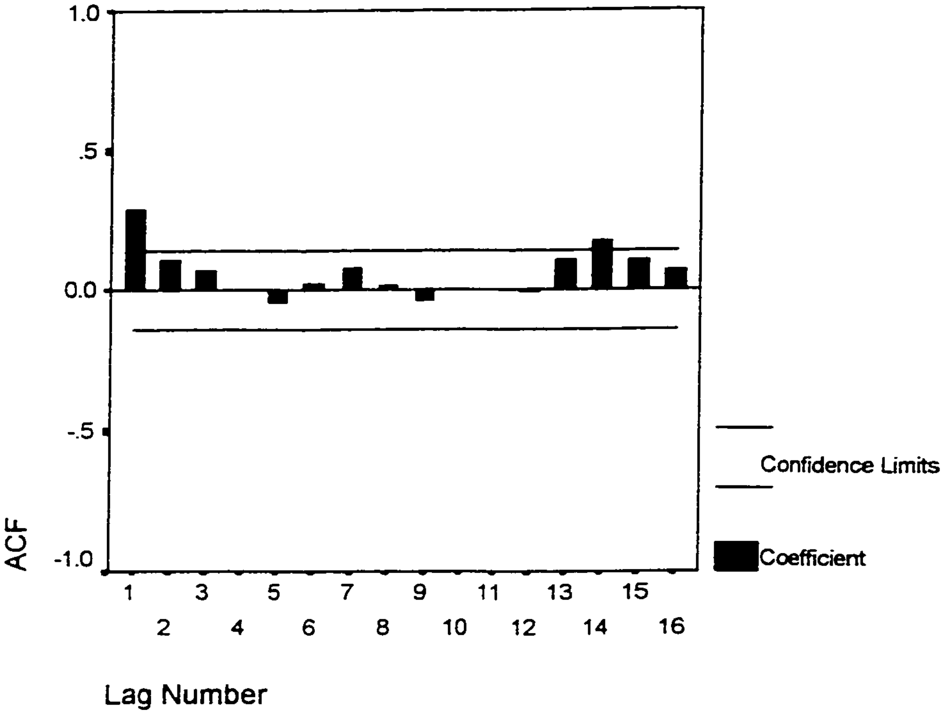


TABLE 20

LAKE ONTARIO NET BASIN SUPPLY
AR (1) MODEL (1,0,0)

FINAL PARAMETERS:

Number of residuals	196
Standard error	.92436368
Log likelihood	-266.01483
AIC	534.02965
SBC	537.30776

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	195	173.238	.8880

VARIABLES IN THE MODEL:

	B	SEB	T-RATIO	APPROX. PROB.
AR1	.27193778	.06983907	3.8937770	.00

FIGURE 33

LAKE ONTARIO NBS AR (1) MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR

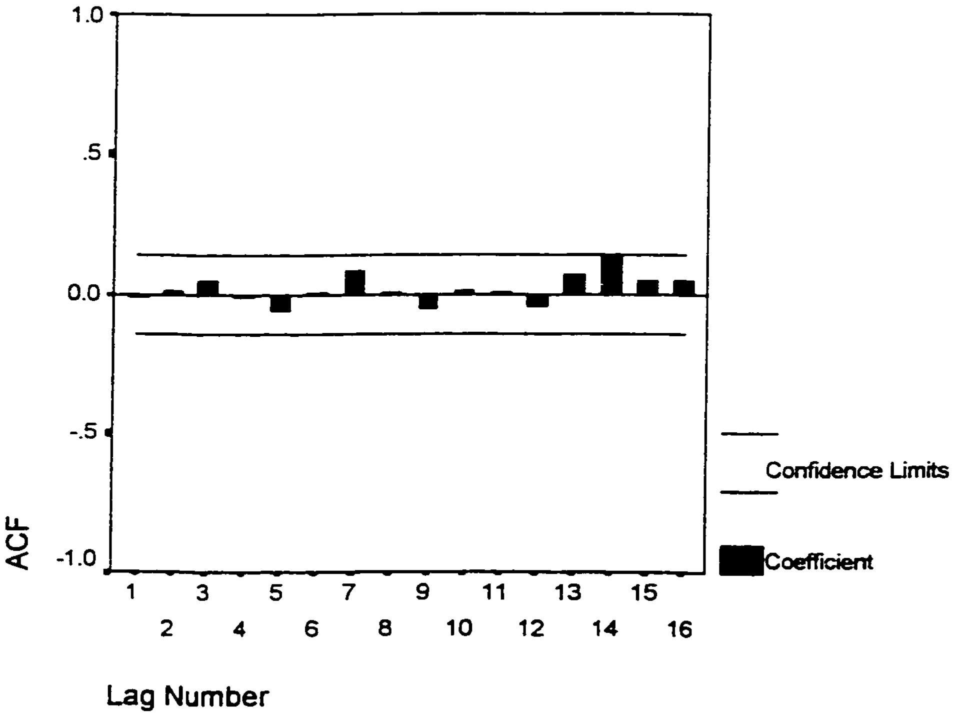


TABLE 21

LAKE ONTARIO NET BASIN SUPPLY AND THE MEI MODEL
VARIABLE: LAKE ONTARIO NBS MODEL AR (1,0,0) REGRESSOR: MEI AT LAG3 (MEIQ3)

FINAL PARAMETERS:

Number of residuals	193
Standard error	.92840272
Log likelihood	-258.54915
AIC	521.09829
SBC	527.62637

ANALYSIS OF VARIANCE:

	DF	Adj. Sum of Squares	Residual Variance
Residuals	191	164.684	.8619

VARIABLES IN THE MODEL:

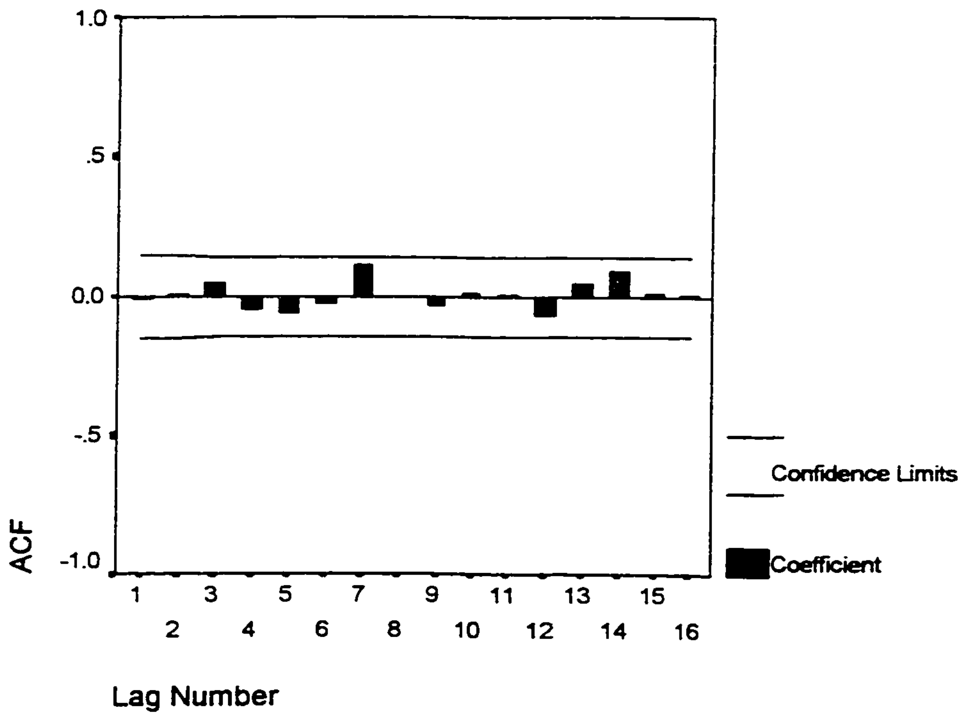
	B	SEB	T-RATIO	APPROX. PROB.
AR1	.24993341	.07066035	3.5371098	.00
MEIQ3	-.23002447	.08566531	-2.6851531	.00

