A Reconstruction of Lake Michigan–Huron Water Levels Derived from Tree Ring Chronologies for the Period 1600–1961

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ABSTRACT. *A dendrochronolgy of annual precipitation and air temperatures from six Great Lakes locations was used to reconstruct Lake Michigan-Huron water levels from 1600–1961 representing the present St. Clair River channel conditions and basin land cover. The reconstructions are based upon a multi-linear regression model relating multi-year annual precipitation and air temperature to annual water levels. An increased frequency of low lake levels was found to occur prior to the twentieth century, accompanied by a major extreme in water levels, greater than that experienced in the historical record, in the early 1600s. The comparison of simulated and measured water levels also indicates that the impact of some of the channel changes in the St. Clair River may be underestimated and that the major drop in lake level in the 1880s may be due to erosion as well as to decreased precipitation. The occurrence of extreme levels around 1640, in 1838, and in 1986 suggests a return interval of 150–190 years for extreme lake levels. The analysis also suggests that the variability of lake levels has greatly decreased over the last century when comparing tree-ring-derived level variability. Thus climatic periods used for the development of the current regulation plans may not be representative of the longer-term climate and lake levels.*

INDEX WORDS: *Lake levels, tree rings, climate change, lake regulation.*

INTRODUCTION

The Laurention Great Lakes (Fig. 1) comprise the largest surface fresh-water resource in the world. They contain approximately 20% of the global fresh-water supply and 80% of the U.S. fresh-water supply. The recent low lake level episode, which began with the 1997–1998 El Niño, focused increased attention on Great Lakes water resource planning. The increased emphasis has resulted in one major study underway on Lake Ontario (IJC 2003) and a likely future study to look at water management in the upper Great Lakes. These studies require the assessment of potential future and past water supplies and levels outside of the past 145 years of recorded levels to provide robustness for future water management plans. The recorded levels may not necessarily be representative of the

last 4,000 years during which the Great Lakes have been in their present hydraulic configuration, or the future under climate change. For example, (Fig. 2) the water supply sequence from 1860–1953 used to develop the Lake Ontario regulation plans is greatly different than the water supplies experienced since the plans were put into effect around 1960. Prior studies to extrapolate lake levels beyond the recorded data include climate transposition (Croley *et al.* 1998, Kunkel *et al.* 1998, Quinn *et al.* 1997), stochastic analysis (Lee *et al.* 1994) , climate change (Lofgren *et al.* 2002, Mortsch and Quinn 1996), and paleo lake level analysis dating submerged tree stumps and paleo-beachheads (Baedke and Thompson 2000, Sellinger and Quinn 1999). The paleo levels preferentially record high lake levels with multi-decadal to century scale over the past 4,500 years with an inferred magnitude of low stands. A second source of paleo data which can be used for lake level reconstructions are tree ring data. Tree rings have been used in hydroclimatic studies such as reconstructing streamflow (Cook and Jacoby 1983), precipitation estimates (Gray *et*
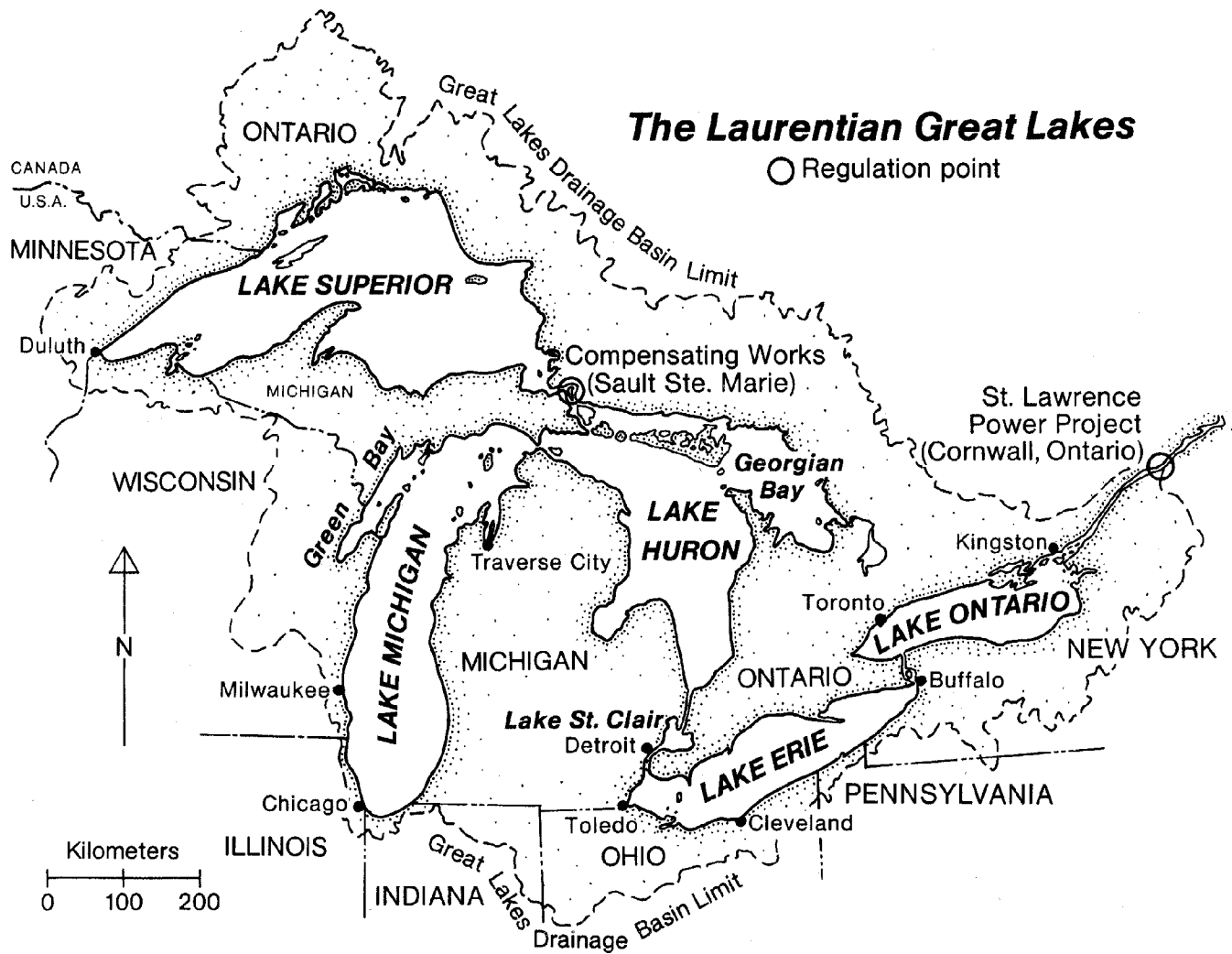
FIG. 1.   The Great Lakes basin.

