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CURRENT PERSPECTIVES ON THE LAKE ERIE WATER BALANCE*

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ABSTRACT. An analysis was conducted of the Lake Erie water balance for 1940–79, based upon the individual hydrologic components, including thermal expansion and consumptive use. Particular emphasis was given to the continuity of the system. Annual and monthly statistics are presented for each of the water balance components. While the Detroit River contributed 87 percent of the Lake Erie total water supply, the variability of the net basin supplies was also found to be of importance in explaining annual water level fluctuations. A major step function was found to occur in the annual water balance between 1958 and 1959, which illustrates the large discontinuities that can occur when calculating the net basin supplies from residuals rather than directly from precipitation, runoff, and evaporation. The annual water balance for 1959–79 was found to be well satisfied with an average annual residual of about 0.5 percent of the Detroit River or Niagara River flow. A distinct seasonality was noted in the mass continuity of the monthly water balance. Also on a seasonal basis, the change in storage due to thermal expansion was significant during the late spring and early fall months.

ADDITIONAL INDEX WORDS: Hydrologic budget, water level fluctuations, evaporation rate, hydrologic data.

INTRODUCTION

Lake Erie (Fig. 1) is the fourth largest of the Great Lakes and a major water resource shared by the United States and Canada. The lake contains 484 km^3 of water with 25,700 km^2 surface area and 58,800 km^2 of land area in the basin. The lake and its connecting channels, the Detroit and Niagara rivers, are intensively used for navigation and recreation and the shoreline is highly developed. In addition, the Niagara River is a major source of hydropower. Use of the water resources is dependent upon lake levels, which are a function of the water balance. Over the past several years, studies of Lake Erie water balance components have been undertaken by Brunk (1964), Sanderson (1966), Jones and Meredith (1972), and Derecki (1976). In the majority of these studies, emphasis was on determining the various components of the water balance without regard to the mass continuity of the system. System continuity is an important consideration in studies of Great Lakes response models (Quinn 1978). In many of these studies, the evaporation was computed as a residual of the water balance rather than independently. For this reason, an overall assessment of the water balance continuity could not be made; however, independent assessment is essential for many forecasting, simulation, and regulation studies of the Great Lakes.

This study examines the Lake Erie water balance based on the individual components for 1940–79 with particular emphasis on the continuity of the system. Consumptive use and thermal expansion are also included as part of the overall water balance. Detroit and Niagara river flows are also assessed. The Niagara River is a major source of hydropower and provides the aesthetic value of Niagara Falls. The connecting channel flows and