MODEL SUMMARY
CORRELATTION BETWEEN INDEPENDENT VARIABLE AND MODEL FIT

R	.324
R SQUARE	.105
DURBIN WATSON	1.983
DF	192
SIG	.00

FIGURE 34

LAKE ONTARIO NBS AND MEIQ3 AR MODEL (1,0,0)
AUTOCORRELATION FUNCTION ERROR



7.0 DISCUSSION

In evaluating processes that are important in influencing the dynamics of a large and complex system such as the Great Lakes, researchers typically look at temporal averages. These time scales can be viewed as "snap shots" of the system being studied, and may reveal important, but transient, responses by the entire system (Flint and Stevens, 1989). Causal mechanisms should be the basis for research questions addressing the level of certainty needed to understand processes in the Great Lakes. These approaches may help to make predictions about the future which, can then be used to formulate policy for successful environmental management.

7.1 SOI and MEI Modeling

The modeling of the SOI and MEI helped to determine that the Multivariate ENSO Index would serve the study in an efficient manner. As previously stated, the attempt to model the SOI and the MEI was somewhat complex. The difficulty in modeling these variables may be due to the fact that the data were divided into quarters. Because each quarter contains 3 months, and the characteristic length of an ENSO event is approximately 4 to 8 months in duration, the lagging of the variables may be a response to the sensitivity of the data sets to the initiation of ENSO at the month of May. If ENSO events progress during the month of May, the time series may require lagging in order to efficiently represent this. This may be interpreted through the lag values of 3 and 5; and 2 and 3; for the SOI and the MEI respectively. The ARMA nature of the time series found within this thesis may be indicative of the lagging of MEI, and the stochastic nature of the factors it represents, and measured within it.

The use of quarterly data may not be the most efficient manner in which to compare the two indices, if there were to be a method that allows one to do so. It did however allow the indices to be measured in the same manner as all of the other variables studied, allowing for consistency in the analysis. The unpredictability of atmospheric factors is often difficult to measure with precision and accuracy making the representative indices them somewhat cryptic. This is evident within the models generated to characterize ENSO events. Despite the complexity however, it is still satisfactory to accept the models produced and use them with confidence.

7.2 Hypothesis # 1

The two upper-most and largest lakes (Superior and Michigan-Huron) were characterized by ARMA (1,0,1) models, most likely due the individual characteristic of each lake. This is in addition to the orientation of the lakes to air masses, bringing precipitation, variation in air temperature, and its resulting effects on evaporation rates. The ARMA (1,0,1) aspect of Lake Superior water levels (LSWL) and Lake Michigan-Huron water levels (LMHWL) is one where the serial behaviour of the time series suggests that disturbances associated with lake levels are cyclic, and shorter in duration than that of an

AR (2) process. Specifically, a pure AR model or a pure MA model would be inappropriate, to describe the data, and thus the most parsimonious step would be to mix the models.

The sheer size and position of Lake Superior may cause many to think that it was the precursor to proceeding lake level fluctuations throughout the system. However, it seems that due to its massive size, and depth, and westerly orientation, the effects of a phenomenon such as ENSO is felt, although not at a suspected impact. According to the results of the statistical analysis with MEI as the independent regressor, the optimum effect of ENSO is not fully realized for 18 lags/quarters. This means that after 4.5 years, Lake Superior may reflect the nature and intensity of a particular ENSO event. It may be the size of the lake compared to its relatively small drainage basin, which plays a role in the dampened outcome of Lake Superior water levels (LSWL).

Likewise, being at the head of the Great Lakes system and without a major source of water inflow by rivers or tributaries; Lake Superior water levels are most affected by inflow via its catchment basin, and precipitation. Precipitation however, is deemed quite important because of the mere size of its surface area. Hence the larger the lake surface area, the greater amount of precipitation it is able to catch. As well, Hartmann (1989) states that during particular months, evaporation rates may be more important in effecting lake levels due to the surface area. This is most significant during the month of December, when the lake temperature and air temperature is most different, creating the greatest rates of evaporation.

Therefore, to considerably change lake levels at a rapid rate, one would require an extreme ENSO event, persisting over a span of at least a few years. Thus, the resulting transformations on lake levels would be one with an initial shock persisting for approximately 3-6 months (an ENSO event), and quickly dissipating thereafter. The 3-6 month nature of the shock persistence is due to the ARMA (1,0,1) characteristic of the model, where both AR and MA only require one term. The damped oscillatory nature of the shock is reflective of the ARMA process where a pure cycle is not likely to occur. This means that Lake Superior water levels exhibit responses to the triggering effects of MEI, that are pseudo-cyclic, where a small reversal in the response occurs, helping to dampen the process.

Lake Michigan-Huron water levels also exhibit an ARMA (1,0,1) process, which suggests that when the lakes are considered to act as one, there is the nature of memory within the system. However, after the shock is presented, its effects last for a finite period of time. It is suggested that because they are situated perpendicular to storm tracks, they are less likely to feel the full effects of ENSO events. As well, Lake Michigan-Huron has only a slightly larger drainage basin to water surface area ratio (2.1), than Lake Superior (GLERL, 1999). Therefore, the effects cumulating on its catchment basin will be somewhat diminished since the land draining into the lakes is comparatively small.

Additionally, the size and depth of the lakes add to the damping of immediate aftereffects, due to the ability to absorb water as storage. This may be, due to the fact that Lake Michigan retains water for a very long time, and is considered a natural cul-de-sac (Beranek, 1999). Beranek believes Lake Huron to be the major conveyor of water from the upper lakes to the rest of the system.

Thus the model with MEI as the independent regressor was found statistically significant at a lag of 14, or 3.5 years. Here, the nature of lake level fluctuation within Lake Michigan-Huron is one where the effects of ENSO are most considerably encountered in a time domain that is synonymous with "text book" events. The most likely explanation maybe simply that the consequences of climatic change are not realized in Lake Michigan-Huron for a longer period of time because of its size and depth, orientation to storm tracks, and relatively small catchment basin. Indeed, the lag time may be somewhat shorter since water is flowing from Lake Superior into Lake Michigan-Huron. Farid *et al.*, (1997) affirm that lake outflows and inflows are more significant to water volume than that of precipitation and evaporation.

Therefore, it may be stated that the responses to ENSO events are also cyclic in nature, but only within a specific period of time. The time series representing Lake Michigan-Huron suggests that the size and depth of the lake would allow substantial responses to take place, and reflect an autoregressive explanation. Here, the responses or disturbances dwindle as time passes. Consequently, the orientation of the lakes may reflect the moving-average nature of the model, allowing intermediate aftereffects to remain in the system for a finite number of periods, and then ceasing to affect it. Hence, the time series is one where the response to ENSO events are evident, and characteristic of Lake Michigan-Huron attributes.