al. 2004, Fritts and Gordon 1980), drought reconstruction and variability (Cook *et al.* 1999, Woodhouse and Overpeck 1998, Cook *et al.* 2004, Fry *et al.* 2003), and for reconstructing Lake Superior water supplies (Brinkmann 1992). Based upon these analyses, tree ring data should be beneficial in reconstructing low lake levels. This study uses a set of precipitation and temperature reconstructions based upon tree ring analysis from six Great Lakes locations, to infer Lake Michigan-Huron water levels from 1600–1900 based upon the present St. Clair River hydraulic conditions and basin land cover. Lake Michigan-Huron was selected as the focus because it is unregulated, has a good distribution of tree ring sites, and in the last low water

episode fell over 1.2 m, the largest water level decline of all of the lakes.

DATA AND METHODOLOGY

The approach consists of relating Lake Michigan-Huron annual water levels to tree-ring-derived annual precipitation and air temperature time series by means of multilinear regressions as shown in equations (1)–(3). Water levels from 1602–1961 will be derived with this model using the tree-ring-derived precipitation and temperature inputs. Finally, the modeled water levels (1600–1859) will be compared to both the measured and modeled annual water levels (1860–2002) to identify trends and differences.
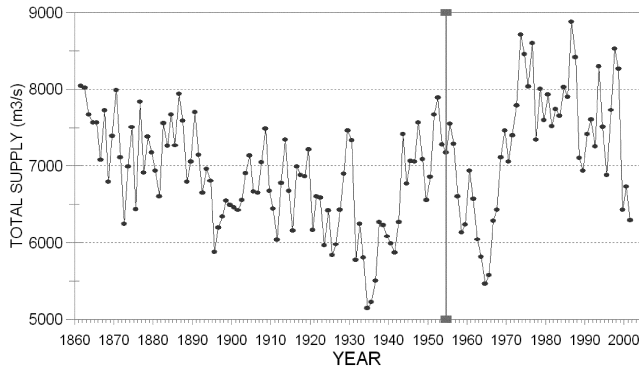
FIG. 2. *Lake Ontario net total water supply.*

$$\Delta L = \sum_{0}^{n} w_i P_i + \sum_{0}^{m} a_i T_i + C \qquad (1)$$

$$L_t = L_0 + \sum_{1}^{t} \Delta L \qquad (2)$$

$$L_t = \sum_{0}^{n} w_i P_i + \sum_{0}^{m} a_i T_i + C \qquad (3)$$

where: ΔL is the difference between annual lake levels at times t and t-1 and has units of mm/year.

L_t is the annual lake level at year t.

w and a are regression coefficients

n is the number of annual lags used for precipitation

m is the number of annual lags used for air temperature

C is a regression constant.

