Evaporation Study in a Humid Region, Lake Michie North Carolina

By J. F. TURNER, Jr.

STUDIES OF EVAPORATION

GEOLOGICAL SURVEY PROFESSIONAL PAPER 272-G

Prepared in cooperation with the city of Durham, N.C.

An evaluation of evaporation using mass-transfer and water-budget techniques

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 20 cents (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

SYMBOLS

δ	Net ground-water seepage rate.
ΔH	Average change in lake stage.
ΔH_A	Average change in lake stage, adjusted for inflow, outflow (including pumpage), and rainfall.
Δt	Error in water-surface temperature.
E	Evaporation from water surface.
e_a	Actual air vapor pressure corresponding to the product of relative humidity, f, and saturation vapor pressure, e_s.

e_0 Saturation vapor pressure corresponding to water-surface temperature, T_0.
e_s Saturation vapor pressure corresponding to dry-bulb temperature, T_a.
f Relative humidity.
I Inflow.
N Slope of the calibration curve; the mass-transfer coefficient.
O Outflow.
$(O-I)$ Outflow minus inflow.
Q_D Dial Creek discharge.
R Rainfall.
T_a Dry-bulb temperature.
T_0 Temperature of lake water surface.
u Wind speed.

STUDIES OF EVAPORATION

EVAPORATION STUDY IN A HUMID REGION, LAKE MICHIE, NORTH CAROLINA

By J. F. Turner, Jr.

ABSTRACT

The mass-transfer and water-budget techniques of calibrating a reservoir for evaporation were evaluated through a study of Lake Michie, N.C. The techniques appear adequate for estimation of lake evaporation and net seepage in humid regions where lake storage is affected by streamflow and ground-water seepage, under conditions no more adverse than those affecting Lake Michie.

The analysis of 25 months of mass-transfer and water-budget data collected at Lake Michie indicates pronounced seasonal variation in both evaporation and seepage.

INTRODUCTION

In past years, water losses by evaporation in humid regions have been given only limited consideration because abundant water resources made concern unnecessary. The growing industry and population of the Eastern United States are now making such great demands on water resources that studies are needed to evaluate evaporation losses from reservoirs.

The Lake Michie investigation is of special significance because of the scarcity of lake evaporation studies in humid regions where lake storage is appreciably influenced by inflow and outflow. Streamflow has commonly been negligible or completely absent as a factor in evaporation studies in arid and semiarid regions. The present investigation is also useful in that it suggests some basic design elements for future evaporation studies in humid areas.

The method of evaluation used in this study requires the establishment and application of a calibration curve (a curve relating observed evaporation rates to a combination of several meteorological variables). The mass-transfer water-budget techniques as described by Harbeck (1962) was chosen for the Lake Michie study primarily because the method is simple to apply, requires inexpensive instrumentation, and allows a seepage estimate to be made. The relative merits of this technique and another frequently used method for determining evaporation are discussed later in the report.

The Lake Michie study is a continuing project, financed through a cooperative program of the city of Durham, N.C., and the U.S. Geological Survey to evaluate the water resources of the upper Neuse River basin.

DESCRIPTION OF LAKE MICHIE

Location and physical features.—Lake Michie is the municipal water supply for the city of Durham and the State Sanitorium at Camp Butner, N.C. Electric power is occasionally generated and supplements the power required to pump water. The dam, completed in April 1926, is a reinforced concrete gravity-type structure situated about 5¼ miles above the mouth of the Flat River and about 13 miles northeast of Durham. (See fig. 37.)

The sparsely populated Lake Michie region is generally wooded and hilly, with some open land that is used for small grain, pasture, and row crops. The lake is narrow, irregular, and meandering, and the shoreline is nearly covered by trees and small brush. Lake Michie has an average surface area of about 480 acres; its volume ranges from about 11,200 to 14,500 acre-feet. The average flow through the lake is about 170 cfs (cubic feet per second).

The drainage at the dam is 170 square miles, of which 155 square miles of the inflow area is continuously gaged, 8 square miles is gaged periodically, and 7 square miles is totally ungaged. (Drainage areas are only approximate.) Thus, about 9 percent of the total drainage is not continuously gaged.

Climatology.—Long-term averages of climatological and hydrologic data pertinent to the evaporation study are listed in the following table:

Annual precipitation (inches)	44.5
Temperature (°F)	60
Wind speed (mph) and direction	7.7 (SW.)
Percent of possible sunshine	60
Relative humidity (percent):	
1 a.m	81
7 a.m	83
1 p.m	53
7 p.m	68
Average runoff (cfs per sq mi)	1.0

