Comparison of Evaporation Computation Methods, Pretty Lake, Lagrange County, Northeastern Indiana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 686-A

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By JOHN F. FICKE

HYDROLOGIC AND BIOLOGICAL STUDIES OF PRETTY LAKE, INDIANA

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Studies using five common computation methods found the mass-transfer method best suited for year-round measurement of evaporation rates

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SYMBOLS

- A Surface area.
- c Specific heat of water.
- E Evaporation.
- E_{EB} Evaporation computed by the energy-budget method.
- E_{MT} Evaporation computed by the mass-transfer method.
- E_{WB} Evaporation computed by the water-budget method.
- e_a Vapor pressure of the air.
- e_0 Saturation vapor pressure at the temperature of the water surface.
- G Net underground seepage.
- I Surface inflow.
- I_p Precipitation falling on lake.
- L Latent heat of vaporization of water.
- N Mass transfer coefficient.
- n Number of days in an evaporation-computation period.
- O Surface outflow.
- P_a Atmospheric pressure.
- p_m Period of the temperature stress on the lake sediment.
- Q_a Incoming long-wave radiation.
- Q_{ar} Reflected long-wave radiation.
- Q_{bs} Long-wave radiation from the water.
- Q_e Energy used for evaporation.
- Q_h Energy conducted from the water as sensible heat.
- Q_m Total heat flow per unit area into the sediment during an annual cycle.
- Q_r Reflected solar radiation.
- Q_s Incoming solar radiation.
- Q_v Net energy advected into the lake.
- Q_w Energy advected by evaporating water.
- Q_x Increase in stored energy.
- R Bowen ratio.
- s Thermal conductivity of the sediment.
- T_a Dry-bulb air temperature.
- T_b Arbitrary base temperature (0°C) used in energy computations.
- T_e Temperature of evaporated water.
- T_m Amplitude of temperature stress on sediments.
- T_0 Temperature of the water surface.
- u_z Windspeed at some height z above the water surface.
- α Part of additional energy from advection or storage that is used in evaporation.
- β Thermal diffusivity of the sediment.
- ΔE_L Effect on lake evaporation caused by advected or stored energy.
- Δe Vapor pressure difference equal to $(e_0 - e_a)$.
- ΔH $(E-G)$ fall in stage, corrected for inflow, outflow, and precipitation.
- ΔS Net increase of storage.
- ΔT Temperature difference equal to $(T_0 - T_a)$.
- γ Constant in the formula used to compute Bowen ratio.
- ρ Density of water.

COMPARISON OF EVAPORATION COMPUTATION METHODS, PRETTY LAKE, LAGRANGE COUNTY, NORTHEASTERN INDIANA

By JOHN F. FICKE

ABSTRACT

Evaporation from Pretty Lake has been computed for a 2½-year period between 1963 and 1965 by the use of an energy budget, mass-transfer parameters, a water budget, a class-A pan, and a computed pan evaporation technique. The seasonal totals for the different methods are within 8 percent of their mean and are within 11 percent of the rate of 79 centimeters (31 inches) per year determined from published maps that are based on evaporation-pan data. Period-by-period differences among the methods are larger than the annual differences, but there is a general agreement among the evaporation hydrographs produced by the different computation methods.

The energy budget was an excellent means of computing unbiased evaporation data for periods of a month or longer from June through September. It is not reliable in the springtime, when Bowen ratios are large and when the large changes in stored energy may be hard to measure accurately owing to errors in the capacity table. The need for sophisticated equipment, frequent temperature surveys, and complex computations makes the energy budget the most expensive of the several methods used. Effective use was made of the Koberg method in estimating long-wave radiation when accurate instrument records were not available. Effects of sediment heating and cooling were computed to have influenced evaporation as much as 0.03 cm day^{-1} (centimeters per day) just after the autumnal overturn. The change is significant during the fall, when the evaporation for Pretty Lake is low, and would be more significant in a shallow lake, where the heat storage by the sediment would be large in proportion to the storage by the water.

The corrected fall in stage computed by the water-budget method agreed well with the evaporation rates computed by other methods during the dryer seasons. Decreased rates of fall in stage during the wet seasons indicated net inflow seepage that was estimated to be equivalent to a stage change of more than 0.2 cm day^{-1} at some times.