The rationale for this approach is the hydrologic cycle for Lake Michigan-Huron as expressed in general terms by Equation (4).

$$P + R + Q_{in} = E + Q_{out} + D \pm \Delta L \qquad (4)$$

where: P is the precipitation on the lake surface in mm

R is the runoff into the lake in mm on the lake surface

Q_{in} is the St. Marys River inflow in mm on the lake surface

Q_{out} is the St. Clair River outflow in mm on the lake surface

E is the evaporation from the lake surface in mm

D is the Lake Michigan diversion at Chicago in mm on the lake surface

ΔL is the change in water level in mm

Monthly and annual data for precipitation, runoff, evaporation, air temperature, St. Marys River and St. Clair River flows, and the Lake Michigan diversion at Chicago for Lake Michigan-Huron are available from the Great Lakes Data Base (Croley and Hunter 1994). The period of record in the data base varies depending upon the parameter ranging from a beginning year of 1860 to a beginning year of 1948. Annual tree-ring-derived precipitation and temperature time series for six Great Lakes stations for the period 1602–1961 were obtained from Fritts (1991). The tree ring data were calibrated with nearby meteorological stations as per Fritts *et al.* (1971). The six tree ring sites are located near Alpena, MI, Chicago, IL, Detroit, MI, Indianapolis, IN, Madison, WI, and Marquette, MI. All stations have derived precipitation time series, but only Alpena, Madison, and Marquette have derived air temperature time series. The lake level data consist of annual means for the Lake Michigan-Huron water levels at Harbor Beach for the period 1860–1999 (National Ocean Service 2002). Table 1, based on Croley and Hunter (1994), gives the statistics for the hydrologic variables important in the water supply.

Both precipitation and temperature play major roles in the rising and falling of Great Lakes water levels. Precipitation plays a direct role in the water balance and also provides the moisture for runoff. Air temperature plays an indirect role by influencing runoff and evaporation. High temperatures in the summer and fall decrease runoff through evapotranspiration while influencing evaporation through changes in the vapor pressure gradient. A major contributor also is the upstream Lake Superior

TABLE 1. *Hydrologic variables. Statistics for period 1954–2003 for annual values in mm on the lake or average annual value in °C.*

Parameter		Average	Std. Dev.	Coeff. Variation
Precipitation	mm	826	82.7	0.14
Runoff	mm	714	118.9	0.17
Evaporation	mm	629	81.3	0.13
St. Marys flows	mm	586	118.9	0.14
Air Temperature	°C	6.3	119.3	0.11

TABLE 2. *Correlation matrix (r) of the annual hydrologic variables, 1954–2003 where QSM is the St. Marys River flows.*

	P	R	E	T	QSM
P	1.0	0.48	−0.61	0.22	0.20
R		1.0	−0.23	−0.20	0.46
E			1.0	0.10	−0.19
T				1.0	−0.43
QSM					1.0

TABLE 3. *Correlation matrix (r) of the 3-year moving average hydrologic variables, 1954–2003.*

	P	R	E	T	QSM
P	1.0	0.67	−0.38	0.33	0.33
R		1.0	−0.26	−0.11	0.49
E			1.0	0.36	−0.37
T				1.0	−0.47
QSM					1.0

water supplies, reflected in the St. Marys River inflows.

To assess the feasibility of this approach, we first analyzed the measured hydrologic data on an annual basis for the period 1954–2003. This is the primary period of record for the air temperature and evaporation data. The correlation matrix between the hydrologic variables is given in Tables 2 and 3 for annual means and 3-year moving averages respectively. The tables and subsequent regressions indicate no significant relationship between annual air temperature and evaporation or runoff. This analysis confirms that evaporation responds primarily to seasonal and not annual air temperatures. The 3-year moving average of precipitation has a much higher correlation with runoff and St. Marys River flows than the annual values, reflecting the probable impact of antecedent basin conditions. The 3-year moving average of evaporation also has a much higher correlation with air temperature. This may be due to residual heat storage or to the seasonal overlapping of the calendar years. The lake outflow through the St. Clair River can also be viewed as a function of the multi-year precipitation time series as the river flow is a function of the lake level. The variability in diversions will be accounted for in the adjusted lake levels used for calibration. Based upon the above analysis, we would expect the lake level represented in equation (1) to respond primarily to a multi-year sequence of pre-

cipitation with little improvement to be achieved by adding annual air temperatures.

It is found that for the lake level for the period 1954–present, the regression representing equation (1) can be adequately expressed in terms of the present year's precipitation plus four annual lags and the present year's temperature plus one annual lag. The regression coefficients were significant at the 0.05 level and have an r^2 and standard error of 0.70 and 0.13 m respectively. The lake levels were reconstructed using the computed deltas and the 1956 water level elevation. The regression representing equation (3) for the present regime can be adequately expressed in terms of the present year's precipitation plus three annual lags and the present years temperature plus two annual lags. It had r^2 and standard error values of 0.73 and 0.22 m respectively. Equation (5), a regression using precipitation alone ($r^2 = 0.71$, SE = 0.22m), also represented the measured levels as well as did the regression incorporating both precipitation and air temperature. This is consistent with the previous correlation analysis. A multi-year precipitation index has previously been found to be a good simulator of Great Lakes annual water levels (Quinn 1991). However, the equally good statistics for equation (1) are misleading. Figure 3 clearly shows that the regression representing equation (3) does a much better job in representing the measured lake levels. This is because all errors in the deltas accumulate as is shown by equation (2) as compared with equation (3). As the addition of annual air temperature does not increase the correlation or re-
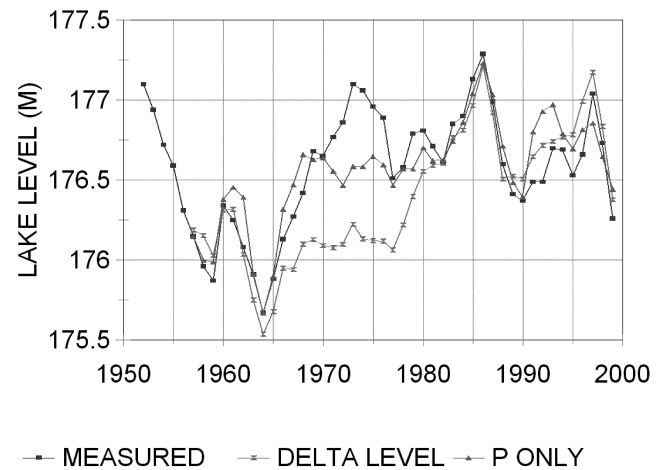