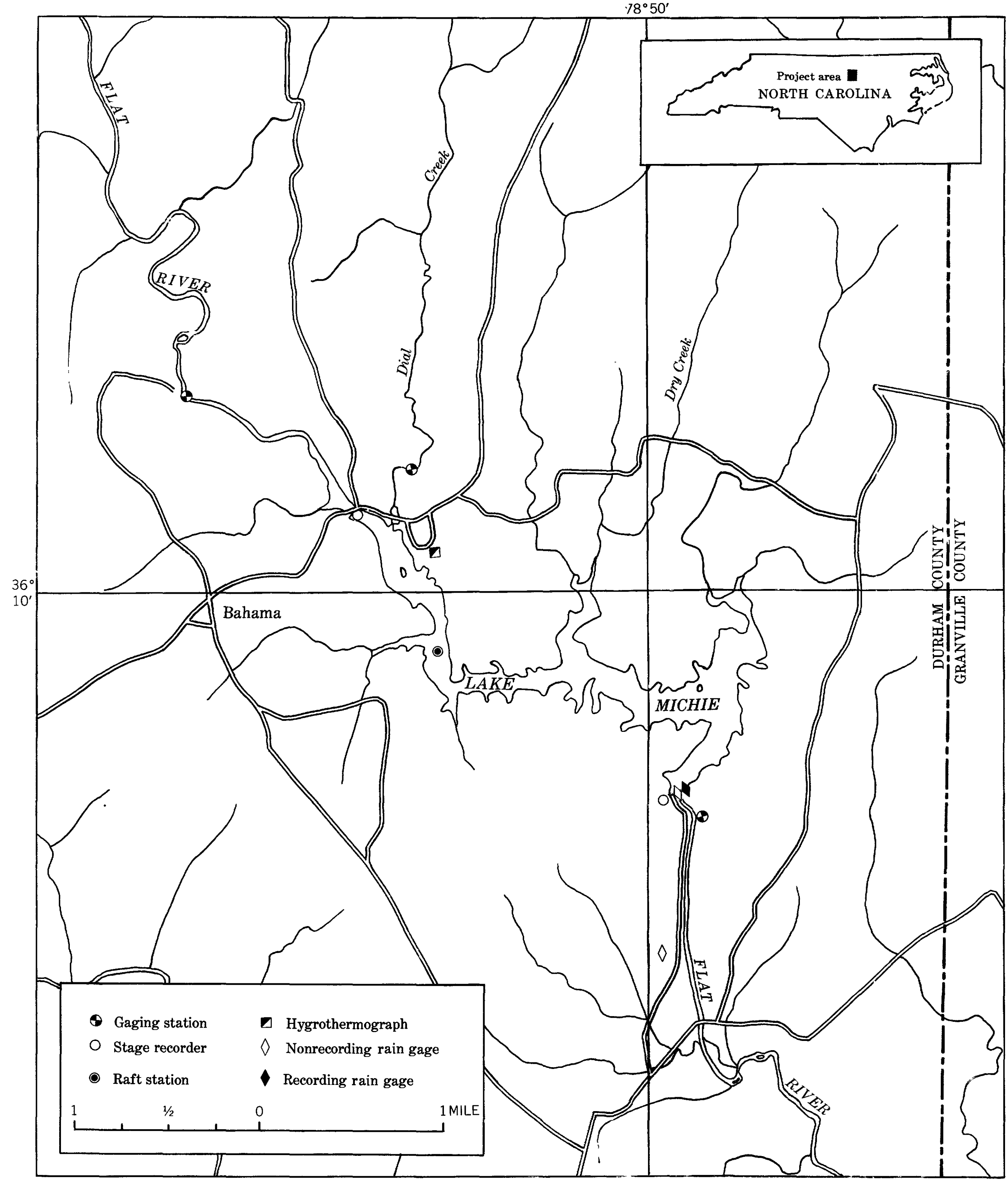

FIGURE 37.—Lake Michie.

FIGURE 38.—Lake Michie raft station.

Except for runoff, the listed values were observed by the U.S. Weather Bureau at Raleigh and Raleigh-Durham Airport.

INSTRUMENTATION OF THE STUDY

The location of the hydrographic and meteorological equipment used in this study is shown on the map of Lake Michie and surrounding area (fig. 37). The instruments are listed in table 1, along with an indication of their location and the types of data collected in the past. The raft station is shown in figure 38, and the anemometer and wind and water-surface temperature recorder are shown in figure 39.

As indicated in table 1, lake-stage records have been collected at the dam since about 1927. These records and the rainfall data used in the study were collected by employees of the city of Durham. Rainfall data are furnished to the Geological Survey monthly. The hourly distribution for the rainfall data is provided by the tipping bucket attachment to the water-level recorder at the dam.

DEVELOPMENT OF THE CALIBRATION

METHODS AND ANALYSES

The calibration for Lake Michie was developed by relating observed changes in lake stage (adjusted for inflow, outflow, and rainfall) to a combination of several meteorological variables observed at Lake Michie and at the Raleigh-Durham Airport.

This technique basically requires a simultaneous solution of the mass-transfer equation as suggested by Harbeck (1962) with a water-budget equation (Linsley

FIGURE 39.—Anemometer and wind and water-surface temperature recorder.

TABLE 1.—*Hydrographic and meteorological instruments*

Instrument	Location	Data collected	Period
Rain gage (nonrecording).	Dam	Rainfall	1926–.[1]
Do	Near dam	do	September 1926–.[1]
Do	Rougemont (in basin).	do	September 1913–.[1]
Floating pan	On lake (near dam).	Evaporation	1946–61.[1,2]
Hydrothermograph	Raft station	Water-surface temperature.	September 1961–.
Hygrothermograph	Weather station	Air temperature and relative humidity.	September 1961–December 1962.
Lake-stage recorder	Bridge	Lake stage	August 1961–.[3]
Do	Dam	do	August 1961–.
Lake-stage recorder	do	do	1927–1961 (about).
Psychrometer (hourly).	Raleigh-Durham Airport.	Dry-bulb temperature and relative humidity.	1944–.[1]
Sparling meters	Dam	Diversion to Durham and Camp Butner.	1927–.[1]
Tipping bucket rain gage.	do	Rainfall	August 1961–.
Totalizing anemometer.	Raft station	Wind movement	September 1961–.[3]
Water-stage recorder	Flat River (below dam).	Outflow (drainage area, 170 sq mi).	August 1927–September 1959; August 1961–.
Water-stage recorder (digital).	Dial Creek (above lake).	Inflow (drainage area, 4.71 sq mi).	October 1925–.
Do	Flat River (above lake).	Inflow (drainage area, 150 sq mi).	July 1925–.

[1] Data collected by other agencies.
[2] Fragmentary.
[3] Except for winter months 1962, 1963, 1964.

and others, 1958, p. 93). Harbeck's equation relates evaporation to several meteorological factors,

$$E=Nu(e_0-e_a), \tag{1}$$

where

E=evaporation, in feet;
N=proportionality constant (mass-transfer coefficient);
u=wind speed, in miles per hour;
e_0=saturation vapor pressure, in millibars, corresponding to temperature at the air-water boundary;
e_a=actual vapor pressure of the air, in millibars.

According to mass-transfer theory, this equation describes the physical process by which water evaporates from a free surface. The difference e_0-e_a reflects the absorptive capacity of air moving across the water surface, and the wind speed, u, represents the rate of transport for the absorbed water vapor.

The water-budget equation (simplified for computational convenience) is of the form

$$\Delta H_A=E+\delta \tag{2}$$

where

ΔH_A=average change in water-surface elevation adjusted for inflow, outflow (including diversions), and rainfall, in feet;
E=evaporation, in feet;
δ=net ground-water seepage, in feet.

Equation 2 was derived from the more complex water-budget equation, in which evaporation and other lake losses are positive:

$$E-\Delta H+(O-I)-R+\delta=0 \tag{3}$$

where

ΔH=average change in water-surface elevation, in feet;
$(O-I)$=total outflow minus inflow, in cubic feet per second, but converted to an equivalent depth in feet over lake surface;
R=rainfall, in feet.

The following substitution is made to simplify computations:

$$\Delta H_A=\Delta H-(O-I)+R \tag{4}$$

and equation 3 reduces to equation 2.

The simultaneous solution of equations 1 and 2 gives,

$$\Delta H_A=(E+\delta)=Nu(e_0-e_a)+\delta \tag{5}$$

the equation by which the parameters δ and N were evaluated to define the Lake Michie mass-transfer and water-budget calibration.

Equations similar in form to equation 5 have been successfully used to develop calibrations for several lakes and small stock ponds in the western United States, where surface water flow was small or nonexistent, and therefore water budgets were determined with relative ease.

The mass-transfer concept is old, and consequently there are many mass-transfer equations predating the one used in this study. Equation 1 was originally suggested in the Lake Hefner and Lake Mead studies; it is very similar to many of the older mass-transfer equations, which show evaporation to be proportional to wind speed and to saturation vapor pressure minus air vapor pressure. Usually, these equations include various complex factors to adjust for minor variations; some include constants of proportionality to impose dimensional exactness; others are mathematically derived (Harbeck and others, 1958, p. 29–35). Equation 1 was primarily designed for practical application. (See Harbeck, 1962.)

Recent evaporation studies indicate that Harbeck's equation is adequate to define lake evaporation whereas other mass-transfer equations are not, because complex structure makes a practical numerical evaluation impossible. The basic advantages of equation 5 are simplicity in application and practicality of field instrumentation.