Evaporation data based upon class-A pan records and computed pan evaporation were too large early in the season and too small late in the season. The differences were caused by energy storage, which affected the lake evaporation as energy was stored in the spring and released late in the season. Energy-storage effects can be corrected, but the corrections require some of the same expensive data that were used in the energy budget.

The mass-transfer system proved to be an effective low-cost means of computing evaporation, a means that is well suited to low evaporation rates. The mass-transfer coefficient was determined to be 0.00560 cm hr day^{-1} mile^{-1} mb^{-1} (centimeter per day per millibar per mile/hour), the relative standard error of the energy-budget calibration being about 6 percent. Springtime and autumn evaporation rates computed by the mass-transfer method were slightly higher than rates computed by other methods, and summer rates from mass-transfer computations were slightly lower than rates computed by other methods. Anemometer stalling is believed to have caused unreliable mass-transfer evaporation data during two periods having very low wind velocities.

Assuming that Pretty Lake is typical of the many small natural lakes in its region, it is concluded that in most cases the evaporation information needed for hydrologic studies can be provided with satisfactory accuracy by a combination of the mass-transfer method and one or two other methods, without the expense of a complex energy-budget study.

The different methods, although poor, agree that evaporation when there is ice cover is generally small (less than 0.1 cm day^{-1}), but the evaporation rates during the few days just before freezeup or just after ice breakup are significant.

INTRODUCTION

This comparison of evaporation computation methods is part of a multiphased project studying the thermal and biological characteristics of Pretty Lake. Other reports in this series will describe studies of palynology, thermal stratification and vertical circulation, and phytoplankton populations and biological productivity.

The purposes of the Pretty Lake evaporation studies were to evaluate the several common methods for computing lake evaporation and to determine their accuracy and general applicability in the central region of the United States. Earlier studies of evaporation have been conducted mainly in the more arid West, and the techniques developed in the western studies have not been fully tested in the more humid climates. Energy-budget, mass-transfer, water-budget, and evaporation-pan techniques have been used to compute evaporation from Pretty Lake. Results and methods have been evaluated for accuracy and for ease and economy of use.

Pretty Lake was a good site for extended evaluation of the evaporation-computation techniques developed in the West. It is located in a region of more abundant rainfall; this region in the past has had only slight concern for evaporation loss, but it is now beginning to feel effects of water shortage as demand exceeds supply. Furthermore, the hydrology of the Pretty Lake basin makes it possible to determine evaporation more precisely than would be possible in most other settings. Small quantities of surface inflow and outflow, which can be measured accurately, provide the criteria for computing a good water budget. The precision of the water budget is supplemented by a condition of small subsurface inflow and outflow. The small surface and subsurface inflow and outflow reduce the magnitude of the advected-energy term, which must be considered in an energy budget or in the application of standard-pan data. The nearly circular shape of Pretty Lake provides the best conditions one would expect to find for measuring the temperature and wind parameters that are part of mass-transfer or energy-budget computations of evaporation.

ACKNOWLEDGMENTS

Studies of evaporation computation for Pretty Lake were operated as a project of the U.S. Geological Survey, Water Resources Division. Harvey Rutstein provided valuable help in the field measurements and computation of data. Additional assistance was provided by Robert G. Lipscomb and Phillip Reed. Technical advice and manuscript review were by G. Earl Harbeck, Jr., Rolland W. Carter, Malcolm D. Hale, W. S. Eisenlohr, and Gordon E. Koberg. Instrumentation advice and calibration were provided by C. R. Daum.

The Indiana Department of Natural Resources generously permitted the project to operate its instrumentation and field laboratory on the public access area it maintains on Pretty Lake. The Indiana University Department of Zoology permitted use of its solar-radiation data.

Special acknowledgment is due the people who reside near Pretty Lake. They have given the use of their property, and their assistance in many instances provided an extremely valuable service.

The Indiana Institute of Technology, Fort Wayne, Ind., has generously provided the project with office space, access to its library, and advice from its faculty. Sincere thanks are given to the college.