The slow moving fluctuations of Lake Michigan-Huron is affirmed in Hartmann (1988) which states that with simulation of lake levels, a study shows that even if Lake Superior outflows and net basin supplies to the lakes were above its long-term average, extreme conditions would have to persist for 2 consecutive years to raise the levels of Lake Michigan-Huron by even 0.5m. As such, one may conclude that there is a slow process within the system, especially between Lakes Superior and Lake Michigan-Huron. This explains quite well the larger lags (characterized by Lakes Superior and Michigan-Huron), or the time it takes to most substantially induce changes in lake levels.

It is interesting to note however, that Meadows *et al.*, (1997) assert that a northward shift of the preferred cyclone track across Lake Michigan exists. Therefore, with the assumption that most intense precipitation is located on the southeastern side of an extra tropical cyclone system, the northward shift would bring precipitation into the lake and its adjacent drainage basin. It is believed that the combining of the two lakes takes away from unique characteristics, despite common similarities. With water quickly flowing from Lake Superior into Lake Huron, the storing nature of Lake Michigan may cause damping of true reactions to climatic events such as ENSO. This may further explain the ARMA nature of lake level fluctuations to MEI.

7.3 Hypothesis # 2

The success of the statistical results suggest that Lake Erie water level fluctuations are typified by memory within the series, in relation to a disturbance or shock. The AR (1) model exhibits a parsimonious fit, with statistically confident results. As suggested by Kite (1992), the orientation of the lower lakes (Lakes Erie and Ontario) would generate an autoregressive process, or one with a memory since the bulk of the water flowing into the lake is generated by the upper lakes and brought via the Detroit River.

The acceptance of this hypothesis is supported by the various physical factors that configure Lake Erie. This means that the small and shallow nature of the lake allows for less storage capacity, making extreme changes in precipitation and inflow, felt for a long period of time. Hartmann (1988) affirms this by stating that evaporation losses for Lake Erie can be quite extreme due to heat storage. Consequently, evaporation losses should be at their greatest during the month of October. Being along the paths of storm tracks and air masses allows it to receive the effects of precipitation, while its position and shallow nature allow for increased heat storage. Therefore, evaporation rates are quite high, illustrating another causal factor associated with lake level change.

The examination of Lake Erie water levels and the MEI, has depicted a relationship where lake levels are most significantly effected after a lag of 14 or 3.5 years. One may expect a shorter lag period, due to the above physical factors; however, Lake Erie may be useful in mimicking the actions of ENSO events. This may also be due to the fact that Lake Erie receives 3.6 times the amount of water from the upper lakes via inflow than it does from precipitation and runoff (Farid *et al.*, 1997). Quinn and Guerra (1986) have also found that improvements can be made to forecast Lake Erie total water supplies by paying special attention to its net basin supplies, and the supply of water it receives from the upper lakes. They found that net basin supply values were useful indicators of future lake level fluctuation.

Therefore, the effects of ENSO induced climate changes may require the 3.5 years to accumulate above and beyond the water it receives from the upper lakes. As with all of the lakes, the triggering affects that cause lake-levels to fluctuate may have existed before it was felt within the system, but took a while longer to be realized. As a result, Lake Erie water level data, depicts a time series where there is a decaying effect of the disturbance over time, all the while persisting within the system. Without the size and complexities of the upper lakes, Lake Erie may experience the affects of

ENSO events, with distinct memory most significantly after 3.5 years. This may also be reflective of the results found for Lake Michigan-Huron, from which it receives a large amount of inflow. Therefore, it appears as though a systematic relationship exists between the lakes, concerning the responses to ENSO.

7.4 Hypothesis # 3

With the acceptance of this hypothesis, Lake Ontario water levels may be stated to be characterized with a lengthened exposure to ENSO induced climate changes and sustain these influences within its system for a longer period of time. This is characteristic of an AR (2) process which was generated through statistical analysis.

The AR(2) nature of the time series data suggests that the introduction of a disturbance into the system is present for a slightly longer period of time, dwindling as it progresses. Lake Ontario water levels will then manifest according to the particular disturbance, with its greatest affect occurring after 3.5 years. The memory or resonance of the disturbance will reside for at least 6 months after the initial shock. The relationship between ENSO events and lake level fluctuation appears to be valid and quite significant, while consistent with the results found with the other lakes. It does however, possess unique characteristics which are responsible for the statistical results. These are described below.

Of all the Great Lakes, Lake Ontario has the largest ratio of watershed land area to lake surface area which indicates a much larger relative draining basin than the other lakes (Flint and Stevens, 1989; Farid *et al.*, 1997). This allows for a quicker response to climatic factors that produce precipitation and runoff over a larger ratio of land to surface water. This also corresponds to its orientation, which allows it to encounter the full effect of residing weather patterns and air masses. Despite its smaller water surface area, its large drainage basin and orientation to weather patterns allows it to experience a full range of weather phenomena, thus the corresponding influences. This is confirmed in Flint and Stevens (1989) that states that Lake Ontario is strongly influenced by meteorological events.

As well, Lake Ontario receives 3.8 times as much volume of water as inflow from the upper lakes than it does via precipitation and runoff (Farid *et al.*, 1997). Its greatest inflow is from the Niagara river, while its dominant outflow is focused into the St. Lawrence River. Much of what Lake Ontario receives as inflow leaves the lake as outflow. This illustrates the dynamic and fast-paced environment in which water fluctuation behaves within this particular system. However, due to the deep nature of the lake (average 86m), storage capacity increases, causing a slight ability to stabilize initial climatic changes. This may explain why it requires 3.5 years to optimally influence Lake Ontario water levels. However, once an extreme disturbance persists, the shock within the system remains longer than any of the other lakes. This is consistent with Lakes Michigan-Huron and Erie, suggesting a temporal pattern within the system.

7.5 Hypothesis # 4

It is thought that NBS should mimic GLWL through time due to its intrinsic kinship with climatic factors, however the statistical relationships generated were weak. One may indeed postulate that essentially, NBS rates are controlled by storm tracks, which influence many local weather and climatic conditions. Yet, these values are representative of discrete point measurements, over the individual lake. Therefore, Lake NBS will be dependent on random averages of air temperature, precipitation, runoff values, and evaporation. The weak, albeit significant relationships can be the result of inaccurate and imprecise data collection, and the sheer magnitude of stochastic elements within atmospheric and climatic patterns. Because NBS values are based on averages (since it is impossible to measure all climatic rates), it seems logical that the statistical analysis pertaining to it and lake levels are weak.

In addition, we know that the hydrologic cycle varies substantially by lake (Lee, 1993), which suggests that conformity would be an unrealistic expectation. These, variations result in distinct and differing factors in the values of net basin supplies. Quinn *et al.* (1997) affirms this while citing that such deviations from each other are typical. For example, in Lake Erie 51% of the water in the cycle leaves the lake through evaporation. On the other hand, 26% of the water added to Lake Ontario by the hydrologic cycle leaves in that manner (Quinn *et al.*, 1997).

Aside, these interpretations may also lend in the explanation of not being able to fit a model to Lake Michigan-Huron NBS with MEI as the independent regressor. The area in which net basin supply data is collected is quite large and combines two separate systems. Discrete point data collection cannot represent all of the unique and characteristic factors of both lakes, and then expect to exemplify them by averaging the data. Proper representation of both lakes is not present, and thus biased results may have been produced. This seems most logical since one would expect even the slightest significant relationship due to common factors within both of the variables.

