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GREAT LAKES WATER LEVEL STATISTICAL TECHNIQUES

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Abstract. Every day, important decisions are made regarding activities affected by variations in water levels and flows on the Great Lakes. These involve large-scale issues, such as lake-level control or land-use regulation, as well as local issues, such as siting and design of structures and protective works. Such decisions can and should make use of statistical models that quantify the variability of levels and flows. To date, the only widespread applications of statistical models have been to estimate the probability distributions of high lake levels for use in shoreline zoning and of waves for use in the design of shoreline facilities and protective works. New statistical models of Great Lakes levels should be able to correctly account for serial correlation in hydrologic levels, provide estimates of the marginal and joint distribution of hydrologic levels and storm surge, provide estimates of the joint distribution of various wave parameters and storm surge, and be readily applied to specific coastal locations. The alternative modeling strategies explored address some of the deficiencies of existing models. To improve Great Lakes water level statistics, a comprehensive, coherent, and unified strategy for modeling Great Lakes hydrology is required. Key elements of such a strategy include user community accessibility, linkage between deterministic and stochastic elements, and validity over a wide range of temporal and spatial scales. With the development of improved hydrologic models, statistics that reflect the level of model sophistication would be derived. These statistics would be conditioned on present levels and existing climate regimes, and incorporate the concept of planning horizon, correctly compute the joint probability of the combined effects of mean levels, surges, and waves, and correct for physical trends such as crustal movement.

1. INTRODUCTION

Deborah H. Lee

On August 1, 1986, the Governments of Canada and the United States, in response to record high water levels on four of five Great Lakes and pursuant to Article IX of the Boundary Waters Treaty of 1909, issued a Reference to the International Joint Commission (IJC) to examine and report on methods of alleviating the adverse consequences of fluctuating water levels in the Great Lakes-St. Lawrence River Basin. The scope of the undertaking led to an early decision to conduct the Reference in two phases. Phase I was completed in July 1989, and a progress report entitled Living with the Great Lakes: Challenges and Opportunities (IJC, 1989) was sent to the Governments. The report identified problems related to management of water level issues, reviewed potential avenues for problem solving, and recommended a broad planning approach for Phase II of the study.

Under Phase I of the study, the need for accurate and reliable statistics on water level fluctuations became apparent. Annex C of the Phase I progress report discussed the prospects for managing water levels issues within the Great Lakes, and found that "there is an urgent need for improvement in information about the probabilistic nature of lake levels..., " and recommended that "governments develop improved information on the probabilistic nature of levels and storms ...." Likewise, Annex A, which discussed past and future water level fluctuations, concluded "(the) serial correlation of annual lake levels requires modification of the traditional probability analyses of lake level data ...." Based on these findings, the Plan of Study for Phase II of the Reference specifically called for "improving scientific techniques for defining lake level frequencies, including development of decision techniques that incorporate the concepts of probability and confidence."

GLERL Contribution No. 829

The record drought and subsequent drop in water levels that followed the extreme highs of 1985 and 1986 eroded the public's confidence in the forecasts and statistics available to them. In response to this public reaction, a symposium on Great Lakes water level forecasting and statistics was held in May 1990, organized by the Great Lakes Environmental Research Laboratory, the Great Lakes Commission, and the U.S. Army Corps of Engineers. The symposium had two objectives: to assess the strengths and weaknesses of water level forecasting techniques and to explore innovative approaches for developing and communicating statistics that would best serve the wide range of user groups in the Great Lakes Basin. The symposium was attended by resource managers, policy makers, and other water level data users, as well as many scientists. Although not a part of the IJC Water Levels Reference Study, the symposium partially addressed the findings in Phase I concerning water level statistics and their communication to the public, and provided a basis for the work to be performed under Phase II.

With the directive in the Phase II Plan of Study to develop improved statistical techniques, a Statistics Advisory Task Force was formed. The Task Force comprised Great Lakes experts with an interest in water levels statistics, many of whom contributed to the May 1990 symposium. The members were

Dr. Steven Buchberger, University of Cincinnati
Dr. Murray Clamen, Environment Canada
Ms. Anne Clites, Great Lakes Environmental Research Laboratory
Dr. Timothy Cohn, U.S. Geological Survey
Mr. David Fay, Environment Canada
Mr. Lynn Herche, Great Lakes Environmental Research Laboratory
Mr. Philip Keillor, University of Wisconsin Sea Grant Institute
Dr. Geoffrey Kite, Environment Canada
Ms. Deborah Lee, Great Lakes Environmental Research Laboratory
Ms. Gail Monds, U.S. Army Corps of Engineers, Detroit District
Dr. Kenneth Potter, University of Wisconsin
Mr. Charles Southam, Environment Canada

The task force took on two challenges: to assess the specific statistical and forecasting informational needs of those affected by Great Lakes water levels, and to develop improved water level statistics. The results of the first task are reported in NOAA Technical Memorandum ERL GLERL-77 (Clites, 1992). The effort to develop improved statistical techniques is presented here.

The task force early on reached the consensus that the development of improved statistics should focus on the development of conditional probabilities. The group also agreed that a modeling or simulation approach was the most desirable for the development of the conditional probabilities and alleviated problems associated with the recorded data. Modeling approaches based on historical lake level data, time-series modeling of net basin supplies, and time-series modeling of precipitation, runoff, and evaporation were considered. The third approach was believed to be the best, but not possible to complete within the time frame of the study. Two simpler approaches, one based on time-series modeling of adjusted recorded water levels and the other based on time-series modeling of recorded net basin supplies, were selected. The results of these efforts are presented in the following sections. In addition, the group believed it was necessary to address the issue of the joint probability of storm surge, wave runup, and hydrologic water levels. A brief section describing aspects of this calculation is also included. These sections are first preceded by a review of existing methods and the need for new statistical methods.

2. REVIEW OF EXISTING METHODS AND NEED FOR NEW METHODS

Dr. Kenneth Potter

Every day, important decisions are made regarding activities affected by variations in water levels and flows on the Great Lakes. These involve large-scale issues, such as lake-level control or land-use regulation, as well as local issues, such as siting and design of structures and protective works. Such decisions can and should make use of statistical models that quantify the variability of levels and flows. To date, the only widespread applications of statistical models have been to estimate the probability distributions of high lake levels for use in shoreline zoning and of waves for use in the design of shoreline facilities and protective works. These applications have been extremely beneficial, but they do not address all the needs of decision-makers. For example, the model used to estimate the probability distribution of water levels does not account for year-to-year correlation. In this section, some alternative modeling strategies that address some of the deficiencies of existing models are explored. But first some of the factors that complicate the problem of modeling Great Lakes variability are discussed.

2.1 Great Lakes Water Levels

Water levels on the Great Lakes vary on a wide range of time scales in response to different physical processes. Variations in net basin supplies, stream flows from and to connecting lakes, and interbasin diversions cause hydrologic variations in lake levels by changing the volume of water in individual lakes. These variations occur over a time scale of months in response to seasonal variations in supplies, as well as over years in response to long-term climatic variations. Storm events cause lake-level variations called storm surges by temporarily redistributing water in the lakes. Storms also produce waves, which are short-term oscillations in the water surface. Statistical modeling of these three kinds of water-level variations and of the damages that they cause requires careful consideration of their temporal and spatial characteristics. Furthermore, damages due to extreme water levels often depend on the joint effects of hydrologic variations, waves, and storm surges. Hence there is a need to develop statistical models that jointly account for these sources of variation.

2.1.1 Temporal Dependence in Lake Levels

With respect to statistical modeling, the most important characteristic of hydrologic water-level variations is that they are not independent from one time period to the next. Temporal dependence in Great Lakes water levels is due primarily to the relatively slow rate at which water can drain from each lake through its outflow channel. This slow drainage also causes the outflow to be temporally dependent, which in turn contributes to temporal dependence in the water levels of downstream lakes.

Temporal dependence in lake levels creates problems in both the estimation and the application of lake-level probabilities. Consider, for example, the problem of estimating the lake level with a specified exceedance probability If traditional flood frequency analysis is applied to a historic sequence of annual maximum lake levels in which there is significant temporal dependence, the resulting estimate will be biased. Furthermore, the estimate would apply only to some time well into the future, since for short times the true probability depends on the initial lake level. Both of these deficiencies in traditional frequency analysis can be overcome by accounting for temporal dependence in the estimation and application of statistical models.

2.1.2 Waves and Storm Surge

Waves and storm surges present different statistical problems than hydrologic lake levels. Waves and storm surges are caused by wind, and are correlated with each other. That is, large waves are likely to occur at the same time as large storm surges. Hence estimation of their probabilities should be done jointly; otherwise estimates of their combined effects will be biased downward. Further, the magnitude of waves and storm surges is site specific, depending on location with respect to dominant wind directions and on local bathymetry. Hence estimation of their probabilities must be tailored for individual locations.

2.1.3 Combined Effects

In most situations, damages due to extreme lake levels result from the combined effects of hydrologic variations, waves, and storm surges. Hence it would be desirable to have statistical models that jointly consider these effects. As previously mentioned, this would require estimation of the joint probability distribution of waves and storm surges. Hydrologic variations are usually assumed to be independent of winds that generate waves and storm surges. However, the waves and storm surges themselves depend to some degree on the contemporaneous hydrologic water level. Furthermore, both winds and hydrologic variations are strongly seasonal, as is the presence of ice, which can dampen or even prevent waves and storm surges. Hence a statistical model of the combined effects of hydrologic variations, waves, and storm surges should account for seasonality.

2.2 Existing Statistical Models

There have been several "official" applications of statistical models to the Great Lakes. The U.S. Army Corps of Engineers (1977, 1988) estimated flood level quantiles for the U.S. coast; the Ontario Ministry of Natural Resources (1989) estimated flood level quantiles for the Ontario coast. The Corps also published wave statistics for the Great Lakes (Resio and Vincent, 1976a, 1976b, 1976c, 1977a, 1977b, 1978; Hubertz et al., 1991; Reinhard et al., 1991a, 1991b). The results of these statistical analyses are widely used in practice, both for coastal management and for engineering design. However, each has limitations.

2.2.1 U.S. Army Corps of Engineers Lake Level Quantiles

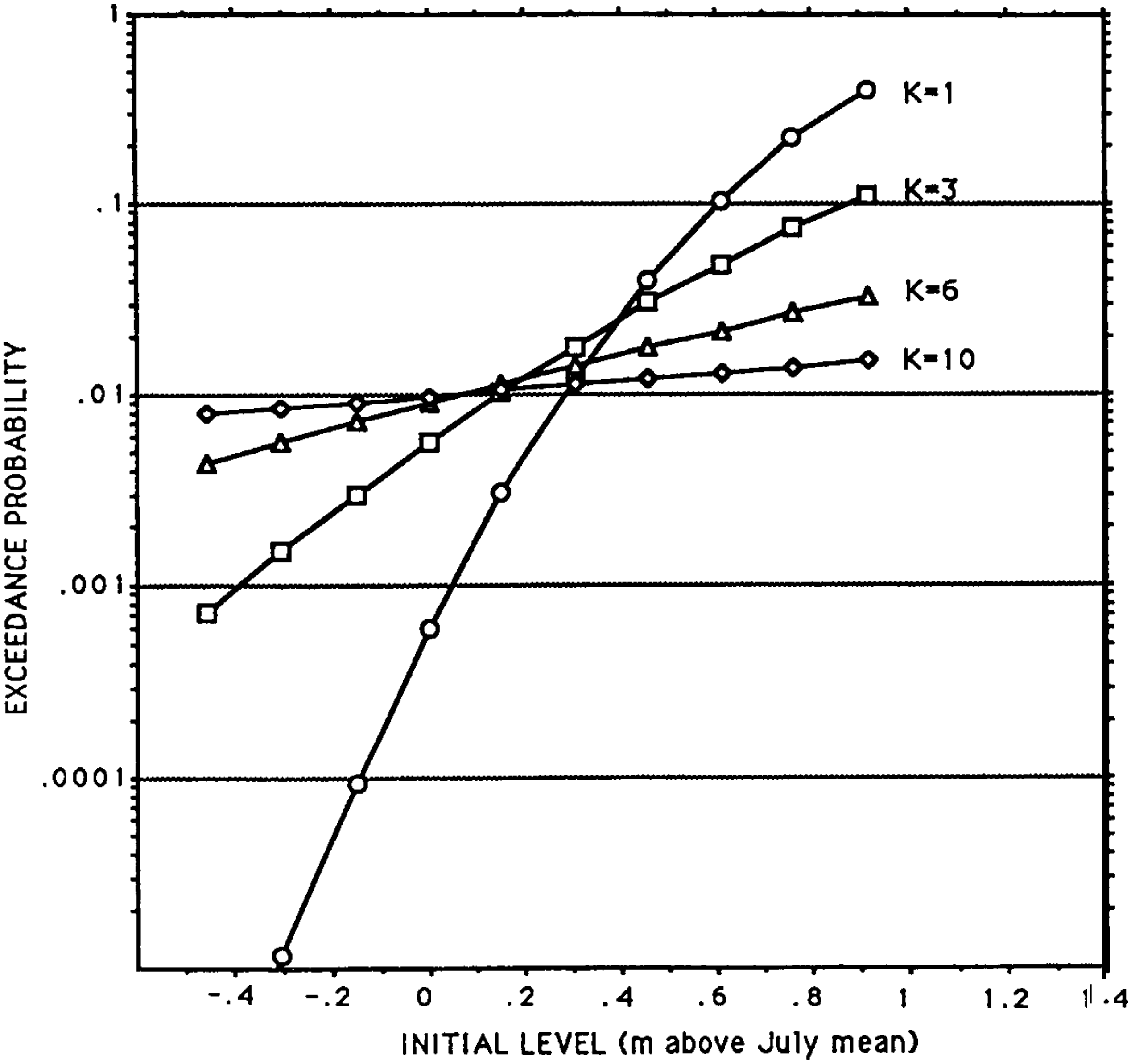
In estimating flood level quantiles, the U.S. Army Corps of Engineers utilized series of maximum annual instantaneous lake levels from gauges around the lakes. The quantiles were estimated in the same fashion as flood discharge quantiles are estimated from streamflow data. As previously mentioned, such an approach ignores the very large year-to-year correlation that exists in the lake level data. Hence the estimates are really "unconditional" quantiles, in that they are not conditioned on past lake levels.

To understand the implications of ignoring year-to-year correlation, consider the .01 unconditional lake level quantile, the quantile used to define the so-called 100-year flood level. If lake levels are high this year, the probability that the unconditional .01 quantile will be exceeded next year will be higher than .01. Similarly, if levels are low, the probability that the unconditional .01 quantile will be exceeded next year will be lower than .01. Note, however, that the probability of exceeding the unconditional .01 quantile at some time in the distant future is .01, since dependence on past lake levels decays to zero over time.

This reasoning is quantified in Figure 1, taken from Potter (1990). The figure illustrates for Lake Erie (at Cleveland) the probability that the .01 unconditional lake level quantile will be exceeded 1, 3, 6, and 10 years in the future, conditioned on the lake levels this year. Note that if the July level this year is more than 0.6 m above the average July level, the probability that the maximum level next year will exceed the unconditional .01 quantile will be greater than 1. Conversely, if the July level this year is less than the mean July level, the probability that the maximum level next year will exceed the unconditional .01 quantile will be less than .001. Note that for levels 10 years from now, the probability is about .01 regardless of this year's level.

Hence to accurately represent the probability of flooding on the Great Lakes, it is necessary to account for year-to-year dependence in lake levels. How could estimates of conditional probabilities be applied in practice? Consider the case of floodplain zoning. Clearly it is not feasible to change the regulatory floodplain level each year. However, it would be possible and perhaps desirable to change floodplain insurance premiums to reflect the true risk of flooding. Annually changing premiums would alert policy holders to the dynamic behavior of the Great Lakes.

Figure 1 .-- Conditional **probabilities** of lake levels.



Conditional probability estimates could be applied readily to design problems on a lake, particularly when design is risk-based, i.e., based (at least in part) on "expected value" risk analysis. In such an analysis, flood risk is accounted for by integrating the product of a damage function (which relates flooding damage to lake levels) and the probability distribution function of lake levels. The resulting integral is the average or "expected" damage associated with a given design in any given year. To account for year-to-year correlation in lake levels, one would compute expected damages for each year of the design life of the project, using an estimated probability distribution conditioned on the lake level at the time of their design. Accounting for correlation would make a significant difference in cases where current levels are either high or low and where the design life is relatively short (10 years or less) or the discount rate is high.

The lake level quantiles estimated by the U.S. Army Corps of Engineers have additional shortcomings. Since they are based on observed annual maximum lake levels, they reflect the superposition of hydrologic lake levels and storm surge effects. For some design problems it would be preferable to separate these factors. The Corps quantiles were estimated for sites on the shoreline where lake level data are available. For other sites it is necessary to interpolate quantiles. But surge effects are strongly dependent on local bathymetric conditions, and there is no way to account for these in interpolating the Corps quantiles. Separating the analysis of hydrologic levels and storm surge would allow for the use of physical models to estimate the latter at specific sites. Finally, the data sets used by the Corps had widely varying record lengths. Separate analysis of hydrologic lake levels would make it possible to rely exclusively on the longest data sets.

2.2.2 Ontario Ministry of Natural Resources Lake Level Quantiles

In estimating water level quantiles for the Canadian coast, the Ontario Ministry of Natural Resources (1989) adopted an approach that did separate hydrologic water levels from storm surge effects. The basic approach was as follows. First, a frequency distribution of highest monthly mean lake levels was estimated for each lake. Then at each gauging station a distribution was estimated for highest annual storm surge. At locations between gauging stations, a physically based model was used to interpolate surge distributions, using an innovative approach exploiting historical wind data. Finally, at each site the estimated distribution of the sum of storm surge and hydrologic water levels was computed by convoluting the two component distributions.

The approach used by the Ontario Ministry of Natural Resources is a significant improvement over traditional methods. Of particular significance is the use of a physical model to interpolate the distribution of surge effects. The approach does have some limitations. First, it does not properly account for the joint occurrence of storm surge and hydrologic lake levels. Simple convolution of the distribution of maximum annual storm surge and maximum annual hydrologic water level assumes that the two occur simultaneously, which is not generally the case. Note that this will cause water level quantiles to be overestimated, and hence will result in conservative estimates. Second, the approach does not account for year-to-year correlations in lake levels.

2.2.3 U.S. Army Corps of Engineers Wind Wave Statistics

The U.S. Army Corps of Engineers wave statistics for the Great Lakes were generated in several steps. First, using the most reliable, long-term, continuous wind data available, a 32-year record of speed and direction was estimated for locations 10 miles apart along the Great Lakes shoreline. An interpolation scheme was then used to estimate overlake wind speed and direction, again at a 10-mile spacing. The wind field information was in turn used as input to a numerical wave model that simulated the growth, dissipation, and propagation of deep water waves. Finally, directional wave spectra and wind and wave parameters were calculated at each location.

The methodology used by the Corps is state-of-the-art, and the results provide very useful information on the probability distribution of offshore waves in the Great Lakes. But these statistics are for waves alone.

There remains the problem of statistically coupling wave parameters with hydrologic water levels and storm surge, and of applying a coupled methodology to specific shoreline locations. This cannot be done without first estimating the joint distribution of wave parameters and storm surge. This has not yet been done, although one approach for doing so is outlined in section 5.

2.3 Summary of Important Issues

It is clear from the preceding discussion that new models of Great Lakes levels should be able to

- correctly account for serial correlation in hydrologic levels,
- provide estimates of the marginal and joint distribution of hydrologic levels and storm surge,
- provide estimates of the joint distribution of various wave parameters and storm surge, and
- be able to be readily applied to specific coastal locations

Proper accounting for serial correlation requires some kind of time series modeling. In the next sections, two approaches for such modeling are presented.

3. TIME SERIES MODELING OF LEVELS

Dr. Geoffrey Kite

It is desirable to improve on the available statistics of lake levels, particularly the statistics of extremely high and extremely low levels. The historical time series provides one set of lake levels with some high years and some low years, but there is no way of knowing whether the observed highs are the highest possible or whether the observed lows are the lowest possible. Time series analysis is one method that can be used to estimate the probability of even higher lake levels and even lower lake levels than observed over the historic period.