FIG. 3. *Lake level simulation used recorded precipitation and air temperature data.*

TABLE 4.   Tree ring statistics, 1931–1961 for precipitation data and 1948–1961 for temperature data. The measured data are the average over the entire Lake Michigan-Huron drainage basin.

Variable	Alpena	Madison	Marquette	Indianapolis	Chicago	Detroit	Meas.
P mean (mm)	685	765	791	977	827	781	801
P std (mm)	29	42	31	56	45	39	79
T mean (°C)	6.3	8.0	5.7				6.42
T std (°C)	.26	.26	.21				.59

duce the standard error, equation (5) will be used in the tree ring analysis

$$L_y = .0009361P_y + .002572P_{y-1} +$$
$$.001940P_{y-2} + .001103P_{y-3} + 170.92 \quad (5)$$

where: y is the current year
L is the lake level in m.

Tree Ring Analysis

The basic statistics for the tree ring proxy precipitation and air temperature data for the fairly stable lake levels regime of 1930–1961 and the equivalent recorded data are given in Table 4. This period was chosen for the regression model calibration because it includes Lake Michigan's record low level of 1934 and the then record high levels of 1952, thus capturing historical extremes. It also minimizes the impact of channel dredging in the St. Clair River (Brunk 1961, Derecki 1985, Quinn *et al.* 1993), and it corresponds with a historically high number of precipitation stations in the basin used to construct the basin-wide means. The channel dredging has resulted in an estimated progressive lowering of Lake Michigan-Huron with time, about 25 cm since 1900 (Derecki 1985, International Joint Commission 1987). There was also an additional lowering of 11–21 cm prior to 1900. Measured basin temperatures are compared for the period 1948–1961 due to the limited historical time series. Table 4 shows good agreement for the means of the tree rings for both precipitation and air temperature while the variability of the tree ring data is greatly reduced. This could hamper the effort to model lake level extremes. It is desirable to adjust the tree ring data to the measured basin-wide averages which are used in most water resource studies, whereas the tree ring data are based upon the meteorology at a limited number of locations and may not be representative of the basin as a whole. We will also be applying the adjusted tree ring data to equation (5)

and comparing the results with the tree-ring-derived equations.

Two methods of combining station data, using the mean of the stations and a multiple regression of the basin data vs. the individual tree ring stations, were assessed for agreement between the historical precipitation and temperature time series and the equivalent tree ring data. A multiple linear regression using precipitation data from the individual tree ring sites gave a higher correlation and lower standard deviation than using the mean precipitation. However, the two methods gave greatly differing values of precipitation and lake levels prior to about 1910. Therefore it was decided to develop separate linear regression equations relating the tree ring precipitation to the measured precipitation for each of the tree ring sites. The sites near Indianapolis and Chicago gave significantly lower correlations for precipitation than the other four sites and will not be used in the analysis. This could be due to their location on the periphery of the basin. The air temperatures were derived from the regression in equation (6) relating the measured over land air temperatures with the mean of the three tree ring stations. The output statistics for these equations are given in Table 5.

$$T = 1.512*(T_{Alpena} - .T_{Madison} + T_{Marquette})/3 - 4.77 \quad (6)$$

Comparisons of the final average proxy tree ring precipitation for the six stations, and air temperature data with the basin historical data, are shown on Figure 4 and Table 5. Figure 5 presents the complete simulated precipitation and air temperature time series.

Lake Level Analysis

As the emphasis in this study is lake levels, the final step in the procedure was to relate water levels to the tree-ring-derived precipitation and air temperature time series through a multi-linear regression. The lake levels used in the regression are the

TABLE 5.   *Comparison of tree-ring-derived data with the measured basin data for the calibration period.*

Variable	Measured	Equat. (4)	Equat. (5)	Equat. (6)
P mean (mm)	801	801		
P std (mm)	79	56		
T mean (°C)	6.42		6.42	
T std (°C)	0.59		0.35	
L mean (m)	176.20			176.20
L std (m)	0.35			0.25

measured annual levels at Harbor Beach, Michigan corrected for the effects of sand and gravel, and navigation dredging projects. The correction factors are: –0.13 m (1938–1961), –0.18 m (1925–1937), –0.27 cm (1907–1924), and –0.43 cm (1860–1906)

