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Causes of variability in monthly Great Lakes water supplies and lake levels

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ABSTRACT: The purpose of this study was to identify those water budget components of the Great Lakes that have most frequently been a major cause of anomalous net basin supplies (NBS) and of rising and falling lake levels at the monthly time scale. Principal component analysis and a simple counting of relative frequencies revealed that on the upper lakes NBS anomalies are most sensitive to over-lake precipitation, but on the lower lakes they are most sensitive to runoff. This shift is due to a downstream increase in the magnitude and variability of runoff. Evaporation variability plays a larger role in the NBS of the upper than the lower lakes and is most important during dry months. During wet months evaporation is not as much suppressed as one might assume from the simple cloud cover/insolation/temperature/evaporation relationship; this is most likely due to an increase in wind speed. High and rising as well as low and falling lake levels are the result of anomalous NBS on all lakes and represent condition beyond the capabilities of lake-level regulations. Changing conditions—low but rising levels or high but falling levels—are the result of anomalous NBS for all of the lakes except Ontario, for which almost all such changes are achieved by regulating the outflow.

KEY WORDS: Water supplies · Lake levels · Great Lakes

1. INTRODUCTION

The Great Lakes represent a major natural resource for the United States and Canada. They are the largest system of fresh water on earth and have been the key to the development of the industrial heartland of North America. The economic benefits from human activities such as navigation, recreation, and hydroelectric power generation can be, however, severely curtailed by extremes in lake levels (Changnon 1987). There is therefore considerable interest in the cause of rising and falling levels.

The water supplies generated within a lake basin, referred to as net basin supplies, or NBS, are the sum of the supply components:

$$\mathrm{NBS} = P + R - E \quad (1)$$

where P is the over-lake precipitation, R is the runoff into the lake, and E is lake evaporation.

Other factors affecting lake levels are the inflows from an upstream lake and the outflows into a downstream lake. Outflows are naturally controlled by the level of the lake and the size of its outlet channel, although artificial regulations are currently modifying the outflows from Lakes Superior and Ontario (Lee et al. 1994). The aim of Lake Ontario's regulation (in effect since 1960) is to maintain its level within a given range to satisfy various interests on Lake Ontario and the St. Lawrence Seaway, such as navigation, recreation, and power generation. The main objective of Lake Superior's regulation (in effect since 1922) is to keep its level within a given range and to balance the levels of Lake Superior and Lakes Michigan-Huron relative to their long-term monthly means. This in effect implies that Lake Superior is being used as a reservoir in which water is stored at times of basin-wide high water supplies and from which water is released at times of drought. The effectiveness of using an upper lake as a reservoir depends, however, on the degree to which variations in water supplies to the upper lake are opposite to those for the lower lakes.

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The Great Lakes region has a relatively homogeneous climate, although there are some differences between the northwestern and southeastern portions, particularly with respect to precipitation (Brinkmann 1983a). Consequently, variations in the water supplies to Lake Superior and the lower Great Lakes differ somewhat, particularly at times of moderate supplies. Very large supply anomalies, however, tend to be of the same sign basin-wide and can persist for several seasons (Brinkmann 1983b). Periods of basin-wide above-average supplies and periods of basin-wide droughts have resulted in several failures of the regulation plans for Lakes Superior and Ontario because the response time of the Great Lakes system is long (Lee et al. 1994). The narrow and shallow connecting channels limit the amount of water that can be moved through the system. For example, it takes 3.5 yr for 60% of a given change in the water supply to Lake Huron to be realized in the outflow into the Atlantic (IJC 1976). Yet, surprisingly large and rapid lake-level changes have occurred. In 1985-1986, the Great Lakes reached record high levels. At that time, Hartmann (1988) estimated that, given the current wet regime that started in the 1970s, the lakes may not return to their normal levels in the foreseeable future unless a drought such as that occurring in the early 1960s developed, in which case it might take a minimum of 3 yr. The lakes started to fall in late 1986 and reached below normal levels within less than 2 yr (Yee et al. 1990).

Precipitation is considered to be the most important factor determining lake levels (IJC 1976, Quinn 1981, Changnon 1987, Rodionov 1994). This is true at the decadal and annual time scales but not necessarily at the monthly scale, as will be shown in this paper. At shorter time scales, the relationship between the water supply components and lake levels are more complex. Runoff, for example, which is strongly related to precipitation at the annual scale, is the result of precipitation as well as evapotranspiration; and some precipitation is temporarily stored in the form of snow pack before turning into runoff. The seasonal maxima and minima of precipitation, evapotranspiration, and snow melt differ so that their sum, runoff, is poorly related directly to precipitation at the monthly time scale.