Time series analysis is the term used to describe with statistics the structure of long series of numbers. Such numbers might be daily values of the Dow-Jones average, the widths of annual tree rings, or any other set of numbers measured or calculated at some time interval. The method used in this case is to derive a set of statistics that adequately describe the historical series of lake levels and then to use those statistics to generate many alternate sequences of levels. The generated sequences are then analyzed to determine the relative frequencies of extremes.

As Klemes (1974) pointed out, there are two possible approaches to time series analysis; the first is to hypothesize a statistical model and see if the data samples correspond to expectations and the second is to work backwards from the data to the model. The first method may show only that simple models are inadequate to describe the actual processes, whereas the second approach can, at best, offer only one possible explanation for the observed data. Data generated by dissimilar physical processes may not be distinguished by the commonly used statistical models.

In this study the first approach is used; a simple model was assumed and the data were then analyzed to derive the parameters of the model. The chosen model was assumed to contain linear trends, periodicities, autoregression, and a random residual. Such a model has been used successfully to analyze many hydrometeorological data series (Kite, 1989; Kite, 1991). The following paragraphs summarize some of the reasons for the choice of such a model.

3.1 Lake Level Components

3.1.1 Expected Trend Components

The trend component of a time series is generally associated with changes in the structure of the time series caused by cumulative natural or anthropogenic phenomena. In the Great Lakes area, trends could be due to isostatic adjustment following the last ice age, the predicted "greenhouse effect" climatic change, increasing consumptive use of water, and the cumulative effects of diversions into and out of the lakes.

Slow long-term movements of the earth's crust in the Great Lakes region have been measured since the middle of the nineteenth century (Kite and Adamowski, 1973) using geological evidence and long-term water level records. The upward movement of the land surface is assumed to be an isostatic rebound resulting from the retreat of the Laurentian ice sheet following the last ice age (10,000-12,000 B.P.). Northern areas of the region are rising faster than southern areas, and the result is a gradually changing relationship between average lake surface level and land reference level. This movement may be assumed to be linear over the historic period, although, if we look at evidence from raised beaches and wave-cut cliffs, it is more likely to be an exponential decay curve over the long term.

Many climatologists believe that the increasing concentrations of carbon dioxide and other greenhouse gases are causing significant warming of the atmosphere. Such a warming, with the associated changes in precipitation regime, might be expected to change land runoff and, consequently, the levels of the Great Lakes. Hartmann (1990) investigated the effects of a transient scenario postulated by the Goddard Institute of Space Studies (GISS) on the levels of Lake Erie. Assuming that the concentration of greenhouse gases reaches twice the current levels by 2060, then Lake Erie levels were estimated to fall by 6.6 mm per year. It is unlikely, however, that effects of any such climatic change would be observable in the historic data (Kite, 1991).

Steam-electric power generation, manufacturing processes, and irrigated farming all consume water; that is, they remove water from the immediate lake system by evaporation or by incorporation into manufactured products. In 1975, consumptive use in the Lake Erie basin was estimated (Quinn and Guerra, 1986) to be 63 m^3/s, which is equivalent to a lowering of the lake level by 25 mm. Cohen and Allsopp (1988) estimated that under a steady-state 2 x CO_2 climate scenario, consumptive use would cause a further drop of 240 mm in the level of Lake Erie. Using these data, the effect of increasing consumptive use over the historic period might be approximated as a linear trend of -0.2 mm per year.

Table 1.-- Expected Linear Trends in Lake Erie Levels

	Cleveland mm/yr	**Buffalo mm/yr**
Isostatic rebound	0	-1.0
Consumptive use	-0.2	-0.2
Diversions	-0.8	-0.8
Total	-1.0	-2.0

Diversions into Lake Superior and out of Lakes Michigan and Erie are estimated (IGLLB, 1974) to have caused a drop of 100 mm in the level of Lake Erie. This drop did not, of course, occur linearly but, for the purposes of this study, can be considered equivalent to a linear trend of -0.8 mm per year.

By combining the trends reported for isostatic rebound, consumptive use, and diversions over the historic period, Table 1 shows the type of linear trend we can expect to see in historic Lake Erie data.

3.1.2 Expected Periodicities

The most important periodicity likely to be found in Great Lakes time series will be the annual cycle and its harmonics caused by the earth's rotation around the sun. The changing seasons cause varying rates of precipitation and evaporation (e.g., Witherspoon et al., 1972) and a corresponding change in runoff and lake level. The cycles of precipitation, evaporation, and runoff have maxima at different times of the year, and the situation on Lake Erie is complicated by the time delays associated with inflows from Lakes Superior and Michigan-Huron.

3.1.3 Expected Autoregression

Autoregression in lake levels is the tendency of high lake levels to follow high levels and for low levels to follow other low levels. Part of this effect is caused by the relatively small capacity of a lake's inlet and outlet compared to its capacity. For example, the volume of Lake Superior is 1200 x 10^{10} m^3, whereas the average annual outflow is only 7 x 10^{10} m^3. In contrast, the volume of Lake Erie is 490 x 10^{10} m^3, and the annual outflow is 186 x 10^{10} m^3. Therefore, the autoregressive component is expected to be more important for Lake Superior than for Lake Erie.

3.2 The Model

The hypothesis is made that a time series X_t can be adequately represented by a linear additive model:

$$X_t = T_t + P_t + R_t \tag{1}$$

where T_t is a trend component, P_t is a periodic component, and R_t is an autoregressive component containing a random residual. Such a time series can be split into its components following the steps shown in Figure 2. After each step in the analysis, the data are converted from the time domain to the frequency domain by spectral analysis. This conversion is useful because individual components can often be more easily identified in the frequency domain (see, for example, Figure 5 in Kite, 1992). A periodic component can be detected and removed using Shuster's periodogram (see Matalas, 1967):

$$P_t = A_o + \sum_{k=1}^{N/2} \left[A_k \cos(2\pi kt / N) + B_k \sin(2\pi kt / N) \right] \tag{2}$$

where t = 1,2,...,N. The coefficients A_k and B_k of the kth harmonic are given by

$$A, = (2 / N) \sum_{t=1}^{N} P_t \cos(2\pi kt / N) \tag{3}$$

$$B_k = (2 / N) \sum_{t=1}^{N} P_t \sin(2\pi kt / N) \tag{4}$$

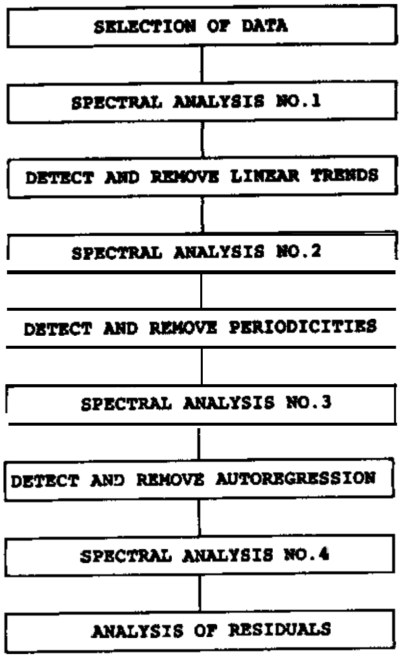


Figure 2.-- Flowchart showing the steps in time series analysis employed.

where k = 0, 1, 2, ..., N/2. If S^2 is the total variance of the time series X_t, the part of the variance accounted for by the kth harmonic is

$$C_k^2 / 2S^2 = (A; + B_k^2) / 2S^2 \tag{5}$$

except for the last harmonic (when k = N/2), which has an explained variance of C_k^2. The significances of the various harmonics are tested using Fisher's "g" statistic (Yevjevich, 1972) as

$$g_k = \frac{C_k^2}{\sum_{k=1}^{N/2} C_k^2} \tag{6}$$

where, at the 5% level, g_k is 0.04429 for daily data, 0.61615 for monthly data, and is defined as

$$g_k = 1.0 - \exp[\log(0.05 / m) / (m - 1)] \tag{7}$$

for annual data, where m is defined as

$$m = n / 2 \tag{8}$$

for an even number of years of data, n, and as

$$m = (n - 1) / 2 \tag{9}$$

for an odd number of years.

A trend component can be analyzed and removed by using a polynomial regression such as

$$T_t = a_o + a_1 t + a_2 t^2 +, \ldots, + a_p t^p \tag{10}$$

where T_t is the trend, t is the decimal indication of the corresponding year and month, and a_0, a_1, ..., a_p are constants. The optimal order of the polynomial is determined by the test of significance based on a comparison of the residual sum of squares between two successive polynomials.

The stochastic component is assumed to be represented by the autoregressive (Markov) model given by

$$R_t = \sum_{j=0}^{k} \alpha_j R_{t-j} + \epsilon_t \tag{11}$$

where a,, j = 0, 1, ., k are constants and ϵ_t is an independent random variable having zero mean and variance σ_ϵ^2 In practice it was assumed that first-order and second-order approximations to the above model would be sufficient. The significance of first- or second-order Markov models is tested using a chi-square test (Matalas, 1967) on the sample and theoretical autocorrelation coefficients.

Spectral analysis is used to display the different components of a time series, and to examine the results of the removal of these components. The spectral density can be estimated from autocovariances (Jenkins, 1961):

$$V_k = 1/m\left[C_o + 2\sum_{j=1}^{m-1} C_j \cos(kj\pi/m) + C_m \cos(k\pi)\right] \tag{12}$$

where $C_j = E(X_t X_{t-j})$, j=0, 1, ..., m and are autocovariance coefficients. The spectral density estimate as given in the above equation is refined by applying Hamming's smoothing function (Jenkins, 1961).

Confidence limits for the plot of the spectral estimates are given by

$$CL_a(N,k) = \tau^2_{100-\alpha}(\Gamma) / \Gamma \tag{13}$$

$$CL'_\alpha(N,k) = \tau^2_\alpha(\Gamma)/\Gamma \tag{14}$$

where $\Gamma = 2N/k$ is the equivalent degrees of freedom, N is the number of observed values in the time series, k is the number of time intervals of lag in the autocovariance function, a is the required confidence level, and $T_\alpha^2(\Gamma)$ is the a % value of the chi-square distribution with Γ degrees of freedom. The factors CL and CL' are then multiplied by the mean spectrum.

Rao (1988) has shown that this form of spectral analysis may not differentiate between periodicities with very close frequencies, but the alternatives available require further assumptions as to the model structure and have not proved reliable. Similarly, there are many tests of significance for trend components, but they do not suit all circumstances. Berryman et al. (1988) describe many of the alternatives and discuss their suitability.

Once a time series has been analyzed, the derived statistics are used to generate many similarly sized sequences. The generation model starts with a pseudo-random number generator initialized from the microcomputer system time. This generates normal deviates using the Box-Muller transformation (Press et al., 1986):

$$\in_1 = \sqrt{-2InR}\cos 2\pi\Theta \qquad (15)$$
$$\bullet_2 = \sqrt{-2InR}\sin 2\pi\Theta$$

where R and Θ are the radius and angle defined by the coordinate positions of two uniform deviates (0,1).

The sequence of standard normal deviates $\in_t$, t=1,N is then adjusted to the correct mean and standard deviation from the historic data and converted to the required autoregressive model as

$$R_t = \in_{t-1} \times \alpha_1 + \in_t \qquad (16)$$

for a first-order model, or

$$R_t = \in_{t-1} \times \alpha_1 + \in_{t-2} \times \alpha_2 + \in_t \qquad (17)$$

for a second order model, where α_1 and α_2 are the parameters derived from the historic series.

Next, any periodic components found in the historic series are added in:

$$P_t = R_t \times \sigma_t + \mu_t \qquad (18)$$

where σ_t and μ_t are the standard deviation and the mean for the particular periodicity.

Finally, any necessary trend component is incorporated as

$$T_t = \sum a_i t^i \qquad (19)$$

and the combined generated series is adjusted to the correct mean and standard deviation.

Many of these simulated sequences are generated, and the extreme values from each sequence are stored. After a sufficient number of sequences have been generated (1000 were used in this study), the extremes from all the sequences are subjected to a frequency analysis. Confidence limits for the frequency analyses are computed from the 1000 generated points available at each frequency for each month of the year.

3.3 Results

3.3.1 Analysis of Historic Lake Levels

Monthly mean levels of Lake Erie as measured at Cleveland for 1860 to 1989 were analyzed. Figure 3 shows the original data, and Figure 4 shows the original spectral analysis. In Figure 4 the high initial spectral density indicates the presence of trends; the convex slope below the frequency of 0.042 cycles per month indicates autoregression, and the peaks at 0.083, 0.166, and 0.25 cycles per month show the annual cycle and its harmonics. The trends were removed (Figure 5 shows the first-order linear trend), leaving the spectrum in Figure 6. This figure again shows the presence of autoregression and periodicity. The annual cycle was removed and left the spectrum in Figure 7, showing only significant autoregression. Finally, the autoregressive component was removed, leaving a spectrum (Figure 8) with no remaining significance.

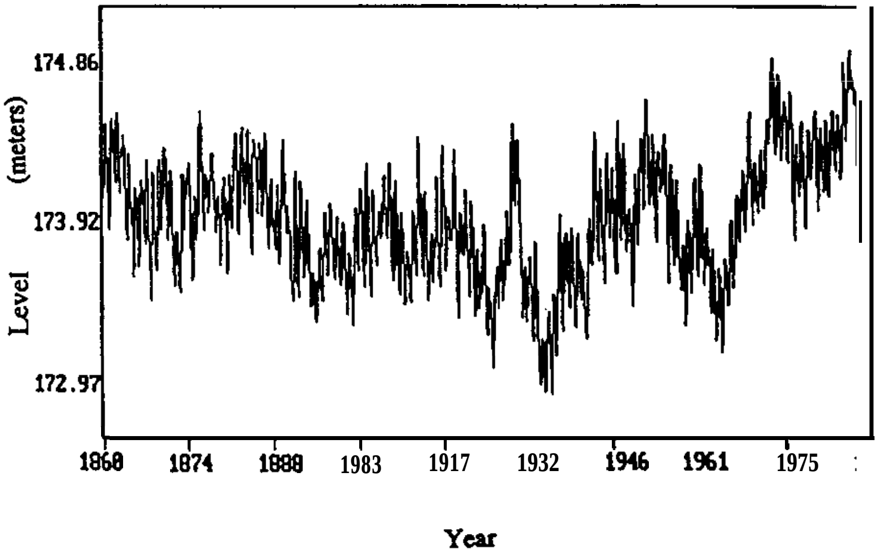
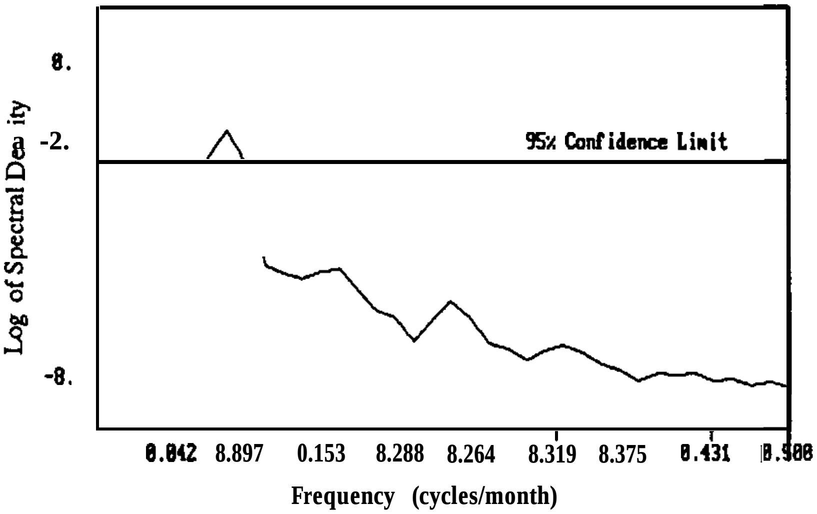


Figure 3.-- Lake Erie monthly mean levels, Cleveland, 1860-1969.

Figure 4.-- Spectral estimate of Lake Erie monthly levels, Cleveland. 1660-l 969.



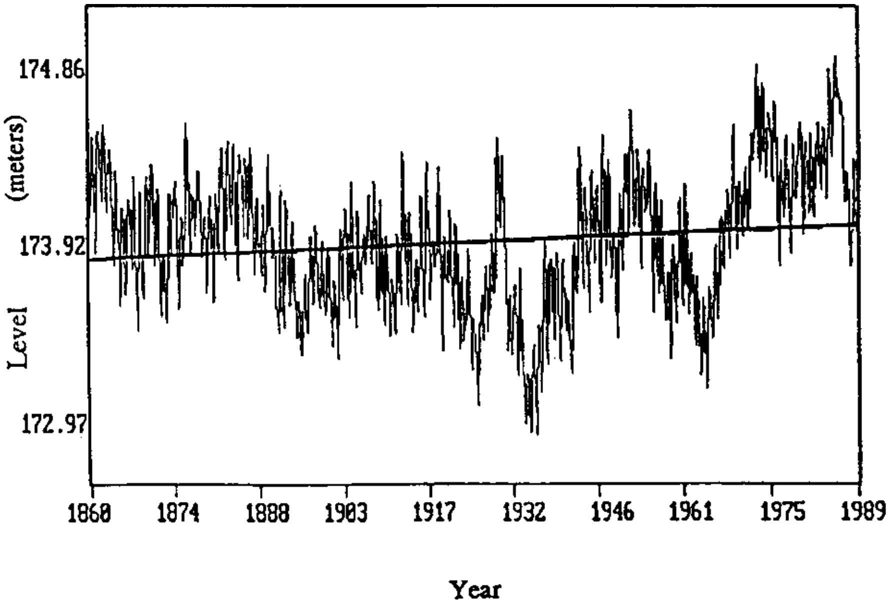


Figure 5.-- Linear trend in Lake Erie levels, Cleveland, 1860-1989.

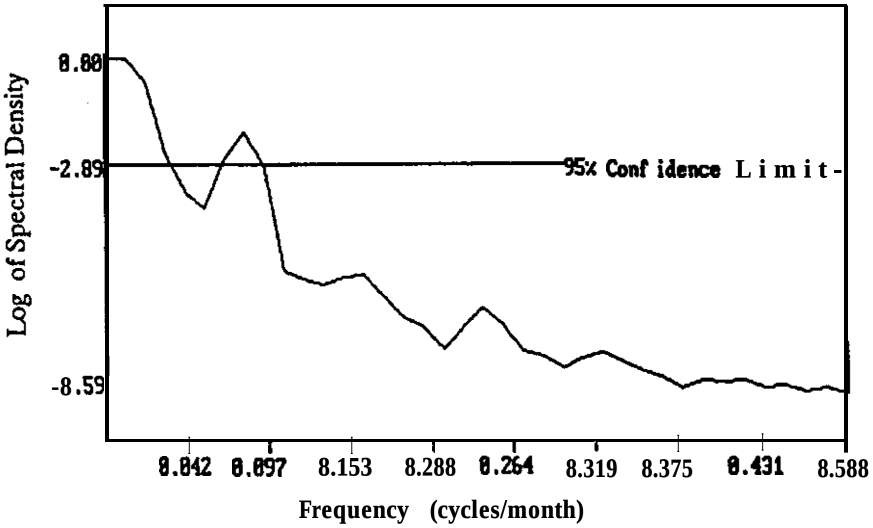
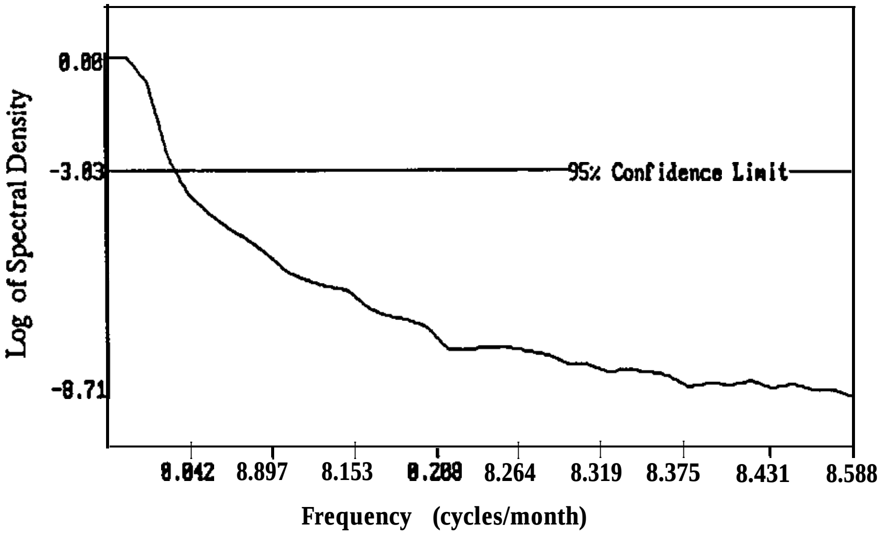


Figure 6.-- Spectral estimate of Lake Erie monthly levels, Cleveland, 1860-1989, after removing linear trend.