DESCRIPTION OF PRETTY LAKE

Pretty Lake is a small natural lake of glacial origin located near the southeast corner of Lagrange County, Ind. (lat 41°34.5′ N., long 85°15′ W.) (fig. 1). It has a water surface covering 184 acres (74.5 hectares) and a maximum depth of about 82 feet (25 meters) near its center (fig. 2). Owing to large shallow areas around the perimeters, the average depth is 25.6 feet (7.8 m), about one-third of the maximum. A sharp-crested steel weir on the outlet is designed to maintain the lake at an elevation of 965.5 feet (294.29 m) above mean sea level. When the lake stage is below the weir crest, there is no outflow. As the water surface rises above the control elevation, outflow varies according to the head on the weir. The weir is designed to open during the winter in order to lower the water surface, thereby protecting waterfront property from ice damage. Owing to the dry summers of 1963 and 1964, it was not necessary to lower the lake surface these years. Therefore, stage fluctuations during these studies were not affected by intentional spilling of water from the lake.

At the water's edge, concrete seawalls or filled lawn waterfronts adjoin the lake in most places. These create a shoreline that is nearly vertical over the range of stage of the lake. As a result, the limited change of lake stage has no significant effect upon the lake's area.

At three places along the south and west edges of Pretty Lake, channels have been dredged to create a longer shoreline. These channels are designated by thermal survey stations T21, T22, and T23 in figure 2. Some of the dredging has been done recently enough that it does not show in the map from which figure 1 was made.

The small inlet that enters at the north edge of the lake drains an area of 1.96 square miles (508 hectares), most of which is wooded or marshlike. Relief is small, elevation within the basin ranging from 965 feet (294 m) above mean sea level at the gage to 1,050 feet (320 m) at the extreme north end of the drainage basin. Consequently, even the hardest rains do not produce great flow volumes. On the other hand, the inlet does sustain a low flow much of the time.

Overland flow into Pretty Lake can be expected during very hard rains. Volumes are generally small owing to the small basin size, the good grass cover on most of the surrounding land, and the numerous depressions which trap small quantities of water.

Pretty Lake generally freezes over during December or early January. Depending upon the severity of the season, ice will attain a thickness of as great as 2 feet (0.6 m). In early March the ice begins to weaken or honeycomb. Rain and warm weather will open zones along the edge. Removal of the main part of the ice cover generally takes place within a day or two. A strong wind on a warm day will break and crush the ice, melting some and piling large mounds of crushed ice on the downwind