Lake evaporation is considered to be negatively related to precipitation and thus to amplify the effect of precipitation (IJC 1976). This assumption stems from the fact that temperature anomalies are largely controlled by insolation and cloudiness. Thus, during wet periods, cloud cover is high, which reduces insolation and surface air temperatures, which, in turn, is considered to reduce evaporation. Lake evaporation is, however, not a function of air temperature but a function of the vapor pressure difference between the water surface and the air, and of wind speed.

The growing interest in the impact of increased concentrations of atmospheric greenhouse gases on the climate and water levels of the Great Lakes has led to a series of studies of NBS and water budget components using *modeled* data (Croley 1990, Croley et al. 1998). A recent study of *observed* component data is the one by Yee et al. (1990). That study reviewed the changes in the components that led to the rapid drop in lake levels during 1987-1988. It concluded that the drop was the result of a combination of reduced precipitation and runoff, high evaporation, and high lake outflows.

The present study aims to clarify the roles of precipitation, runoff, and evaporation in the generation of high and low NBS totals and the roles of the water budget components, inflow, outflow, and NBS in rising and falling lake levels over a 36 yr period. The focus is on the monthly time scale which is that time scale at which lake-level forecasts are currently being made and at which the impact of increasing concentrations of atmospheric greenhouse gases on the variability of NBS components is now beginning to be evaluated.

2. DATA AND METHODS

The water-supply components used in this study are the monthly values compiled from a variety of sources by Croley & Hunter (1994). Several of the time series start in 1900 but some are shorter. The evaporation record for Lake Huron is the shortest and starts in 1955. All records end in 1990, with the exception of the Welland Canal Diversion between Lakes Erie and Ontario, which ends in 1989. This diversion represents about 3% of the total flow between the 2 lakes. To substitute for the missing year, the average monthly values for the 3 years 1987 to 1989 were used. The period of records employed in this analysis of NBS and its components thus extends from 1955 through 1990; it consists of 36 years or 432 months. (Note: The runoff values for Lake Huron as given in Croley & Hunter [1994] are incorrect; a corrected data file has been available since August 1999 at http://www.glerl.noaa.gov).

The magnitudes of the NBS components, over-lake precipitation, runoff, and evaporation are estimates because they are not directly measurable for large water bodies. Over-lake precipitation is estimated from land-based measurements using lake/land precipitation ratios; runoff is derived from the stream gauge network, extrapolating over ungauged areas; and evaporation is derived from an evaporation model based on air temperature, humidity, wind speed, cloud cover, and lake heat storage (Croley 1989). However, the NBS can be computed indirectly as a residual of the water balance for a lake:

$$NBS = \Delta S + O - I \pm D \quad (2)$$

where ΔS is the change in water storage, or CIS, computed from the difference in lake levels over a time interval, such as the beginning and the end of a month, O is the outflow, I is the inflow, and D is the total diversion over the time interval. The published records of inflows, outflow, and lake levels extend from 1900 through 1990 (Croley & Hunter 1994).

There are some differences between the NBS derived from the estimated values of its components (Eq. 1), hereafter referred to as NBS-C, and the NBS computed as a residual (Eq. 2), referred to as NBS-R, because of uncertainties in the independent variables in both equations (Croley & Lee 1993). In the present study, NBS-C will be used in the analysis of the NBS components and NBS-R will be used in the analysis of the water-budget components.

All data are expressed as 'depth of water' spread over the lake area rather than as volume of water or flow rates, since depth is more directly related to lake levels and their changes. For most variables, the magnitude of the seasonal cycle is comparable to the magnitude of the variability about the seasonal cycle. Since the focus of this paper is to determine the roles of NBS and the water-budget components in the generation of high and low NBS and levels rather than their roles in the generation of the seasonal cycle, the seasonal rise and fall in lake levels, NBS components, and budget components were removed. All data were converted to anomalies by subtracting the mean for the calendar month and were converted to z-scores by dividing the anomalies by their standard deviation for the calendar month. The use of anomalies and z-scores does of course require some care in interpreting the results. For example, lake levels might be rising from one month to the next in spring but if the rise is not as fast as expected from the long-term mean rise for those months then the anomaly would in fact be negative.

The method employed is rotated (Varimax) principal component analysis (PCA). This type of analysis permits the reduction of a 2-dimensional field of variables into a small set of principal components (PCs) that account for the observed covariance among the variables. The first PC is defined in such a way as to maximize the explained variance. The second PC is defined to explain the largest portion of the remaining variance, with the additional condition that is must be orthogonal to the first, and so on. In this way, a comparatively small set of PCs will usually express a large portion of the variation of the observed field, and the lower-order PCs will portray the most important modes of variation of the observed field with time (Preissendorfer 1988, Yarnal 1993). The mode of decomposition used in this study is the S-mode. In this mode, the variables are the water-supply components for a lake and the observations are the monthly values, and groups of supply components that covary similarly are identified.