Figure 7.-- Spectral estimate of Lake Erie monthly levels, Cleveland, 1860-1989, after removing linear trend and periodic components.



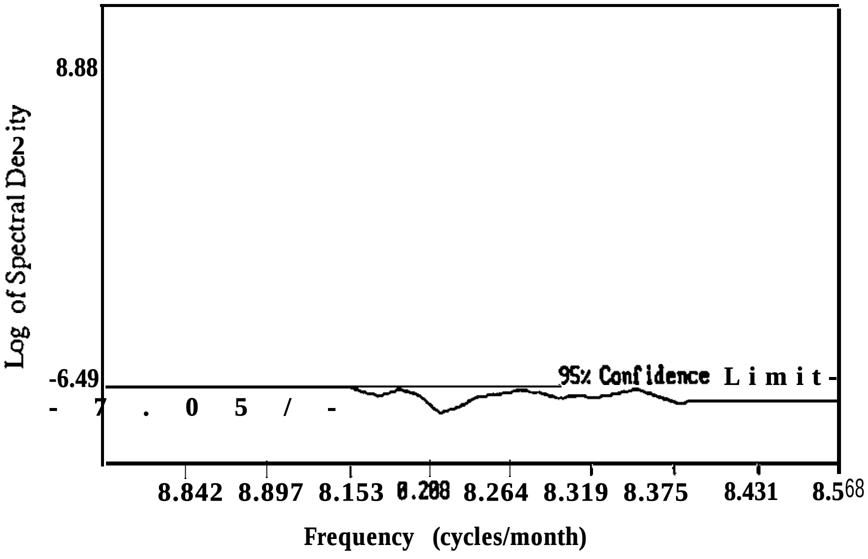


Figure 8.-- Spectral estimate of Lake Erie monthly levels, Cleveland, 1660-1969, after removing linear trend, periodicities, and autoregressive components.

The results of the analysis are given in Table 2 and show that the most significant component is autoregression followed by periodicity and an insignificant trend. Curiously, the trend in levels at Cleveland is positive at a rate of 0.13 mm per year, whereas it had been expected that a negative trend would result. The unexplained random residual is responsible for only 3% of the original variance.

Table 2.-- Analysis of Variance in Monthly Lake Levels, Cleveland, 1860-1989

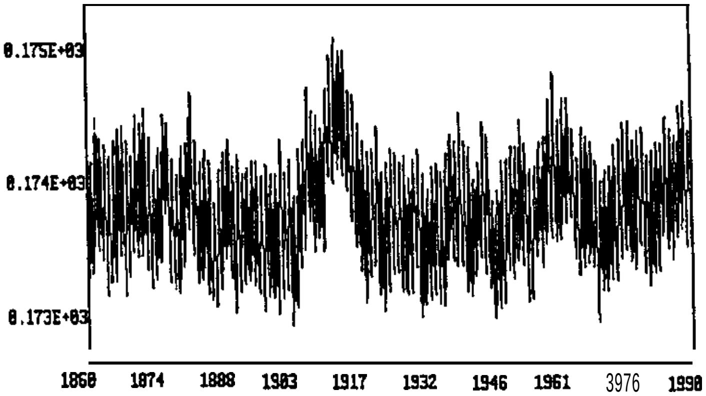
Trend	2%
Periodicity	17%
Autoregression	76%
Residual	3%

3.3.2 Generation of Lake Levels

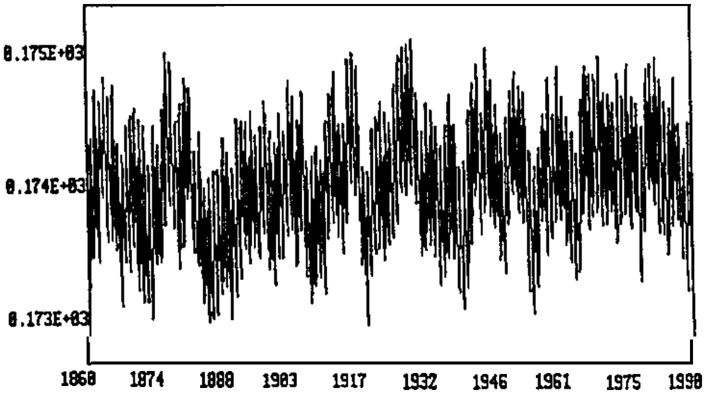
The results from the time series analysis were then used to generate 1000 sequences of 1560 events (12 months x 130 years). Figure 9 shows two examples of the generated sequences.

Figure 9.-- Examples of generated time series.

Cleveland Monthly Levels, 1860-1989
Generated Time Series No. 1



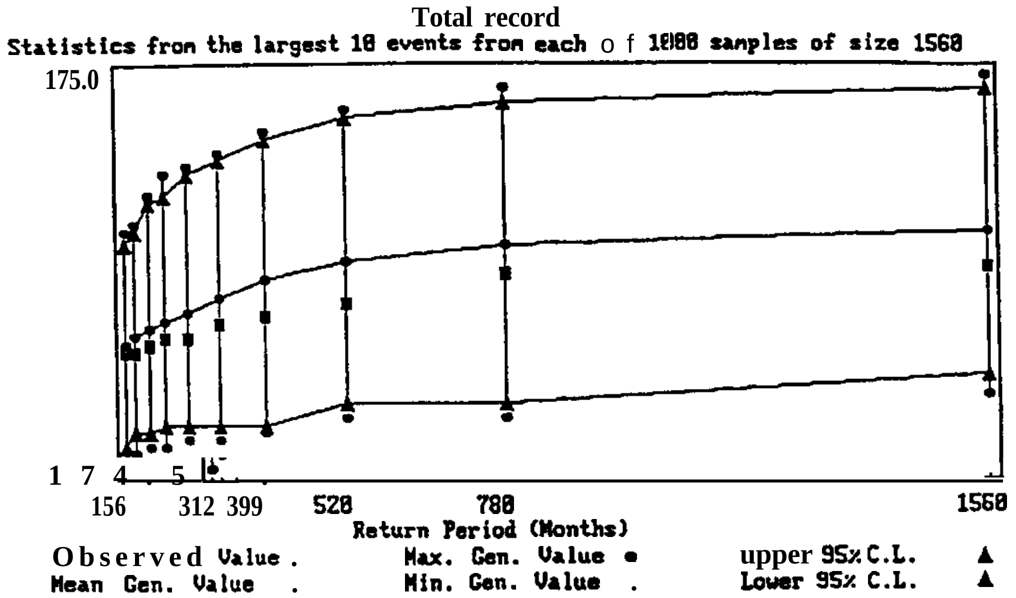
Generated Time Series No. 2



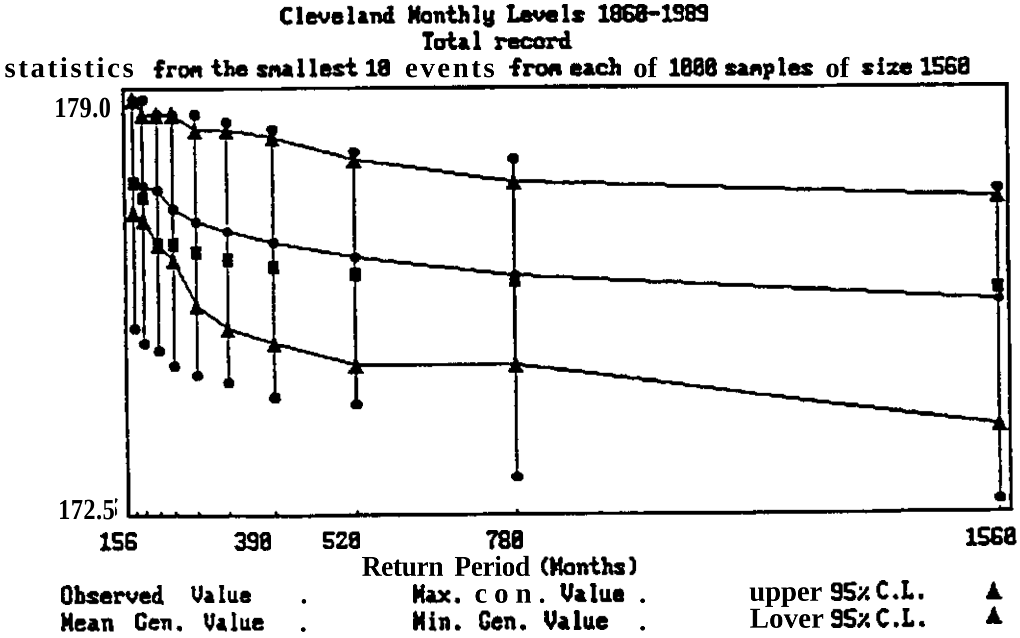
The 10 highest and the 10 lowest events for each month of each generated sequence were written to a file for later analysis. At the end of the generation process a frequency analysis was carried out on the maxima and minima for each month. Table 3 and Figure 10 show examples of the resulting frequency curves together with 95% upper and lower confidence limits. The complete sets of results month by month in tabular form are given in Appendix A.

In all cases, the observed maximum and minimum levels at all return periods lie within the 95% confidence limits established from the generated levels, although some of the maximum recorded levels come close to the upper 95% level.

Figure 10.--Frequency analysis of 1000 generated time series of 190 years of mean monthly Lake Erie levels at Cleveland.


Total record

Statistics from the largest 10 events from each of 1000 samples of size 1560


Cleveland Monthly Levels 1860-1989

Total record

statistics from the smallest 10 events from each of 1000 samples of size 1560

Tables 3a. and 3b.--Comparison of Statistics, Recorded and Generated Data.

Table 3a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
Total Record
Statistics from the largest 10 events from 1000 samples of size 1660

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	175.13	175.11	174.91	174.71	174.68	174.86
780	175.11	175.09	174.89	174.67	174.05	174.85
520	175.08	175.07	174.87	174.67	174.65	174.81
390	175.05	175.04	174.84	174.64	174.63	174.79
312	175.02	175.01	174.82	174.64	174.62	174.78
260	175.00	174.99	174.80	174.64	174.62	174.76
222	174.99	174.96	174.78	174.64	174.61	174.76
195	174.96	174.95	174.77	174.63	174.61	174.75
173	174.92	174.91	174.76	174.63	174.60	174.74
156	174.91	174.89	174.75	174.61	174.58	174.74

Table 3b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly **Levels, 1860-1989, in meters**
Total **Record**
Statistics **from the** smallest 10 **events from** 1000 **samples** of **size** 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.22	173.22	173.11	173.07	172.92	173.11
173	173.22	173.20	173.11	173.06	172.90	173.09
195	173.20	173.20	173.10	173.03	172.89	173.03
222	173.20	173.20	173.08	173.01	172.87	173.03
260	173.20	173.18	173.06	172.95	172.86	173.02
312	173.19	173.18	173.05	172.92	172.85	173.01
390	173.18	173.17	173.03	172.90	172.83	173.00
520	173.15	173.14	173.01	172.87	172.82	172.99
780	173.14	173.11	172.99	172.87	172.72	172.98
1560	173.10	173.09	172.96	172.79	172.69	172.97

The maximum and minimum generated monthly levels from the 1000 series may be compared with the recorded maxima and minima, as in Table 4 and Figure 11. Tables for each month are in Appendix A.

Table 4.-- Comparison of Generated and Recorded Levels - Lake Erie at Cleveland, 1860-1989, in meters.

	Recorded			Generated	
Month	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Minimum**
January	174.67	173.76	173.01	174.82	172.83
February	174.60	173.75	172.97	174.82	172.69
March	174.68	173.83	173.02	175.05	172.82
April	174.79	173.99	173.19	175.12	173.01
May	174.78	174.08	173.26	175.07	173.17
June	174.86	174.12	173.27	175.11	173.20
July	174.85	174.11	173.27	175.13	173.22
August	174.76	174.05	173.24	175.01	173.15
September	174.64	173.96	173.20	174.95	173.13
October	174.74	173.86	173.11	174.84	173.01
November	174.65	173.79	173.00	174.77	172.95
December	174.68	173.77	172.99	174.77	172.88

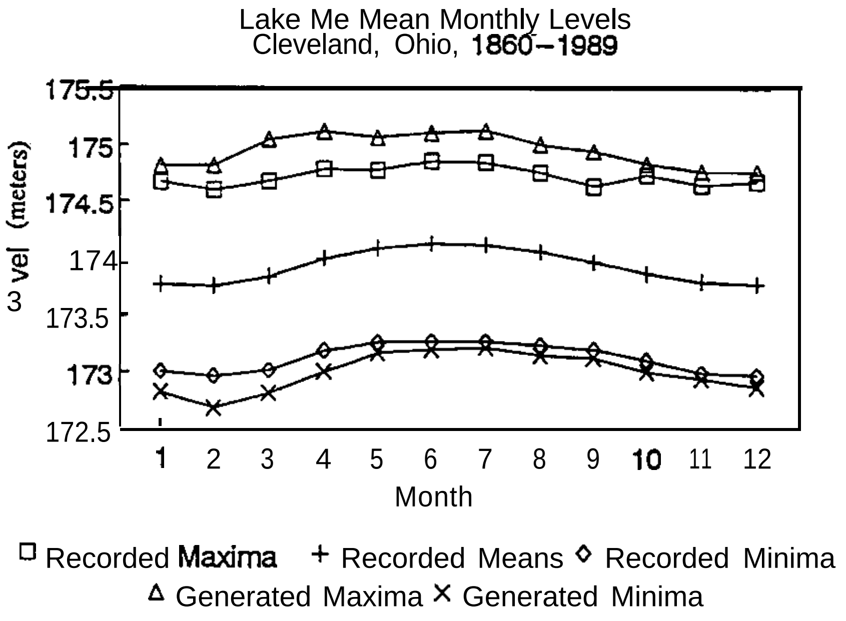


Figure 11 .-Comparison of statistics, recorded and generated data.

3.4 Conclusions

A time series of mean monthly Lake Erie levels recorded at Cleveland, Ohio, from 1860 to 1989 was analyzed. The major components were autoregression and periodicity. Only 3% of the total variance remained unexplained. The statistics from the observed data were then used to generate 1000 similar time series. The confidence limits derived from a frequency analysis of the generated sequences provide a measure of the likely maximum range of mean monthly levels at Cleveland. For example (from the tables in Appendix A), the 95% confidence limits for January levels at a return period of 130 years are 174.80 m to 172.87 m. This compares to a maximum recorded mean January level of 174.67 m and a minimum recorded mean January level of 173.01 m. Such ranges of levels are useful for designing shoreline structures such as marinas, water intakes, and hydroelectric plants, as well as for designing regulation plans for control structures. In interpreting such ranges, it must be remembered that this is only a statistical analysis and account must be taken of physical limits to maximum and minimum lake levels. For Lake Erie, it has been estimated that the maximum and minimum physical lake levels are 175.26 m and 169.35 m, based on outflow channel constraints.

4. TIME SERIES MODELING OF NET BASIN SUPPLIES

Dr. Steven Buchberger

Water contained in the Great Lakes originates from one of two sources: either an upstream lake or the surrounding watershed and atmosphere. Water that originates from the surrounding watershed and atmosphere is called net basin supply (NBS). The NBS to a lake during time interval Δ t is defined as the sum of overlake precipitation P and basin runoff R minus water losses due to evaporation E and seepage G, or

$$NBS(t) = P(t) + R(t) - E(t) - G(t). \qquad (20)$$

This fundamental definition has been used by GLERL to compute monthly net basin supplies (Hunter and Croley, 1991). Since individual terms in (20) are difficult to measure, NBS is often indirectly estimated as the residual component of the lake water balance equation:

$$NBS(t) = \frac{A[H(t) - H(t - \Delta t)]}{\Delta(t)} + Q(t) - I(t) \pm D(t) \qquad (21)$$

where A is the surface area of the lake, H(t) - H(t - Δt) is the change in the lake elevation, Q(t) is the average flow out of the lake, I(t) is the average flow into the lake (from the upstream lake), and D(t) is average diversion into or out of the lake. Using Eq. (21), annual and monthly coordinated NBS data from 1900 to 1989 for each of the Great Lakes have been computed by the U.S. Army Corps of Engineers Detroit District. These NBS data are included in Appendix B.

4.1 Properties of Annual Net Basin Supplies

Time series plots of annual NBS are shown in Figure 12. These data, expressed as meters, represent a *water yield per unit area* over the entire basin. Rescaling the supply data compensates for the tremendous disparity in total watershed size among the Great Lakes (see Table 5) and aids in comparing annual NBS. Some sample statistics of annual NBS are given in Table 6. Negative annual NBS occur when annual evaporation from the lake exceeds annual precipitation and runoff into the lake.

Figure **12.--Great** Lakes annual net basin supplies.