Lakes Erie and Ontario NBS data sets adequately fit an AR (1) model, while with MEI as the independent regressor, the data also fit an AR (1) model with MEI lagged at 8, and 3 respectively. The Lake Erie NBS time lag of 2 years may be explained by an increased sensitivity to NBS factors, that are spread over a larger relative catchment basin. This of course is coupled with upper lake inflows and the propensity of residing weather patterns. The even shorter lag period associated with Lake Ontario NBS, 0.75 years, may be the result of the same factors associated with Lake Erie NBS, while the statistical results tend to exceed those of the others. The AR process associated with these models indicates the hypothesized effect of random shocks, whereby feedback remains in the system after the associated disturbance.

In reference to Lake Superior NBS, it was found that a weak AR (1) model could not adequately describe the time series, while an ARMA (1,0,1) model could. The ARMA (1,0,1) process may be a particularly proficient model concerning how Lake Superior functions with perturbations. The slower response to ENSO (concerning the lag value of 4 years) mirrors the physical properties of the lake, where the enormity, and lack of a major inflow of water, allows for a slow but most definitely, positive relationship. Here, ENSO acts as a random shock, which triggers damped oscillations of change within the system. This means that the cycle of ENSO events are creating a change in the NBS rates, although the effects are felt for a finite period of time, being eventually damped out.

Therefore, NBS time series are affected by ENSO events as indicated by the MEI, and reflect the stochastic elements of the variables that make up the data set. Compared to that of GLWL the lag times are reduced, while the statistical results are not as confident or convincing. It is assumed that the changes is NBS associated with the changes in MEI, are weak, and cannot assuredly explain more suitably, how the effects of ENSO effect the Great Lakes. The foundation to this lies in the fact of weak statistical results and the vague nature of both variables. It is difficult to determine the aftereffects of ENSO when NBS values are most abstract and indeterminate. Consequently, it is deemed that for the purposes of this thesis, the use of NBS values were not overly helpful in supporting the results of change of Great Lake water levels.

7.6 SYSTEM RESPONSES

7.61 Lake Level Modeling

One may assume that due to its large size and position within the system, Lake Superior would set the stage for the lower lakes in regard to response mechanisms to lake level extremes. This apparently, is not so. Farid et al. (1997) confirms this by stating that not all effects of water level fluctuation will be directly proportioned to those of Lake Superior. The differences in precipitation patterns, air temperatures, related evaporation rates, runoff, drainage basin area, and lake inflow, and outflow rates all exercise distinct patterns on the individual lake. In relation to lake-level modeling, the system may be concluded to be one where the larger lakes (Superior and Michigan-Huron) experience shorter responses to disturbances, due to their size, depth and relatively smaller drainage basins. Meanwhile, the smaller and lower lakes (Ontario and Erie) experience longer disturbance memory with shorter periods of equilibrium after an initial shock.

Lake Superior and Lake Michigan-Huron encounter damped oscillations, or a pseudo-cyclic process, where lake level fluctuations are present, but without significant memory or immediate outcomes. The ARMA process representing past lake fluctuation suggests that there are strong autoregressive processes present in the systems, while there are points in the series where lake level fluctuation disintegrates on a more curt basis. Lake Erie was modeled with an AR (1) process, where there is a definite memory within its system, as it receives random disturbances. Lake Erie water level fluctuations may behave in this manner due to its orientation to storm tracks, its small and shallow nature, thus making it more susceptible to the effects of extreme meteorological events. Greater water inflow from the upper lakes also adds to the disorder within its system. This makes the agitation felt at a longer rate than both Lakes Superior and Michigan-Huron. Lake Ontario receives water from the upper lakes, and Lake Erie, while the AR (2) aspect of the modeling, suggests that the fluctuations are characterized with long memory, or feedback as well. Here, disturbances to the system will generate a long memory, whereby lake level fluctuations are influenced by shocks that occurred in the distant past. This makes it more sensitive to climatic anomalies such as ENSO, more so than what is encountered in the upper lakes.

As a whole, the system modeled here may be approximated to one where there is increasing sensitivity and longevity to the effects of variables, triggering changes and fluctuation in lake levels. This is approximated by the ARMA processes of Lake Superior and Lake Michigan-Huron, and the AR processes of Lakes Erie and Ontario, AR (1) and AR (2) respectively. Although various climatological factors are distinct to each lake, the overall effect increases throughout the system. This is defined by the size and orientation of each lake, the inflow of water to the system, as well as the ratio of drainage basin area to the size of the lake surface area. As a result, the system clearly illustrates an increase of lake level fluctuation by way of susceptibility and duration of shocks to the system.

7.62 Lake Levels and the Multivariate ENSO Index

In regard to lake-level fluctuation and ENSO, it was found that with MEI as the independent regressor, the models generated for each lake resembled those of the original models. With MEI acting as the triggering mechanism, the lag time in the time series represents the period of time between the change in the MEI (ENSO-inducing values), and its strongest or most significant effect on water level fluctuation. Therefore, Lake Superior water levels are designated with a lag of 4.5 years, while Lake Michigan-Huron, Lake Erie, and Lake Ontario water levels are characterized with a 3.5 year lag. Quinn (1992) states that Lakes Erie and Ontario (due to their low ratio of volume to outflow) are affected by normal climatic variations of less than 20 years in duration. Extreme lake-level conditions over the period of 2 to 8 years can also significantly affect the residence time of Lake Erie and Ontario. This affect is by way of an increase (or decrease) of water flowing through the lakes. Further, this is confirmed by Farid *et al.* (1997) which asserts that the lower lakes receive a greater percentage of inflow, and will be more sensitive to random shocks to their system.

Lake Michigan-Huron, Lake Erie, and Lake Ontario may contain the same lagged MEI value because of the possible complements between Lakes Michigan and Huron. Although Lake Erie and Lake Ontario water level fluctuations are designated with a long memory, Lake Michigan-Huron may realize ENSO inducing effects at a similar lag, but with a less distinct memory and consequence to the disturbances. This is illustrated in the ARMA nature of its model. As well, Lake Superior with its large size and deep waters may be able to dampen any extreme effects of ENSO inducing climate variances, or simply, not fully actualize the effects for approximately 4.5 years.

It is suggested that perhaps the water levels of Lake Michigan may be closer to the modeling of Lake Superior due to its small catchment basin, "cul-de-sac" nature, and perpendicular orientation. Lake Huron as stated previously, acts as the conveyor of water from Lake Superior to the lower lakes, and may resemble the models of the lower lakes. Lake Huron has a larger catchment basin, and thus, receives the lion's share of Lake Superior's outflow, and may be more susceptible to changes in climatic factors. Consequently, despite hydraulic similarities, water level fluctuations of the two lakes may stifle long-term patterns, creating a balancing of important characteristics. This may explain why such a large lake may share similar lagged MEI values as Lake Erie and Lake Ontario.

The MEI as the independent regressor to lake-level fluctuations is indicative of a system wide swing of fluctuation, in regard to extreme weather patterns. We may state that ENSO definitely affects water level, although there are many factors at play within the Great Lakes. The ability to stabilize disturbances into the system may be purely characteristic of the individual lake, and may be cumulative over time, as the disturbance persists. With the peculiar lagged forms, it may be implied that there is a temporal pattern present regarding ENSO events and GLWL. Therefore, with the results generated from this research, it may be implied that with the introduction of an ENSO event, GLWL are shifted most significantly after 3.5 years, with the exception of Lake Superior, which experiences modifications after 4.5 years.