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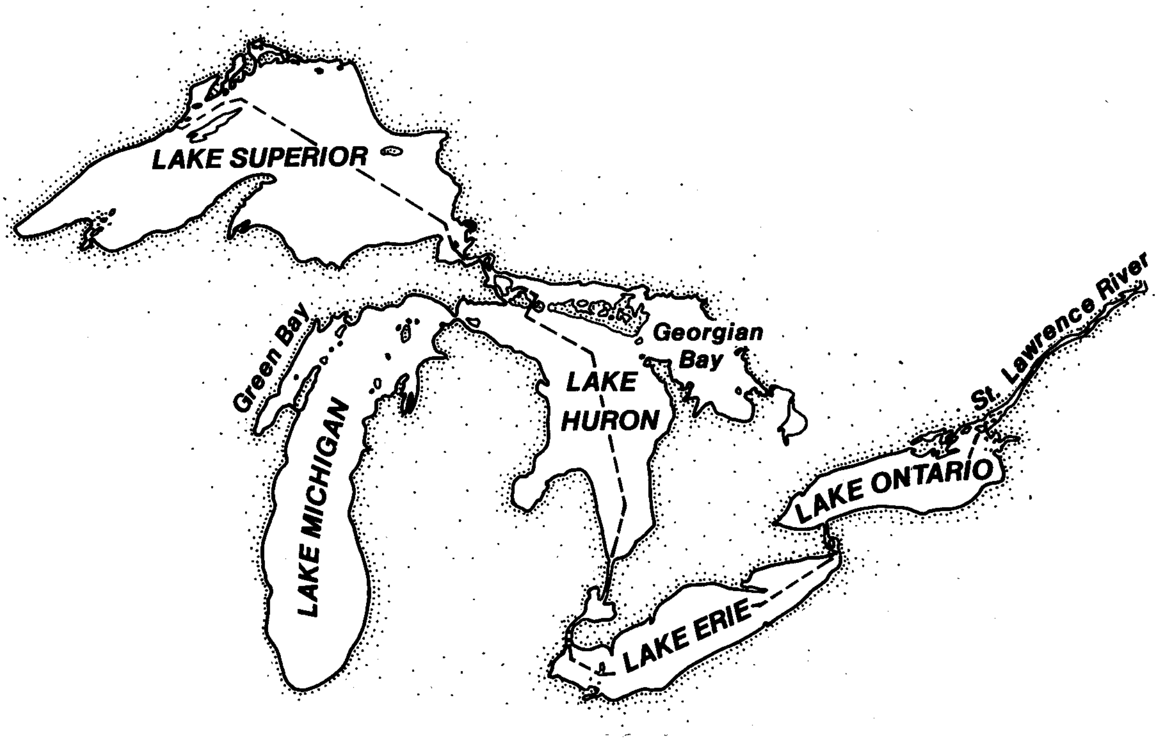

FIG. 1. Great Lakes basin.

changes in storage have been used in the past to indirectly compute net basin supplies required for water resource studies, such as lake regulation, consumptive use, and interbasin diversions. Information on the individual components of the net basin supplies, now available for 1940–present, allowed independent computation of the net basin supplies and assessment of the relative accuracy of the connecting channel flows.

PROCEDURE

The water balance was analyzed on both an annual and monthly basis for 1940–79. This period was selected because it is the longest for which all water balance variables are available. First, the individual variables were examined and then the system continuity was analyzed on an annual and monthly basis. The continuity equation for Lake Erie is expressed as

$$Q_n + D + CU \pm S - S_t - Q_d - P - R + E = r \quad (1)$$

where Q_n is the outflow through the Niagara River,

D is the outflow through the Welland Diversion,

CU is the consumptive use of water from the lake,

S is the change in lake storage as measured by the water level gauges,

S_t is the change in lake storage due to thermal expansion,

Q_d is the inflow from the Detroit River,

P is the precipitation falling on the lake surface,

R is the runoff from the lake drainage basin,

E is the evaporation from the lake surface, and

r is a residual (if continuity is satisfied; then $r = 0$)

All units are cubic meters per second for this analysis. The basic hydrologic data are taken from Derecki (1976) and Quinn and Kelley (1983). The precipitation, runoff, evaporation, and changes in storage components were computed in a homogeneous manner over the period of study with changes due primarily to the number of stations or gauges used in the computations. This was not the case for the Detroit or Niagara river flow computations. The procedures for taking and reducing discharge measurements in the Detroit River were changed effective with the 1959 measurements, which could cause a discontinuity in the water balance computations at this time. The procedure for calculating the Niagara River flows was also changed in July, 1957 (Coordinating Committee 1976). At that time, the computation of the portion of the Niagara River flow passing over the falls was changed to use a rating equation using the newly installed Ashland Avenue water level gauge in the Maid-of-the-Mist Pool. This rating equation was reevaluated and modified in 1981. The modification increases the computed flows by about 100 $m^3 s^{-1}$ for January–March, November, and December; by about 20 $m^3 s^{-1}$ for April through August; and by about 30 $m^3 s^{-1}$ for September and October. This results in an average annual increase of about 55 $m^3 s^{-1}$, approximately 1 percent, over the published values. The published flows using the Ashland Avenue gauge rating, 1958–79, were adjusted accordingly for this study.