Lakes and reservoirs that have large inflows, outflows, and seepage rates usually produce large errors in water-budget computation; consequently, it may be impossible

209-983 O - 66 - 2

to develop a calibration using hydrographic data. Because of this inadequacy or for other reasons, a measure of evaporation by energy-budget techniques may be substituted for the water budget to develop a mass-transfer coefficient, N. However, this use of the energy-budget method is expensive and also restrictive in that it eliminates seepage (δ) from equation 5. This may or may not be a desirable feature in a particular situation.

COMPUTATIONS

HYDROGRAPHIC DATA: ADJUSTED CHANGE IN STAGE, ΔH_A

The change in lake stage, ΔH, is the average difference between midnight readings (for a calibration period of the two stage gages. This average change in stage, when adjusted for inflow, outflow, and rainfall, is the water-budget estimate of evaporation and seepage and is denoted by ΔH_A. The computational procedure is shown schematically in figure 40 and is demonstrated by two examples in table 2. At the beginning of the study, computations such as those in table 2 were made for each day, and trial plotting points were obtained by averaging selected groups of days. After final selection of plotting points full periods were recomputed as shown, thus eliminating computational errors. The plotting points finally selected are summarized in table 4. The calibration is shown in figure 44 and is discussed later in this report.

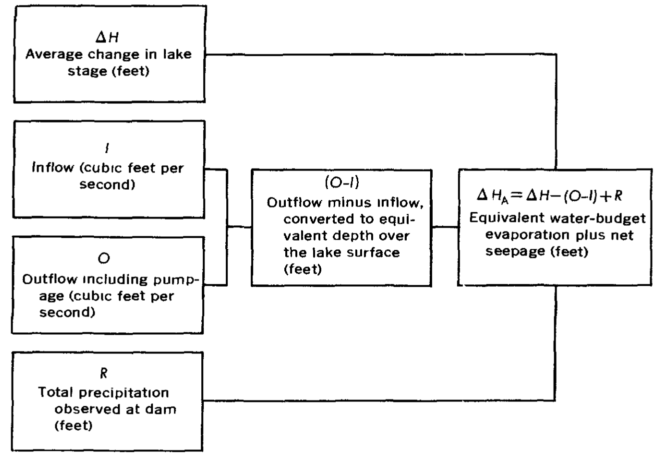

FIGURE 40.—Determination of adjusted change in stage, ΔH_A.

TABLE 2.—*Examples of computation of adjusted change in stage,* ΔH_A, *for calibration points*

Date	Calibration Point 7, Nov. 1–6, 1961							Calibration Point 24, Oct. 23–26, 1962				
	1[1]	2	3	4	5	6[2]	Total period	23[1]	24	25	26[2]	Total period
Lake stage, in feet:												
At bridge	11.34					10.91		12.35			11.94	
Net change							0.43					0.41
At dam	26.52					26.09		27.54			27.14	
Net change							.43					.40
ΔH							.43					.405
Rainfall, R, in feet	0	0	0.005	0.008	0	0	.013	0	0	0	0	0
Streamflow, in cfs:												
Inflow, I:												
Flat River at Bahama	11	11	11	12	12	12		11	11	11	11	
Dial Creek near Bahama	.7	.7	.7	.8	.8	.8		.6	.5	.5	.5	
Ungaged	.3	.3	.3	.3	.3	.3		.2	.2	.2	.2	
Total inflow	12.0	12.0	12.0	13.1	13.1	13.1	75.3	11.8	11.7	11.7	11.7	46.9
Outflow, O:												
Pumpage	18.7	20.4	20.4	19.3	19.1	20.4		18.4	18.6	24.1	21.3	
Flat River at dam near Bahama	11	11	11	11	11	11		12	12	12	12	
Total outflow	29.7	31.4	31.4	30.3	30.1	31.4	184.3	30.4	30.6	36.1	33.3	130.4
Outflow minus inflow $(O-I)$							109					84
Lake area, in million sq ft	19.0	19.0	19.0	19.0	18.9	18.9		19.6	19.6	19.6	19.5	
Average							19.0					19.6
Outflow minus inflow, in feet							.496					.370
$\Delta H_A = \Delta H-(O-I)+R$:												
In feet							−.053					.035
In feet per day							−.009					.009

[1] 0000 hours.
[2] 2400 hours.

OUTFLOW AND INFLOW

Inflow (I) is the sum of streamflow observed at the gaging stations (Flat River at Bahama, N.C., and Dial Creek near Bahama, N.C.) and the estimated inflow from about 15 square miles of ungaged drainage. The ungaged surface inflow was estimated from a regression (shown in fig. 41) established by relating discharge at the Dial Creek gage to estimates of the ungaged inflow. The estimates were based on periodic observations of streamflow, made primarily during base-flow periods, at eight sites on small tributaries.

The total outflow, O, is computed as the sum of the discharge observed at the outflow gage (Flat River at dam near Bahama) plus diversions to Durham and Camp Butner. The diversion is recorded daily at the Lake Michie dam and is furnished monthly to the Geological Survey by the city of Durham.

Stage-area relation.—A stage-area curve of relation is required for conversion of outflow minus inflow, $O-I$ (in cfs), to an equivalent depth in feet over the lake surface as is shown in table 2. Unfortunately, a usable relation was not available for the Lake Michie study; a stage-area relation was developed from data collected from a local engineering firm, the U.S. Soil Conservation Service, and the North Carolina Department of Conservation and Development. Data from those sources were supplemented by surface-area estimates made from aerial photographs and from reservoir and high-flow records.

Lake areas estimated from high-flow records were used as a supplement because the relation was poorly defined at intermediate lake stages and there were disagreements between the various sources of information. These computed data provided the additional information necessary to define the relation for stages ranging from 322 to 350 feet above mean sea level. They were computed from the observed incremental changes in lake stage and flood volumes gaged during flood periods of a few hours. Areas were computed as the quotient of gaged volume and change in stage and were plotted against the average lake stage observed during the incremental flood period. The stage-area curve is shown in figure 42. Although this relation is probably the most accurate that could be obtained with available data, a certain degree of error is inherent in the basic relation, and this error probably varies with stage.