7.63 Net Basin Supply

The modeling of Great Lakes net basin supply values illustrate some interesting system response indicators. Like the previous models produced concerning Lake level fluctuation, there seems to be an increase in sensitivity to various factors as you go down the lake system. This examination could not be fully acquired however, because Lake Michigan-Huron could not fit a model with NBS. With Lake NBS as the independent regressor, Lake Superior required 16 lags, Lake Erie required 8 lags, and Lake Ontario required 3 lags. Thus, there seems to be a decrease in lag time, or in other words, a decrease in the time in takes for a particular ENSO event to significantly effect the lakes, as it progresses within the system. Even without the modeling of Lake Michigan-Huron, there seems to be the same trend apparent, with NBS. This is quite logical since net basin supplies should mimic the hydrologic properties of each lake. This is comparable to the system conclusions found concerning the MEI, an indicator of ENSO events. Overall, the results generated were weak, although statistically significant. This attests to the large outflow rates for most of the lakes compared to that received by runoff and precipitation.

The models generated might be explained by the study completed by Hostetler (1996) which states that under transient climatic conditions, there is an assumption that climatic variables and lake levels change together for basins where the surface area of the lake is large compared with the total catchment area. Here, the migratory short memory shocks may be a result of changes directly related to net basin supply. Quinn *et al.* (1997) has found using flood climate scenarios, that Lakes Michigan-Huron, and Lake Erie experience the greatest impacts concerning NBS variables. This is reinforced with the statement that although Lake Superior averages were displaced accordingly, the changes were considerably less than the lower lakes. Croley *et al.*, (1995) states that within the realm of transposed climates, it is always Lake Superior that receives the driest portion. The lower lakes on the other hand, may realize the resonant transformations to their systems due to a slight increase in sensitivity. As well, it is thought that sensitivity, no matter the origin of the shock, increases within the system because the lower lakes receive a greater percentage of inflow (Farid *et al.*, 1997). Of course, Lake Superior and Michigan-Huron are effected by this due to the lack of major inflows. Therefore, the affects concerning net basin supplies may follow the same logic. The difference remains in the lack of required descriptive data to represent Lake NBS.

8.0 CONCLUSIONS

A statistical assessment between the Southern Oscillation Index and the Multivariate ENSO Index determined that the sufficiently serves the examination of Great Lakes water level fluctuation, and net basin supply rates. Time series analysis was run on the variables to determine parsimonious models of the variables themselves, and those completed with MEI as the independent regressor. Historical patterns were examined to determine if insight into the system could be generated, and whether significant relationships existed between lake level phenomena and specific climatic variables. The final analysis involved taking the information gained through time series analysis, and relating it to physical aspects of the system under study.

In general, the acting system comprising the Great Lakes is one where individual components (the lakes), behave in a manner characteristic of the climatic, physical, and geographic features it possesses. However, there are also systematic influences responsible for lake performance and activity, which generate an intrinsic relationship. This is realized in the analyses performed within this research project. In summation, the following was found.

1. For the purposes of this thesis, the MEI was believed to be the more suitable and useful, indicator of ENSO events. The data series made into quarterly periods needed quite complex models, although a preferred model was still evident. With semester data of both indices, the MEI was deemed more applicable as well.
2. Lakes Superior and Michigan-Huron both exhibited mixed model characteristics, whereas the existence of short and long-term memory resided in the series. Random shocks to the system are designated by a pseudo-cyclic nature, whereas the effect of ENSO events are felt within the system for a finite time-period. Statistical analysis revealed strong relationships between water levels and the MEI. The size and orientation of these lakes make for contrasted models, which indicate a damping affect to the influences of ENSO events. Lake Superior was regressed against MEI lagged at 18, while Lake Michigan-Huron was lagged against MEI at 14.
3. Lake Erie water levels were found to exhibit an AR (1) model, and with MEI as the independent regressor the best-fit model was that of an AR (1) with the MEI lagged at 14. This suggests that the variables associated with an ENSO event will be most significantly triggered after approximately 3 ½years. This is best explained by Quinn (1992) which states that extreme lake level conditions over the period of 2 to 8 years will increase the amount of water flowing through the lake, while also affecting residence times of both Lake Erie and Ontario. The shallow nature of

Lake Erie makes it vulnerable to ENSO events, especially concerning evaporation rates due to the lack of heat storage capacity.

4. Lake Ontario water levels fit an AR (2) model with the independent regressor, MEI, lagged at 14 as well. Although possessing a relatively small water surface area, Lake Ontario has great depth and a comparatively large catchment basin. Together these allow for sensitivity within the time series, which is illustrated through the AR (2) aspect of the data. The resonance of an ENSO event remains within the system longer than the other Lakes, while requiring 3½years to optimally affect Lake Ontario water levels.
5. Generally, Great Lakes net basin supplies were found to have weak, although significant relationships with the MEI. One may postulate that essentially, NBS values are closely linked to prevailing weather systems, especially those that persist for a long period of time. As such, Lake NBS values carry weak relationships with the MEI due to simple stochastic processes. Essentially, precipitation, evaporation, and runoff rates are random processes, and thus, almost impossible to predict due to the nature of these factors. If Lake Michigan-Huron could have been modeled it may have been seen that the lags required to fully effect the lake data decreased as the system progressed. The results of this thesis point to that conclusion although it is not appropriate to finalize.
6. Systematically, it was found that as a whole, the general models created here may be approximated to one where there is increasing sensitivity and longevity to the effects of variables, triggering changes and fluctuation in lake levels. This is approximated by the ARMA processes of Lake Superior and Lake Michigan-Huron, and the AR processes of Lakes Erie and Ontario, AR (1) and AR (2) respectively.
7. Using MEI as the independent regressor to water level data, it is indicative of a system wide swing of fluctuation, in regard to extreme weather patterns. We may state that ENSO events definitely affect water level, despite the many other factors present within the Great Lakes. With the peculiar lagged forms, it may be implied that there is a temporal pattern present regarding ENSO events and GLWL. Therefore, with the results generated from this research, it may be implied that with the introduction of an ENSO event, GLWL are shifted most significantly after 3.5 years, with the exception of Lake Superior, which experiences modifications after 4.5 years.
8. Using MEI as the independent regressor against Lake NBSI data, it was found that significant relationships existed although its weak nature suggests that ENSO events (represented through MEI values) influence these levels, while the random nature of both NBS and developing atmospheric conditions, make model creation somewhat troublesome. A temporal systematic

pattern could not be identified without modeling Lake Michigan-Huron net basin supply values. It could be presupposed that if there were a systematic trend present, it would follow that of the other two identified above.

8.1 Suggestions For Further Study/Theoretical Implications

The question remains, how long does it take the ENSO to trigger the critical factors long enough to make lake levels deviate from their long term averages. It is important to pay closer attention to the lagging of the MEI term, because it means that it takes *n* lags to effect observed changes in lake levels. However, we cannot at this point say when the factors that influence lake levels, (precipitation, evaporation, temperature, run off) begin to alter to substantially affect them. Furthermore, since climate change is not linear, with rapid and large changes in averages and in variability occurring in the recent past, it is often difficult to put climate change and its effect on the Great Lakes into perspective (Quinn, 1998).

Furthermore, it is stated that the natural complexity of the Great Lakes, has features which make it difficult to handle analytically. Flint and Stevens (1989) defined these complexities below:

1) The components or subsystems are connected in a selected manner. Not everything is closely tied to everything else.
2) The impact of ecological events is not uniform. Different areas react in different ways.
3) Dramatic changes in behaviour are natural to many ecosystems, such as lake systems, and many of these are beyond man's means to predict.
4) Variability, not consistency is the characteristic of such systems, that enable them to adjust and therefore persist.