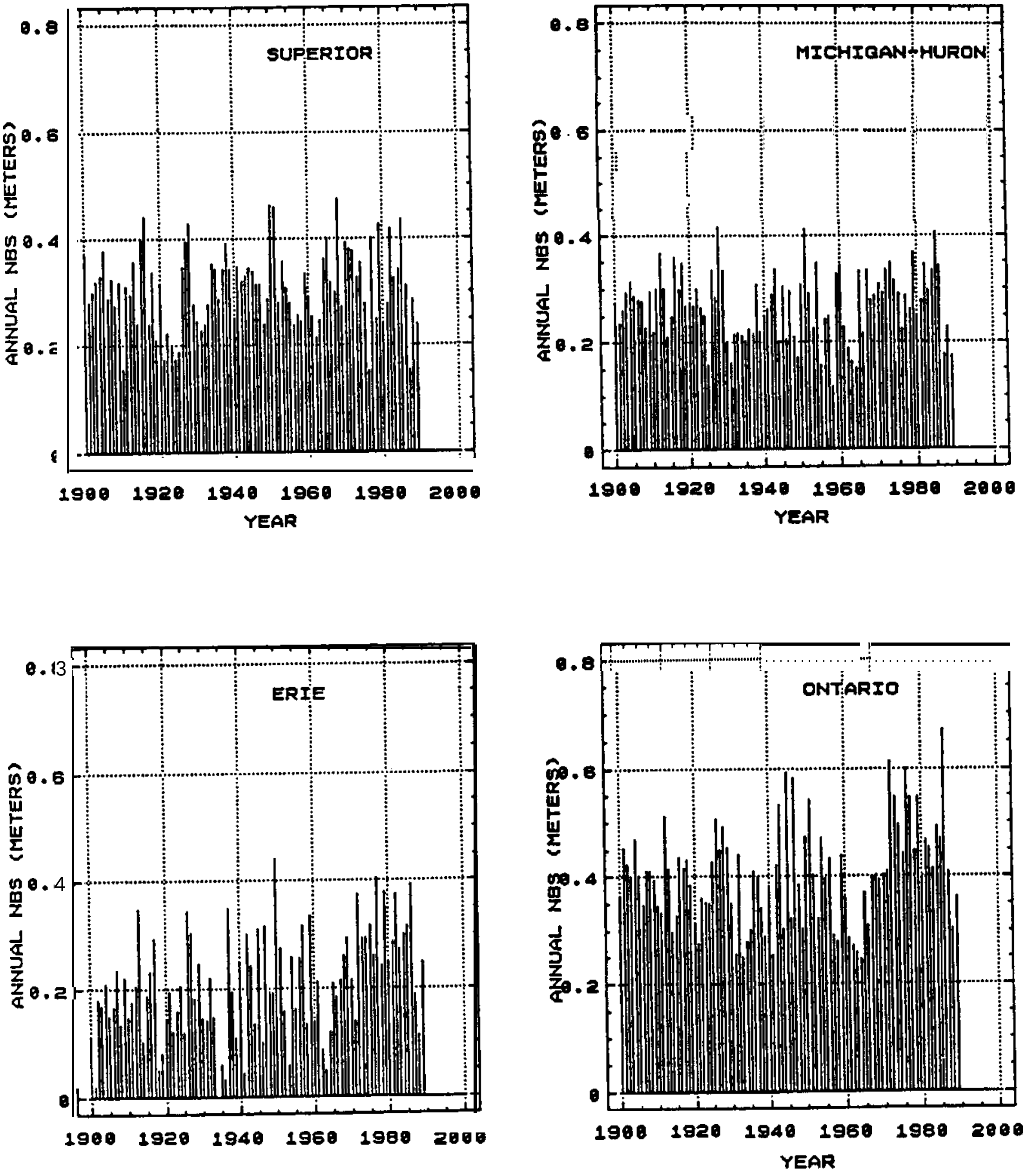


Table 5.--Some Features of the Great Lakes

Feature	Superior	Michuron	St. Clair	Erie	Ontario
Land area (km^2)	127,700	252,000	12,400	58,800	60,600
Lake area (km^2)	82,100	117,300	1,110	25,700	19,000
Total area (km^2)	209,800	369,300	13,510	84,500	79,600
Land area/total area	0.609	0.682	0.918	0.696	0.761
Lake volume (km^3)	12,100	8,460	4.2	484	1,640
Shoreline (km)	4,390	8,790	410	1,400	1,150

(Source: “an der Leeden et al., 1990)

Table 6.-- Statistics of Great Lakes Annual Net Basin Supplies (1990-I 969)

Statistic (units)	Superior	Michuron	St. Clair	Erie	Ontario
average (m^3/s)	2,053	3,172	122	558	1,015
avg/area (m)	0.309	0.271	0.285	0.208	0.402
std dev (m^3/s)	482	737	64	260	231
stdev/area (m)	0.072	0.063	0.149	0.097	0.092
coefficient variation	0.23	0.23	0.52	0.47	0.23
skewness	0.03	-0.05	0.31	0.10	0.49
maximum (m^3/s)	3,153	4,866	288	1,180	1,694
minimum (m^3/s)	1,015	1,371	-2.4	-14	623
lag-1 autocorrelation	0.16	0.19	0.50	0.18	0.29
portmanteau α	0.746	0.917	<0.001	0.196	0.003
NBS/annual outflow	0.96	0.60	0.02	0.10	0.15

Interestingly, extreme NBS behavior occurs at the two adjacent lower lakes. Lake Ontario has the highest average annual yield with 0.402 m, whereas Lake Erie (with the highest evaporation losses) has the lowest average annual yield with 0.208 m. The variance of the scaled annual NBS decreases as lake drainage area increases. For example, standard deviations of yield per unit area are less at the large upper lakes than at the small lower lakes.

In terms of relative variability, the annual NBS at Lakes Ontario, Michigan-Huron, and Superior are all similar, and coefficients of variation are near 0.23. Due to Lake Erie's low annual average NBS, its coefficient of variation is 0.47. Sample skewness of each annual NBS series is small, though there is a tendency for skewness to increase in the downstream direction.

Sample autocorrelation functions of the annual NBS are shown in Figure 13. Significance levels of the portmanteau test for temporal independence (Table 6) suggest that annual supplies at the upper lakes are random. At the lower lakes, however, there may be significant interannual persistence in the yearly NBS series. The presence of long-term memory in the data would have important ramifications for time series models of NBS.

The relative contribution of annual NBS to the total lake outflow decreases dramatically in the downstream direction. NBS at Lake Superior constitute nearly 96% of the outflow, while at the lower lakes, NBS represent only about 10% of the outflow from Lake Erie and 15% of the outflow from Lake Ontario. There are two factors behind this reduction in the NBS contribution. First, lake outflows increase when moving downstream through the Great Lakes system. Second, NBS decrease downstream since the lower lakes are much smaller than the upper lakes (see Table 5).

4.2 Properties of Monthly Net Basin Supplies

Time series plots of monthly NBS are shown in Figure 14. Monthly NBS display a yearly cycle reflecting seasonality in the region's precipitation, runoff and evaporation processes. This annual cycle is clearly evident in Figure 15 which shows subseasonal time series plots of the monthly NBS series. Sample statistics of the monthly NBS series are summarized in Table 7.

In general, monthly NBS are greatest and most variable during the spring runoff season. The upper lakes also show a slight rise in supply variance during the autumn even though the average supply tends to decrease. Monthly NBS are lowest and least variable during the late summer and autumn for the lower lakes and during the late fall and winter for the upper lakes. During these periods, negative monthly NBS are common. Overall, negative monthly supplies occur most often on Lake Erie (37% of the data are below zero) and least often on Lake Ontario (12% of data). NBS skewness is positive in all months in all lakes with the exception of December for Lake Superior. The magnitude of monthly NBS skewness tends to increase when moving from the upper to the lower lakes.

4.3 Modeling Net Basin Supplies

Four time series models of Great Lakes monthly NBS are listed in Table 8. Other models are available, the most notable of which are the quasi-physical approach developed by GLERL (Croley and Hartmann, 1984, 1987) and the trend-regression model used by the Corps of Engineers (DeCooke and Megerian, 1967). The discussion that follows considers only the time series models given in Table 8.

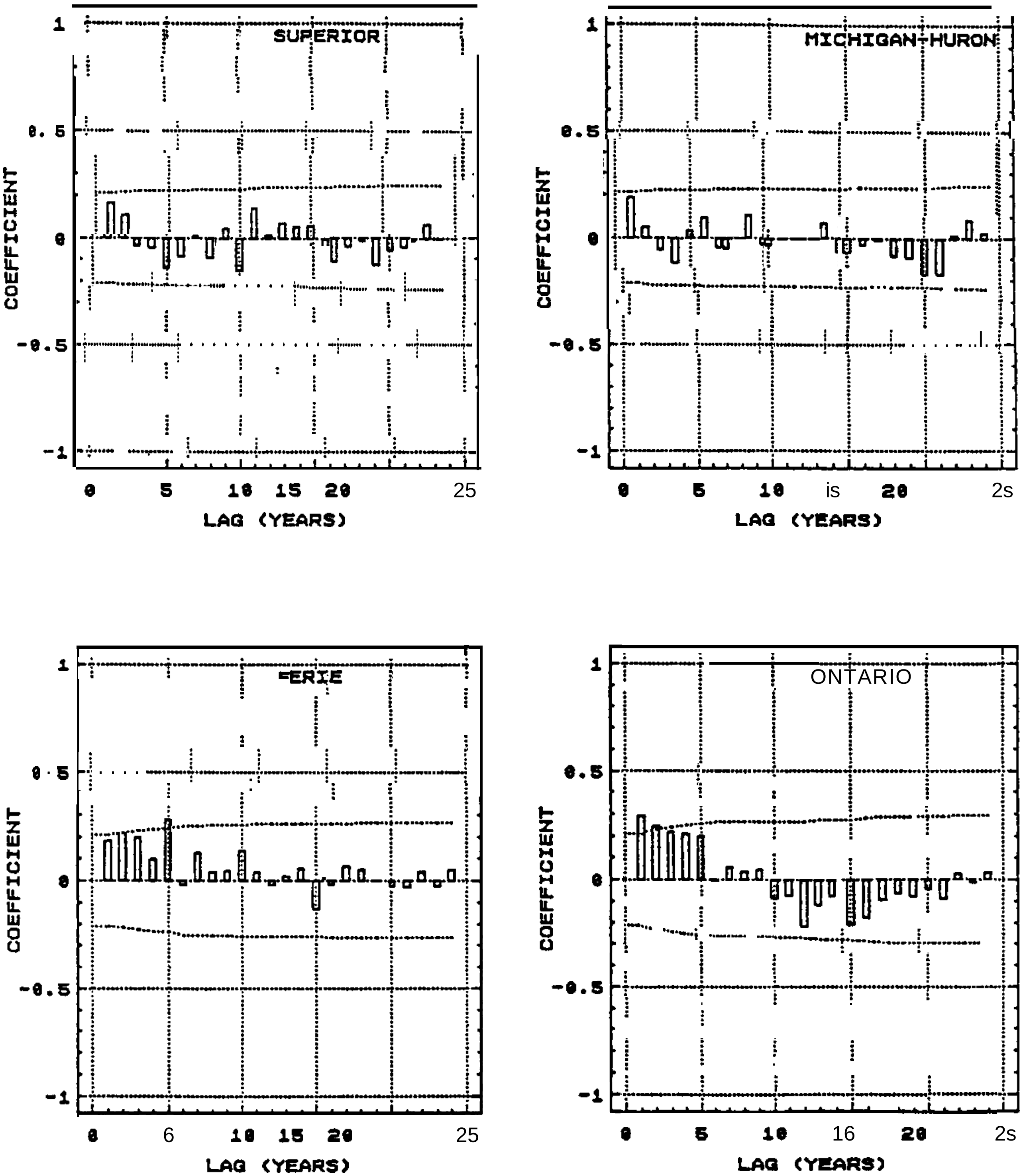
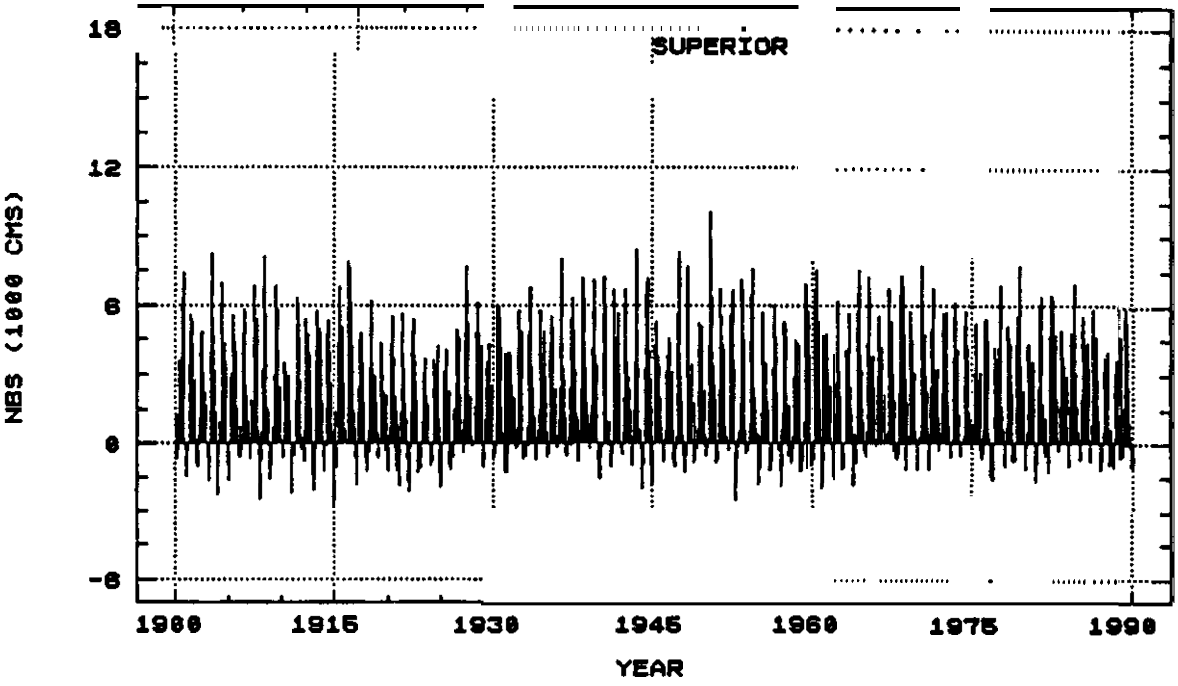


Figure **13.--Autocorrelation** function of annual net basin supplies.

Figure **14a.--Great** Lakes monthly net basin supplies.