To supplement the PCA, a simple counting scheme, hereafter referred to as 'major contributor' analysis, was adopted. This consists of identifying the major contributors to the monthly NBS on the basis of the magnitude of their anomalies. For example, when the NBS anomaly for a month is positive and all 3 components contribute to this positive anomaly (precipitation and runoff anomalies are positive and evaporation is negative), the component(s) contributing $\geq 33\%$ to the NBS anomaly is(are) considered the major contributor(s). If in this example the evaporation anomaly is positive, then the larger of the remaining two is considered the major contributor and evaporation contributes negatively to the NBS anomaly.

3. SETTING

The monthly means and standard deviations of NBS and its components, over-lake precipitation, runoff, and evaporation, are shown in Tables 1 & 2 for Lakes Superior and Erie, representing the uppermost and lowermost Great Lakes in terms of latitude. Both the means and their variability exhibit a seasonal cycle. Snowmelt is responsible for the spring peak in runoff. Precipitation is at its maximum in summer. Evaporation is highest in fall and early winter, when the lakes are warmest and the arrival of cool, dry Canadian air generates a large vapor pressure difference between the air and the water surface. Inflows (negligible for Lake Superior and therefore not listed) and outflows are relatively constant. CIS are most positive in spring and early summer in response to the spring runoff peak and most negative in fall and early winter, coinciding with the peak in evaporation.

Annual precipitation totals increase from west to east (downstream) across the Great Lakes basin. This is a reflection of the larger-scale increase between the northern Great Plains and the east coast (Phillips & McCulloch 1972) and is mainly the result of an increase in cold-season precipitation due to the convergence of several storm tracks over and to the east of the Great Lakes (Eichenlaub 1979). The downstream increase in runoff is the result of the increase in overland precipitation and the decrease in the lake surface area over which it is spread. Lake Superior's water surface area, for example, covers 39% of the Lake Superior basin while Lake Erie occupies only 30% of its basin. For Lake Ontario, the annual runoff total is twice the annual precipitation total. Lake evaporation is greatest for Lake Erie, the shallowest of the lakes (with

Table 1. Monthly means (1961 to 1990 normals) and standard deviations (following the slash) of water-budget components for Lake Superior (depth in cm over the lake). NBS-C: net basin supplies derived from the estimated values of its components (Eq. 1); CIS: change in water storage

Month	Precipitation	Runoff	Evaporation	NBS-C	Outflow	CIS
Jan	6.2/2.2	3.5/0.9	9.7/1.6	0.1/2.2	6.7/0.9	–7.1/2.1
Feb	4.1/1.5	3.1/0.8	5.2/1.6	2.1/2.5	6.0/0.8	–5.0/2.5
Mar	4.9/2.4	4.1/0.9	3.9/1.7	5.1/3.5	6.6/1.0	–0.9/4.1
Apr	4.8/1.7	9.1/2.5	1.8/0.7	12.1/3.2	6.5/1.1	7.7/4.0
May	7.0/2.6	9.3/2.6	0.4/0.4	15.8/4.5	7.6/1.6	9.0/5.5
Jun	8.0/2.7	6.0/1.7	–0.2/0.1	14.3/4.0	7.4/1.7	7.3/4.7
Jul	7.4/2.9	4.3/1.3	–0.1/0.3	11.7/3.7	7.9/1.9	3.7/4.3
Aug	8.3/3.2	3.7/1.1	1.9/1.1	10.2/3.9	8.2/1.9	2.0/4.7
Sep	8.7/3.2	3.9/1.3	5.5/1.4	7.1/4.7	7.9/1.8	–1.1/5.4
Oct	7.3/2.7	5.0/1.8	6.9/1.5	5.4/4.2	7.6/2.0	–2.7/4.6
Nov	6.4/2.8	4.8/1.6	9.3/1.3	2.0/4.1	7.4/2.1	–5.1/4.5
Dec	6.3/1.6	4.0/1.1	11.1/1.5	–0.8/2.0	7.2/1.5	–8.8/4.9
Annual totals	79.6	60.9	55.5	85.0	86.9	–0.8

Table 2. Monthly means (1961 to 1990 normals) and standard deviations (following the slash) of water-budget components for Lake Erie (depth in cm over the lake)