The consumptive use data are from the International Great Lakes Diversions and Consumptive Uses Board (1981), which gives 63 $m^3 s^{-1}$ as the total basin consumptive use and 48 $m^3 s^{-1}$ as the use directly from the lake in 1975. As there were no data given for prior years the latter value will be assumed to be constant over the study period. The changes in a storage due to thermal expansion, computed specifically for the monthly analysis, are discussed later.

ANNUAL ANALYSIS

The primary basin water supply variables (precipitation, runoff, and evaporation) in equation (1) are shown on an annual basis in Figure 2. Several observations are of interest. With a few exceptions, primarily in the early 1960s, the precipitation for the current period has remained above the 1900–39 mean. The mean precipitation for the current period (736 $m^3 s^{-1}$) is about 5% higher than that (699 $m^3 s^{-1}$) during 1900–39. Thus, the present regime is wetter than that during the early part of the century.

Runoff exhibits the largest annual variations, being a function of both the amount of precipitation and the season in which it falls. The same amount of precipitation produces higher runoff if it occurs during late fall through spring than if it occurs during the summer growing season. Because precipitation is higher during the present period, it is also probable that the present runoff is considerably higher than that during 1900–39. The average annual runoff of 623 $m^3 s^{-1}$ is 85% of the average annual precipitation.

Evaporation from the lake surface has the highest degree of uncertainty of any of the basin variables; it is indirectly computed rather than measured. A discussion of possible errors in the computations is given by Derecki (1981). Because of the uncertainty, the average annual evaporation could be in error by 10–20%. The annual average evaporation of 561 $m^3 s^{-1}$ is also of the same magnitude as the precipitation and runoff. An apparent

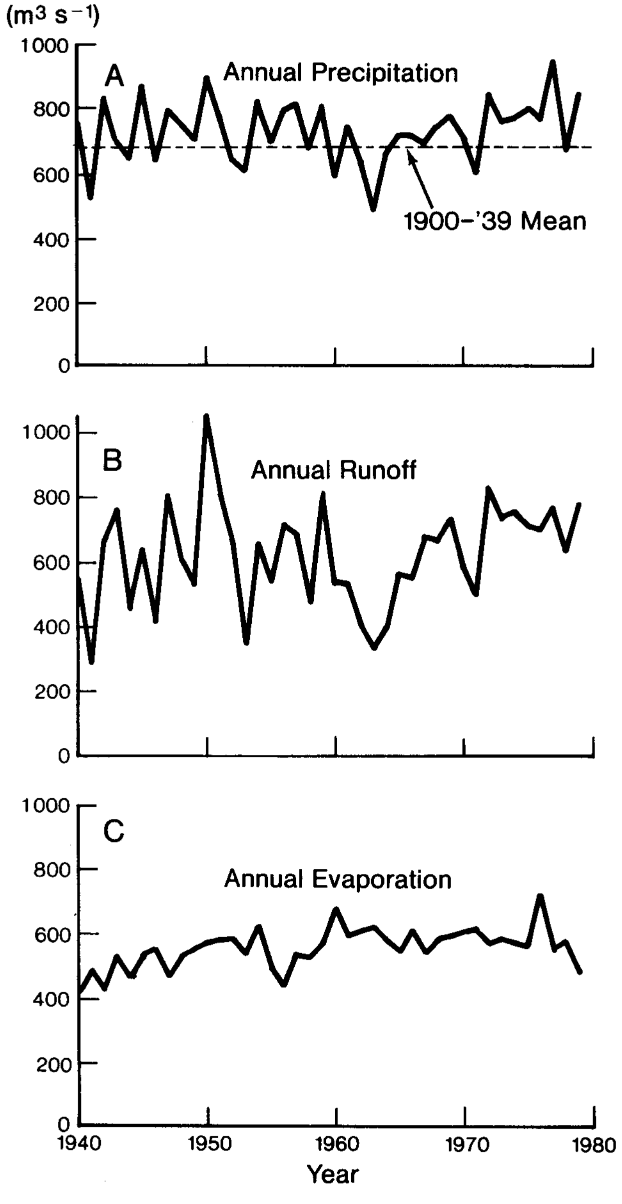

FIG. 2. Lake Erie annual precipitation (A), runoff (B), and evaporation (C) (all in $m^3 s^{-1}$), 1940–79.