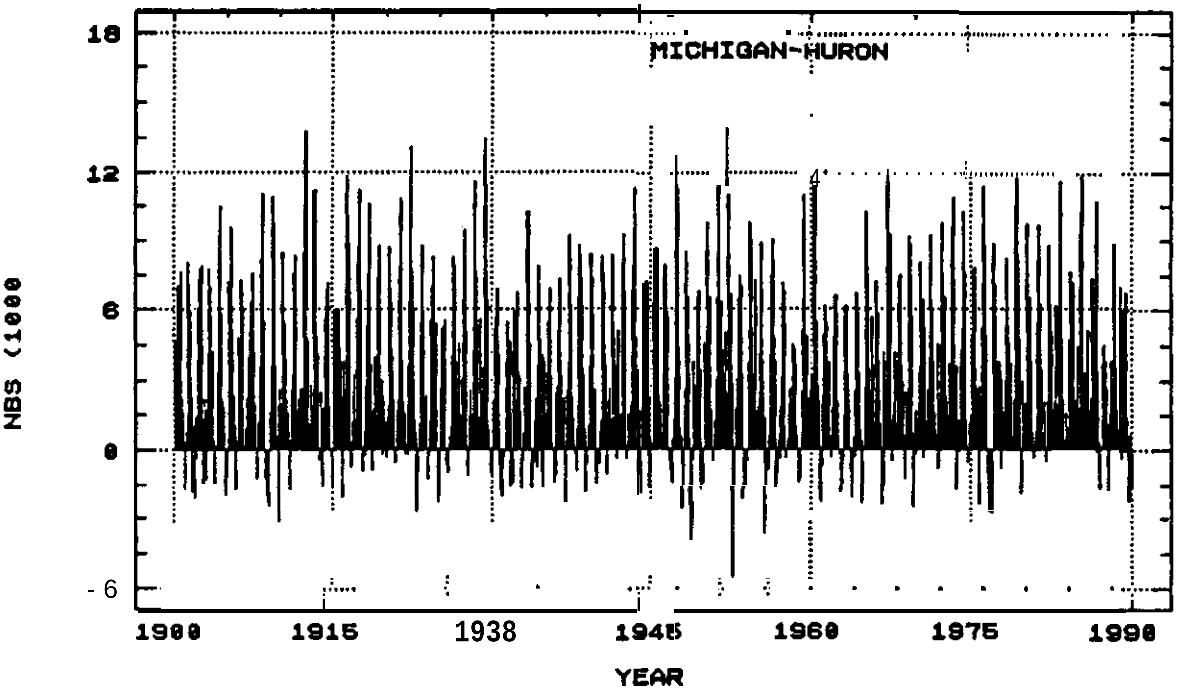


Figure **14b.--Great** Lakes monthly net basin supplies

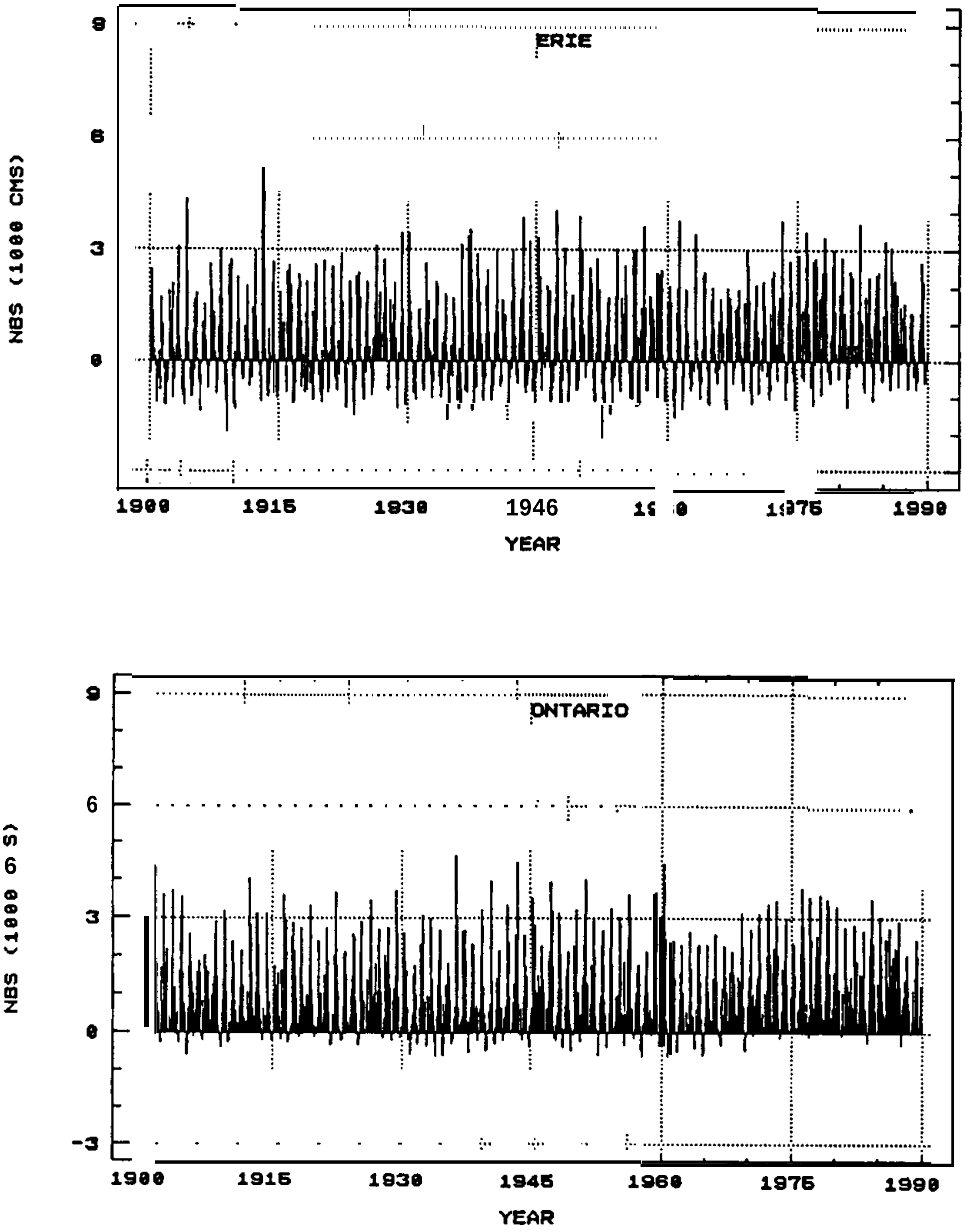


Figure **15.--Great** Lakes monthly net basin supplies

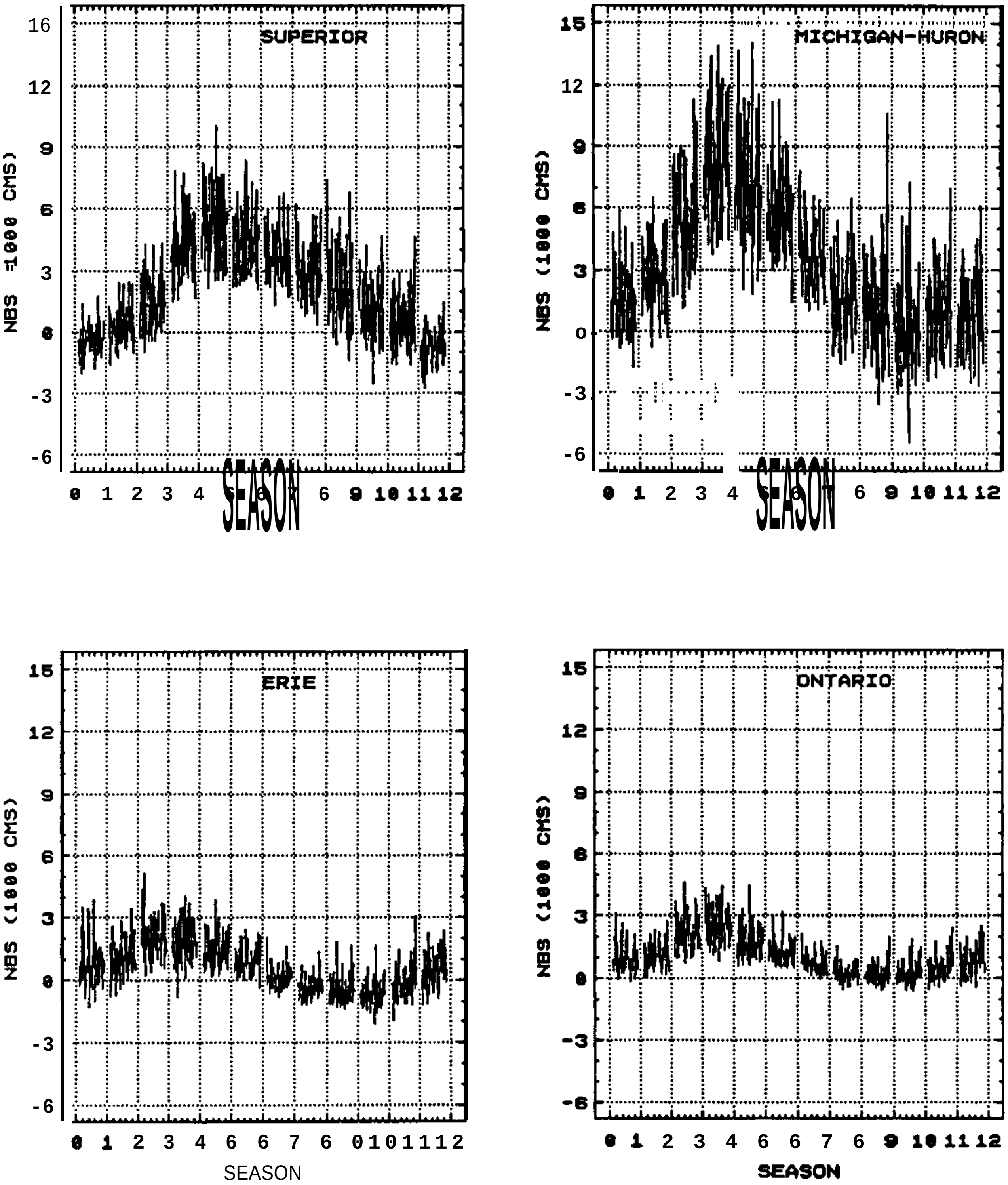


Table 7.--Statistics of Great Lakes Monthly Net Basin Supplies (1900-1989)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lake Superior												
avg	-384	295	1,282	4,211	5,256	4,466	3,670	2,849	2,076	1,073	515	-669
stdv	688	791	1,212	1,409	1,678	1,480	1,135	1,219	1,583	1,317	1,262	819
skew	0.22	0.48	0.59	0.38	0.23	0.41	0.56	0.47	0.81	0.18	0.57	-0.13
max	1,784	2,464	4,332	7,844	10,024	8,382	6,768	6,258	7,391	4,672	4,616	1,472
min	-2,067	-1,614	-991	1,501	2,152	2,095	1,359	368	-1,415	-2,549	-1,614	-2,832
Lake Michigan-Huron												
stdv	1,494	2,478	5,219	8,090	7,096	5,845	3,605	1,559	[illegible]	26	1,030	810
skew stdv skew	1,431 0.56	1,406 0.35	2,263 0.40	2,319 0.41	2,327 0.48	1,760	1,501	1,696 0.28	2,172	1,948	1,902	1,874
						0.61	0.60		1.06	0.74	0.33	0.31
max	5,890	6,513	11,298	13,875	14,045	11,270	7,815	6,513	10,619	7,249	6,966	6,145
min	-1,784	-793	1,133	3,738	1,841	1,416	1,019	-1,614	-3,596	-5,465	-2,435	-2,718
Lake St. Clair												
ava	166	188	265	226	148	97	74	37	34	41	60	139
skew	171	181	203	197	160	81	7s	63	69	80	91	158
max skew	0.50	0.36	0.04	0.16	1.13	0.2s	1.02	0.98	0.86	1.31	1.83	0.68
max	680	595	765	850	793	340	368	283	227	340	538	680
min	-266	-283	-283	-227	-198	-85	-67	-85	-142	-113	-85	-266
Lake Erie												
stdv g	699	997	2,039	1,871	1,305	840	121	-349	-623	-651	-141	484
skew stdv skew	970	827	871	828	716	602	483	463	595	527	721	805
	1.16	0.27	0.60	0.04	0.86	0.68	1.09	1.14	1.52	0.97	1.17	0.21
max	3,879	3,455	5,154	4,021	3,851	2,464	a,067	1,388	1,841	1,699	3,058	2,379
min	-1,274	-765	198	-793	170	-396	-821	-1,161	-1,387	-2,067	-1,897	-1,189
Lake Ontario												
avg	914	1,046	2,126	2,631	1,697	1,177	679	227	146	211	571	755
stdv	637	571	783	776	706	509	417	351	428	496	675	642
skew	0.98	0.56	0.61	0.07	1.08	1.26	0.97	0.70	1.31	0.93	0.73	0.44
max	3,115	2,775	4,644	4,446	4,474	3,200	2,180	1,586	2,011	1,897	2,463	2,520
min	-170	-28	736	821	566	453	-57	-566	-595	-623	-566	-425

Note: Units are ^{3}/s except for skewness, which is dimensionless.

Table E.--Net Basin Supply Time Series Studies

Author	Record	Superior	Michuron	Erie	Ontario
Yevjevich (1975)	Jan 1900 to Dec 1967	ARMA(2,0)	ARMA(2,0)	ARMA(2,0)	ARMA(2,0)
		Multivariate approach developed for NBS simulation. Skewness modeled with LN-3 distribution.			
Loucks (1989)	Jan 1900 to Dec 1978	ARMA(1,1)	ARMA(1,1)	ARMA(2,0)	ARMA(2,0)
		Multivariate approach developed for NBS simulation. Skewness ignored (assumed normal).			
Buchberger (1991)	Jan 1900 to Dec 1986	ARMA(2,0) ARMA(1,1)	ARMA(2,0) ARMA(1,1)	ARMA(2,0) ARMA(1,1)	ARMA(2,0) ARMA(1,1)
		Multivariate model for NBS simulation and forecasting. Skewness removed with transformation.			
Corps Engr (1991)	Jan 1900 to Dec 1989	ARMA(1,1)	ARMA(1,1)	ARMA(1,1)	ARMA(1,1)
		Univariate models used for monthly NBS forecasting. Skewness removed with transformation.			

Yevjevich (1975) and Loucks (1989) developed multivariate time series models to simulate monthly NBS. Buchberger (1991) and the Corps of Engineers (1991) developed time series models to forecast monthly NBS. Aside from the period of record, chief differences among these studies are the treatment of skewness in the monthly NBS and the approaches used to account for autocorrelation and cross correlation in the NBS.

The treatment of skewness in time series modeling is a problem that has not been properly resolved. For parameter estimation and model forecasting, it is desirable to work with a time series that has nearly zero skewness because the best techniques in stochastic analysis are developed for normal processes. Near normality can often be achieved with a data transformation. The transformation option was used by Buchberger (1991) and the Corps of Engineers (1991) to normalize monthly data. In contrast, Loucks (1989) avoided the skewness issue by assuming nearly normal NBS.

Data transformations may introduce biases in the statistical properties of the modeled time series. An alternate approach is to develop a time series model for the skewed data and then fit a suitable probability distribution to the uncorrelated residuals. This approach was used by Yevjevich (1975) who fitted model residuals to a three-parameter log normal distribution. Estimation and testing of this model, however, is not as efficient as with the normal case.

The series of NBS contain significant temporal and spatial correlations. At present, time series models for the Great Lakes use relatively simple autoregressive moving average (ARMA) processes to describe temporal correlations in the NBS. One clear message from Table 8 is that the ARMA(1,1) and ARMA(2,0) models consistently emerge as the top candidates for Great Lakes monthly NBS. The univariate ARMA(1,1) is written

$$Z(t) = \phi_1 Z(t-1) + \varepsilon(t) - \theta_1 \varepsilon(t-1) \tag{22}$$

and the univariate ARMA(2,0) is written

$$Z(t) = \phi_1 Z(t-1) + \phi_2 Z(t-2) + \varepsilon(t) \tag{23}$$

where Z(t) is the deseasonalized monthly NBS for a single lake, $\epsilon(t)$ is the random error, and ϕ_1, ϕ_2 and θ_1 are parameters to be estimated from the monthly NBS data. Deseasonalized supply data are obtained by subtracting the monthly mean and then dividing by the monthly standard deviation (see Table 7). The deseasonalized series has approximately zero mean and unit variance, but the monthly skewness is unchanged from the values listed in Table 7.

Spatial correlation (also called cross correlation) among the NBS is preserved by linking together the ARMA models which are used to describe the temporal correlation. This linkage can be accomplished several ways. For example, Yevjevich (1975) and Buchberger (1991) used a multivariate ARMA(2,0) model

$$Z(t) = AZ(t-1) + BZ(t-2) + C\varepsilon(t) \tag{24}$$

where A, B, and C are parameter matrices and Z(t) is a vector of deseasonalized monthly NBS for all five lakes. Method of moments estimates of A, B, and C are given by Bras and Rodriguez-Iturbe (1985)

$$A = (M_1 - BM_1^T)M_0^{-1} \tag{25}$$

$$B = (M_2 - M_1 M_0^{-1} M_1)(M_0 - M_1^T M_0^{-1} M_1)^{-1} \tag{26}$$

$$CC^T = M_0 - AM_1^T - BM_2^T \tag{27}$$

where M_0, M_1, and M_2 are the covariance, lag one covariance, and lag two covariance matrices, respectively, of the Z(t) series. The multivariate ARMA(2,0) model will preserve the process covariance at lags of zero, one, and two.

An alternative approach to handle cross correlations among NBS is based on a “contemporaneous” autoregressive moving average (CARMA) model. This method permits the use of individual univariate ARMA models for each lake. These models are then linked through a common array of lag zero cross-correlated ARMA residuals. The CARMA approach was used initially by Loucks (1989) and was also examined during this task force study. In both cases, the ARMA(1,1) model worked best on the upper lakes, whereas the ARMA(2,0) model was best for the lower lakes. Advantages of the CARMA approach include its flexibility and ease of implementation. A possible shortcoming is that the CARMA formulation does not explicitly account for the covariance of the process at lags greater than zero. However, since the CARMA formulation preserves correlation over time and accounts for lag zero cross correlation, this approach will implicitly generate some cross correlation at non-zero lags (Salas et al., 1985).

The U.S. Army Corps of Engineers (1991) proposed using individual ARMA(1,1) models for each lake. In contrast to the multivariate and contemporaneous modeling approaches, the univariate ARMA(1,1) models are not explicitly linked. This strategy will preserve the temporal correlation of the NBS but will not capture spatial correlation in the supply data. This drawback actually may not be too serious for forecasting purposes because the chief concern is with the expected value of NBS over relatively short time horizons, typically periods lasting only a few months. However, a time series model without cross correlation would be inappropriate for Great Lakes simulation studies where one of the key issues is the variability of NBS over project horizons spanning many years or decades.

The collection of univariate ARMA(1,1) models proposed by the Corps could readily be linked through a multivariate ARMA(1,1) formulation

$$Z(t) = AZ(t-1) + B\varepsilon(t) - C\varepsilon(t-1) \tag{28}$$

where all terms have been defined previously. This approach has the advantage of preserving multilag cross correlations between the NBS. However, estimation of the parameter matrices A, B, and C is considerably more difficult here than with the multivariate ARMA(2,0) model.

4.4 Performance of Net Basin Supply Models

Two tests were performed to check the adequacy of the CARMA model for simulating monthly NBS. The first test compared moments of the simulated NBS against sample moments of the historical NBS. The second test compared means and variances of monthly lake levels obtained from simulated NBS against means and variances of monthly lake levels obtained from historical NBS.

Lake level simulations were carried out under the same conditions used to establish the "Basis of Comparison" (BOC) for Phase II of the Levels Reference Study (Task Group 2, 1992). The BOC conditions refer to assumptions about diversions, consumptive use, regulation plans, channel flows, and starting lake elevations that have been made to establish a consistent hydraulic regime in the Great Lakes system over the study period. Outflows from Lake Superior follow plan 1977-A; outflows from Lake Ontario follow plan 1958-D without discretionary actions.

The experimental procedure was as follows. Ninety years of simulated monthly NBS were generated for each of the Great Lakes. These supplies were routed through the Great Lakes under BOC conditions to produce 90 years of simulated monthly levels for each lake. Monthly statistics were computed from the simulated NBS and from the simulated lake levels. This simulation process was repeated many times to generate empirical distributions of sample statistics for simulated supplies and levels. In addition, the parent sequence of historical NBS was routed once through the Great Lakes under BOC conditions to yield a single 90-year realization of monthly lake levels. Results from this benchmark sequence of historical NBS were compared against statistics from the water supply and lake level simulation exercise.

Preliminary findings from the first test indicate that the CARMA model preserves, within the limits of sample variation, the mean and lag-zero covariance of the historical monthly and annual NBS for all lakes. Yevjevich (1975) reports similar success in preserving sample properties of NBS with the multivariate ARMA(2,0) model. However, results from the second test show that the variance of monthly lake levels tends to be less when simulated rather than when historical NBS are used. The discrepancy between simulated and historical lake level variability does not affect Lake Superior but instead first appears on Lake Michigan-Huron and amplifies in the downstream direction.

Strategies to remedy the level variance problem fall into three categories: (1) develop alternative time series models, (2) modify existing regulation plans, or (3) review historical monthly NBS. The rationale for each is summarized below:

(1) Develop Alternative Models: There may be important properties in the historical NBS data that are not adequately preserved by the current ARMA class of time series models. It might be necessary, for example, to account for long-term interannual persistence or to strengthen multilag cross covariance among NBS. Brinkmann (1983) found that extreme anomalies in NBS are almost always of the same sign throughout the Great Lakes and that they tend to persist for several seasons.

Much of the region experienced above-average precipitation, high NBS, and record lake levels during the 1970s and 1980s (see Figures 16 and 17). It may be worthwhile to consider a model that allows shifting climatic regimes. Quinn (1981) argues that the period from 1900 to 1979 consists of two distinct precipitation regimes at the Great Lakes, four dry decades followed by four wet decades. Incorporating features like long-term persistence, additional cross correlations, and shifting climatic regimes into an enhanced NBS simulation model would increase the variability of simulated lake levels.

(2) Modify Regulation Plans: When historical NBS are routed through the Great Lakes system under BOC conditions, resulting annual average water levels on Lake Ontario are confined essentially within a 0.3 m range (elevation 74.37 m to 74.68 m) for the first 60 years of record. During the final 30 years, however, annual average water levels fluctuate over a 2.5 m range (elevation 74.07 m to 76.50 m). Despite extreme wet conditions that persisted on Lake Ontario during the 1970s and 1980s, it seems likely that part of this large jump in lake level variability is an artifact of regulation plan 1958-D. If so, judicious modifications to the plan could reduce this artificial influence.

(3) Review Historical NBS: Monthly NBS, computed with Eq. (21), are subject to large errors due to uncertainty in estimating lake inflows and outflows. Quinn and Guerra (1986) indicate that "a 5% error in the Detroit or Niagara River flows would result in a 34% error in the NBS" to Lake Erie. Further, it can be shown that random errors in connecting channel flows reduce the cross covariance between estimated supplies and this, in turn, can lead to a loss of variance in simulated lake levels. Hence, relatively small errors made in computing the connecting channel flows can lead to large errors in the mean and covariance of estimated NBS. Other errors in historical supplies have been identified and should be corrected (Buchberger, 1991).

In summary, preliminary results from limited simulations suggest that monthly NBS generated with conventional multivariate ARMA time series models have difficulty preserving the variance of monthly water levels, especially on the lower Great Lakes. Potential remedies to this problem include development of improved time series models, modification of regulation plan 1958-D, and screening of the historical monthly NBS data base.

5. ESTIMATING THE JOINT PROBABILITY OF WAVES, STORM SURGE, AND STATIC WATER LEVELS

Dr. Kenneth Potter

As discussed earlier, the Corps of Engineers has estimated probabilities of various wave parameters based on a reconstruction of a 32-year wind field for the Great Lakes (Hubertz et al., 1991). This represents the state of the art in estimating wave probabilities. In applying these results to a problem in coastal design, an engineer would typically assume a mean water level for the site in question. However, under current practice, there is no way to estimate the probability of the combined effect of a given design wave and the assumed mean water level, even if the probabilities of the wave and mean water level have been estimated. Combined "effect" refers to any single variable that represents some combination of wave height and mean water level. Examples include the sum of the significant wave height and the mean level, and the runup associated with the significant wave height. The choice of a particular effect depends on the nature of the design problem. To estimate the

Figure I&-Great Lakes **standardized** annual precipitation.