Month	Precipitation	Runoff	Evaporation	NBS-C	Inflow	Outflow	CIS
Jan	5.4/2.4	6.8/3.9	3.8/1.7	8.5/5.7	52.8/7.0	62.0/7.8	–3.1/6.7
Feb	5.2/2.6	9.3/5.8	1.6/0.9	12.8/8.3	48.1/6.0	55.6/6.7	4.6/9.2
Mar	7.1/2.7	15.4/6.3	1.4/0.6	21.1/8.3	57.7/5.8	64.0/7.6	15.1/8.3
Apr	7.8/3.0	12.0/4.2	0.7/0.7	19.0/6.6	56.4/5.8	64.8/7.7	10.1/9.1
May	8.1/3.2	6.9/3.3	1.4/1.1	13.6/5.8	59.1/5.3	69.1/7.0	3.2/5.9
Jun	9.0/2.8	4.6/3.5	3.6/1.3	10.4/6.0	58.0/5.3	66.7/6.8	0.8/4.7
Jul	8.2/2.5	2.9/1.6	7.0/1.5	4.1/4.3	60.5/5.5	67.3/7.2	–4.5/4.3
Aug	9.2/3.9	2.0/1.0	11.5/2.1	–0.3/4.8	60.6/5.4	66.3/6.9	–7.4/4.8
Sep	9.1/3.5	2.5/2.1	15.6/2.4	–4.0/6.1	58.4/5.2	63.0/6.8	–8.3/5.4
Oct	7.2/2.7	3.0/2.5	18.1/2.7	–7.9/4.2	60.1/5.5	64.2/7.0	–10.3/4.9
Nov	8.8/3.9	5.7/3.9	13.9/2.0	0.7/7.9	57.8/5.6	61.9/6.9	–1.6/8.1
Dec	8.1/2.1	9.2/5.4	9.8/1.7	7.5/7.4	58.1/5.7	64.6/7.6	2.2/7.3
Annual totals	93.3	80.4	88.1	85.6	687.6	769.5	0.9

the least heat storage, making its surface water temperature in the fall the highest of all lakes), and least for Lake Superior, the deepest lake. Inflows and outflows increase downstream because the long-term average outflow from a lake has to equal the inflow into that lake plus the NBS for that lake. Consequently, the NBS decrease in importance compared to the total water supplies (NBS plus inflow) moving through the lake. For Lake Ontario, the NBS represent only 15% of the total water supply to that lake.

4. RESULTS: NBS-C COMPONENTS

The first step in determining the cause of falling and rising lake levels at the monthly scale is to determine the relative importance of over-lake precipitation, runoff, and evaporation in the generation of NBS, which is one of the components in the water budget for the lakes. (The role of inflows and outflow, the other components of the water budget, will be examined in the next section.) Two approaches are used.

First, PCA was applied to the covariance matrix of the anomalies of NBS-C and its components. This was done separately for each lake. The first 2 PCs, each accounting for over 10% of the variance, were rotated. Their loadings are presented in Table 3. The magnitudes of the loadings are a measure of the magnitude of a variable (such as runoff or evaporation) represented by a PC, and the sign of the loadings are an indication of the direction of covariation among the variables.

The loading patterns for PC1, which accounts for 50 to 75% of the variance, highlight the difference between the lakes in the sensitivity of NBS-C to its components. The NBS-C anomalies for the upper lakes, Superior and Michigan, are most sensitive to over-lake precipitation anomalies, while the NBS-C anomalies for the lower lakes are most sensitive to runoff anomalies. This shift in sensitivity can be understood in terms of a shift in the magnitude of the monthly standard deviations (Tables 1 & 2). For the upper lakes, the standard deviation of precipitation exceeds that for runoff during all months except for 1 or 2 in spring, when runoff peaks due to snowmelt and runoff variability becomes important. (The magnitude of the monthly standard deviation is a measure of the magnitude of the monthly anomalies, since, for a normal distribution, one-third of the anomalies exceed ±1 standard deviation). Thus over-lake precipitation drives the NBS on the upper lakes. The downstream increase in runoff is accompanied by a disproportionately large increase in variability compared to precipitation. For example, the small downstream increase in precipitation during the high-precipitation season is accompanied by a comparable increase in variability, and the difference in the coefficient of variability (standard deviation/mean) between Lakes Superior and Erie is nearly zero. On the other hand, the downstream increase in runoff of roughly 50 % during the high-runoff season is accompanied by a doubling and tripling of the standard deviation, and the coefficient of variability is increased by 10 to 30 %. This results in a growing number of months with runoff variability exceeding over-lake precipitation and evaporation variability. Thus runoff drives the monthly NBS on the lower lakes.

The loading patterns for PC2, accounting for 25 to 45 % of the variance, show that for the upper lakes, Superior and Michigan, the importance of evaporation variability approaches that of runoff variability. This can again be understood in terms of the seasonal cycle in means and standard deviations. At the upper lakes, where runoff and its variability are relatively low, evaporation variability during the high evaporation season—fall and winter—is comparable to and even exceeds that for runoff. On the lower lakes, runoff variability is so high that evaporation becomes the least-variable component for almost the entire year.