increase in evaporation of about 13% occurred in about 1960. The cause of the increase is under investigation, but it coincided with an overall cooling trend over the Lake Erie basin beginning in the late 1950s. Statistics for the water balance components of the continuity equation are presented in Table 1 for the study period.

The annual total water supply to the lake (Fig. 3) is the sum of the Detroit River flow and the net basin supply (NBS) defined as

$$NBS = P + R - E . \qquad (2)$$

Approximately 87% of the total water supply is provided by the Detroit River, while only 13% is provided by the net basin supply. This comparison, however, may be misleading as it is not the relative magnitudes of the supply components (but their relative variabilities) that determine their respective impacts on lake level variations. While the magnitude of the Detroit River flow is about seven times the magnitude of the annual net basin supply, its variability is only twice as large. This results in the net basin supply being a significant factor in the simulation and forecasting of Lake Erie water levels. During the study period the range in the annual net basin supply has been 1,200 m^3 s^{-1}, which translates into a 0.6 meter range in lake levels. For comparison, the range in annual Lake Erie levels during the same period has been 1.1 meters.

The outflows from the lake are through the Niagara River and the Welland Diversion. The Niagara River carries 97% of the outflow compared with 3% for the Welland Diversion. The Niagara River outflows are primarily a function of lake levels in eastern Lake Erie and therefore respond to changes in the total water supply.

The mass continuity of the annual water balance for the period 1940–79 is examined by solving equation (1) on an annual basis. The resulting residuals are shown in Figure 4. Two characteristics become apparent. First, there is an overall negative bias to the residuals; that is, the inflow into the system is larger than the outflow and change in storage. Second, there is a well-defined shift in the

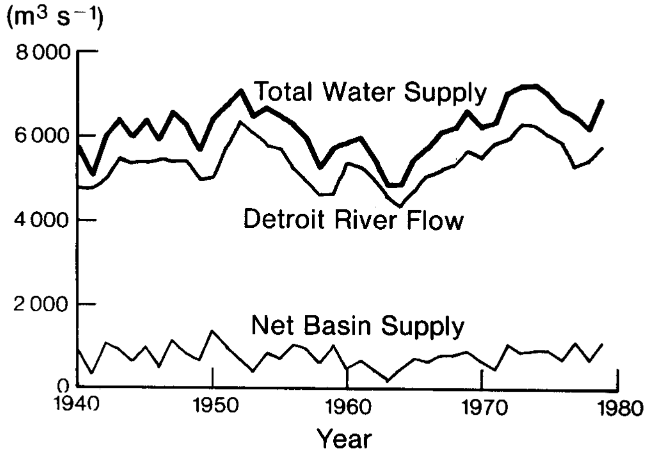

FIG. 3. Lake Erie annual water supply (m^3 s^{-1}), 1940–79.

TABLE 1. Water balance statistics (m^3 s^{-1}), 1940–79.