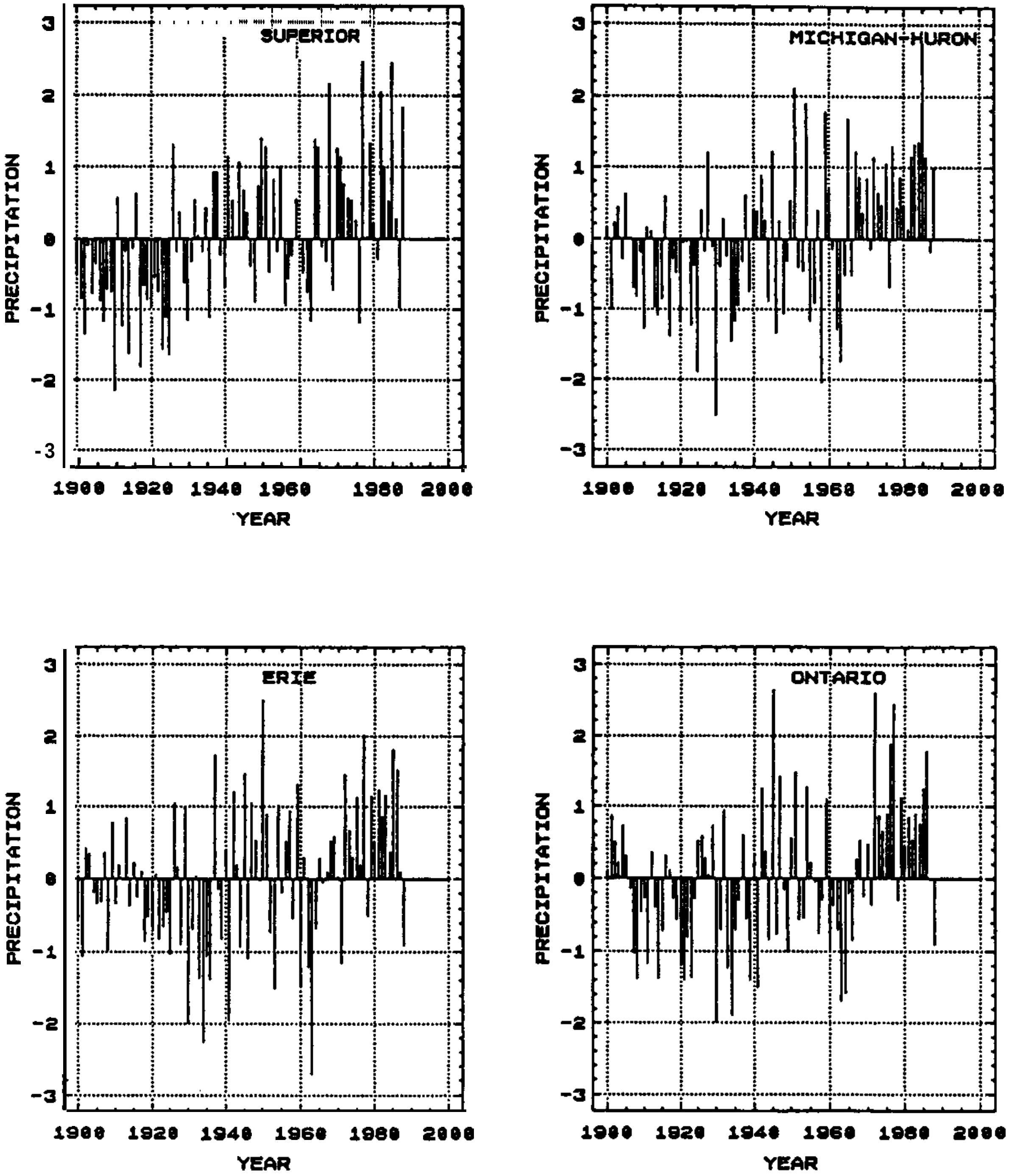
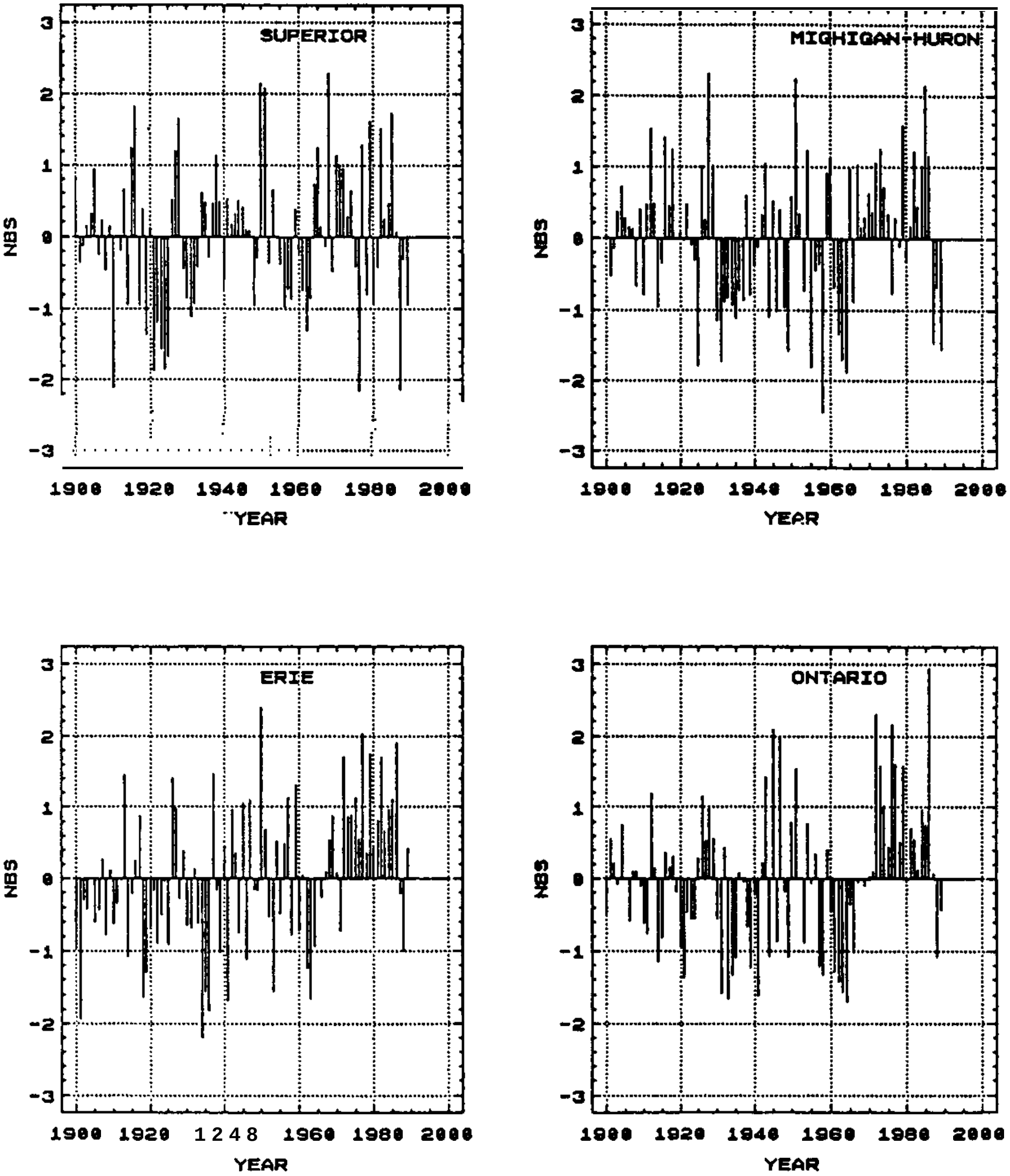


Figure **17.--** Great Lakes **standardized** annual net basin supplies.



probability of a combined effect it is necessary to integrate the joint probability distribution of the contributing factors. In this case there are three factors: hydrologic water level, storm surge, and storm wave height. The time series models discussed in the previous sections can be used to estimate the probability distribution of hydrologic water levels. The Corps of Engineers has already estimated the probability distribution of wave heights. Although there may be some slight correlation between hydrologic water levels and wave heights, it is not likely to be of much significance. Hence the joint distribution of hydrologic water levels and wave heights is just the product of the individual distributions. The difficult problem is estimating the joint distribution of wave heights and storm surge. Clearly these variables are strongly correlated, and their distributions are site-specific.

One way to estimate at a specific shoreline site the probability distribution of a combined effect of waves and storm surge is to simulate waves and storm surge using the 32-year wind field data reconstructed by the Corps of Engineers (Hubertz et al., 1991). In principle, a user could use this data set as input to site-specific surge and wave models in order to simulate a 32-year series of storm surge and wave parameters. In practice, of course, this would be impractical because of the enormous size of the wind-field dataset. It is likely, however, that only a subset of the wind-field dataset is critical to the estimation of storm surge and parameters at any site. In such a critical dataset there would be a reduction in the amount of wind data in both space and time. It may be possible to develop a screening model to identify critical datasets for individual segments of the Great Lakes shoreline. In essence, such a screening model would be a grossly simplified wave/surge model that is capable of preserving the relative ranking of storm events, without necessarily providing accurate estimates of the resulting wave and surge statistics. One possibility would be for a federal agency to develop and use such a model to define critical wind datasets for all Great Lakes shoreline segments. These datasets could then be distributed to individual users.

6. FUTURE STUDY AND RECOMMENDATIONS

Dr. Steven Buchberger and Deborah H. Lee

The past four decades have witnessed great strides in understanding and modeling Great Lakes water levels and NBS. This progress can be attributed to three key factors:

(1) acquisition of large hydrologic data bases for calibrating and testing models,

(2) application of sophisticated statistical and quasi-physical procedures for modeling water levels and NBS, and

(3) increasing availability of high performance computers.

Much work remains, however. Some modeling problems with Great Lakes hydrology are still unresolved. Information requirements of various Great Lakes user groups are becoming increasingly specialized. For instance, conventional multivariate ARMA time series models have difficulty preserving the long-term variability of monthly water levels on the lower Great Lakes, and decision makers who once relied on monthly lake level forecasts may now need estimates of the risk associated with site-specific seasonal storm surges.

Certainly future efforts to improve statistical techniques should build on past progress. Time series models of NBS must be further refined; robust lake regulation plans must be developed and optimized; the Great Lakes hydrologic data base, especially NBS, must be carefully screened and adjusted where necessary. Although these steps point in the right direction, they are not enough to meet future expectations.

What is most needed here is a comprehensive, coherent, and unified strategy for modeling Great Lakes hydrology. This strategy must anticipate and exploit impending explosions in computer technology and information management. In addition, the strategy must emphasize improved methods to assist users in generating and interpreting hydrologic data needed to optimize decisions on issues affecting Great Lakes resources. At the heart of this strategy is the development and demonstration of a next-generation computer model for Great Lakes hydrology. Key features of such a model would include:

(1) Available to entire user community--In the past, computer models of Great Lakes hydrology were developed, applied, and maintained primarily by federal agencies. These models have been used for forecasting and simulation. There are many other potential applications of Great Lakes hydrology models, including reliability-based coastal design, floodplain management, and maintenance of lake shore facilities. To realize these applications, however, it is imperative that next-generation hydrology models be distributed to all interested users in the Great Lakes community. To maximize program utility in the hands of the user, it is important that model results be displayed using intuitive visual formats to assist in interpreting output for research, consulting, or compliance needs.

(2) Linkage between deterministic and stochastic elements--Recent advances in deterministic modeling permit short-term forecasts of lake surges and wave effects over time horizons extending from a few hours up to a day. The deterministic approach solves the governing equations of motion subject to specified disturbances within well-defined lake boundaries. Concurrent progress in stochastic modeling provides long-term forecasts of mean lake levels and seasonal surges for time horizons extending from 1 month up to 1 year. The stochastic approach is based on time series models that preserve historical temporal and spatial correlations among supplies throughout the Great Lakes system. Both the deterministic and stochastic modeling approaches should be linked so that the best features of each can focus on a given problem. For example, generated sequences of stochastic disturbances could be used to drive a deterministic wave model. If this linkage were applied to a coastal design project, the range of model inputs and resulting model responses would provide the consultant with valuable insight about the performance of the proposed design.

(3) Valid over wide range of temporal and spatial scales--Problems associated with fluctuating Great Lakes water levels encompass a wide range of time and space scales. Next-generation models must be flexible enough to adequately describe transient hydrologic events on a very local basis and still capture persistent hydrologic behavior on a basin-wide scale. For instance, on a microscopic level, the hydrologic model must be capable of generating near-instantaneous, site-specific wave forecasts for local users. In comparison, on a macroscopic level, the model must be able to simulate long-term, system-wide water elevations to support regional optimization of lake regulation plans.

With the development of improved hydrologic models, statistics that reflect the level of model sophistication should be furnished to users. These statistics would

(1) be conditioned on present levels and existing climate regimes, and incorporate the concept of planning horizon;

(2) correctly compute the joint probability of the combined effects of mean levels, surges, and waves; and

(3) correct for physical trends such as crustal movement.

In view of rapidly evolving workstation technology, growing access to remotely sensed data, proliferation of geographic information systems, and advances in deterministic and stochastic analysis of lake levels, many of the essential elements needed to implement this modeling strategy already exist. These developments must be focused into a unified coherent modeling framework. This goal is within reach. Potential benefits to the Great Lakes community are great.

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Appendix A: Results of Data Generation Lake Erie Monthly Levels at Cleveland

Table A-1a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
January
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.82	174.80	174.54	174.36	174.26	174.67
780	174.61	174.60	174.44	174.27	174.26	174.46
520	174.56	174.54	174.39	174.27	174.22	174.46
390	174.49	174.47	174.34	174.26	174.22	174.34
312	174.44	174.41	174.31	174.23	174.20	174.31
260	174.43	174.36	174.28	174.20	174.15	174.25
222	174.39	174.34	174.25	174.17	174.14	174.23
195	174.32	174.31	174.22	174.14	174.13	174.23
173	174.31	174.30	174.20	174.13	174.12	174.22
156	174.29	174.29	174.19	174.13	174.11	174.22

Table A-1b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels. 1860-1989, in meters
January
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.38	173.37	173.30	173.22	173.22	173.34
173	173.37	173.37	173.30	173.22	173.19	173.33
195	173.35	173.35	173.28	173.20	173.18	173.32
222	173.34	173.33	173.26	173.19	173.17	173.27
260	173.30	173.29	173.23	173.17	173.15	173.27
312	173.28	173.27	173.20	173.15	173.12	173.26
390	173.27	173.25	173.16	173.11	172.95	173.16
520	173.22	173.22	173.13	173.07	172.87	173.13
780	173.20	173.20	173.10	173.00	172.85	173.03
1560	173.14	173.13	173.02	172.87	172.83	173.01

Table A-2a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in **meters**
February
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.82	174.81	174.57	174.36	174.23	174.60
780	174.65	174.64	174.44	174.29	174.22	174.60
520	174.57	174.55	174.39	174.28	174.22	174.51
390	174.48	174.47	174.36	174.28	174.20	174.46
312	174.46	174.41	174.32	174.25	174.20	174.36
260	174.41	174.36	174.30	174.22	174.18	174.36
222	174.38	174.34	174.27	174.21	174.16	174.31
195	174.33	174.31	174.24	174.18	174.15	174.28
173	174.33	174.31	174.21	174.15	174.14	174.25
156	174.30	174.30	174.20	174.13	174.13	174.21

Table A-2b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
February
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.35	173.34	173.27	173.19	173.18	173.34
173	173.34	173.34	173.26	173.18	173.14	173.33
195	173.33	173.32	173.24	173.16	173.13	173.33
222	173.32	173.30	173.23	173.16	173.12	173.32
260	173.29	173.28	173.20	173.12	173.11	173.29
312	173.27	173.26	173.18	173.11	173.09	173.29
390	173.23	173.22	173.13	173.07	173.03	173.11
520	173.22	173.22	173.09	172.33	172.89	173.03
780	173.16	173.15	173.04	172.97	172.72	172.99
1560	173.13	173.10	172.96	172.79	172.69	172.97

Table A-3a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels. **1860-1989,** in meters
March
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	175.05	175.04	174.69	174.46	174.35	174.68
780	174.76	174.72	174.56	174.41	174.33	174.61
520	174.67	174.62	174.50	174.36	174.33	174.60
390	174.65	174.60	174.46	174.35	174.32	174.59
312	174.58	174.53	174.41	174.31	174.28	174.59
260	174.48	174.47	174.37	174.30	174.23	174.56
222	174.46	174.44	174.36	174.29	174.22	174.50
195	174.43	174.42	174.33	174.27	174.22	174.43
173	174.41	174.39	174.30	174.24	174.21	174.37
156	174.40	174.39	174.29	174.22	174.20	174.31

Table A-3b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
March
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.44	173.42	173.33	173.26	173.23	173.41
173	173.40	173.39	173.31	173.24	173.22	173.41
195	173.40	173.37	173.28	173.20	173.20	173.40
222	173.40	173.36	173.26	173.19	173.19	173.39
260	173.39	173.35	173.24	173.18	173.17	173.39
312	173.33	173.31	173.22	173.15	173.13	173.38
390	173.33	173.30	173.20	173.13	173.10	173.19
520	173.31	173.25	173.15	173.08	172.97	173.15
780	173.28	173.22	173.10	172.92	172.86	173.09
1560	173.18	173.18	173.05	172.87	172.82	173.02

Table A-4a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in meters
April
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	175.12	175.11	174.82	174.59	174.49	174.79
780	174.96	174.89	174.69	174.58	174.48	174.76
520	174.85	174.79	174.63	174.52	174.48	174.74
390	174.76	174.73	174.60	174.50	174.48	174.71
312	174.69	174.68	174.57	174.49	174.46	174.65
260	174.65	174.64	174.52	174.46	174.38	174.61
222	174.59	174.58	174.50	174.45	174.37	174.55
195	174.57	174.57	174.48	174.43	174.36	174.52
173	174.56	174.56	174.46	174.40	174.36	174.47
156	174.54	174.54	174.44	174.40	174.35	174.47

Table **A-4b.** Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in meters
April
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.58	173.58	173.50	173.43	173.41	173.55
173	173.58	173.56	173.47	173.41	173.40	173.54
195	173.57	173.55	173.44	173.37	173.36	173.54
222	173.56	173.53	173.43	173.36	173.35	173.54
260	173.54	173.51	173.42	173.33	173.33	173.53
312	173.53	173.50	173.39	173.32	173.29	173.49
390	173.49	173.48	173.37	173.30	173.24	173.42
520	173.43	173.43	173.34	173.27	173.17	173.39
780	173.43	173.40	173.29	173.18	173.10	173.22
1560	173.37	173.33	173.21	173.02	173.01	173.19

Table **A-5a.** Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-l 989, in meters
May
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	175.07	175.06	174.86	174.65	174.61	174.78
780	174.94	174.92	174.75	174.60	174.57	174.74
520	174.90	174.86	174.70	174.57	174.53	174.73
390	174.75	174.74	174.65	174.57	174.53	174.71
312	174.73	174.72	174.63	174.56	174.50	174.62
260	174.73	174.70	174.60	174.54	174.50	174.61
222	174.67	174.66	174.58	174.52	174.48	174.58
195	174.66	174.64	174.56	174.50	174.47	174.53
173	174.63	174.63	174.54	174.48	174.46	174.51
156	174.61	174.60	174.53	174.47	174.44	174.50

Table A-5b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860.1989, in meters
May
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.70	173.69	173.61	173.52	173.52	173.65
173	173.68	173.66	173.59	173.52	173.52	173.60
195	173.65	173.64	173.57	173.51	173.50	173.59
222	173.64	173.64	173.56	173.50	173.49	173.59
260	173.64	173.64	173.55	173.48	173.47	173.54
312	173.62	173.61	173.52	173.46	173.45	173.54
390	173.59	173.56	173.48	173.42	173.39	173.50
520	173.58	173.54	173.46	173.40	173.33	173.50
780	173.55	173.54	173.41	173.33	173.29	173.32
1560	173.53	173.52	173.34	173.20	173.17	173.26

Table A-6a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly **Levels,** 1860-l 989, in meters
June
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	175.11	175.11	174.90	174.67	174.62	174.86
780	175.02	175.02	174.82	174.64	174.61	174.81
520	174.93	174.92	174.76	174.62	174.58	174.72
390	174.87	174.84	174.71	174.62	174.58	174.71
312	174.74	174.73	174.66	174.59	174.54	174.59
260	174.73	174.72	174.64	174.58	174.54	174.58
222	174.73	174.72	174.62	174.57	174.54	174.57
195	174.70	174.69	174.60	174.55	174.50	174.57
173	174.69	174.67	174.58	174.53	174.50	174.52
156	174.68	174.67	174.56	174.51	174.43	174.52

Table A-6b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels. 1860.1989, in meters
June
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.75	173.74	173.67	173.58	173.58	173.67
173	173.73	173.72	173.65	173.57	173.57	173.64
195	173.71	173.71	173.63	173.55	173.55	173.64
222	173.70	173.69	173.61	173.54	173.52	173.63
260	173.69	173.67	173.59	173.52	173.50	173.63
312	173.66	173.66	173.57	173.50	173.49	173.52
390	173.64	173.64	173.54	173.48	173.44	173.51
520	173.61	173.61	173.51	173.43	173.39	173.50
780	173.58	173.57	173.46	173.39	173.35	173.37
1560	173.56	173.55	173.40	173.27	173.20	173.27

Table A-70. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in meters
July
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	**Maximum**	**Upper 95% CL**	**Mean**	**Lower 95% CL**	**Minimum**	**Recorded**
1560	175.13	175.10	174.88	174.68	174.67	174.85
780	174.96	174.95	174.78	174.65	174.63	174.75
520	174.89	174.89	174.73	174.57	174.56	174.67
390	174.78	174.77	174.68	174.55	174.55	174.65
312	174.75	174.74	174.65	174.55	174.53	174.60
260	174.72	174.72	174.63	174.54	174.47	174.58
222	174.71	174.70	174.60	174.53	174.47	174.52
195	174.67	174.66	174.58	174.51	174.47	174.52
173	174.66	174.65	174.56	174.51	174.46	174.51
156	174.64	174.63	174.54	174.48	174.46	174.50

Table A-7b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-l 989, in meters
July
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	**Maximum**	**Upper 95% CL**	**Mean**	**Lower 95% CL**	**Minimum**	**Recorded**
156	173.75	173.73	173.66	173.61	173.57	173.66
173	173.74	173.72	173.65	173.59	173.57	173.65
195	173.71	173.70	173.63	173.57	173.55	173.63
222	173.70	173.68	173.61	173.55	173.53	173.59
260	173.67	173.67	173.58	173.52	173.52	173.59
312	173.65	173.64	173.56	173.51	173.49	173.51
390	173.63	173.61	173.54	173.48	173.46	173.48
520	173.63	173.58	173.51	173.44	173.40	173.48
780	173.61	173.56	173.48	173.39	173.30	173.41
1560	173.51	173.50	173.39	173.26	173.22	173.27

Table A-8a. Comparison of Statistics, Recorded **and** Generated **Data**

Cleveland Monthly Levels, **1860-1989,** in meters
August
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	upper 95% CL	Mean	**Lower** 95% CL	Minimum	Recorded
1560	175.01	175.00	174.78	174.60	174.56	174.76
780	174.89	174.87	174.69	174.58	174.57	174.66
520	174.81	174.79	174.63	174.49	174.47	174.57
390	174.72	174.70	174.60	174.49	174.45	174.55
312	174.65	174.65	174.57	174.49	174.44	174.52
260	174.64	174.62	174.55	174.48	174.43	174.51
222	174.62	174.61	174.52	174.46	174.41	174.51
195	174.61	174.61	174.51	174.45	174.40	174.50
173	174.59	174.58	174.48	174.42	174.38	174.46
156	174.57	174.57	174.47	174.40	174.38	174.45