It is worth noting that there is a general lack of association between the NBS components at the monthly time scale. No indication of an association between over-lake precipitation and runoff or between over-lake precipitation and evaporation emerges from the PCA.

Another approach, and one that comes perhaps even closer to answering the question 'What drives the NBS?', is simply to count the number of months during which an NBS component was a major contributor (see Section 2). An important advantage of this approach is that it permits a separate analysis of opposite conditions. In the present case, it permits a separate exploration of high and low NBS to determine whether the driving forces behind them are the same. This is different from PCs, which represent a pattern—or set of associations between NBS and its components—as well as its inverse, depending on the sign of the weight. Each PC has associated with it a time series of weights or scores whose magnitudes vary over time, which is an indication of the relative importance of that PC for a given month. The weights may be either positive or negative; thus a basic assumption in PCA is that the PC patterns or sets of associations between variables are reversible. Consequently, any differences between a pattern and its inverse are averaged out in a PCA.

The results of a simple counting of major contributors, presented in Table 4, confirm the major findings from the PCA, namely that over-lake precipitation drives the NBS on the upper lakes and runoff drives the NBS for the lower lakes, and that evaporation is more important on the upper lakes. In addition, the data in Table 4 show that evaporation is twice as important a driving force when NBS anomalies are negative than when they are positive: evaporation is a major contributor 20 to 25 % of the time during dry months but only about 10 % of the time during wet months. This difference is significant for all lakes except Ontario. The physical explanation of this difference is as follows: Wet months for areas as large as the lake surfaces are the result of frontal passages, even in summer. Since the strong winds associated with fronts are an important factor in the rate of evaporation, evaporation is not as frequently suppressed during

Table 3. Variance (%) accounted for and loadings for the first 2 principal components (PCs) of NBS-C anomalies and their components

Lake	Variance	Precipitation	Runoff	Evaporation	NBS-C
PC 1					
Superior	68.3	2.47	0.55	0.05	2.98
Michigan	64.3	2.71	0.74	−0.07	3.52
Huron	48.1	0.27	2.34	−0.54	3.16
Erie	57.5	0.92	3.66	−0.36	4.94
Ontario	74.3	0.68	5.48	−0.29	6.45
PC 2					
Superior	24.6	−0.11	1.10	−0.99	1.87
Michigan	29.8	0.25	1.32	−0.88	2.57
Huron	46.2	2.37	0.61	−0.06	3.04
Erie	37.4	2.75	1.15	−0.13	4.05
Ontario	23.2	2.52	1.10	−0.26	3.86

Table 4. Relative frequencies with which NBS components are major contributors to high and low monthly NBS anomalies (%)

Lake	NBS-C z-score ≤ –0.5			NBS-C z-score ≥ 0.5		
	Evaporation	Precipitation	Runoff	Evaporation	Precipitation	Runoff
Superior	27	63	25	14	69	33
Michigan	24	62	35	12	74	35
Huron	20	54	51	10	53	56
Erie	20	47	61	9	51	65
Ontario	8	33	80	4	35	86

wet months as one might assume from on the simple cloud cover/insolation/temperature/evaporation relationship—and thus does not as frequently contribute positively to a positive NBS anomaly as compared to its opposite (dry months). For Lake Ontario, however, runoff is so overpowering that evaporation is rarely an important factor, and the difference in evaporation between high and low NBS becomes negligible.

It is worth noting that during the 2 yr period 1986 to 1988, during which the Great Lakes experienced the largest drop in levels in this century, evaporation was a major contributor 25 to 33% of the time on all lakes, including Lake Ontario. Over-lake precipitation and runoff were less frequent contributors compared to the 36 yr averages shown in Table 4.

5. RESULTS: CIS COMPONENTS

The second question addressed in this study concerns the roles of inflow, outflow, and NBS in rising and falling lake levels. Two approaches are used.

First, the covariance matrix of monthly anomalies of CIS and its components was subjected to PCA. Those components accounting for over 10% of the variance—the first two for Lakes Superior, Erie, and Ontario but only the first component for Lakes Michigan and Huron—were rotated, and the loading patterns are presented in Table 5.

For Lakes Superior, Michigan, and Huron, the loading patterns for PC1, accounting for about 90% of the variance, show that lake-level changes are most sensitive to variations in NBS. For Lake Erie however, this same pattern of a positive association between CIS and NBS accounts for only half the variance. The PC1 loading pattern for Lake Ontario, accounting for 70% of the variance, is dominated by a positive association between inflows and outflows.