ERRORS IN HYDROGRAPHIC DATA

The errors associated with the determination of ΔH_A result from errors in ΔH, and $O-I$. The errors in ΔH

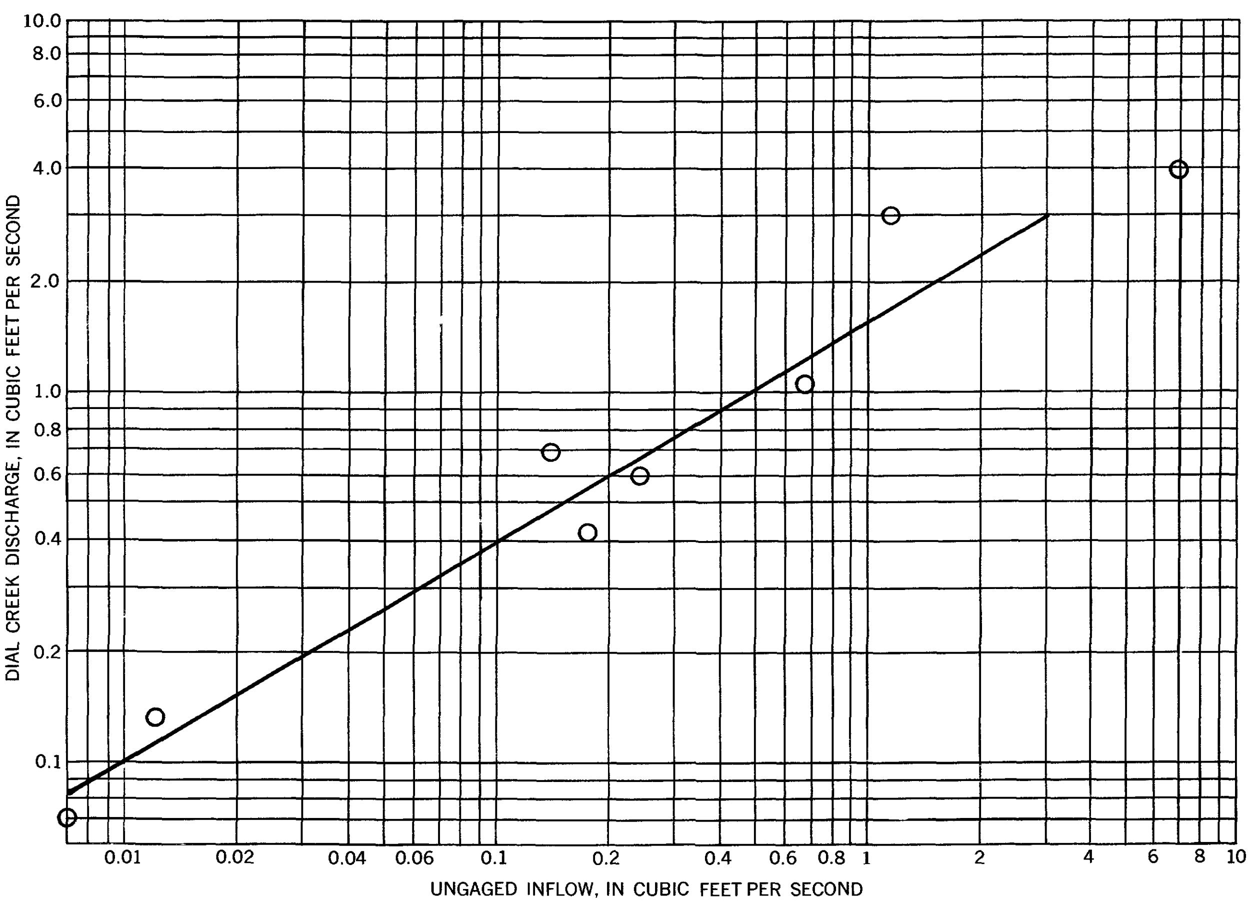

FIGURE 41.—Ungaged inflow plotted against Dial Creek discharge.

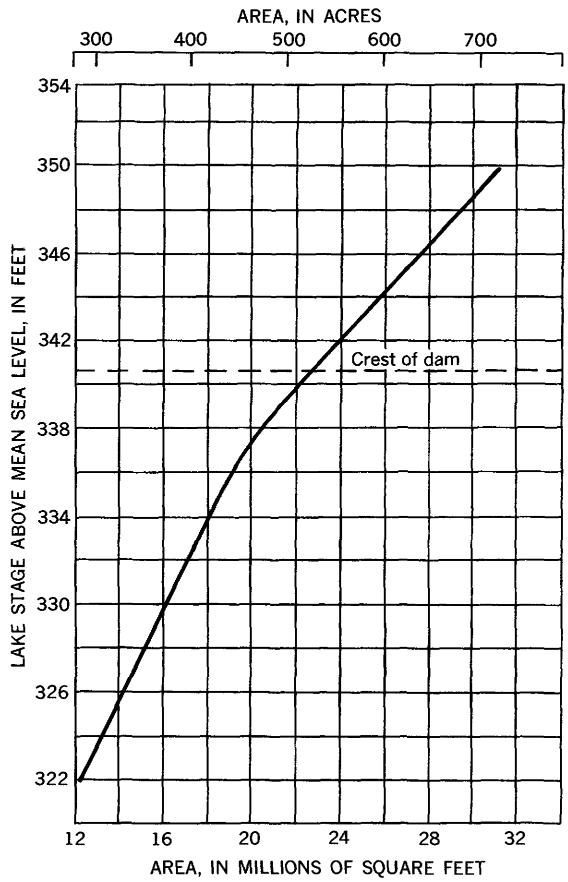

FIGURE 42.—Stage-area relation.

are the result of wave action, seiche action, areal variation (slope in lake), and purely instrumental inadequacies. Most of the errors were avoided by rejection of certain lake-stage data for use in developing the calibration, as discussed later.

Discharges are subject to errors of 5 percent or more in the components O and I; therefore, the consequent error in the difference $O-I$ could be larger than the error in either individual component and could influence the accuracy of the calibration curve.

An analysis was made of the water-budget calibration data to determine the relative errors in the computed adjusted change in lake stage, resulting from errors occurring in the total surface inflow. The analysis is shown in table 3.

Inflow rates ranging from 3 to 40 cfs are typical of the periods used in determining the calibration. The percentages shown in the last column are computed on the basis of $\Delta H_A=0.0056$ feet per day, which is the average (disregarding signs) of those data shown in the fourth column of table 4. Gaging-station records used in the Lake Michie study are rated excellent or good (5–10 percent), and pumpage records may be assumed to be reliable.

The size of the errors shown in table 3 demonstrates the necessity of placing restrictions on flow data selected for computing calibration points. The errors vary inversely with the lake area, a fact which indicates the critical relationship between lake size and streamflow.

Outflow is an additional source of error in computing calibration points. Errors in each of the gaging station records are independent; the combined effect is reduced to a single random error component and does not seriously restrict calibration computation.

TABLE 3.—*Errors in adjusted change in stage resulting from normal errors in streamflow records*

Inflow (cfs)	Recurrence interval of minimum annual flow (years)	5 percent error in inflow		Error in ΔH_A (percent)
		cfs	feet per day	
46	1.05	2.3	0.0095	170
27	1.2	1.4	.0058	104
17	1.5	.85	.0035	62
10.5	2	.52	.0021	37
5.5	3	.28	.0012	21
3.0	5	.15	.0006	11
1.5	10	.08	.0003	5

The total error in ΔH is also due to errors in the stage-area relation, and in pumpage and stage records, and to variations in net seepage. All such errors cause points on the calibration curve to scatter. To minimize this scattering, the following limiting conditions were used in evaluating the water-budget equation:

1. Uniform stage hydrograph: $|\Delta H|<0.20$ feet per day.
2. Negligible rainfall during period.
3. Small, uniform discharge at inflow stations:
   (a) Dial Creek discharge <2 cfs.
   (b) Flat River discharge <40 cfs.
   (exceptions: points 12 and 25, table 4).
4. Uniform outflow.
5. Accurate gaging station and pumpage records—no periods of estimated record were included.