Parameter	Stat.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Precipitation	M	606	566	700	825	803	827	724	802	785	666	786	693	733
	Std	266	231	255	300	296	246	225	331	323	373	249	228	96
Runoff	M	766	920	1,474	1,256	719	418	249	169	183	227	417	694	623
	Std	593	535	517	541	415	272	159	111	157	197	286	484	160
Evaporation	M	381	213	144	14	41	128	504	905	1,105	1,200	1,368	687	559
	Std	132	71	-103	71	79	98	207	256	264	323	267	224	64
Storage	M	-163	197	1,461	1,382	540	142	-469	-721	-997	-914	-379	147	17
	Std	967	763	751	972	758	511	436	441	520	593	569	724	186
Storage (T)	M	17	-1	-15	4	92	131	73	-18	-105	-73	-93	-15	0
Niagara River	M	5,550	5,516	5,691	5,912	6,178	6,176	6,044	5,929	5,822	5,706	5,753	5,759	5,838
	Std	660	666	670	692	632	609	597	577	580	567	560	580	577
Detroit River	M	4,822	4,695	5,220	5,456	5,542	5,606	5,681	5,664	5,636	5,580	5,529	5,410	5,407
	Std	691	708	624	510	496	502	518	519	500	486	480	486	502
Welland Diversion	M	173	176	180	193	199	198	193	201	201	204	203	193	193
	Std	52	48	45	51	49	48	47	47	47	47	46	45	43
Consumptive Use		48	48	48	48	48	48	48	48	48	48	48	48	48
Net basin Supply	M	990	1,273	2,031	2,068	1,482	1,117	470	66	-136	-307	-164	701	797
	Std	810	704	739	833	677	503	467	513	536	616	537	766	256
Residual		-222	-30	144	7	-151	-290	-408	-255	-321	-155	354	51	-107

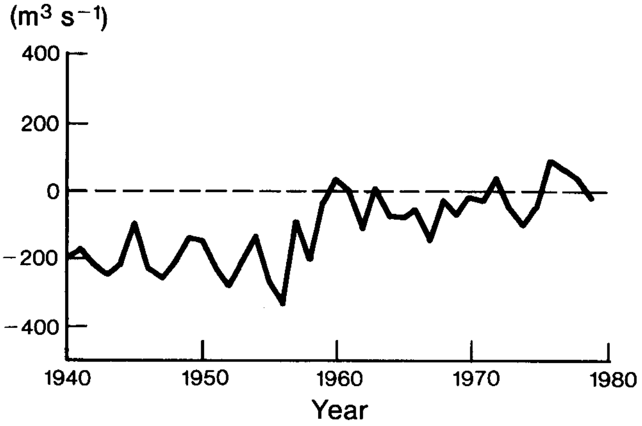

FIG. 4. Lake Erie annual residuals (m^3 s^{-1}), 1940–79.

residuals about 1959, reducing the mean residual by about 80%, which Guerra (1983) found to be statistically significant. The remaining residual for 1959-79 (-28 m^3 s^{-1}) is equivalent to only 0.5% of either the Detroit or Niagara river flows or 6% of the annual evaporation, so it is well within reason. It would, however, result in a slight rise in Lake Erie of about 1 cm above the recorded levels in a simulation analysis using the recorded data and the present rating equations for the Niagara River. Reasons for the change in residuals around 1959 include the increase in annual evaporation occurring at this time as noted earlier, and the changes in procedures for computing the Niagara and Detroit river flows as previously discussed.

In many regulation and management studies (IGLLB 1973), the net basin supply has been computed as a residual from equation (1) rather than independently as in equation (2). The net basin supply can be computed by setting the residual r equal to 0 and arranging equation (1) as

$$NBS = Q_n + D + CU + S - S_t - Q_d \qquad (3)$$

The differences between the net basin supply computed from equation (2) and from equation (3) are equal and opposite in sign to the residuals shown in Figure 4. The significance of the differences between the two procedures is that, when evaluating management alternatives, it is necessary to evaluate past water supplies under current channel conditions. The use of equation (3) would therefore bias the computations by incorporating errors in connecting channel flow measurements due to measurement techniques or the computation of regime changes. As noted by Quinn (1982), this could result in a considerable error in computing net basin supplies in the early 1900s. As an example, a 5% error in the Detroit or Niagara river flows would result in a 34% error in the net basin supply as computed from equation (3). A corresponding 5% error in the precipitation, runoff, or evaporation terms in equation (2) would result in a 4-5% error in the net basin supply. Thus, while there is also uncertainty in the evaluation of the components of equation (2), the relative impacts are considerably less than in the case of the connecting channel flows.