The PC2 loading pattern for Lake Superior, accounting for 10% of the variance, is a pattern of positive association between NBS and outflows; it appears to represent the effects of lake-level regulations. The PC2 loading pattern for Lake Erie, accounting for 45% of the variance, represents a positive association between inflows and outflows, similar to the PC1 pattern for Lake Ontario, but accounting for less variance. The PC2 loading pattern for Lake Ontario, accounting for 24% of the variance, represents the sensitivity of CIS to variations in NBS, similar to the PC1 pattern for Lakes Superior, Michigan, and Huron, but accounting for less variance.

Additional insight was gained by simply counting the number of occurrences of positive NBS-R anomalies, positive flow (outflow minus inflow) anomalies, and their difference. This was done separately for each lake and for 4 different sets of extreme water-supply conditions. The results indicate that when levels are high and rising (z-scores of monthly lake levels and CIS ≥0.5) more water is generated by the NBS than is let out (the difference between outflow and inflow) about 90 to 100% of the time for most of the lakes and slightly less (80%) for Lake Ontario. When levels are low and falling (z-scores for both ≤–0.5), the reduction in NBS is greater than the amount of water kept in the lake about 90 to 100% of the time for most of the lakes and slightly less for Lake Ontario. These extreme conditions have occurred about 15 to 20% of the time and represent situations when the outflows, including

Table 5. Variance (%) accounted for and loadings for the first 2 PCs of CIS anomalies and their components

	Variance	CIS	NBS-R	Inflow	Outflow
PC 1					
Superior	89.5	4.24	4.08	0.01	–0.15
Michigan	94.3	5.66	5.73	0.15	0.22
Huron	95.3	6.20	6.21	0.19	0.20
Erie	49.9	6.72	6.39	0.63	0.30
Ontario	70.4	1.28	–3.51	–8.76	–13.54
PC 2					
Superior	10.5	0.58	–0.95	–0.01	–1.54
Erie	45.3	0.16	–1.25	–5.46	–6.87
Ontario	23.6	7.58	5.68	1.33	–0.57

Table 6. Relative frequencies of the occurrence of positive CIS components and differences for months with changing water-supply conditions (%)

Lake	Low but rising levels			High but falling levels		
	NBS-R > 0	Flow > 0	NBS-R > flow	NBS-R > 0	Flow > 0	NBS-R < flow
Superior	95	8	76	0	83	75
Michigan	96	29	84	4	77	87
Huron	98	33	89	2	78	94
Erie	85	13	65	5	84	65
Ontario	36	3	12	48	92	22

those regulated, are simply incapable of handling high supplies or when keeping water in a lake is difficult when there is little water in the system.

Equally interesting are those months when conditions are changing, i.e. when levels are high but falling and when levels are low but rising. The results for these are presented in Table 6. When lake levels are low (z-score ≤–0.5) but rising (CIS z-score ≥0.5) NBS-R are positive nearly 100% of the time for the upper 3 lakes. Also, the NBS are larger than the amount of water kept in about 80% of the time for the upper 3 lakes, indicating the high degree to which NBS are the cause of changing water-supply conditions on those lakes. For Lake Ontario, rising levels occur in spite of negative NBS anomalies (positive only 36% of the time) because of a reduction in outflow (only for 3% of the months is the outflow greater than the inflow); positive NBS anomalies exceed the amount of water kept in the lake about 12% of the time. When lake levels are high but falling, low NBS anomalies are the cause of the falling levels 75 to 95% of the time for the upper lakes but only 22% of the time for Lake Ontario, representing again the degree to which Lake Ontario's level has been controlled through the outflow. These changing water-supply conditions have occurred about 20 to 25% of the time; they are caused by changing NBS anomalies for the upper lakes and by controlling the outflow from Lake Ontario. Table 6 also shows that the regulation of Lake Superior does have an effect but it is small compared to that for Lake Ontario.

The relatively large impact regulation appears to have on Lake Ontario's levels could be substantiated by comparing level fluctuations for all lakes before and after 1960. Differences between the 2 periods, however, also could be due to a differential climate change across the Great Lakes basin. The 2 effects can be separated by analyzing changes in both lake levels and NBS-R (not NBS-C because the evaporation record is too short).

As a first step, PCA was applied to the levels of all 5 lakes combined. The data were standardized using the means and standard deviations for each calendar month and lake, and the PCs were extracted from the correlation matrix. The analysis was done separately for the 2 periods, 1922 to 1959 and 1960 to 1990. The first 2 PCs were rotated. The variance accounted for as well as the loading patterns are given in Table 7.