Calibration points still scatter, despite these precautions; nevertheless, the average curve is well defined in the range where all but rare periods of evaporation occur. Thus estimates of evaporation are possible within acceptable limits of accuracy.

METEOROLOGICAL DATA: THE MASS-TRANSFER PRODUCT, $u(e_0-e_a)$

The meteorological instruments used in the Lake Michie evaporation study are listed in table 1 and several are shown in figures 38 and 39. The computational procedure is diagrammed in figure 43.

SATURATION VAPOR PRESSURE

The water-surface temperature was continuously recorded at the Lake Michie raft station, first by a weekly recorder and later by a continuous recorder, shown in figure 39.

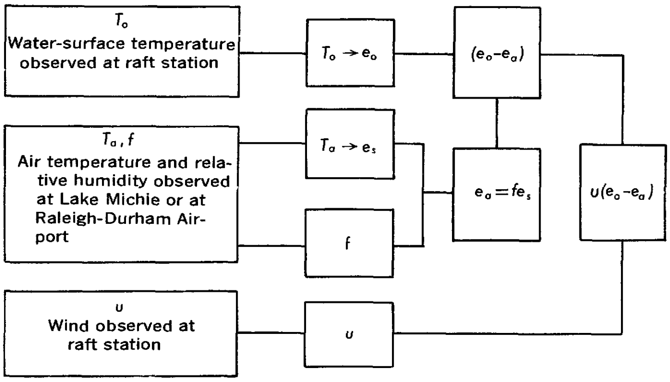

FIGURE 43.—Daily computation of the mass-transfer product, $u(e_0-e_a)$.

Graphical daily averages of water-surface temperature, T_0, are determined from recorder charts and converted to saturation vapor pressure, e_0, by means of standard vapor-pressure tables. During early stages of the study, analytical comparisons were made to find the most feasible computational method for determining daily average vapor pressures, since the relation of temperature and vapor pressure is curvilinear. These comparisons indicated that vapor pressures determined directly from daily average temperatures are sufficiently accurate, and determination from smaller incremental averages is unwarranted.

WIND SPEED

The wind movement, u, at a height of 2 meters above Lake Michie is recorded by a totalizing anemometer on the raft, and the data are averaged for 24-hour periods and tabulated in units of miles per hour. Some wind records used in the study were incomplete in minor details, and it was necessary to use estimated values adjusted to the total wind movement during a chart period.

AIR VAPOR PRESSURE

The air vapor pressure, e_a, is defined as the product of saturation vapor pressure, e_s, and relative humidity, f. Observed dry-bulb temperature, T_a, and standard tables of vapor pressure are used to determine e_s. Air vapor pressure, e_a, is a product involving the daily average relative humidity and is subject to an additional error from averaging. Preliminary investigations to find the most feasible method of determining e_a indicated that the product of daily averages resulted in values of usable accuracy, and that the added refinement of subdividing the factors T_a and f was not necessary.

Dry-bulb temperature and relative humidity were recorded at the Lake Michie weather station by a hygrothermograph for the period September 1961 to December 1962. A statistical analysis of 475 daily means of air vapor pressure observed at Lake Michie and at Raleigh-Durham Airport (about 20 miles south of Lake Michie) indicated that vapor pressures at the two locations are almost identical and are related by the equation

$$Y=1.00X+0.35 \qquad (6)$$

where

Y=Lake Michie air vapor pressure, in millibars;
X=Raleigh-Durham Airport air vapor pressure, in millibars.

The standard error of estimate is 1.20 millibars, or about 8.8 percent of the mean vapor pressure observed at Lake Michie during the period September 1961 to December 1962, and the correlation coefficient is 0.99. This similarity eliminated the need for continuing operation of the hygrothermograph at the Lake Michie weather station.

ERRORS IN METEOROLOGICAL DATA

Errors in e_0 and e_a resulting from instrumental or computational errors in the daily average of T_0 and T_a should be kept to a minimum because errors of 2°F could produce errors in $u(e_0-e_a)$ up to 25 percent or more, depending upon the season. For example, if the mass-transfer product, $u(e_0-e_a)$, is subject to an error in e_0 resulting from an error of Δt degrees in determining T_0,

$$\text{relative error, in percent} = \frac{(e_{0+\Delta t}-e_0)\times 100}{(e_0-e_a)} \qquad (7)$$

where

$e_{0+\Delta t}$=the erroneous vapor pressure corresponding to $T_0+\Delta t$.

The following table indicates the possible relative errors in $u(e_0-e_a)$ resulting from an error of 2°F in T_0, for typical Lake Michie seasonal values (February and July) of T_0 and T_a. Vapor pressures are in millibars.

T_0	e_0	$e_{0+2°F}$	e_a	Relative error
(July) 83°F	38. 5	41. 0	25. 2	19
(Feb) 42°F	9. 1	9. 8	6. 5	28

Because errors of 2°F in the daily water-surface temperature cause large errors in the daily term, $u(e_0-e_a)$, care was taken to correct recorded temperatures to agree with accurate reference thermometers, insuring that errors are largely random and noncumulative and thus have a small effect on average values computed from 7 to 25 days of record. Such errors in the different plotting periods undoubtedly tend to compensate; but when the plotting period is short, as in the upper end of the calibration curve, which is defined by some 2-day averages, the lake calibration computations may be influenced. Similar errors in T_a and f also produce errors in $u(e_0-e_a)$.

Another source of error in evaluation of the calibration equation is the lack of homogeneity in data observed at the raft location during the calibration period. The assumption was made that data observed at the present raft location and true lake data are proportional; or more simply, that actual changes in the lake's environment are equivalent to changes in data observed at the raft. Hence, if calibration equations were developed for two different points on the lake (two different mass-transfer coefficients), the evaporation values computed from these two equations would be nearly equivalent—if no serious sampling errors were inherent in the data.

Sampling errors involve both wind and temperature data. Water temperature data collected during periodic thermal surveys have shown areal variations to be small and of minor concern. Wind movement offers greater possibility of error. One could hypothesize that a comparison of variation in the wind data observed at the raft with variations in actual wind conditions (if known) for the entire lake would exhibit an extremely high degree of correlation and that slight differences would average out in a sufficiently long period. On the other hand, significant variations in the data, such as a seasonal bias, could occur during the usually short calibration period. This type of effect could cause large errors in the mass-transfer coefficient, and therefore a raft location must be chosen that will assure representative data (good sampling). Such a location may be assumed to be an adequate precaution.

THE CALIBRATION CURVE

PLOTTING AND LIMITATIONS OF PERIODS

The Lake Michie calibration curve is shown in figure 44. The plotting points, which represent averages of ΔH_A (ordinate) and $u(e_0-e_a)$ (abscissa) for 41 selected periods ranging in length from 2 to 25 days, were compiled using the limitations discussed above in the section titled "Errors in Hydrographic Data." The plotting points are shown in table 4.