MONTHLY ANALYSIS

The monthly means of each of the water balance parameters are plotted in Figure 5. The seasonal variations of runoff, evaporation, and changes in storage are readily apparent. Precipitation is fairly uniformly distributed throughout the year. Of particular interest is the proportion of the change in storage due to the thermal expansion of the lake volume.

The importance of the thermal expansion in the monthly change in storage was first discussed by Meredith (1975). He derived dimensionless temperature profiles from a limited number of measured profiles, which were used in conjunction with surface water temperatures to derive monthly mean effects of expansion and contraction. In this study, the recently published detailed temperature profiles for the eastern, central, and western basins of the lake (Schertzer *et al.* In Press) were used to derive integrated monthly values of the change in water volume due to thermal expansion and contraction. The limited data sets and current state-of-the-art in thermal modeling preclude the computation of temperature profiles and thermal expansion throughout the study period. The computed values were therefore assumed to be constant for the study period. In Table 3, these values are compared with the mean of Meredith's 1946-65 values. It is seen that during late spring and early fall the thermal expansion is a significant component of the monthly water balance.

The net basin supply and total water supply are shown in Figure 6. While the total water supply is positive throughout the year because of the Detroit River inflow, the net basin supply becomes negative in late summer due to increased evaporation and decreased runoff.

The monthly continuity of the water balance is analyzed by solving equation (1) for the period 1959-79 to eliminate any bias introduced by the