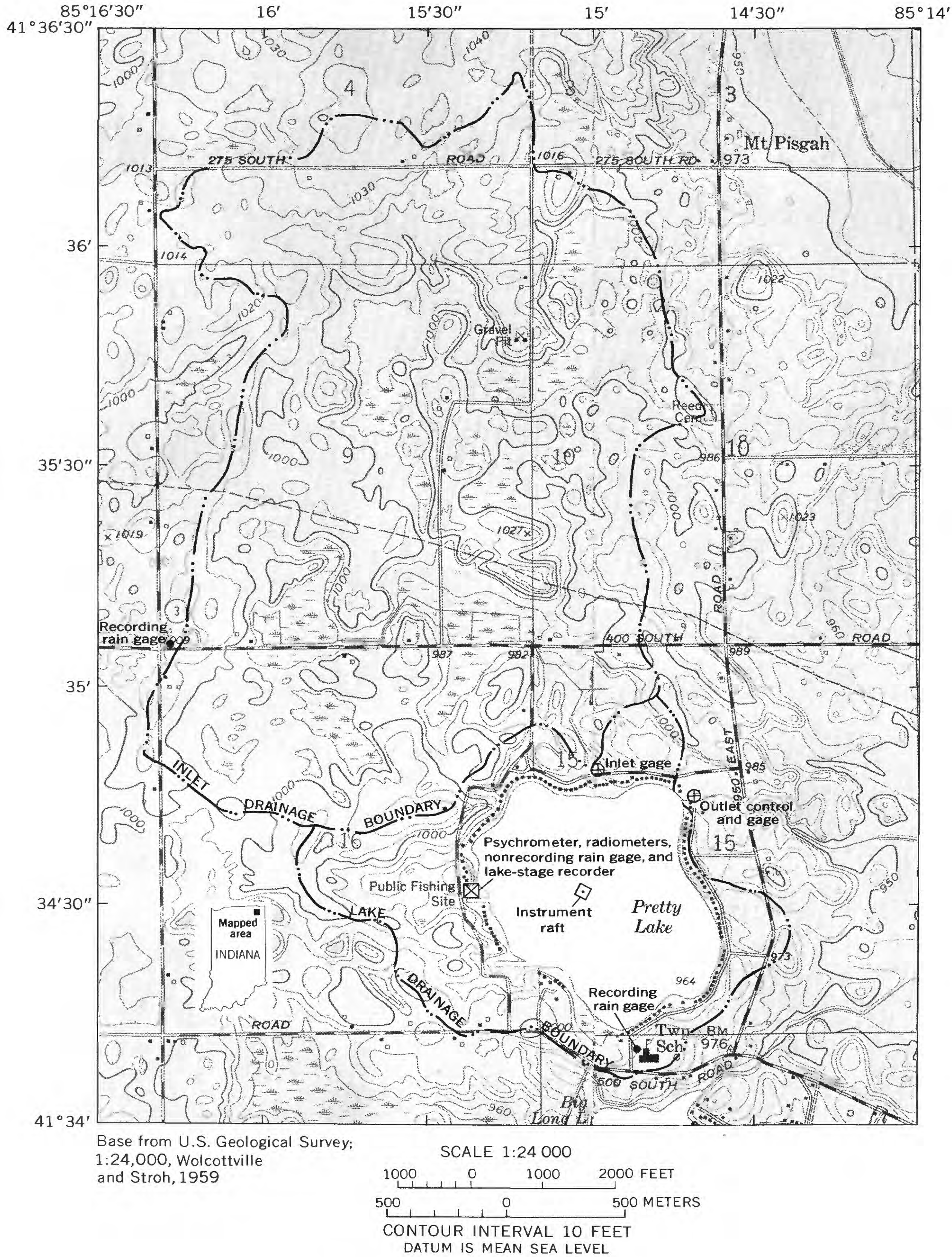

FIGURE 1.—Pretty Lake study site.

FIGURE 2.—Bottom configuration of Pretty Lake.

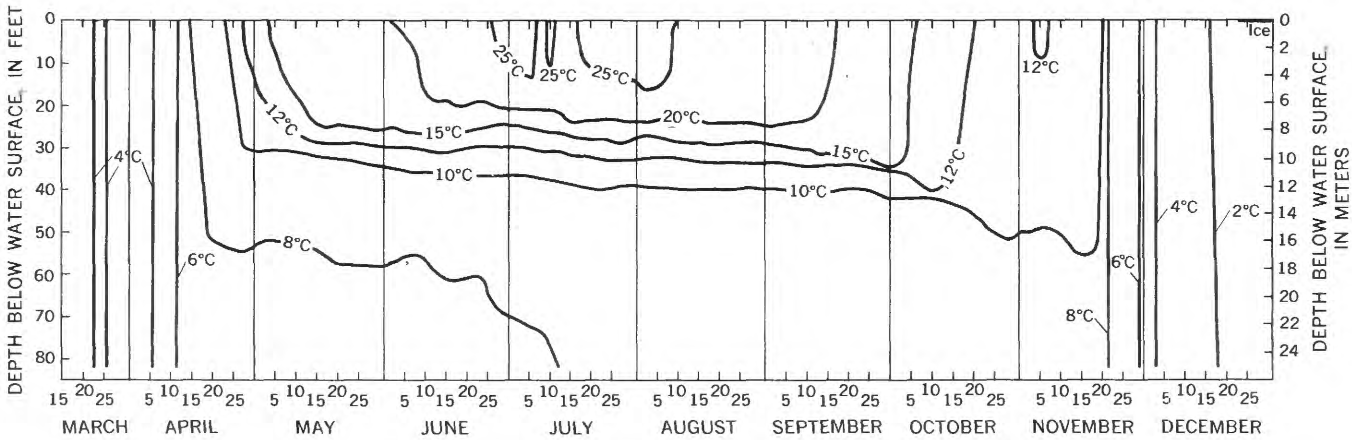

FIGURE 3.—Temperature structure during 1964 open-water period.

side of the lake and generally inflicting damage on docks, seawalls, and other waterfront improvements.

TEMPERATURE PATTERNS

The water of Pretty Lake is sufficiently deep to undergo thermal stratification during the summer. Stratification begins in late April as the water at the lake surface begins to warm above the temperature of maximum density. Maximum stratification is reached in midsummer, after which the surface begins to cool and the stratification is erased (Ficke, 1965) in late November. The seasonal pattern for 1964 is described by the temperature lines in figure 3. A form of stratification also takes place during the winter, when the surface is cooled to below the temperature of maximum density, 4°C. There is considerable warming of the lake during the winter, during which stratification is retained more by density differences caused by variations in chemical concentration than by temperature differences. During this period the ice cover protects the water from the wind actions which would otherwise erase stratification dependent upon such small differences in density.