During the first year of hydrographic record at Lake Michie (September 1961 to August 1962) few periods were suitable for computing points for the calibration curve because frequent rains made streamflow excessive, and the required accuracy in determining changes in lake storage could not be met. Weather

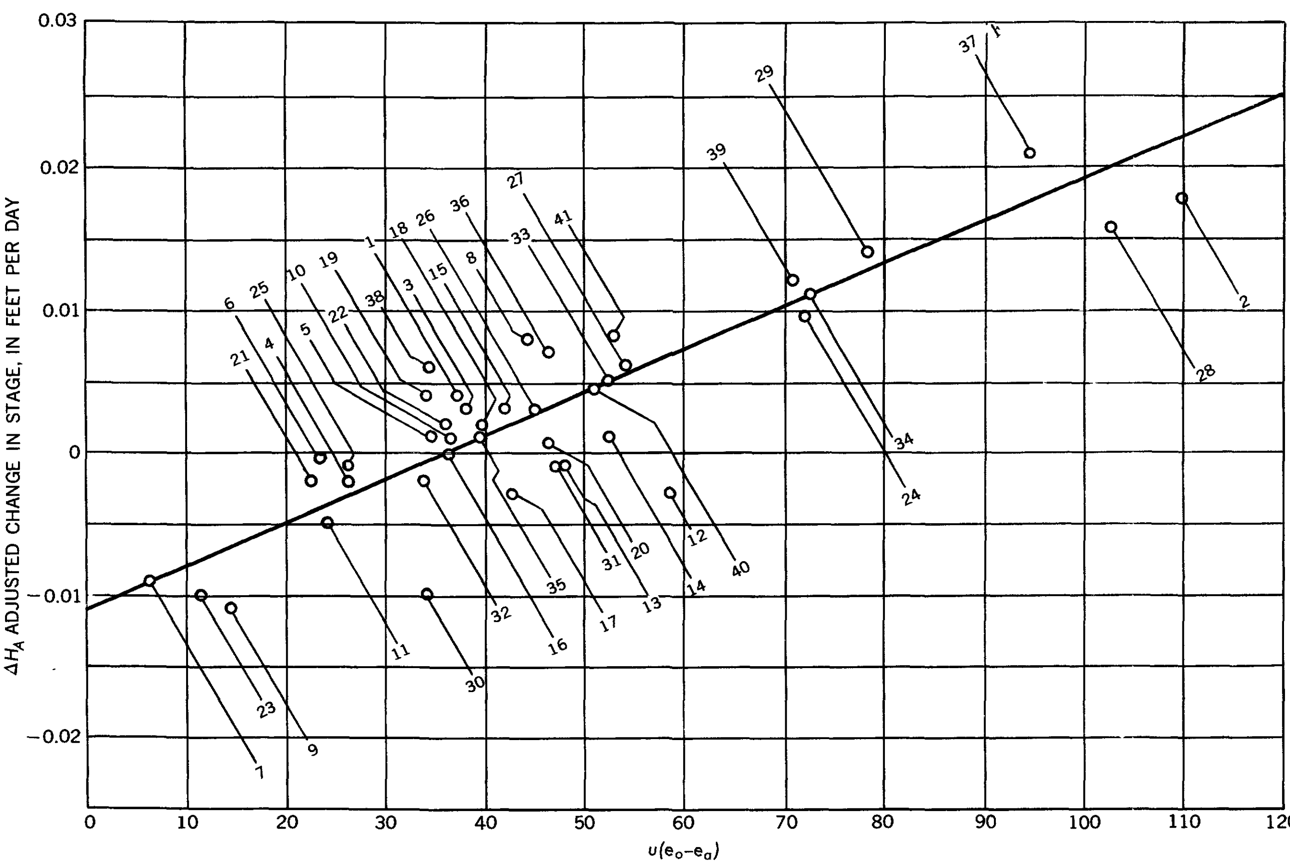

FIGURE 44.—Calibration curve.

conditions during the next season (summer of 1963) were more favorable. Deficiency of the normally abundant rains during the spring and early summer caused a drought in the Lake Michie drainage basin. Streams receded to annual minimum flows having recurrence intervals of 2–5 years; thus, the streamflow data needed for accurate determination of changes in the water budget became available. These low flows, in conjunction with wide variations in the meteorological data (especially in wind speed), provided the records used to define the calibration. Without this drought, the necessary low flows would have been rare, and several more seasons might have been required to develop the calibration.

As indicated in table 4, several 2-day averages were used to compute calibration points. This was necessary to obtain better definition of the upper portion of the calibration. Also, some of the high plotting points were necessarily dependent; that is, several periods of 2–4 days of high evaporation occurred during longer periods for which points were plotted (Nos. 2 and 28, table 4, for example). The upper end of the curve should be better defined; therefore, the necessary water-budget instruments are being kept in operation and additional (and possibly longer) periods of high evaporation will be plotted as they occur (for example, see points 40 and 41, table 4).

TABLE 4.—*Calibration data*

Number	Period		Adjusted change in stage, ΔH_A (feet per day)	Average $u(e_0-e_a)$ u in miles per hour e in millibars
	Dates	Number of days		
	1961			
1	Sept. 5–15	11	0.004	37.4
2	15–16	2	.018	110
3	25–Oct. 4	10	.003	38.1
4	Oct. 5–14	10	−.002	26.4
5	15–19	5	.001	34.7
6	22–Nov. 2	12	0	23.4
7	Nov. 1–6	6	−.009	6.5
8	7–11	5	.008	44.3
9	13–18	6	−.011	14.5
10	20–22	3	.001	36.7
11	24–Dec. 9	16	−.005	24.1
	1962			
12	June 7–11	5	−.003	58.7
13	July 8–11	4	−.001	48.2
14	18–24	7	.001	52.7
15	26–Aug. 2	8	.003	42.0
16	Aug. 12–15	4	0	36.7
17	18–20	3	−.003	42.9
18	23–Sept. 3	12	.002	39.7
19	Sept. 6–15	10	.004	34.2
20	18–25	8	0	46.6
21	28–Oct. 3	6	−.002	22.6
22	Oct. 6–30	25	.002	36.2
23	13–16	4	−.010	11.6
24	23–26	4	.009	71.8
25	Dec. 6–18	13	−.001	26.3
	1963			
26	May 9–15	7	.003	45.1
27	June 7–15	9	.006	54.1
28	12–13	2	.016	103
29	12-15	4	.014	78.1
30	19–30	12	−.010	34.1
31	July 12–22	11	−.001	47.5
32	24–27	4	−.002	34.0
33	Aug. 3–20	18	.005	52.5
34	13–15	3	.011	72.4
35	23–Sept. 9	18	.001	39.5
36	Sept. 16–27	12	.007	46.7
37	22–24	3	.021	94.8
38	Oct. 1–15	15	.006	34.5
39	20–21	2	.012	70.7
	1964			
40	June 11–14	4	.004	51.2
41	July 3–7	5	.008	53.4

CHARACTERISTICS OF THE CALIBRATION

The equation of the Lake Michie calibration shown in figure 44 is

$$\Delta H_A=(E+\delta)=0.00030\ u(e_0-e_a)-0.011 \quad (8)$$

where

ΔH_A = adjusted change in lake stage (also equivalent to water-budget evaporation and net seepage), in feet per day;

$0.00030\ u(e_0-e_a)$ = mass-transfer evaporation, in feet per day;

-0.011 = net seepage (seasonal average), in feet per day.