For these reasons, it is believed that the data concerning Lake Michigan-Huron should be separated and not lumped together so that they are considered one lake. Although they are connected by the deep straits of the Mackinaw, Lake Michigan and Huron behave differently and should be treated so, especially when studying system dynamics. It is hypothesized that Lake Huron and Michigan often damp out the dynamics of each other, missing important aspects of the individual lake.

Therefore, to further research the dynamics of the Great Lakes Basin, it is suggested that increased study on system analysis be accomplished. This should include increased study on the climatological factors that influence lake levels (precipitation, temperature, evaporation, and runoff) outside of the net basin supply, for each lake. This would allow for valuable knowledge on how the individual lake is effected on a local basis by ENSO events. There is growing evidence that the changing composition of the atmosphere is beginning to influence specific components of the hydrologic cycle. Notwithstanding, it is not yet possible to differentiate such effects from the natural variability of Great Lakes water levels. It would be interesting to see how climatological factors effect each lake, and how this is incorporated into the system dynamics. There is a large "assumption" of observed lake levels by not specifying exactly what the climate changes are, that are taking place other than those that are quite general.

Finally, the concepts, statistical analyses, and summations depicted here may be applied to the vast collection of research being completed concerning the changing fates of the Great Lakes. Perhaps a more elegant model could be developed that could efficiently describe the exact forces working within the individual lake, and those that culminate within the entire system. As exploration into ENSO events increase, precise examination may be performed to delineate the mechanisms involved in lake level fluctuation. Subsequently, the natural, dynamic, and sensitive system comprising the coastal environment may benefit from information gained through further research, and a more cooperative balance between nature and human.

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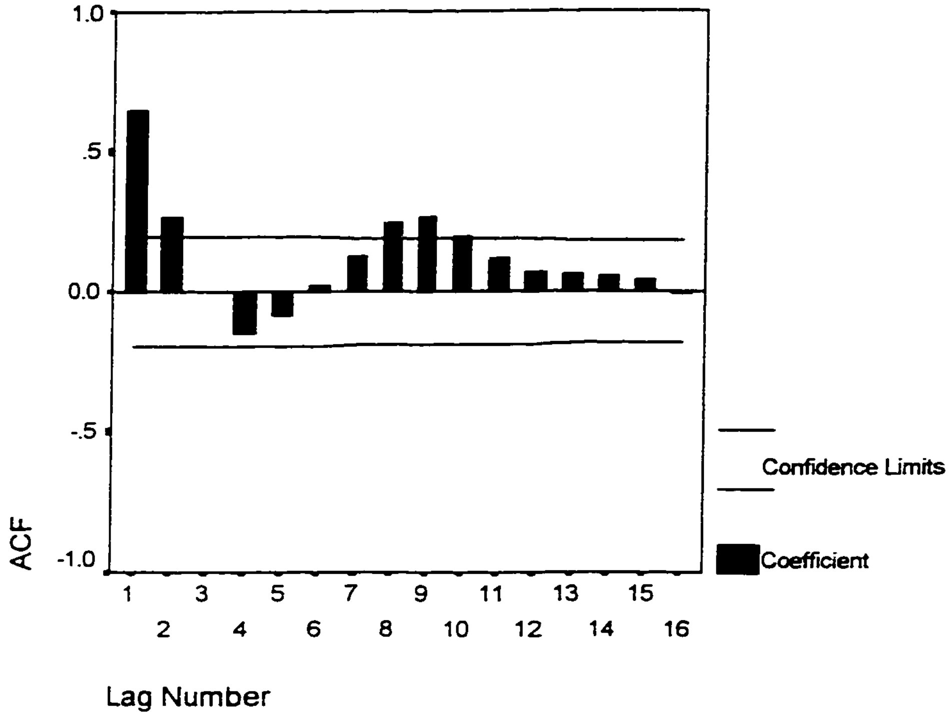
APPENDICES