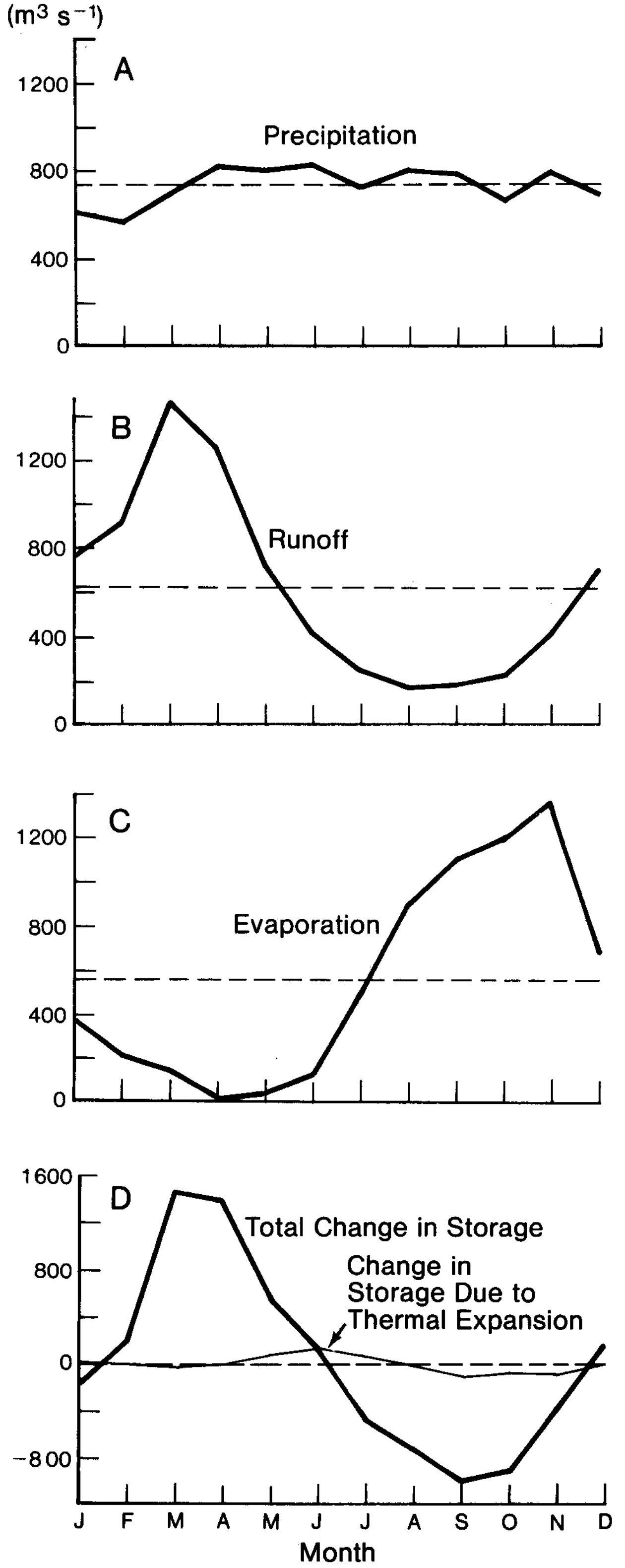

FIG. 5. Lake Erie monthly mean precipitation (A), runoff (B), evaporation (C), and change in storage (D) (all in $m^3\ s^{-1}$), 1940–79.

1959 change in annual residuals as previously noted. The water balance statistics for this period are given in Table 2. The residuals are plotted in Figure 7 which shows a distinct seasonality in the residuals. Guerra (1983) did a correlation analysis of the residuals, without thermal expansion and consumptive use, with the individual water balance terms, but could find no explanation for the high residuals in either November or the June–July summer trough. The most probable reason is that no seasonal corrections are applied in the computation of the Detroit River flows and that the computed November evaporation may be too large. The Niagara River flows exhibit a significant seasonal retardation in the growing season owing to weed growth. A similar retardation occurs in the Detroit River, but has not been incorporated in the flow computations.

SUMMARY AND CONCLUSIONS

This study provides the most comprehensive overview of the Lake Erie water balance undertaken to date and delineates several areas for future research. The annual precipitation suggests that the Lake Erie water supply regime since 1940 has been high compared with the first 40 years of the century. A continuation of this regime, resulting in continued high water levels, will have major implications for Lake Erie interests in the years to come. For example, during the spring of 1985, Lake Erie set new record high lake levels. The analysis of the individual water balance components indicating high variability of runoff, as compared with precipitation and evaporation, suggests that rainfall-runoff modeling is an important area for further research.

The analysis also illustrates the influence of net basin supply variations on annual water level fluctuations. Major improvements in forecasting Lake Erie total water supplies can best be achieved by focusing on both the Lake Erie net basin supplies and the water supplies to the upper lakes, which funnel into Lake Erie through the Detroit River.

The continuity of the system, which is extremely important in simulation studies, is fairly well satisfied, with the average annual residual for 1959–79 being about 0.5 percent of the Detroit or Niagara river flows. This is well within the accuracy of the computations. The large variations in the monthly residuals are probably due primarily to the lack of

TABLE 2. Water balance statistics (m^3 s^{-1}), 1959–79.

Parameter	Stat.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Precipitation	M	609	531	681	812	733	831	737	814	812	627	813	768	731
	Std	259	238	256	311	236	222	230	383	344	268	270	234	99
Runoff	M	720	942	1,529	1,229	650	361	256	182	214	220	468	804	630
	Std	443	606	525	463	245	198	154	91	192	128	320	541	142
Evaporation	M	423	237	142	1	31	128	541	929	1,200	1,326	1,394	746	593
	Std	145	76	106	51	77	101	225	209	274	276	216	253	48
Storage	M	-164	345	1,548	1,267	313	42	-442	-616	-885	-1,401	-240	330	36
	Std	647	758	693	885	429	408	448	454	556	463	622	758	173
Storage (T)	M	17	-1	-15	4	92	131	73	-18	-105	-73	-93	-15	0
Niagara River	M	5,609	5,609	5,817	5,996	6,245	6,209	6,069	5,944	5,843	5,759	5,814	5,853	5,899
	Std	783	772	762	804	722	701	725	696	719	680	690	695	705
Detroit River	M	4,845	4,833	5,342	5,502	5,533	5,617	5,691	5,698	5,673	5,631	5,593	5,456	5,454
	Std	724	699	608	543	550	560	576	567	553	517	513	522	547
Welland Diversion	M	186	189	200	221	226	223	219	226	224	225	222	215	215
	Std	44	40	20	20	21	25	26	23	23	31	33	23	17
Consumptive Use		48	48	48	48	48	48	48	48	48	48	48	48	48
Net basin Supply	M	906	1,236	2,068	2,040	1,352	1,064	452	67	-173	-479	-113	827	-768
	Std	644	766	761	744	468	450	487	480	602	416	628	881	256
Residual		-88	122	218	-15	-144	-289	-323	-143	-164	-87	458	179	-24