(International Joint Commission 1987). These corrections were necessary to adjust historical lake levels to reflect the current hydraulics in the St. Clair River. In addition to equation (5), derived using measured data, it is desired to derive a similar equa-
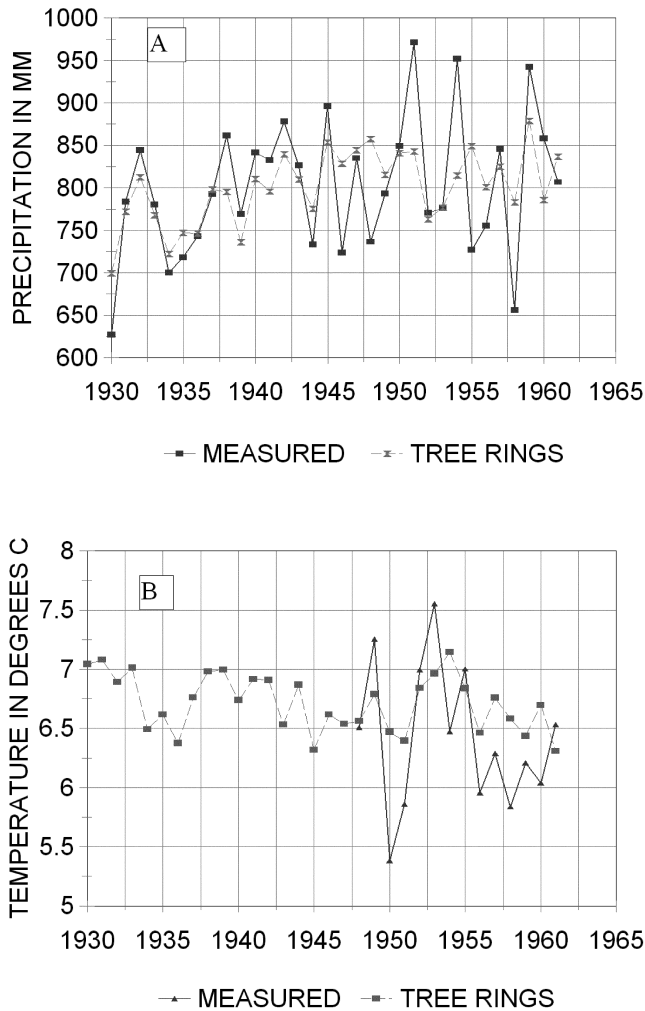
FIG. 4.   *Comparison of simulated four station average precipitation (A) and air temperature (B) with the measured basin data.*
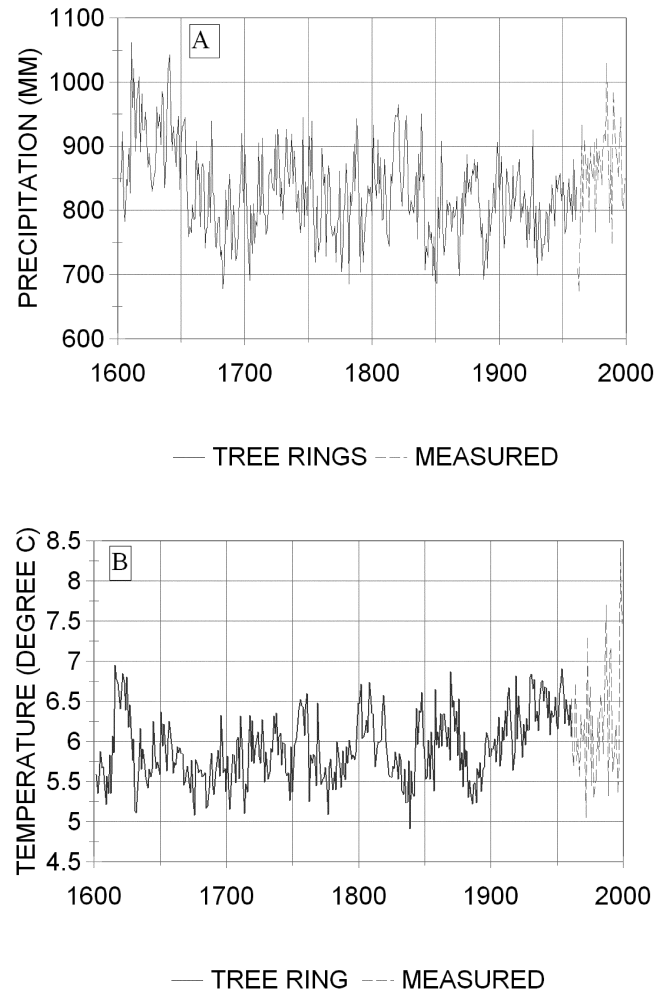