APPENDIX I

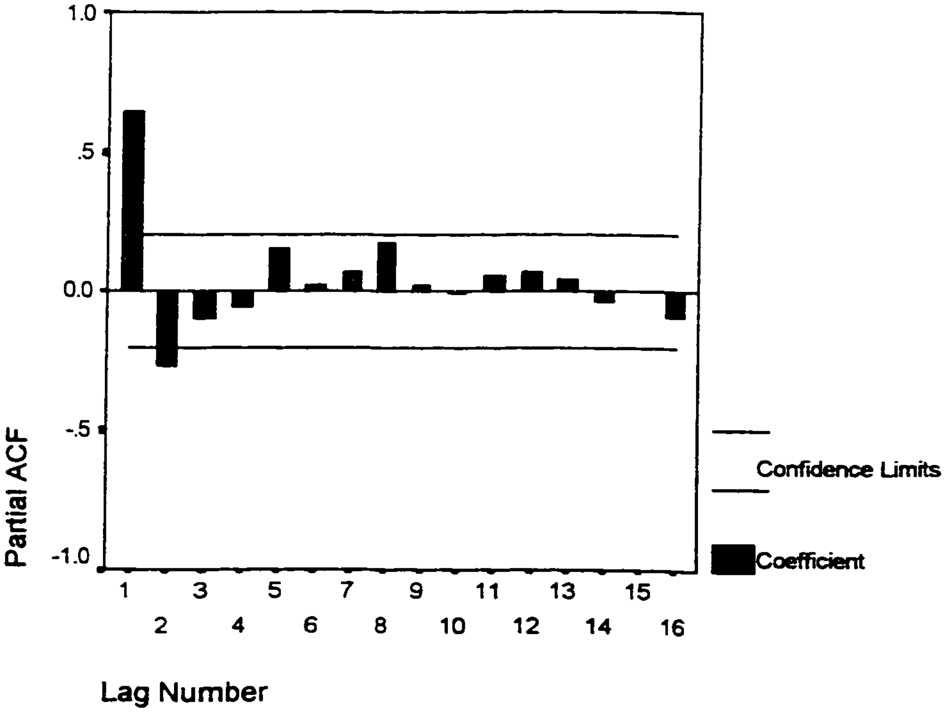
SEMESTER SERIES RESULTS

THE MEI AND SOI

MODEL: THE MEI AUTOCORRELATION FUNCTION SEMESTER DATA



THE MEI PARTIAL AUTOCORRELATION FUNCTION



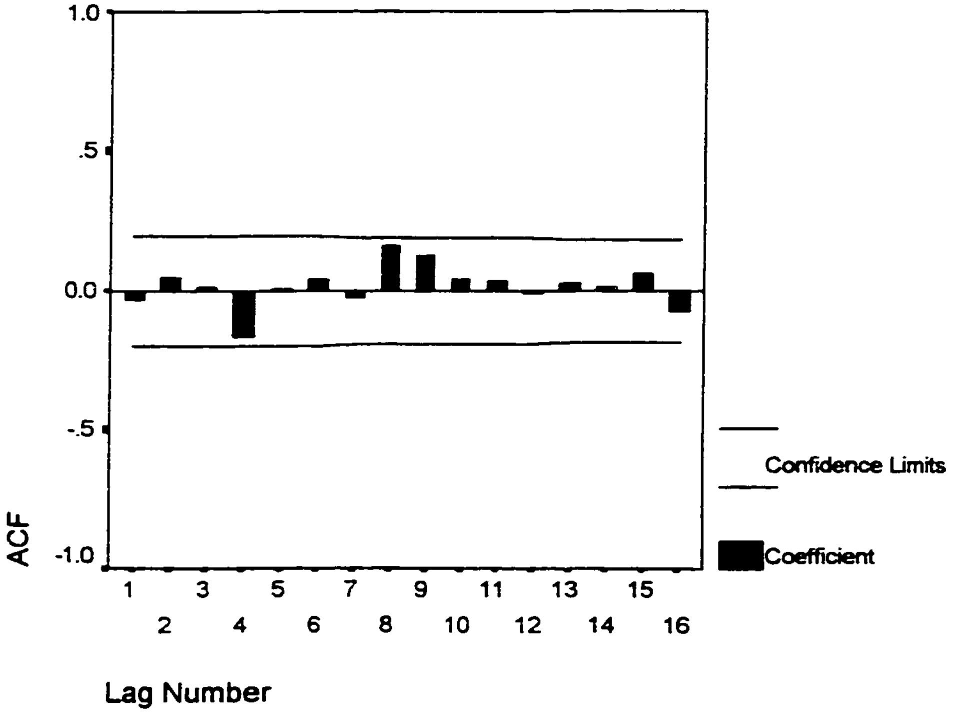
MEI AR MODEL (2,0,0) SEMESTER DATA

```
FINAL PARAMETERS:                 .       ANALYSIS OF VARIANCE:

Number of residuals    98                                DF     ADJ.SUM OF SQ.     RESIDUAL VARIANCE
Standard error        .61299044           RESIDUALS      96      36.3320                 .3757
Log likelihood       -90.439313
AIC                   184.87863
SBC                   190.04856

VARIABLES IN THE MODEL:

            B            SEB        T-RATIO    APPROX. PROB.

AR1    .82602698    .09834818    8.3990065      .00
AR2   -.25614745    .09890054   -2.5899500      .01
```

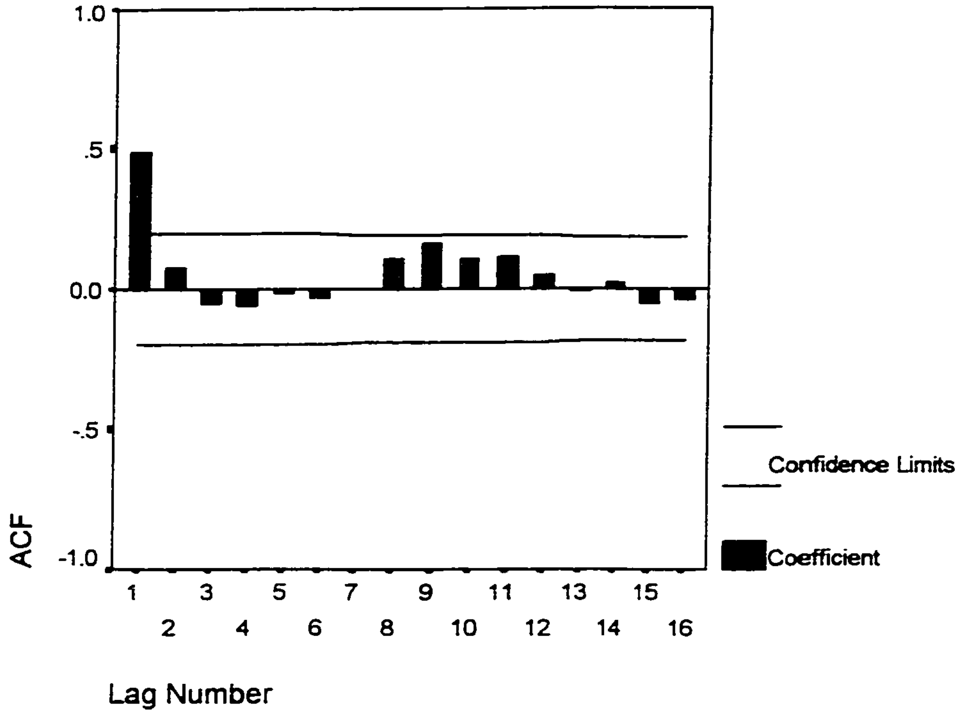
MODEL SUMMARY

```
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R   .681
R SQUARE    .463
DURBIN WATSON   2.014
DF    97
SIG   .00
```

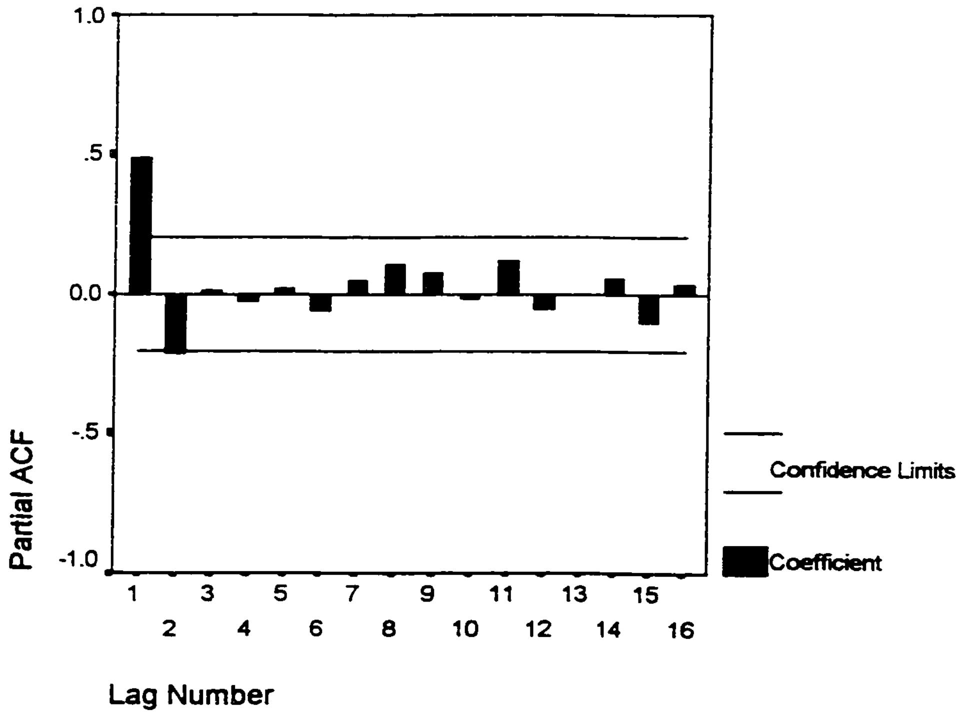
THE MEI AUTOCORRELATION FUNCTION
AR MODEL (2,0,0)