TABLE 3. Mean monthly change in storage due to thermal expansion and contraction (m^3 s^{-1}), 1940–79.

Month	Change in storage (Meredith 1975)	Change in storage (Present study)
January	11	17
February	1	-1
March	-10	-15
April	-1	4
May	33	92
June	102	131
July	106	73
August	16	-18
September	-92	-105
October	-91	-73
November	-72	-93
December	-5	-15

seasonal corrections in the Detroit River flows and secondarily to errors in evaporation. Changes in storage due to thermal expansion were found to be significant during the late spring and early fall. The step function in the annual residuals, occurring between 1958 and 1959, is significant for simulation and regulation studies and illustrates the large discontinuities that can occur when calculating the net basin supplies from residuals rather than directly from the precipitation, runoff, and evaporation.

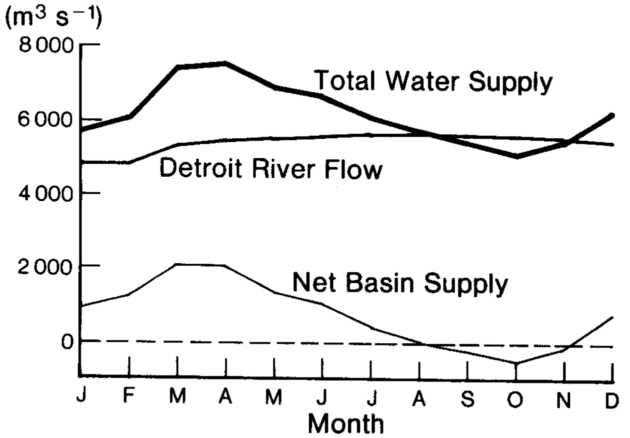

FIG. 6. Lake Erie monthly mean water supply (m^3 s^{-1}) 1959–79.

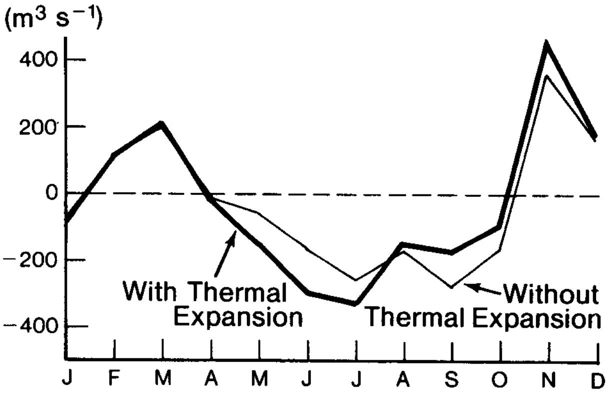

FIG. 7. Lake Erie monthly mean residuals with and without thermal expansion (m^3 s^{-1}), 1959–79.

In conducting simulation studies the residuals will result in Lake Erie computed levels not matching the recorded values. It is recommended that in this event the Niagara or Detroit river flows be adjusted to minimize the root mean square error in the lake levels. The required adjustments will be well within the accuracy of the flow computations.

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