FIG. 5.   *Simulated precipitation for four station average (A) and air temperature (B) time series 1602-1961. Measured data are shown between 1962 and 2000.*
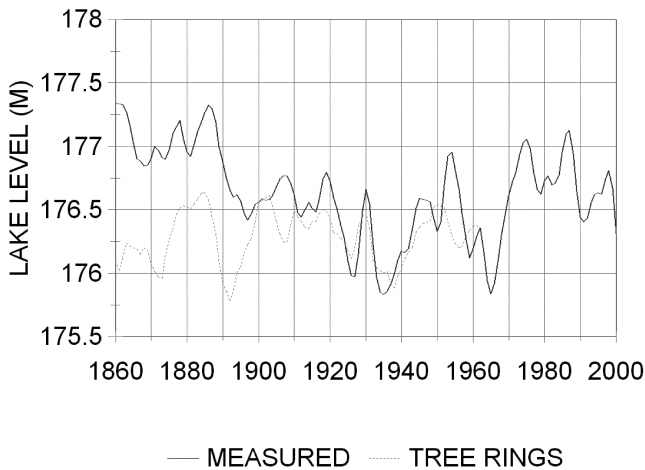
FIG. 6. *Comparison of tree ring generated lake levels with recorded levels. A 3-year moving average.*

tion relating the lake levels to the tree-ring-derived precipitation. In this study, a regression using the prior 4 years of tree ring precipitation explained about 42 percent of the lake level variance with a standard error of 0.29 mm and which represented both high and low levels. Adding air temperature resulted in an unrealistic regression with water levels increasing as air temperatures rise.

The final equation is:

$$Ly = .0025644P_{y-1} + .00017398P_{y-2} + .0026738P_{y-3} + .0019975P_{y-4} + 168.98 \quad (7)$$

where: y is the current year.
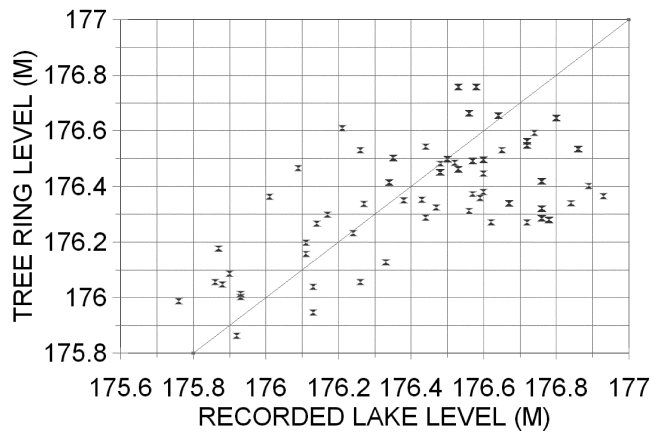
Equation (7) is compared with the measured lake

FIG. 7. *Scatter diagram comparing recorded and tree ring generated levels for 1900–1961.*

levels in Figure 6. Equation (7) accurately replicates the low lake levels in the 1920s and 1930s but does not replicate well the extreme high levels in the late 1920s and the early 1950s. Figure 7 shows a comparison of the tree-ring-based levels and the recorded annual levels for 1900–1961. It may be that tree growth responds more to drier or drought conditions than to extreme wet conditions or flooding and thus may provide more insight into past low levels than high ones. Also the upstream influence of water coming down from Lake Superior may not be well represented in the model.

RESULTS AND DISCUSSION

Most of the analysis is expressed in terms of longer-term running averages of the mean and standard deviation as per Changnon (2004). The tree rings by their nature are more indicative of multi-year averages of precipitation and air temperature because of the integrating effect of several years of climate on an individual tree ring (Fritts 1991). There are several interesting results from this study in terms of both climate and lake levels. From a climatological perspective the air temperature time series, Figure 5b, shows that the air temperatures for the period 1602–1899 averaged about 0.5°C below that of the twentieth century. This shows the impact of the latter part of the northern hemisphere's little ice age. The twentieth century, which serves as our base climate for most water resource studies, has the highest temperatures of the past 400 years. This could be due to natural climate variability or the beginning of global warming. Under the cooler conditions of the earlier time period we would expect higher lake levels, for a given amount of precipitation in the past, because of less evaporation and evapo-transpiration. Figure 5a shows that the last half of the twentieth century experienced much higher precipitation than occurred over the prior years. Thus, in general, we would expect lower lake levels under the present connecting channel hydraulics in the past than those experienced over the past 50 years. Of particular interest are the seven low precipitation episodes equivalent to the mid-1930s episode (Fig. 8). This episode resulted in record low lake levels on Lake Michigan-Huron. This would indicate a higher frequency of low lake level events in the past than we experienced in the twentieth century, which would increase the emphasis on water resource planning for low lake levels. The precipitation time series shows two very high prior precipitation episodes: 1610–1650 and
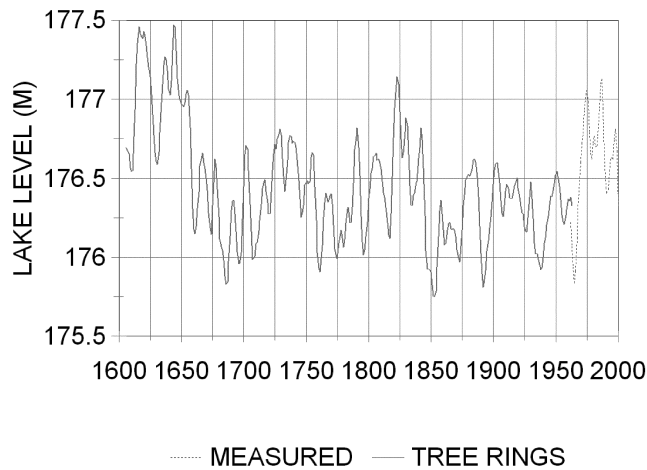
FIG. 8.   Simulated four station average lake level time series, 1602-1961. A 3-year moving average. Measured data are shown between 1962 and 2000.