Table A-8b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860.1989, in meters
August
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	upper 95% CL	Mean	**Lower** 95% CL	Minimum	Recorded
156	173.68	173.67	173.61	173.56	173.53	173.60
173	173.67	173.66	173.60	173.55	173.52	173.60
195	173.66	173.64	173.58	173.52	173.50	173.57
222	173.64	173.63	173.57	173.50	173.48	173.57
260	173.63	173.62	173.55	173.48	173.48	173.54
312	173.62	173.61	173.53	173.47	173.42	173.52
390	173.60	173.58	173.49	173.44	173.40	173.47
520	173.57	173.55	173.46	173.36	173.35	173.42
780	173.55	173.51	173.42	173.34	173.31	173.40
1560	173.50	173.45	173.33	173.19	173.15	173.24

Table A-9a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
September
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.95	174.92	174.70	174.53	174.44	174.64
780	174.77	174.76	174.60	174.49	174.44	174.50
520	174.66	174.66	174.54	174.42	174.42	174.48
390	174.64	174.62	174.52	174.42	174.39	174.47
312	174.61	174.59	174.48	174.41	174.38	174.44
260	174.56	174.54	174.45	174.39	174.37	174.43
222	174.52	174.51	174.42	174.37	174.36	174.41
195	174.50	174.50	174.39	174.37	174.34	174.38
173	174.50	174.49	174.38	174.34	174.33	174.38
156	174.47	174.47	174.36	174.33	174.32	174.36

Table A-Sb. **Comparison** of **Statistics,** Recorded and Generated Data

Cleveland Monthly Lev**els, 1860-1989,** in meters
September
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.60	173.59	173.53	173.46	173.45	173.54
173	173.59	173.59	173.52	173.45	173.45	173.52
195	173.58	173.57	173.50	173.45	173.43	173.51
222	173.56	173.55	173.48	173.44	173.43	173.47
260	173.54	173.54	173.47	173.42	173.37	173.46
312	173.54	173.52	173.44	173.40	173.36	173.44
390	173.53	173.51	173.42	173.37	173.33	173.43
520	173.48	173.48	173.39	173.33	173.29	173.34
780	173.47	173.42	173.35	173.24	173.21	173.30
1560	173.40	173.35	173.27	173.14	173.13	173.20

Table A-l 0a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
October
Statistics from the largest 10 events from 1000 sample of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.84	174.80	174.59	174.41	174.35	174.74
780	174.70	174.63	174.48	174.39	174.34	174.39
520	174.60	174.60	174.44	174.34	174.26	174.37
390	174.51	174.51	174.39	174.32	174.25	174.35
312	174.50	174.49	174.37	174.29	174.24	174.33
260	174.45	174.43	174.35	174.26	174.23	174.29
222	174.41	174.40	174.32	174.25	174.23	174.26
195	174.40	174.40	174.30	174.25	174.23	174.28
173	174.39	174.39	174.27	174.23	174.22	174.27
156	174.38	174.38	174.26	174.22	174.22	174.26

Table A-10b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860-1989, in meters
October
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.52	173.51	173.42	173.35	173.31	173.43
173	173.51	173.50	173.41	173.34	173.30	173.39
195	173.49	173.47	173.39	173.33	173.30	173.38
222	173.46	173.46	173.37	173.31	173.27	173.34
260	173.44	173.44	173.35	173.29	173.26	173.32
312	173.44	173.44	173.34	173.28	173.25	173.32
390	173.43	173.42	173.33	173.25	173.23	173.30
520	173.41	173.38	173.29	173.23	173.14	173.29
780	173.38	173.36	173.24	173.16	173.13	173.18
1560	173.32	173.32	173.17	173.02	173.01	173.11

Table A-11a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly **Levels, 1860-1989,** in meters
November
Statistics from the largest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.77	174.76	174.53	174.36	174.28	174.65
780	174.64	174.63	174.44	174.31	174.27	174.51
520	174.55	174.53	174.38	174.28	174.27	174.40
390	174.45	174.44	174.33	174.25	174.22	174.28
312	174.42	174.37	174.30	174.23	174.20	174.28
260	174.36	174.35	174.28	174.20	174.20	174.25
222	174.34	174.34	174.26	174.19	174.19	174.25
195	174.33	174.32	174.24	174.19	174.18	174.24
173	174.31	174.31	174.23	174.18	174.16	174.21
156	174.31	174.30	174.21	174.16	174.15	174.21

Table A-11b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, 1860.1989, in meters
November
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.42	173.41	173.34	173.29	173.26	173.36
173	173.40	173.39	173.33	173.27	173.24	173.36
195	173.37	173.37	173.31	173.23	173.22	173.31
222	173.36	173.35	173.29	173.23	173.14	173.30
260	173.35	173.34	173.27	173.21	173.11	173.28
312	173.33	173.32	173.25	173.19	173.08	173.23
390	173.31	173.30	173.21	173.16	173.05	173.21
520	173.30	173.29	173.18	173.14	173.01	173.20
780	173.28	173.27	173.14	173.05	172.99	173.15
1560	173.20	173.18	173.06	172.95	172.95	173.00

Table A-12a. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in meters
December
Statistics from the largest 10 events from 1000 samples of size 1580

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
1560	174.77	174.72	174.52	174.33	174.27	174.68
780	174.70	174.69	174.45	174.31	174.27	174.52
520	174.60	174.59	174.40	174.29	174.26	174.45
390	174.47	174.45	174.32	174.24	174.24	174.31
312	174.37	174.35	174.29	174.23	174.21	174.29
260	174.36	174.31	174.26	174.20	174.17	174.25
222	174.33	174.30	174.25	174.20	174.16	174.24
195	174.33	174.30	174.22	174.18	174.15	174.22
173	174.31	174.30	174.21	174.16	174.14	174.21
156	174.29	174.29	174.20	174.14	174.13	174.18

Table A-12b. Comparison of Statistics, Recorded and Generated Data

Cleveland Monthly Levels, **1860-1989,** in meters
December
Statistics from the smallest 10 events from 1000 samples of size 1560

Return Period	Maximum	Upper 95% CL	Mean	Lower 95% CL	Minimum	Recorded
156	173.39	173.39	173.33	173.23	173.23	173.32
173	173.39	173.38	173.31	173.23	173.23	173.31
195	173.37	173.36	173.29	173.21	173.19	173.28
222	173.34	173.34	173.27	173.20	173.19	173.26
260	173.33	173.32	173.24	173.16	173.09	173.26
312	173.31	173.31	173.22	173.16	173.07	173.20
390	173.31	173.30	173.19	173.13	173.05	173.18
520	173.30	173.29	173.15	173.05	172.99	173.17
780	173.23	173.22	173.10	173.02	172.92	173.15
1560	173.19	173.18	172.90	172.90	172.88	172.98

Appendix B: Net Basin Supply Data Provided by the U.S. Army Corps of Engineers

Lake superior
Monthly Net Basin Supply
(1000 Cubic **Feet** per Second)

Year	**Jan**	Peb	**Mar**	**Apr**	**May**	**Jun**	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1900	-22	44	-11	124	127	78	200	221	261	77	-7	-51
1901	-39	-9	52	121	126	197	187	86	13	98	-7	-29
1902	-35	11	40	129	167	171	108	75	71	58	58	-15
1903	-20	-57	94	146	290	94	164	97	113	47	12	-79
1904	-13	34	34	70	245	149	84	154	121	124	-31	-37
1905	-58	37	101	108	197	183	155	137	140	25	54	-18
1906	-20	26	-10	160	165	204	88	89	71	35	33	-22
1907	7	20	67	53	241	163	117	189	142	20	-16	-87
1908	-26	19	14	113	287	196	136	54	51	-3	-56	-10
1909	-34	27	3	104	242	80	204	93	59	25	86	7
1910	-17	-21	24	123	108	80	83	104	35	0	-2	-77
1911	-12	-18	-3	65	221	174	210	130	96	11	-8	7
1912	-28	20	36	189	161	165	98	136	53	54	-49	-2
1913	-73	-7	125	145	203	120	174	108	127	63	61	-43
1914	-31	1	-3	165	188	140	126	93	80	2	18	-100
1915	50	-1	-35	131	154	240	125	76	177	92	93	22
1916	20	2	36	277	268	216	115	104	149	51	-21	23
1917	-63	19	84	71	158	168	100	124	62	21	-20	-43
1918	-2	20	-13	115	218	163	113	103	40	103	63	24
1919	-20	15	5	154	139	104	77	42	59	-10	73	-42
1920	12	25	150	132	153	193	129	72	-8	51	-43	28
1921	-66	-7	48	198	176	82	115	61	37	-22	-57	-74
1922	-40	-5	49	171	189	137	126	67	32	-25	-44	-27
1923	-28	-37	33	100	107	103	129	72	58	46	-2	-28
1924	-34	-28	-3	127	76	94	120	148	76	29	-44	-69
1925	-20	-6	45	110	110	143	111	66	81	-31	-41	-37
1926	-19	-20	53	54	144	172	171	109	160	71	62	18
1927	-12	38	108	169	272	169	184	57	72	50	11	-3
1928	-2	4	56	168	194	216	167	154	138	148	-2	-35
1929	5	38	88	124	125	113	152	38	88	36	-2	-25
1930	-16	31	-3	97	176	209	144	28	54	15	5	-43
1931	-25	-44	-15	81	139	134	117	34	89	69	70	-4
1932	-8	25	-3	114	202	89	171	121	-22	4	5	-16
1933	-18	27	-4	163	238	117	107	44	85	42	8	-24
1934	20	6	47	117	203	121	108	64	170	55	102	-21
1935	19	-15	97	153	140	194	175	71	42	84	10	-6
1936	4	35	85	129	283	117	48	100	40	-14	-18	5
1937	10	85	-4	190	221	89	173	113	32	46	38	-27
1938	2	18	84	252	186	222	99	114	62	27	43	-7
1939	28	26	56	145	250	246	133	119	45	0	-25	-56
1940	-10	-20	-4	83	255	212	117	34	26	-3	34	-7
1941	-36	-9	-14	235	150	159	103	89	198	106	2	-5
1942	-16	-8	69	139	234	99	124	101	58	85	51	-34
1943	-6	19	50	124	261	296	116	109	22	21	-8	-71
1944	-31	-19	28	114	246	252	188	141	97	-34	52	-62
1945	-2	52	149	185	134	130	118	118	70	0	25	-27
1946	14	21	110	98	134	159	100	60	110	84	22	-26
1947	-35	-7	12	199	217	292	86	103	66	12	-17	-44
1948	-29	-19	41	272	89	93	103	120	0	-29	62	-25
1949	3	-7	23	115	184	178	178	48	28	82	-3	-19
1950	11	-6	59	150	354	224	189	121	75	90	67	-29
1951	-24	83	80	237	195	194	120	152	143	79	26	9
1952	7	-10	30	195	106	201	234	119	21	-90	5	-23
1953	-3	21	60	159	250	234	158	129	23	-14	-8	-6
1954	-11	30	3	226	267	203	85	46	53	16	16	-64
1955	-38	10	47	201	140	98	124	104	30	66	52	-43

Lake Superior
Monthly Net Basin Supply
(1000 Cubic Feet par Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	-1	-28	-15	114	212	124	162	78	36	1	-9	0
1957	-65	22	48	185	127	175	112	51	59	-18	57	-30
1958	-4	-8	11	101	90	158	153	101	88	8	40	-42
1959	-24	1	34	110	244	138	92	202	136	62	-33	-17
1960	2	-24	5	235	265	128	110	83	35	1	53	-71
1961	-25	40	66	120	166	106	88	32	88	51	-4	-7
1962	-51	44	30	94	217	97	85	110	72	-16	-41	-37
1963	1	0	71	142	128	198	80	86	46	4	8	-66
1964	15	-30	8	203	265	177	90	135	113	17	36	-12
1965	-18	19	48	152	253	131	119	118	133	65	87	17
1966	-4	14	100	137	193	112	108	146	3	76	9	4
1967	14	18	48	237	105	185	101	106	-11	68	-6	-22
1968	-22	-15	78	228	148	257	239	166	167	100	-39	29
1969	63	9	9	203	159	123	108	108	15	19	-3	-39
1970	9	7	15	172	271	138	167	50	77	103	77	14
1971	-40	87	52	175	237	162	113	83	60	115	40	-9
1972	16	14	77	153	198	118	173	200	104	-2	29	-17
1973	-20	6	130	116	215	152	135	143	40	43	-16	-18
1974	1	3	11	187	177	202	152	145	42	48	38	-8
1975	27	30	4	106	183	160	98	31	52	-11	108	-22
1976	-15	21	96	190	91	155	80	13	-50	-37	-57	-57
1977	-14	19	147	130	98	115	147	130	241	39	57	23
1978	-36	-15	25	87	179	143	160	152	77	-28	-12	-24
1979	-27	44	153	193	271	224	119	65	67	82	46	-39
1980	19	-3	0	150	113	115	103	126	117	26	-22	-59
1981	-32	84	64	207	124	225	60	60	-12	40	-18	-16
1982	-45	-7	44	163	226	87	219	96	111	165	67	52
1983	-9	13	56	150	173	132	118	87	51	103	80	-35
1984	-21	58	27	169	120	244	117	109	57	57	10	17
1985	-25	33	68	178	193	128	142	127	153	118	125	-19
1986	-27	28	88	204	98	161	158	89	98	35	-7	-43
1987	-28	0	17	58	130	74	138	69	4	-34	23	-15
1988	-24	-37	54	109	127	75	62	211	56	32	163	-20
1989	19	-17	57	136	207	185	67	87	-4	32	-36	-40

Lakes Michigan-Huron
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	NO”	Dec
1900	-1	162	60	246	175	156	268	145	78	73	56	-61
1901	10	27	284	230	223	175	208	79	-64	35	-74	48
1902	-12	52	212	207	257	272	276	8	45	-52	78	-45
1903	59	144	273	215	245	155	147	107	148	12	-51	4
1904	44	115	304	334	370	207	134	76	64	24	-68	-40
1905	**1**	79	254	190	337	286	181	82	27	-60	36	13
1906	169	122	149	255	215	214	103	5	32	3	80	41
1907	141	71	184	224	267	226	148	62	68	-44	-7	40
1908	3	125	210	288	389	187	192	-43	-45	-71	-86	-12
1909	57	116	126	384	343	207	126	36	20	-109	69	92
1910	69	55	162	298	194	138	76	76	56	24	13	-60
1911	91	82	114	266	293	187	61	47	78	83	92	95
1912	47	93	90	299	484	170	170	164	125	39	98	44
1913	66	59	272	395	306	172	143	43	-15	21	88	-55
1914	57	64	146	199	240	251	124	66	15	-9	-56	-49
1915	91	128	64	148	195	211	154	100	134	-73	80	7
1916	135	90	194	416	354	311	117	-25	10	42	25	114
1917	45	43	197	306	236	395	240	35	**3**	-32	28	-9
1918	96	187	264	235	374	146	129	50	**-30**	**63**	76	141
1919	25	50	260	302	309	106	104	-7	24	**80**	40	43
1920	-10	67	305	307	157	223	141	75	66	-5	-20	61
1921	74	34	258	383	147	135	49	73	55	-6	6	127
1922	-7	164	223	461	270	217	214	**4**	46	-95	26	-34
1923	5	40	191	308	306	208	108	**59**	83	**10**	-45	42
1924	-7	106	196	245	291	202	172	190	22	**-80**	-21	-68
1925	-1	93	183	150	71	195	121	-21	-7	-34	17	20
1926	34	80	141	292	250	277	133	100	80	60	161	**51**
1927	54	107	223	225	333	179	143	-38	52	3	91	**50**
1928	51	99	185	407	267	269	188	131	**48**	198	133	86
1929	124	47	317	474	401	225	124	29	**-35**	1	**-8**	-37
1930	**74**	182	143	200	240	242	143	-24	-62	-71	**-50**	-24
1931	**-29**	-9	121	132	192	156	62	-56	163	-25	149	-50
1932	208	73	59	180	236	116	109	46	-58	24	-16	94
1933	54	71	79	361	360	158	78	-57	-20	-22	-18	42
1934	77	-28	126	276	150	166	49	-33	143	-55	131	54
1935	29	114	192	174	137	242	110	8	0	-50	86	-39
1936	86	94	178	195	258	112	36	71	80	23	-80	67
1937	87	116	**40**	325	217	173	80	47	-1	-6	33	-32
1938	119	230	**310**	260	244	216	111	81	29	-65	-22	15
1939	36	124	122	297	236	257	80	91	-32	-51	-38	-22
1940	-22	28	44	195	291	264	124	127	54	-36	72	92
1941	71	46	44	293	169	120	89	-13	126	181	128	51
1942	53	52	274	220	323	236	106	-12	55	**28**	**54**	53
1943	68	149	241	276	363	398	170	84	-34	**-36**	**59**	-67
1944	41	65	152	189	223	254	92	-9	77	-58	14	-34
1945	6	67	221	230	304	298	135	41	82	29	70	23
1946	113	108	279	146	209	202	59	-15	-5	-30	-50	15
1947	45	47	107	447	395	279	152	53	32	19	-20	-89
1948	-1	89	298	291	229	158	91	-8	-81	-136	134	-16
1949	97	88	94	228	166	239	120	-49	-59	-41	-49	22
1950	160	99	198	343	215	229	163	60	26	-17	4	45
1951	105	141	228	490	200	183	223	102	18	151	110	90
1952	179	83	192	366	208	198	233	100	-61	-193	63	60
1953	56	107	228	261	230	246	112	67	-74	-37	-57	-17
1954	-17	130	162	344	228	317	113	40	78	256	53	23
1955	45	64	143	313	176	135	49	-19	-127	47	-13	-30

Lakes Michigan-Huron

Monthly Net Basin Supply
(1000 Cubic Feet. per Second)

Year	Jan	Peb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	25	61	144	262	317	179	170	132	-58	-34	-13	21
1957	-13	64	109	239	251	238	180	-11	15	2	69	92
1958	49	21	74	159	65	152	128	27	34	-36	-49	-43
1959	28	88	180	386	262	111	94	171	30	78	89	112
1960	103	108	75	424	496	266	193	98	-1	-60	75	-80
1961	-24	82	173	216	147	191	125	57	134	22	19	-10
1962	63	103	169	232	232	146	71	61	-6	-25	-64	-51
1963	-14	51	210	215	216	113	113	62	-4	-33	-37	-74
1964	19	-10	90	236	209	107	116	30	29	-82	13	2
1965	58	95	146	360	263	122	62	88	201	42	84	126
1966	38	98	254	205	150	134	38	12	-84	-55	148	134
1967	98	68	161	435	187	326	81	42	-18	54	81	148
1968	38	92	130	256	202	264	124	126	101	-42	21	78
1969	88	67	108	321	291	312	202	23	-88	55	59	-6
1970	46	29	119	282	283	225	226	-11	184	22	43	91
1971	40	139	206	323	212	176	133	56	20	21	-29	160
1972	-20	74	159	343	254	179	186	230	79	21	51	117
1973	130	82	336	299	381	250	104	126	-61	43	-4	45
1974	151	101	182	360	286	266	140	45	-20	-15	40	30
1975	51	158	171	273	275	240	94	91	16	-83	97	66
1976	18	184	399	308	260	172	98	-37	-78	-94	-22	-96
1977	-63	143	311	248	87	132	111	134	131	-28	117	104
1978	56	24	105	290	267	163	126	109	131	16	18	4
1979	74	64	369	412	294	229	94	168	-67	30	104	64
1980	71	42	98	342	184	227	137	134	26	-10	-10	5
1981	28	191	118	338	177	219	79	122	24	72	42	-17
1982	72	13	231	308	218	172	176	60	73	45	139	217
1983	66	94	197	276	408	181	75	57	12	28	56	32
1984	23	166	150	268	247	250	120	64	49	76	92	157
1985	62	192	359	419	249	114	109	118	93	59	180	58
1986	54	77	258	258	204	207	211	-5	375	118	-61	
1987	1	29	128	156	143	134	47	93	36	-62	53	1328
1988	36	65	143	312	123	50	59	29	20	21	246	28
1989	47	-10	211	214	215	238	49	23	-78	-14	23	-56