The PC1 loadings, accounting for about 75% of the variance, are all of the same sign for both time periods, indicating that the lakes tend to be either all above normal (with a positive weight or score) or below normal (with a negative score). Superimposed upon this general pattern are differences between the lakes, as represented by the magnitude of their loadings. During the 1922 to 1959 period, Lake Superior's lake-level variations were considerably independent of those for the other lakes, which is partly due to a difference in climate and partly due to the regulation in effect since 1922. Since 1960, Lake Ontario's level fluctuations have also become independent of those for the middle lakes. PC2 for the earlier period represents Lake Superior's independence while PC2 for the more recent period indicates a certain out-of-phase relationship between Superior and Ontario. The rotated PCs of standardized NBS-R (not shown) do not show this marked change toward independence for Lake Ontario since 1960 that is so evident in the lake levels and which therefore appears to be due to regulation rather than climate.

Table 7. The first 2 rotated PCs of the standardized lake levels for 2 time periods

	1921–1959		1960–1990	
	PC1	PC2	PC1	PC2
Variance (%)	77.8	16.1	75.8	17.6
Loadings				
Superior	0.199	0.980	0.766	0.569
Michigan	0.946	0.216	0.964	0.022
Huron	0.948	0.206	0.971	0.008
Erie	0.945	0.191	0.949	–0.123
Ontario	0.929	0.157	0.792	–0.439

A more insightful analysis of this change in levels, because it considers the direction of change, is a simple count of the number of months with z-scores of lake levels and NBS-R ≥0.5 and ≤–0.5 for the 2 time periods. These counts were expressed as a percent of the number of months within a time period, and the percent changes between the 2 time periods are given in Table 8.

Every lake experienced a decrease in the frequency of low NBS and an increase in high NBS between the 2 periods. This is a reflection of the dry 1920s and 1930s and the cloudy, cool, and wetter 1970s and early 1980s (Quinn 1981, Changnon 1987). The magnitude of this change toward wetter conditions appears to be increasing downstream. However, NBS-R is computed as a residual from several variables characterized by large magnitudes and high persistence. Buchberger (1994) has shown that that leads to an artificial persistence in the computed supplies which increases downstream. Using changes in annual over-land precipitation as an independent check (Table 8) reveals that the apparent downstream trend in NBS-R is not supported by the precipitation data.

The change in the frequency of high and low lake levels between the 2 time periods (Table 8) is for most of the lakes of the same sign as the change in NBS-R—fewer low and more frequent high levels during the more recent period—but magnitudes are larger because of the persistence that characterizes lake levels. For Lake Ontario, the reduction in low levels is less than that for the middle lakes, and high levels have become less frequent as well, reflecting the impact of regulation. For Lake Superior, both high and low levels have increased slightly. The increase in low levels in spite of a decrease in low NBS and an increase in precipitation is a reflection of the use of that lake as a storage basin at times of high water supplies. These results agree with Southam & Larsen (1990), who found that regulation has increased both the minimum and maximum levels of Lake Superior and has raised the minimum and lowered the maximum levels of Lake Ontario.

Table 8. Changes in relative frequencies (%) of high and low NBS-R and lake levels, and changes (cm over land) in annual over-land precipitation between 1920 to 1959 and 1960 to 1990

Lake	NBS-R z-score ≤ –0.5	NBS-R z-score ≥ 0.5	Annual precipitation	Lake-level z-score ≤ –0.5	Lake-level z-score ≥ 0.5
Superior	–5	+4	+5.9	+9	+5
Michigan	–7	+1	+4.6	–32	+16
Huron	–2	+4	+7.3	–31	+22
Erie	–10	+3	+3.6	–46	+32
Ontario	–14	+7	+3.6	–27	–11

6. SUMMARY AND DISCUSSION

The purpose of this study was to identify those water-budget components that have been most frequently a major cause of high and low NBS and those components that have been most frequently a major cause of rising and falling lake levels. At the annual and decadal time scale and for the Great Lakes basin as a whole, precipitation is the most important component. One can speak therefore of the 'dry 1930s' or the 'wet 1970s' and associated extremes in lake levels. However, this generalization is not true at the monthly time scale, as was shown in this paper.

Rotated PCA and a simple count of major contributors to high and low NBS showed that on the upper lakes monthly NBS anomalies are most sensitive to variability in over-lake precipitation, but on the lower lakes they are more sensitive to variability in runoff. The reason for this downstream shift is the downstream increase in runoff and in runoff variability. Runoff increases downstream because of a downstream increase in over-land precipitation and, most importantly, because runoff is generated from land areas that are increasing relative to the lake surface area over which runoff is spread. The land/lake ratio is 1.5 for Lake Superior but 3.4 for Lake Ontario. The downstream increase in mean runoff is accompanied by a disproportionate increase in variability, leading to an increasing number of calendar months with runoff variability exceeding precipitation variability. This is particularly true for winter and spring, which suggests that it is the variability in snowpack and snowmelt that are the key factors.