MODEL: THE SOI AUTOCORRELATION FUNCTION SEMESTER DATA



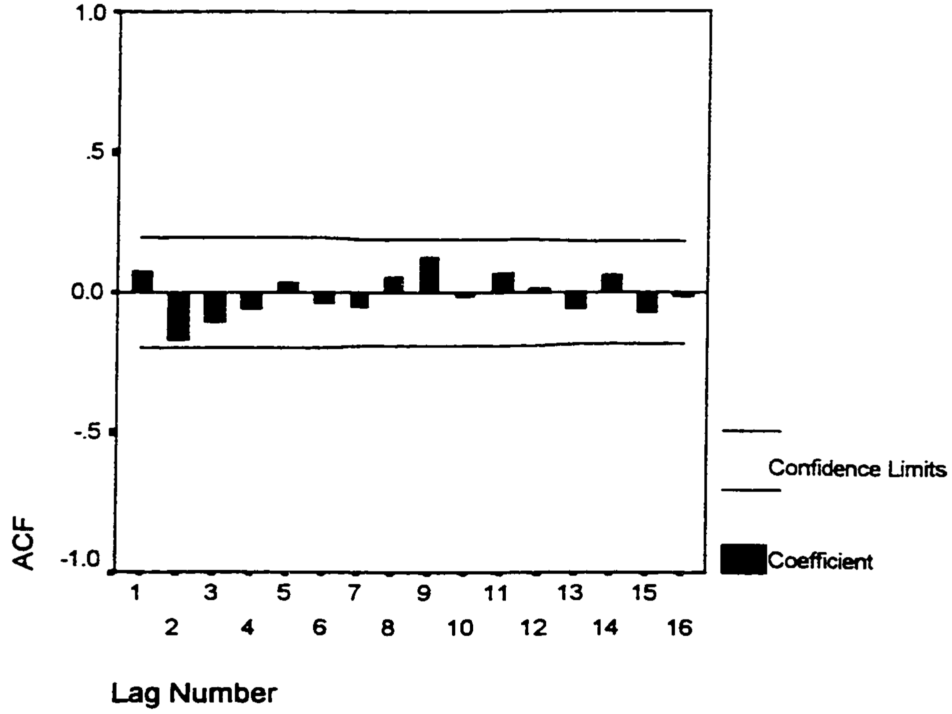
THE SOI PARTIAL AUTOCORRELATION FUNCTION



SOI AR MODEL (1,0,0) SEMESTER DATA

```
FINAL PARAMETERS:                      .          ANALYSIS OF VARIANCE:

Number of residuals   98                                  DF     ADJ.SUM OF SQ.     RESIDUAL VARIANCE
Standard error        .71152845           RESIDUALS       97      49.268                  .5063
Log likelihood        -105.36043
AIC                    212.72086
SBC                    215.30582

VARIABLES IN THE MODEL:

            B            SEB         T-RATIO     APPROX. PROB.

AR1    .52209925    .08620780    6.0562881        .00

MODEL SUMMARY
CORRELATION BETWEEN DEPENDENT VARIABLE AND MODEL FIT

R    .491
R  SQUARE    .241
DURBIN WATSON    1.74
DF    97
SIG  .00
```

THE SOI AUTOCORRELATION FUNCTION
AR MODEL (1,0,0) SEMESTER DATA



APPENDIX II

GREAT LAKES DIVERSIONS
INFORMATION AND DATA

IMPACT OF EXISTING DIVERSIONS ON LAKE LEVELS

DIVERSION	AMOUNT (CFS)	SUPERIOR (FEET)	MICH-HUR (FEET)	ERIE (FEET)	ONTARIO (FEET)
OGOKI-LONG LAC	5600	+0.21	+0.37	+0.25	+0.22
CHICAGO	3200	- 0.07	- 0.21	- 0.14	- 0.10
WELLAND	9400	- 0.06	- 0.18	- 0.44	0
COMBINED		+0.07	- 0.02	- 0.33	+0.08

Source: Croley (1986)

Also in Croley (1986) is the consideration of diversion effects, which are deemed small in comparison with the 1.5 foot seasonal cycle and the 6ft range of annual variations (values also stated in Croley 1986). In addition, the small diversion effects coupled with the long system response time, are stated to make diversion plans unsuitable for Great Lakes regulation of lake levels. The slow response time to man-induced changes would not produce changes responsive to natural fluctuations.

APPENDIX III

STATISTICAL DEFINITIONS

Statistical Definitions

Autocorrelation Function (ACF)

Is often in the form of a bar chart of the coefficients of correlation between a time series and the lags itself. These should already be differenced. By looking at the ACF plot, you should be able to identify the numbers of AR and/or MA terms needed. Autocorrelation is an indication of whether past behaviour of a variable affects its present value (SPSS, 1994).

Akaike Information Criterion (AIC)
Schwartz Bayesian Criterion (SBC)

Measures how well the model fits the series taking into account the fact that a more elaborate model is expected to fit better. Choose between different models for a given series. The model with the lowest AIC or SBC is best (SPSS , 1994).

Box-Jenkins Methodology

The basic idea behind self-projecting time series forecasting models is to find a mathematical formula that will approximately generate the historical patterns in a time series.

Box-Jenkins Forecasting Method

The univariate version of this methodology is a self-projecting time series forecasting method. The underlying goal is to find an appropriate formula so that the residuals are as small as possible, and exhibit no pattern. The model building process involves 4 steps: Repeated as necessary, to end up with a specific formula that replicates the patterns in the series as closely as possible and also produces accurate forecasts (Chatfield, 1985; Arsham, 2000).

Is also based on statistical concepts and principles and are able to model a wide range of time series behaviour. It has a large class of models to choose from and a systematic approach for identifying the correct model form. These are both statistical tests for verifying the model validity and statistical measures of forecast uncertainty. In contrast, traditional forecasting models offer a limited number of models relative to the complex behaviour of many time series with little in the way of guidelines and statistical tests for verifying the validity of the selected model (Chatfield, 1985; Arsham, 2000).

Box-Ljung Q Statistic

Are probability values associated with the correlation among the residuals of the composed model. Ideally once fit to a correlogram, the Box-Ljung Statistic should be over the value of 0.05 (the significance level) (SPSS, 1994).

Lag

Lag versions of the variable are often used in regular models. This allows varying amounts of recent history to be brought into the forecast.Lagging independent variables is often necessary to be able to predict the future. To predict what will happen in period t based on what happened up to period t-1 (Arsham, 2000).

A transition that brings past values of a series into the current case. The case prior to the current case is a lag of one. Two cases prior to the current case is a lag of two... (SPSS, 1994)).

Lag Time

Is the difference in time units of a series value and previous series values. In time series analysis, the lag typically represents the period of time between the change in the independent or predictor (exogenous) variable and its strongest (most significant) effect on the dependent or predicted (endogenous) variable (Arsham, 2000).

AR 1 (1,0,0)

A time series is said to be governed by a first order autoregressive process if current values of the time series can be expressed as a linear function of the previous value of the series and a random shock.
The AR process is characterized with memory or feedback and therefore, the system can generate internal dynamics (Chatfield, 1985).

AR 2 (2,0,0)

The 2 means that you have 2 autoregressive terms. Therefore, the current values of the time series can be expressed as a linear function of the two previous values of the series and a random shock (Chatfield, 1985).

THE AR Parameter

The AR parameter describes the effect of unit change in zt-1 on zt, and which needs to be estimated. The random shocks, also known as errors or white noise in the series are assumed to be normally distributed with mean = 0, constant covariance's and independent of zt-1 (Chatfield, 1985).

Moving Average Process (MA)

Moving average processes are simple mathematical processes. The moving average process is merely a moving, fixed interval average of a time series data used to smooth fluctuations and distortions in the data and provide a more meaningful representation of underlying trends and cycles. An MA process is one whereby future data values are expressed as a linear combination of past errors. These processes have known intrinsic cycles (Chatfield, 1985.)

A t-1 represents random shocks of one or more prior points of the series. Shocks are assumed to come from common (normal) distributions with common location and scale. Random shocks are propagated to future values of the series (non-linear). The events or disturbances will not only have an immediate effect but also affect 'level' indicators to a lesser extent in several subsequent time-periods (Chatfield, 1985).

Autoregressive Moving Average(ARMA) Process

Is a multiplicative model which includes one or more nonseasonal parameters with one or more seasonal parameters. Both long and short-term memory resides within the model. The MA depicts abrupt, short-term memory, where the disturbance effects the system for a finite period (the order of the MA), and stops effecting it. The order of the MA specifies how many previous disturbances are averaged into the new values. The AR disturbance dwindles as time passes (Chatfield, 1985).

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