The mass-transfer coefficient (N=0.00030, evaporation in feet per day; or 0.0036, evaporation in inches per day) shows general agreement with coefficients from lakes and reservoirs similar to Lake Michie in size, when plotted on an approximate relation suggested by Harbeck (1962, fig. 31).

Variation of the seepage rate with different water-table conditions was investigated to evaluate its effect on the lake calibration. The conclusion was that the deviations of the plotted points on the calibration curve could be assumed to be partly due to the variation in seepage and could be isolated (approximately) by relating the total deviation to Dial Creek discharge.

The equation of the multiple relation shown in figure 45 is

$$(E+\delta)=0.00030\,u(e_0-e_a)-(0.0087+0.0031\,Q_D) \quad (9)$$

where evaporation is given by $0.00030\ u(e_0-e_a)$, the variable seepage component is $-(0.0087+0.0031\,Q_D)$, and Q_D is Dial Creek discharge.

Dial Creek discharge is probably a fair indicator of the surrounding ground-water conditions because base flow is primarily a function of the ground-water conditions. However, the Dial Creek gage is at a higher elevation and some distance from Lake Michie, and the relation between ground-water levels (as reflected by streamflow records) and seepage may be partly obscured by time lag resulting from the slow movement of ground water.

Generally, in determining the calibration parameters mass-transfer coefficient, N, and seepage, δ, the seepage rate (although it is a secondary consideration to the water budget) must be known, nonexistent, or nearly constant. Where net seepage variation is significant, a reliable calibration may be difficult or impossible to develop if an adjustment for seepage cannot be made.

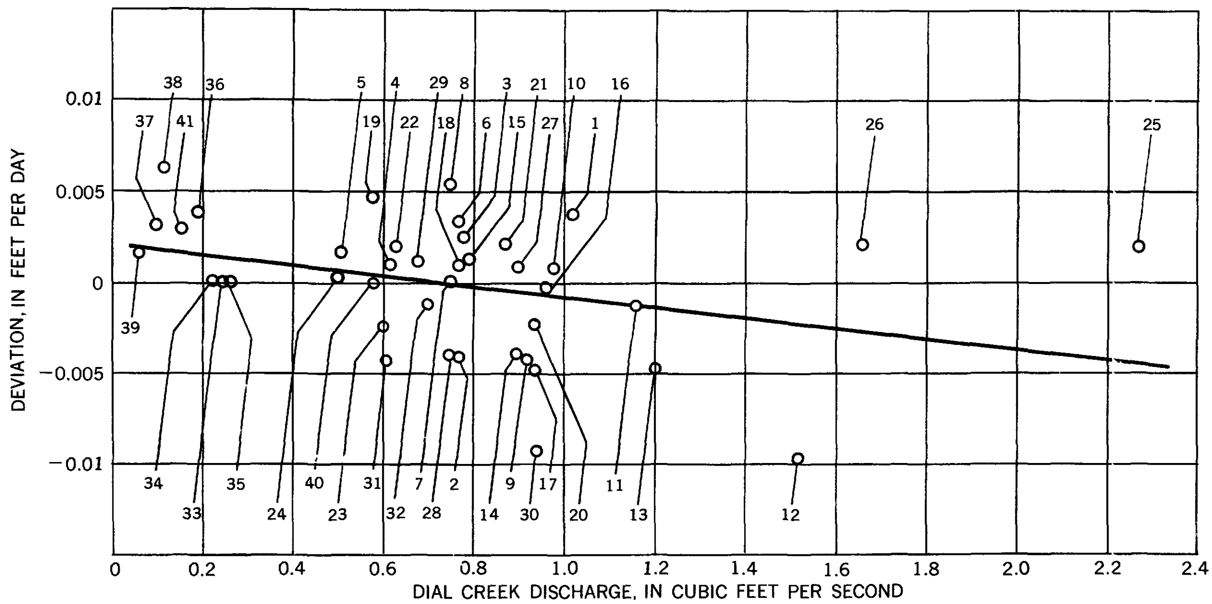

FIGURE 45.—Deviations from the calibration curve plotted against Dial Creek discharge.

Seepage (net) at Lake Michie is variable, as demonstrated; hence all winter records that were characterized by exceedingly high and probably varying seepage rates were eliminated. After the best data were selected, points on the calibration still displayed a certain amount of variation. Although these residual variations contain many error components, the seepage rate is a significant one. It is not sufficiently large, however, to render calibration impossible for Lake Michie.

The relation in figure 45 was not used to estimate seepage but was developed to demonstrate its variability. More data would be required to develop a relation sufficiently well defined to allow derivation of reliable estimates of seepage.

Nearly complete streamflow, rainfall, and pumpage data are available for Lake Michie from 1927 to the present. Thus it was possible to make a comparison of the seasonal seepage rate with an approximate long-term estimate of annual ground-water seepage, using the expanded water-budget equation 3:

$$E-\Delta H+(O-I)-R+\delta=0$$

where ΔH is virtually zero over a long period; evaporation was estimated from current short-term data. Annual net seepage is estimated to be about $-5\frac{1}{4}$ cfs as compared with the seasonal (May through November) estimate of $-2\frac{3}{4}$ cfs, which corresponds to the negative intercept of the calibration curve. Probable errors are too large to permit quantitative comparisons between these two estimates, but the difference suggests that winter seepage is probably much greater than that during other seasons.

APPLICATION OF THE CALIBRATION

The monthly totals of Lake Michie mass-transfer evaporation shown in table 5 were computed using the equation

$$E=0.0036\ \Sigma u(e_0-e_a) \qquad (10)$$

which shows monthly evaporation (in inches) as the product of the monthly sum, $\Sigma u(e_0-e_a)$, and the mass-transfer coefficient, $N=0.0036$.

TABLE 5.—*Monthly evaporation, in inches*

	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1961	-------	-------	-------	-------	-------	4.03	3.46	2.65
1962	3.68	5.10	5.39	4.85	4.38	3.78	3.58	2.78
1963	4.44	4.20	4.32	5.14	5.20	5.02	4.04	-------
1964	2.61	4.50	4.10	4.52	4.05	4.57	2.89	-------

Records of monthly evaporation and precipitation are graphically shown in figure 46. Precipitation is the average of that observed at Lake Michie dam and at Rougemont, several miles northwest of the lake. Rough approximations of typical monthly values of evaporation plus seepage (shown in fig. 47) indicate a net water loss for May through September of about 110 acre-feet. Annual evaporation is estimated to be about 39 inches or 1,550 acre-feet.

Reliable estimates of normal monthly evaporation cannot be determined from data collected to date, and therefore a program of data collection is being carried on so that adequate estimates can eventually be made. Mass-transfer data and computed evaporation will be compiled in a future report.