INSTRUMENTATION AND ITS OPERATION

Pretty Lake was instrumented for evaporation measurement by the water-budget method, the energy-budget method, the mass-transfer method, and the pan method. In some instances, records from certain measuring instruments were useful in the computations made by more than one method.

INSTRUMENTATION FOR WATER BUDGET

The study of a lake's water budget requires the best possible measurements of water flowing into and out of the lake. The largest source of inflow to Pretty Lake is precipitation falling directly upon the lake's surface. Additional water enters from the inlet channel, from direct overland flow to the lake, and, as will be shown later, from underground seepage. Outflow may occur as direct surface flow through the outlet channel or as seepage. The water budget, like any other budget system, also requires a measurement of change in the storage term in order that it can be balanced.

Inlet station. The station for the measurement of inlet flow is about 300 feet (92 m) upstream from the point where the inlet enters the lake along its north shore (fig. 1). A reference point was established at the site, and the first regular discharge measurement was made on March 29, 1963. A staff gage was installed on May 3, 1963. A water-stage recorder was installed (fig. 4), and daily streamflow records were begun on June 26, 1963.

FIGURE 4.—Stream-gaging station on Pretty Lake inlet. A steel V-notch weir and recording gage are shown. The continuous-type recorder shown was preceded by a weekly recorder.

Initially the channel served as control for the stage-discharge relation at the station. A wooden weir was installed on September 6, 1963, in order that the stage-discharge relation might be better defined. The temporary wooden weir was replaced with a steel weir having a notch capacity of 0.5 cubic foot (0.014 cu m) per second. It was set in the channel on April 17, 1964, and washed out during the spring of 1965. Consequently, the steel weir plate was reset in concrete on June 2, 1965.

Rating of the streamflow station was by current-meter or volumetric measurements and by use of the theoretical rating for the V-notch weirs. Water temperatures were read at the time of discharge measurements, at the time of the weekly recorder inspections, and at various intermediate inspections.

Outlet station. A control structure on the Pretty Lake outlet was built in 1951 by the Indiana Department of Conservation. The State of Indiana and the U.S. Geological Survey have used this site and other sites for the collection of lake-stage data at various times since the lake level was stabilized.

The control structure is located 140 feet (43 m) downstream from the point where the channel forms at the northeast corner of the lake (fig. 5). During the term of the project, the control was a sharp-crested weir with its crest at an elevation of 965.47 feet (294.28 m) above mean sea level. Weir width is 4.0 feet (1.22 m). Miscellaneous measurements at the station were begun March 29, 1963. A continuous record of discharge was begun with the installation of a water-stage recorder on June 26, 1963. The stage-discharge relation at the station was established by current-meter and volumetric measurement. Water temperatures at the outlet were measured during weekly inspections of the gage.

FIGURE 5.—Lake-stage control weir and recording gage on Pretty Lake outlet channel.

Precipitation gage. Two recording rain gages were located within the Pretty Lake study area (fig. 1). One, about a mile northwest of the lake, was intended to measure rainfall within the inlet drainage basin. The other, a few hundred feet south of the lake, is considered to be a good indicator of precipitation actually falling on the lake. Resolution of the record on the weekly charts generally was within 0.02 inch (0.05 cm). Neither of the gages was equipped with a windshield. They were unmodified for winter operation and consequently provided a poor record of snowfall.

A simple nonrecording precipitation gage was mounted at the water's edge along the west side of the lake (fig. 6). This was a bucket and funnel 8 inches (20 cm) in diameter fitted with a measuring cylinder. It usually was inspected at weekly intervals, at about the same time as the inspection of the recording gages. The catch was measured to the nearest 0.01 inch (0.03 cm).

Lake-stage recorder. A weekly water-stage recorder to measure changes in the lake's contents was situated in a boat-slip setback along the west side of the lake (figs. 1, 7). From January 1963 to November 5, 1963, it operated at a 1:5 vertical chart scale, with resolution to the nearest 0.01 foot (0.3 cm). Thereafter it operated on a 1:1 vertical scale; the gage-height was readable to

FIGURE 6.—Simple nonrecording rain gage at edge of Pretty Lake. Photograph shows cattails that grow along parts of the shoreline and lily-pad complex with associated submerged rooted aquatic plants that cover less than an acre along the west shore.