1820–1840. The latter period corresponds to the record high lake levels set in 1838 (Quinn and Sellinger 1990). The early 1600s episode is remarkable for both its magnitude and duration, lasting approximately 40 years. A recurrence of this type of episode would likely cause severe water resource problems including flooding and shore erosion throughout the Great Lakes St. Lawrence system. The high precipitation regime of the mid 1880s does not appear to be as extreme in the tree ring precipitation series as in the measured series. It should be noted that there were few precipitation stations available during this period, which could have a significant effect on the basin-wide estimates. Figure 9a also shows that the precipitation variability from about 1860–1960 is considerably less than for the prior years. The air temperature variability, Figure 9b, corresponds with that shown over the earlier period of the record. In general, the precipitation for the 1860–1953 period used in the design of the regulation plans is within the bounds of that experienced over the past 350 years but with a lower frequency of low events and nothing on record corresponding to the early 1600 highs. The air temperatures are well above those recorded in the prior 300 years. It should be noted that the final years of the twentieth century were the warmest ever recorded on a global and U.S. basis.

The lake level response to the temperature and precipitation time series is shown in Figures 8 and 10. It shows that the high water levels of the past 30 years are atypical of those occurring over the prior
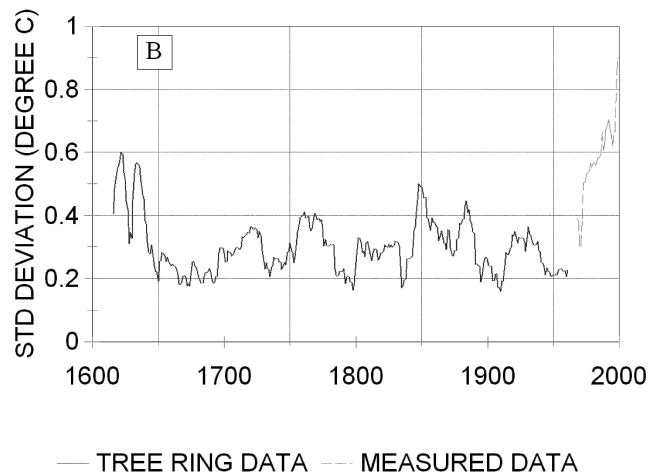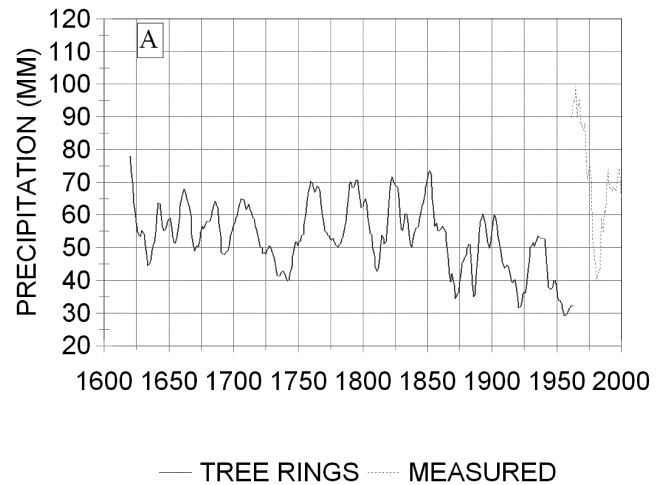

FIG. 9.   15-year moving standard deviation for (A) precipitation(mm) and (B) air temperature (°C) . Measured data are shown between 1962 and 2000.

300 years, under the present system hydraulics. The extreme high-level episode of the 1600s, with water levels peaking about 0.5 m above the 1986 highs, would cause widespread damage to a large number of Great Lakes interests if it were to occur at the present time. It also implies that the record high water levels of 1838 are equivalent to those of 1986 when the channel dredging in the Detroit and St. Clair rivers is taken into account. The frequency of low lake levels during the twentieth century is also much lower than for the first 300 years of the record. This is important because it is much harder to develop robust regulation plans for high frequencies of low lake levels than for high levels. Also
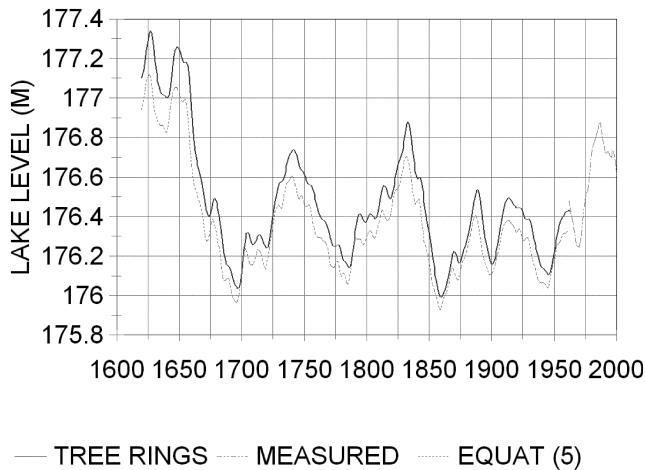
— TREE RINGS ---- MEASURED ---- EQUAT (5)

FIG. 10.   15-year moving average lake level. Measured data are shown between 1962 and 2000.