Lake St.. Clair
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1900	3	8	10	6	3	3	3	3	-1	-1	0	-2
1901	2	16	10	-7	-6	-2	1	1	-1	-1	0	6
1902	-6	6	1	-4	1	4	13	2	2	1	-2	9
1903	11	3	12	9	9	8	9	3	2	-2	2	20
1904	2	21	13	13	8	1	2	2	0	-1	0	6
1905	4	17	18	-2	4	6	6	4	1	2	2	2
1906	1	-6	3	-8	3	6	5	2	1	1	3	-1
1907	19	5	6	5	8	1	3	3	2	2	1	4
1908	6	17	15	8	10	6	4	4	-1	4	-1	0
1909	6	8	0	12	9	2	1	-1	-2	1	7	5
1910	16	0	-1	7	7	4	0	0	-1	1	2	3
1911	-4	8	0	2	2	2	-1	0	0	1	3	3
1912	4	0	7	9	10	4	5	3	3	3	4	3
1913	4	-2	6	17	10	2	0	-1	-1	2	5	-2
1914	7	5	2	-1	8	2	1	4	2	0	3	14
1915	-4	11	-10	0	7	2	5	6	3	-1	0	3
1916	17	7	-2	5	12	0	-1	2	0	1	0	11
1917	-8	0	-1	9	12	6	2	3	-4	4	4	1
1918	5	12	-5	20	12	2	4	2	4	2	4	4
1919	14	0	14	15	11	4	0	4	4	5	5	-4
1920	0	8	8	4	-4	2	1	2	-1	2	1	-3
1921	-1	-10	14	8	0	1	0	0	-1	4	-1	3
1922	12	4	10	1	-5	2	1	0	0	0	1	3
1923	9	2	8	4	2	2	1	-1	1	1	2	-5
1924	8	-2	2	0	2	3	1	0	0	1	1	6
1925	8	2	10	-7	-7	3	1	0	1	1	4	-9
1926	2	-2	9	3	3	-2	-2	-1	2	4	9	5
1927	-1	0	8	4	3	0	3	-2	-1	0	5	3
1928	17	18	4	-4	2	3	1	0	0	3	0	3
1929	13	3	10	22	15	8	8	1	-1	-2	0	7
1930	11	6	7	13	10	4	4	0	0	5	-3	0
1931	0	2	2	5	-2	0	1	-1	2	2	2	6
1932	3	8	-3	0	8	1	2	0	0	-1	1	17
1933	4	16	7	11	8	8	2	-1	-2	-2	0	2
1934	4	1	11	9	1	1	0	-2	0	-2	-1	4
1935	5	8	1	0	7	-3	0	0	-1	0	-2	-2
1936	4	5	2	-3	-2	0	-1	-1	3	-2	-1	0
1937	9	6	-1	17	5	2	0	-2	-5	0	-2	-1
1938	1	11	15	5	3	0	0	-1	-1	-1	0	1
1939	-3	7	10	12	1	1	-1	-3	0	-2	0	-2
1940	6	0	1	4	2	5	1	-1	1	1	6	8
1941	4	1	-4	-1	1	1	1	-2	0	0	1	-3
1942	4	2	4	5	3	4	2	0	2	-4	2	5
1943	12	4	17	4	21	7	9	2	1	2	1	-4
1944	1	-1	5	7	5	7	4	0	1	-1	-1	6
1945	2	-1	5	6	16	9	7	2	5	8	0	6
1946	5	9	9	0	3	7	2	1	-2	-1	-2	0
1947	10	2	6	30	14	12	8	8	4	2	-1	3
1948	9	10	19	8	15	6	6	4	2	-1	0	2
1949	12	18	4	7	3	1	0	-2	-1	0	-2	8
1950	20	14	18	22	5	4	4	0	3	3	1	8
1951	6	15	13	13	6	8	6	4	3	2	4	16
1952	18	11	15	13	6	4	5	4	4	-2	2	2
1953	1	4	10	7	5	6	6	2	0	-2	0	1
1954	-3	15	14	12	5	7	4	0	2	8	1	3
1955	10	7	14	8	4	4	5	0	6	6	2	6

Lake St. Clair
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	1	3	14	13	28	7	6	10	8	5	1	2
1957	2	2	4	10	8	2	9	3	6	2	2	7
1958	-9	4	7	-4	3	4	5	2	3	2	-3	7
1959	2	5	18	12	6	1	1	2	0	4	5	11
1960	9	8	6	20	6	8	0	1	0	-1	0	1
1961	0	7	7	12	6	4	3	3	2	0	1	3
1962	0	1	15	4	1	3	0	1	0	0	3	2
1963	1	0	12	8	3	3	2	0	0	0	-1	4
1964	2	3	9	8	4	2	2	3	1	-1	0	3
1965	5	13	14	15	3	1	2	1	1	1	2	10
1965	3	6	10	8	3	4	1	2	1	0	5	12
1967	6	4	13	15	3	7	4	2	1	6	5	14
1968	5	17	12	6	5	7	3	2	0	0	2	8
1969	9	12	7	12	8	5	3	0	-2	-1	3	2
1970	1	4	8	10	3	2	2	-1	0	1	2	6
1971	1	8	13	6	-1	1	-2	-1	0	0	-1	5
1972	5	2	13	12	3	1	2	2	0	1	7	9
1973	11	5	25	6	4	5	1	0	0	0	4	8
1974	16	11	15	11	8	1	0	0	-2	1	2	3
1975	9	11	13	12	1	3	-1	4	4	2	2	6
1976	2	19	22	7	6	1	6	1	0	1	1	2
1977	24	14	24	10	2	1	3	0	7	7	6	24
1978	8	13	17	20	5	4	1	2	3	0	0	9
1979	4	1	17	20	5	2	2	0	0	-1	6	9
1980	6	2	14	12	5	5	5	4	4	0	1	3
1981	1	19	5	9	5	4	4	3	8	12	5	5
1982	5	3	27	15	3	6	4	2	2	2	8	14
1983	7	9	7	12	12	5	4	6	3	4	5	15
1984	6	21	19	8	5	8	2	3	5	4	5	10
1985	9	17	25	14	3	2	3	3	3	6	19	10
1986	8	7	21	6	3	7	3	1	7	11	3	10
1987	5	2	11	8	2	1	1	1	2	1	5	13
1988	3	4	10	5	1	-3	1	0	1	3	8	4
1989	6	3	7	8	3	5	0	-1	1	2	5	2

Lake Brie
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1900	-9	61	**86**	48	25	12	5	-4	-39	-32	-8	-16
1901	10	-27	**60**	51	36	24	-7	-21	-41	-41	-21	0
1902	-4	-18	67	42	45	48	73	-35	11	-17	-16	8
1903	15	61	108	90	12	23	11	-5	-28	-33	-22	-42
1904	32	21	153	84	48	18	11	-18	-21	-34	-33	-24
1905	30	-8	57	59	65	55	2	-18	-18	-48	-4	-2
1906	37	8	32	54	17	23	**1**	-4	-25	-5	-3	53
1907	92	1	68	19	46	48	**9**	-31	4	-6	-18	34
1908	42	62	106	54	59	0	-2	-22	-37	-36	-67	-7
1909	15	91	52	62	96	42	-9	-15	-42	-46	9	-6
1910	0	37	80	66	40	4	8	-12	-18	-10	-11	-16
1911	34	29	33	71	21	12	-23	-3	2	-12	-16	51
1912	26	13	81	105	42	20	1	9	-3	-14	-38	-7
1913	123	36	182	87	23	11	2	-27	-34	-31	32	-8
1914	7	-1	59	74	94	7	-1	-9	-28	-35	-26	-24
1915	28	65	7	14	36	20	37	26	12	-30	-26	25
1916	85	25	90	74	72	54	-3	-41	-38	-37	-20	2
1917	32	1	68	82	69	75	38	-24	-16	6	7	-5
1818	-30	45	76	-28	32	**4**	-6	-20	-21	-7	-37	**48**
1919	-11	-3	92	53	90	**6**	-14	-14	-29	-7	-32	**-39**
1920	10	-26	54	95	31	33	10	-7	-30	-25	8	10
1921	25	33	89	88	23	14	-16	-18	-27	-20	20	8
1922	-13	24	79	101	56	14	-2	-21	-17	-45	-42	4
1923	19	-4	75	46	61	12	-4	-38	0	-51	-18	81
1924	24	**27**	59	84	54	60	4	-25	-3	-28	-36	13
1925	-11	**55**	76	30	7	14	-1	-6	6	-32	22	-24
1926	24	15	55	109	16	36	6	15	65	22	27	1
1927	12	**45**	96	39	69	23	20	-27	-18	-25	52	58
1926	28	**35**	36	54	22	74	22	-17	-45	-18	8	8
1929	37	32	92	121	49	3	1	-41	-27	-24	2	34
1930	121	50	62	47	6	23	-21	-30	-29	-36	-28	-1
1931	13	19	44	49	32	26	6	-21	-11	-27	-5	36
1932	93	37	26	49	57	12	9	-12	-35	-19	6	27
1933	40	10	76	72	71	-1	-15	-23	-20	-34	-26	18
1934	5	-8	28	64	10	9	-20	-16	-1	-55	-12	-10
1935	15	-15	61	17	42	22	7	-19	-37	-21	-19	12
1936	-45	11	110	48	17	1	-20	-28	-14	-20	-30	6
1937	117	61	12	124	35	87	27	6	-46	-21	-24	20
1938	10	101	78	56	35	26	16	-15	-15	-37	-21	-15
1939	24	36	71	86	16	28	4	-24	-37	-29	-29	-22
1940	-7	27	48	104	58	46	6	7	-18	-24	-20	58
1941	18	9	30	44	23	19	-2	-25	-42	-16	-9	2
1942	-7	57	104	70	55	24	17	-14	-21	-3	18	42
1943	10	47	**59**	67	136	40	29	-24	-30	-22	-16	-21
1944	-9	30	**58**	113	58	25	-29	-19	-9	-42	-15	-7
1945	-11	37	116	60	80	64	7	-27	27	9	-3	-6
1946	14	**5**	**71**	3	**54**	67	-6	-38	-26	-13	-19	**2**
1947	43	**-5**	**59**	142	**98**	71	0	8	-41	-8	-40	**30**
1948	-18	**41**	107	64	67	32	-9	-14	-38	-23	7	4
1949	56	**63**	50	41	41	20	-2	-28	-26	-18	-12	33
1950	137	67	105	93	26	26	11	-14	-15	-3	24	43
1951	62	82	88	74	45	27	-7	-30	-38	-23	9	24
1952	97	46	68	63	39	2	-21	-16	-36	-73	-8	17
1953	34	14	55	34	61	15	-13	-19	-49	-41	-11	-15
1954	17	62	76	106	8	10	-19	-16	-29	60	**-1**	19
1955	28	45	90	63	12	0	-10	-6	-35	-5	**-3**	5

Lake Erie
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	-36	47	103	79	106	28	15	24	-42	-23	-40	30
1957	22	51	35	127	46	51	26	-27	-12	-27	6	62
1958	8	12	36	50	22	40	33	2	-1	-32	-10	-9
1959	63	82	78	86	55	7	-6	-6	-38	0	3	57
1960	41	50	35	71	56	45	4	-4	-37	-54	-19	-30
1961	-6	47	69	132	38	36	17	4	-22	-46	-15	-13
1962	16	28	68	28	16	20	-15	-14	-27	-22	3	-2
1963	-9	0	119	51	21	4	-6	-18	-36	-32	-20	-20
1964	11	16	81	84	24	18	-7	1	-39	-41	-26	13
1965	34	58	70	56	32	8	-10	-9	-10	-21	-7	38
1966	-6	40	59	48	30	27	-3	-2	-40	-46	33	69
1967	18	17	55	60	53	27	2	-20	-21	-6	11	50
1968	50	40	53	34	68	42	7	-4	-20	-28	20	34
1969	56	30	26	106	90	45	58	-26	-30	-40	7	11
1970	-4	40	49	72	46	29	24	-31	-2	-3	3	22
1971	-8	76	53	23	36	23	-14	-4	-11	-36	-27	46
1972	-5	31	80	85	50	53	17	3	17	-18	49	62
1973	38	16	132	56	48	66	8	-11	-36	-19	-2	37
1974	54	52	95	60	68	31	-11	-18	-21	-47	34	37
1975	57	64	62	38	40	46	-14	49	-16	-18	0	52
1976	37	122	102	45	42	30	12	-24	-6	-23	-42	2
1977	5	33	97	90	30	28	20	33	60	-32	12	84
1978	22	14	116	84	58	28	-8	-9	-17	-14	-20	21
1979	26	46	91	104	48	29	8	8	4	-16	18	64
1980	4	13	98	74	34	47	30	31	-10	-44	-10	16
1981	-15	85	21	67	40	80	7	1	17	9	-4	18
1982	48	49	129	63	40	37	-2	-21	-5	-29	54	62
1983	12	22	46	80	74	27	23	-4	-37	-20	35	52
1984	14	82	80	60	84	31	-6	-4	-7	-19	-16	44
1985	12	87	113	50	22	16	2	-12	-26	-10	108	-4
1986	36	74	77	49	54	64	22	-23	27	16	-2	52
1987	15	19	42	55	26	35	14	-2	0	-25	-4	38
1988	17	46	44	40	18	-14	5	-21	-26	-18	22	14
1989	30	16	47	60	94	75	14	-20	-17	-19	-7	9

Lake Ontario
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	**Jan**	Feb	Mar	**Apr**	**May**	Jun	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1900	29	58	38	106	34	30	28	10	-1	-2	32	23
1901	24	4	79	153	54	64	26	18	10	-9	0	61
1902	28	8	128	64	45	55	77	23	2	0	15	**7**
1903	11	59	132	92	20	41	43	17	-1	20	-2	**-9**
1904	11	58	106	125	82	56	43	27	7	18	-20	-10
1905	22	-1	61	91	60	65	47	36	-3	17	6	30
1906	57	28	34	67	37	56	34	-3	-7	30	21	19
1907	72	10	61	57	57	37	30	10	11	15	35	45
1908	37	52	91	88	103	52	39	6	-7	0	-8	-13
1909	30	50	41	113	106	27	39	11	-9	-7	11	**8**
1910	23	29	85	76	64	30	23	20	8	**3**	8	**0**
1911	25	PO	42	76	43	44	14	4	11	**8**	10	39
1912	24	26	48	143	99	56	25	16	22	14	36	38
1913	110	1	111	82	51	34	12	11	-6	5	23	10
1914	15	15	70	111	59	29	12	17	4	-6	-2	-6
1915	40	62	36	44	31	27	25	56	15	3	-5	16
1916	59	26	50	128	94	104	19	-6	-9	-5	1	4
1917	7	30	88	102	34	76	54	**2**	-1	32	7	15
1918	-3	60	96	86	44	39	26	**6**	22	33	17	35
1919	29	26	62	92	118	40	26	8	-3	6	5	3
1920	0	14	85	58	23	27	36	8	3	13	15	54
1921	23	31	96	66	45	19	9	-11	-10	-2	17	13
1922	4	47	72	130	44	62	37	5	2	-7	-5	-7
1923	24	18	73	75	56	54	9	10	6	1	14	36
1924	40	23	52	91	88	36	30	17	16	-2	-11	-5
1925	11	75	103	57	**38**	29	25	1	27	11	49	31
1926	19	28	59	122	**56**	45	20	32	36	34	64	27
1927	32	39	95	39	60	37	37	-4	-1	13	64	72
1928	65	49	58	97	50	56	42	25	-7	20	30	41
1929	52	27	98	132	91	33	29	**-4**	**-2**	5	14	**9**
1930	69	59	92	67	58	43	22	**-6**	**-3**	-19	-2	**-5**
1931	7	17	49	54	62	35	24	-10	7	-3	10	23
1932	81	54	44	108	55	25	29	18	-12	8	34	28
1933	32	16	49	105	49	20	3	6	-8	-21	2	15
1934	44	10	66	94	29	34	7	-20	27	-20	19	9
1935	44	31	64	44	52	53	30	-10	-1	-6	9	13
1936	18	24	164	107	40	23	6	1	11	9	14	21
1937	93	49	28	94	67	40	11	9	-18	14	24	15
1938	28	82	82	68	36	20	25	5	21	-7	0	5
1939	21	43	71	114	43	26	17	8	-16	-4	-15	2
1940	8	19	26	141	74	47	35	-7	4	-10	21	50
1941	35	23	35	76	22	16	22	-6	3	9	14	24
1942	18	29	118	84	64	33	25	1	10	5	28	36
1943	46	54	90	87	158	63	27	17	-2	13	23	-7
1944	12	28	52	90	62	53	21	-4	6	-13	1	16
1945	22	31	124	89	100	56	39	4	36	54	37	43
1946	31	40	80	29	49	38	12	1	6	22	16	22
1947	66	41	75	139	108	113	61	12	-4	-6	7	11
1948	16	40	110	88	73	42	22	3	-13	2	25	4
1949	53	59	53	75	34	20	7	-16	3	0	-2	38
1950	80	42	68	114	38	37	24	16	-8	17	34	45
1951	52	68	103	142	51	47	45	1	5	0	27	40
1952	63	49	79	104	71	30	15	2	1	-20	10	27
1953	33	29	81	53	94	30	17	4	-2	-13	0	18
1954	16	78	79	115	63	44	3	5	10	33	34	25
1955	35	27	106	101	37	18	6	16	-11	67	17	5

Lake Ontario
Monthly Net Basin Supply
(1000 Cubic Feet per Second)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	21	29	77	128	104	37	22	22	0	-1	-4	28
1957	29	37	57	63	45	46	22	-15	6	-22	9	34
1958	12	21	54	75	37	35	17	3	21	-2	14	12
1959	31	43	73	130	56	26	25	-1	-12	12	20	66
1960	37	61	34	157	87	51	11	1	-21	-11	-7	-15
1961	-6	37	68	85	61	51	22	1	-9	-17	4	7
1962	15	26	56	82	38	17	6	14	1	8	19	8
1963	0	7	69	93	59	16	10	15	-14	-12	21	13
1964	21	15	79	82	47	23	13	10	-20	-17	-4	15
1965	18	52	49	81	39	23	10	12	11	8	42	50
1966	27	45	91	48	32	29	-2	3	-4	-11	30	42
1967	34	16	38	80	52	37	21	4	11	31	57	45
1968	32	24	75	56	52	46	18	9	16	4	53	45
1969	48	30	49	110	78	56	25	-4	-16	-2	22	26
1970	15	40	53	95	53	33	36	-2	9	25	31	45
1971	11	53	79	111	66	35	14	18	8	5	2	38
1972	26	34	72	119	86	74	64	28	7	10	57	78
1973	57	52	122	111	72	54	14	3	-4	20	25	60
1974	58	43	68	106	91	46	32	10	0	0	33	44
1975	44	43	84	82	54	50	4	8	20	20	23	41
1976	32	74	134	99	97	71	52	18	11	28	10	16
1977	-3	17	125	86	27	25	23	34	46	46	72	89
1978	74	38	79	128	62	27	6	14	12	3	7	31
1979	68	30	123	118	56	30	14	12	22	22	34	57
1980	22	5	86	117	40	41	39	2	-2	8	30	38
1981	6	98	51	52	44	38	25	22	40	44	52	27
1982	22	20	80	100	49	67	14	8	20	1	48	55
1983	30	39	54	94	94	22	6	11	-9	0	30	72
1984	22	88	58	123	83	46	17	20	10	0	12	46
1985	37	55	107	66	42	30	18	2	14	16	87	30
1986	49	43	96	91	54	63	47	31	71	55	40	78
1987	42	24	77	103	32	44	17	-11	26	1	33	48
1988	17	41	52	72	43	16	21	0	0	11	40	12
1989	13	11	51	73	86	71	4	2	7	16	44	10

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