FIGURE 7.—Lake-stage gage located at public access area on Pretty Lake.

the nearest 0.001 foot (0.03 cm). At the 1:1 ratio the recorder trace at times showed considerable surge and at times registered low as a result of westerly winds and the gage's location in a setback along the west shore. Resulting difficulty in setting the instrument necessitated constant application of corrections to the recorded lake levels.

The 1:1 vertical scale of the lake-stage recorder made the record useful as a measure of the amount of precipitation falling directly on the lake. During periods of extended precipitation and significantly large inflow or outflow, it was necessary to correct the stage change for the inflow and outflow effect in order to get a measurement of precipitation. For instance, on this 184-acre (74.5-hectare) lake, each cubic foot per second inflow, or inflow-outflow difference, would result in a stage change of 0.005 inch (0.127 mm) per hour. The record of lake stage also provided a measurement of the quantity of direct overland flow to the lake during and immediately after storms. Significant differences between the quantities of precipitation caught by the rain gages and shown on the stage recorder were attributed to overland flow. At times the overland flow could be computed from recorded rates of rainfall and changes of lake stage. An obvious increase of stage that continued for several hours after the rain gages showed that rain had stopped and that was unaccounted for by inlet flow was attributed to direct overland flow into the lake.

Temperature-volume correction. The instrument that measures changes of lake stage not only records the effect of changes of lake contents but also registers the effect of changes in lake volume resulting from thermal expansion and contraction of the water. Measurements of heat storage made as part of the energy-budget studies provided the data necessary to correct lake-stage changes for the effects of thermal expansion over periods between thermal surveys; such effects sometimes amounted to more than 0.02 foot (0.6 cm).

INSTRUMENTATION FOR ENERGY BUDGET

Measurement for a lake's energy budget requires a quantitative determination of all the forms of energy entering or leaving the lake as well as a determination of the change in storage of energy within the lake. Specifically, these determinations are the direct measurement of incoming radiation, advected energy, and heat storage. Other terms are estimated as functions of temperatures of the air and water, vapor pressures, and other measured phenomena.

Psychrometric measurements. A continuous record of wet- and dry-bulb temperatures for the computation of vapor pressure was provided by a recording psychrometer located along the west side of the lake (fig. 1). The device consisted of two thermocouples, one wet and one dry, and a water reservoir mounted beneath a radiation shield (fig. 8) (Anderson and others, 1950). Situated on the side of the lake from which the prevailing winds generally blow, the instrument provides measurements of vapor pressure and air temperature largely unaffected by passage of the air over the lake.

The instrument was serviced at weekly intervals, at which time temperatures were measured with a mercury-in-glass sling psychrometer. Generally, the reading

FIGURE 8.—Temperature- and radiation-measuring equipment located at the west side of Pretty Lake.

of the sling psychrometer agreed with the readings of the recording psychrometer within ¼° C. The output of the copper-constantan thermocouples, calibrated to 25° C per millivolt, were referenced and recorded by a recording potentiometer.

Pyrheliometer. A 10-junction Eppley pyrheliometer was used to measure solar radiation. It was mounted on the west side of the lake near the other recording instruments and was connected to the same recording potentiometer that was used with the recording psychrometer. The glass bulb covering the black-and-white thermopile was cleaned during weekly inspections. No operating difficulty was experienced during the entire study period. A voltage divider was used to reduce the manufacturer's calibration to a convenient factor of 1 millivolt equal to 1 cal cm^{-2} min^{-1} (calorie per square centimeter per minute).

Flat-plate radiometer. A Beckman-Whitley flat-plate radiometer was used to measure total radiation. The sensing part of this instrument consists of a black upper plate and a reflective lower plate.

A motor-driven ventilator fan provided uniform airflow past the upper and lower surfaces. The amount of long-wave radiation was computed by subtracting solar radiation from the total radiation as measured by the flat plate. The complexity of the measuring unit provides several potential sources of error, including unlevel mounting, weathering of the plate finish, poor ventilation, and the condensation of water on the sensing surface. The flat-plate radiometer and pyrheliometer are shown in figure 8.

Different flat-plate radiometers were used in each of the three different seasons of Pretty Lake study. Each instrument was calibrated before installation and was fitted with a voltage divider designed to reduce the thermopile outputs to a common calibration that most suitably fit the range of the recording potentiometer. After the reduction of the 1963 data, it became obvious that the measured values of long-wave radiation were not correct and that instrumental error might be the source. Subsequent testing found that instrumental error was present in both the 1963 and 1964 data. Additional calibration produced enough data to make correction of the 1964 data possible, but such a correction could not be made to the 1963 data.