CONCLUSIONS

This study uses dendrochronologic data to provide a 400 year perspective of the primary water supply forcing variables of precipitation and air temperature. The data were applied to a set of regression equations yielding a 360 year time series of Lake Michigan-Huron water levels under the present hydraulic regime of the St. Clair River. Thus, these are the levels that would occur if the precipitation and temperature time series were to occur today. These are not the water levels that would have occurred in the past under the same forcing conditions. The analysis indicated an increased frequency of low lake levels prior to the twentieth century accompanied by a major extreme in water levels, greater than that experienced in the historical record, in the early 1600s. The low precipitation episodes do not occur at the same times as nationwide droughts with the exception of the 1930s. Because the Great Lakes cover several climatic zones, they respond differently than the country as a whole. An example is the low water regime in the mid 1960s, which set record low lake levels on Lake Michigan-Huron but did not have a significant effect on the U.S. as a whole. The comparison of simulated and measured water levels also indicates that the impact of the channel changes in the St. Clair River may be underestimated and that the major drop in lake level in the 1880s may be due to erosion as well as to decreased precipitation. The occurrence of extreme levels around 1640, in 1838, and in 1986 suggests a return interval of 150–190 years for extreme lake levels. The data are not sufficient to make a definitive statement, but do agree with the findings of Baedke and Thompson (2000) who found evidence of quasi-periodic lake level fluctuations, based upon high lake levels, of about 160 years (120–200 years)

when considering the recent drop in lake levels (1997–2002) with respect to a larger lake level history (1600–2002), the magnitude of the drop is not abnormal. The moving average lake levels (Fig. 10) show that the first and last 50-year segments of record, including the period 1961–2002, are abnormally high. Figure 10 also shows that equation (5) based upon the measured data gives similar results, although slightly lower overall levels, as equation (7). This agreement increases the confidence in the results. Figure 11 also suggests that the variability of lake levels has greatly decreased over the last century when comparing tree-ring-derived level variability.
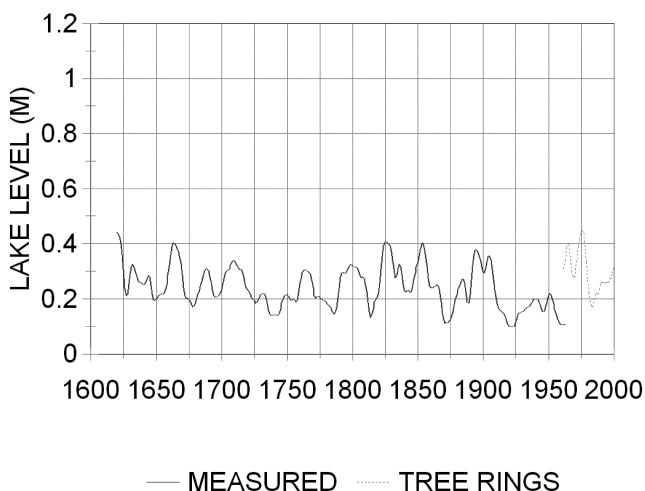
The climatic periods, 1860–~1915 and 1860–1953, used for the development of the current water regulation plans for Lakes Superior and Ontario respectively, are not representative of the climate of the last 400 years. In particular, these periods do not capture the higher frequency of low episodes or the extremes of the early 1600s and 1830s as indicated in the tree ring data. The variance of lake levels and precipitation also appears to be greatly reduced in comparison with the 1600–1885 period of the tree ring data. The period 1860–1953 may not necessarily be representative of the longer-term climate and lake level time series, being warmer and drier than average over the

— MEASURED ---- TREE RINGS

FIG. 11.   15-year moving standard deviation for lake levels. Measured data are shown between 1874 and 2000.

past 400 years. The high precipitation regime between 1602 and 1650 has not reappeared in the past 250 years. Also from a lake levels perspective, the record high lake levels in the late 1830s would approximate those in 1986 under today's hydraulic and land use regimes. There is the potential, though, for extremely high lake levels, about 0.7 m above the present record high, if we were to get a recurrence of the water supply conditions of the first half of the seventeenth century. Its reappearance would cause widespread damage and probable failure of the existing regulation plans. The shifting means noted in the air temperature and precipitation time series emphasize the importance of using stochastic analysis, based on the recorded water supplies, and a shifting mean stochastic model for simulating water supply time series to generate episodes more extreme than the current historical data for use in the development of regulation plans. We have had considerable experience over the past 50 years in dealing with high water supplies, but relatively little experience with low supply episodes. Also, it would be advantageous to continue this approach as additional tree ring records become available, which would include the low level episodes of the mid 1960s and late 1990s as well as the high episode of 167–1988.

ACKNOWLEDGMENTS

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