Evaporation variability plays a larger role in the NBS of the upper lakes, for which runoff variability is relatively small—compared to the lower lakes—and evaporation variability is comparable to and even exceeds runoff variability during the high evaporation season, fall and winter. An interesting aspect of evaporation is that its importance depends on the sign of the NBS anomaly. When conditions are dry (NBS z-score ≤–0.5), high evaporation rates are a major contributor and thus amplify the effect of over-lake precipitation 20 to 25% of the time. During wet months (NBS z-score ≥0.5), reduced evaporation rates are a major contributor only about 10% of the time. This is because wet months for areas as large as the lake surfaces are the result of frequent passages of fronts. High winds associated with frontal passages reduce the frequency of negative evaporation anomalies during wet months. The simple cloud cover/insolation/temperature/evaporation relationship is therefore an oversimplification.

These complex relationships between NBS and its components have important implications with respect to the forecasting of lake levels. Croley & Lee (1993) evaluated the forecast methods of 4 different agencies. Level forecasts basically consist of routing NBS outlooks through connecting channel-flow routing models, given the initial lake levels and current channel flow. The greatest uncertainties are in the NBS outlooks. Three of the forecast methods are based on antecedent NBS-R and use as additional predictors such variables as the National Weather Service (NWS) temperature and precipitation outlooks, NBS-R trends or the previous month's forecast error; these 3 methods forecast NBS-R. The fourth method (Great Lakes Environmental Research Laboratory, or GLERL) forecasts the NBS-C using physically based runoff and evaporation models. All 4 methods performed better for the upper than the lower lakes. Evaluation of the GLERL method revealed that forecasting the components separately rather than forecasting NBS-R gives superior results. Furthermore, for the 1 mo (first month) forecast the component with the largest RMS error was found to be precipitation for the upper lakes and runoff for the lower lakes, both errors being largely the result of NWS forecast errors rather than model errors. The large runoff error for the lower lakes is a surprise. Theoretically, there should be less error associated with runoff than with precipitation, since the initial conditions for the runoff model (the moisture stored in the basin) represent a considerable amount of information. Croley & Lee's (1993) results simply reflect the large variability in runoff for the downstream lakes.

How might the increasing concentration of atmospheric greenhouse gases affect the NBS components and their variability? While GCM (general circulation model) simulation results agree as to the direction of change in temperature for most regions of the world, they do not agree as to the direction of change in precipitation. Thus the most likely effect on the Great Lakes will be a reduction in snowpack because of rising temperatures (Cohen 1986, Croley 1995, Croley et al. 1998). This is likely to decrease runoff variability in spring, thus making the lower lakes more sensitive to over-lake precipitation variability. Evaporation may increase but predictions are not straightforward because of uncertainties in cloud cover and wind speed, and because the air masses that currently drive evaporation—cool, dry Canadian air—will most likely be less cool and dry.

The second question raised in this study concerns the roles of inflow, outflow, and NBS in changing lake levels. Results of rotated PCA, applied to the monthly anomalies of CIS and its components, indicated that NBS are the driving force behind rising and falling levels, but the flow of water through the lake becomes an increasing factor in the water budgets of downstream lakes. Additional insight was gained using a simple counting scheme, which showed that during months with low and falling levels (z-scores ≤ -0.5) and months with high and rising levels (z-scores ≥ 0.5), NBS were the main cause for all of the lakes. Such 'grief' situations occur with persistent extremes in water-supply conditions and regulations fail because either the total water supplies are greater than the permissible outflow or they are smaller than the minimum outflow specified by the regulation plan and hence levels rise and fall beyond the regulation limits. At times of changing water-supply conditions, when levels are high but falling or low but rising, NBS anomalies are again the major cause of the changing levels for the unregulated lakes. For Lake Superior, the net flow out of the lake is responsible for changing levels in about 25% of those months. For Lake Ontario, however, such relief situations are achieved by the net flow about 80 to 90% of the time. This suggests a far more successful regulation scheme for Lake Ontario than for Lake Superior.

Further exploration of conditions during the 2 periods 1922 to 1959, when only Lake Superior regulations were in effect, and 1960 to 1990, when both Lake Superior and Lake Ontario were regulated, indicated that conditions in the Great Lakes basin have become wetter and that low lake levels are now less frequent and high levels are more frequent for the unregulated lakes. For Lake Ontario, however, both high and low lake levels have become less frequent, confirming the success of that lake's regulation. For Lake Superior, low levels have increased slightly rather than decreased, reflecting the use of that lake as a storage basin at times of high water supplies.

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