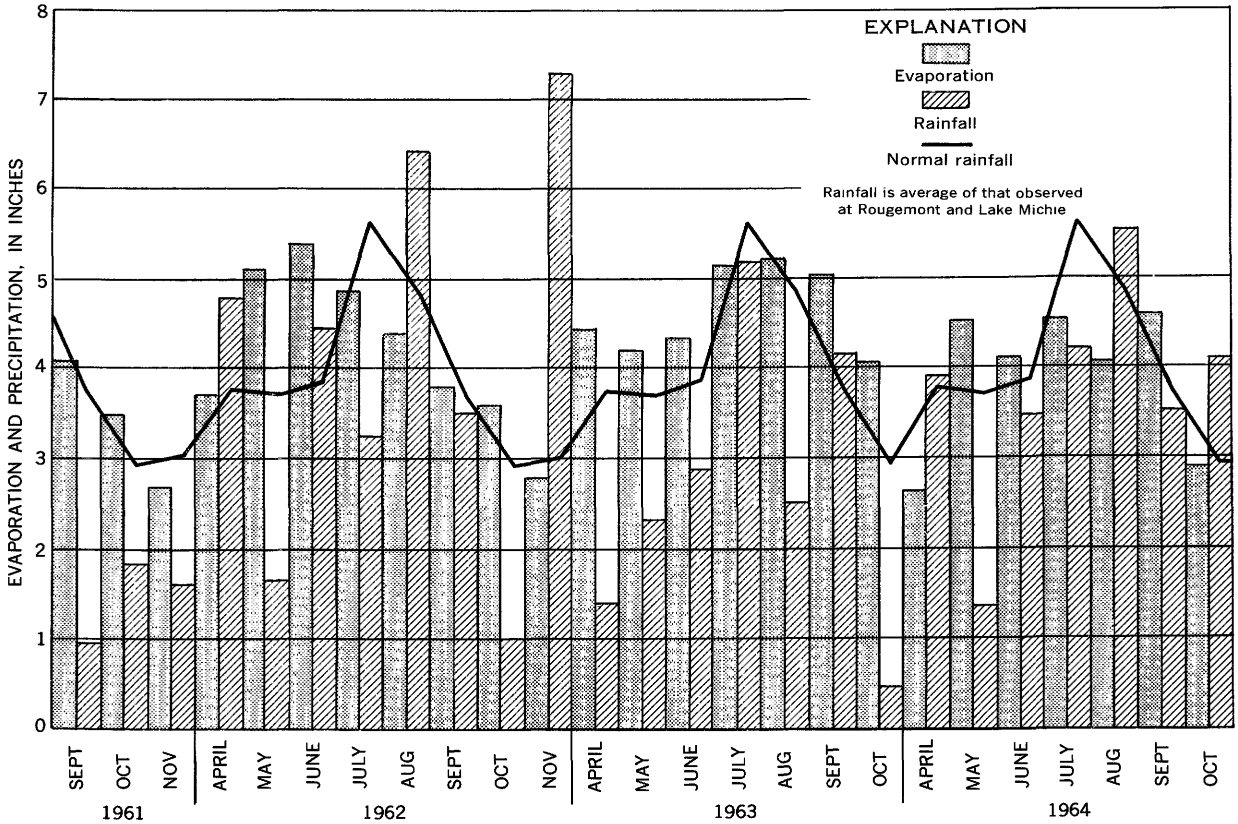

FIGURE 46.—Lake Michie monthly evaporation and precipitation.

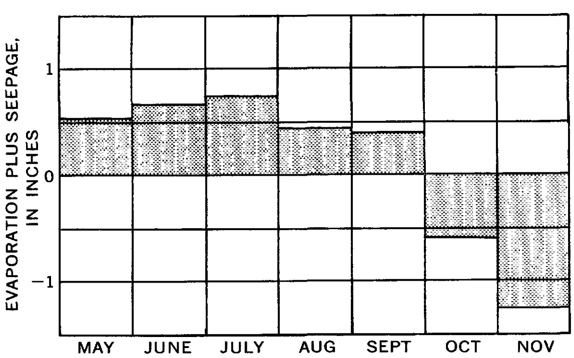

FIGURE 47.—Approximate monthly average of evaporation plus seepage.

SUMMARY

The data thus far collected indicate annual evaporation to be approximately 39 inches or 1,550 acre-feet, and the seasonal (May through November) net seepage gain to be about 1,100 acre-feet.

Figure 45 indicates the possibility (under more favorable conditions) of estimating the net groundwater seepage of a lake by relating deviations from a mass-transfer calibration curve to a good indicator of the surrounding ground-water regime.

The amount of inflow and outflow of the lake, its size, the availability of an accurate stage-area relation, and the amount and variability of net ground-water seepage are the major factors that determine whether or not a lake can be calibrated by application of the mass-transfer water-budget method. Probably the most critical of these considerations is the inverse relationship of net flow to lake size.

The calibration constants were adequately evaluated for Lake Michie in two summer seasons (September 1961 to October 1963). A drought having a recurrence interval of 2–5 years occurred in the drainage basin during the summer of 1963 and enabled the rapid development of a fairly reliable calibration. The data used to develop the calibration were Lake Michie hydrographic and wind and water-surface temperature data and Raleigh-Durham Airport relative humidity and air temperature. The resulting calibration equation,

$$\Delta H_A=(E+\delta)=0.00030\ u(e_0-e_a)-0.011 \qquad (8)$$

indicates a seasonal net seepage rate (δ) of −0.011 feet per day (about −2¾ cfs), which is an average value for periods similar to those used to define the calibration. The equation also has a mass-transfer coefficient (slope of the calibration curve, N) of 0.00030.

SELECTED REFERENCES

Harbeck, G. E., Jr., 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory: U.S. Geol. Survey Prof. Paper 272–E, p. 101–102, 104.

Harbeck, G. E., Jr., Golden, H. G., and Harvey, E. J., 1961, Effect of irrigation withdrawals on stage of Lake Washington, Mississippi: U.S. Geol. Survey Water-Supply Paper 1460–I, 367–373.

Harbeck, G. E., Jr., Kohler, M. A., Koberg, G. E., and others, 1958, Water-loss investigations, Lake Mead studies: U.S. Geol. Survey Prof. Paper 298, p. 29–35, 75.

Langbein, W. B., Hains, C. H., and Culler, R. C., 1951, Hydrology of stock-water reservoirs in Arizona: U.S. Geol. Survey Circ. 110, p. 13–15.

Langbein, W. B., and Iseri, K. T., 1960, General introduction and hydrologic definitions: U.S. Geol. Survey Water-Supply Paper 1541–A, p. 1–29.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H., 1958, Hydrology for engineers: New York, McGraw-Hill Book Co., p. 90–121.

Robinson, T. W., and Johnson, A. I., 1961, Selected bibliography on evaporation and transpiration: U.S. Geol. Survey Water-Supply Paper 1539–R, p. R1–R25.

U.S. Geological Survey, 1954, Water-loss investigations, Lake Hefner studies, technical report: U.S. Geol. Survey Prof. Paper 269, p. 46–69, 136–151.

U. S. GOVERNMENT PRINTING OFFICE : 1966 - 209-983