Recording potentiometer. The psychrometer, pyrheliometer, and flat-plate radiometer were all connected to the same multipoint recorder. This recorder had eight channels and a range from −1.0 to 2.0 millivolts. It recorded one signal each 30 seconds or went through its eight-channel cycle once each 4 minutes.

A five-channel integrator device was attached to the recorder to simplify the computation of psychrometric and radiation data. The mechanical device was connected to the moving stylus of the multipoint recorder by a cable assembly. As the stylus moved to balance the potentiometer circuit on each signal input, it rotated a simple revolution counter, so that the degree of rotation of the counter was proportional to the size of the signal recorded from one of the sensing instruments. The total revolution of one of the counters over several cycles was proportional to the integral of one of the measured signals. Therefore, the average of one of the variables, dry-bulb temperature for instance, could be computed simply from any two simultaneous readings of the integrator totalizing dials.

During the period of operation of the Pretty Lake study, the integrator totalizing dials were read every time the field site was visited by project personnel. The intervals between consecutive inspections ranged from less than a day to as great as 7 days. Except for simple infrequent failure of such minor parts as cable, springs, or switches, the recorder and its integrator operated very well.

Advectate-heat measurement. Heat is advected to the lake directly by the inflow, outflow, and rainfall. Temperatures of the water in the inflow and outflow channels were measured as a part of recorder inspections. For the outflow channel, however, it is possible that the water may have been warmed or cooled in its flow through the channel, especially at low velocities. Because of this possibility, the temperature of the water surface of the lake was a better measurement of the outflow temperature than was the temperature measured at the streamflow station.

The wet-bulb temperature recorded at the psychrometric station at the time of rainfall was considered to be a satisfactory measurement of the temperature of the precipitation.

Lake-surface temperature. Temperature of the water at the lake's surface was recorded by a thermograph mounted on the raft anchored near the lake center (figs. 1, 2, and 9). This instrument's sensing unit was mounted beneath the raft 1 or 2 cm (0.2 to 0.4 inch) below the water surface. Calibration of the thermograph was checked with a mercury-in-glass thermometer at the times of the weekly chart change. The recorded values were adjusted to within 0.3°C of the true temperature.

Data from the periodic temperature surveys show that at times the temperature over the surface of the lake varied over a range of more than 2° C, from place to place. When there was wind, the warm, less dense water piled up on the downwind side, while the cold water stayed on the upwind side. Under these conditions the temperature at the center of the lake was always nearly the same as the mean of the survey points. On calm days, there was greater warming in the shallow areas, and the temperature measured at

FIGURE 9.—Instrument raft anchored in Pretty Lake. Pontoon floats are 20 feet long.

the raft station was sometimes 0.5°C less than the mean. However, the evaporation rate also was low on these calm days, and the error in the evaporation computation caused by use of the thermograph data is believed to be minimal.

THERMAL SURVEYS

Thermal surveys to measure heat storage of Pretty Lake were conducted at intervals ranging from 7 to 56 days. Normal procedure was to measure at each of the 24 points shown in figure 2 (T1 through T23, and raft). At each survey point the temperature profile was measured at 2.5-foot (0.76 m) intervals. In those instances where the lake was ice covered, the measurements were more closely spaced in the zone near the ice, where temperature changes more rapidly with depth. Readings were made using a thermistor thermometer which incorporated an out-of-balance bridge circuit. Temperatures were read to the nearest 0.1°C. Instrument calibration was maintained by frequent comparison with a precision mercury-in-glass thermometer.

A complete survey of the lake generally could be completed in 2 or 3 hours. Points of survey were located by sextant angles; six prominent shore points were used as targets. In early surveys, buoys submerged about 2 feet (0.6 m) below the water surface were located and used to confirm the sextant technique. As familiarity with the sextant increased, use of the buoys was abandoned. Sextant-located positions were generally within 20 or 30 feet (6 or 9 m) of the true location of the measuring points.

INSTRUMENTATION FOR MEASURING MASS-TRANSFER PARAMETERS

Computation of evaporation by the mass-transfer method requires a determination of the vapor pressure of the air, the saturation vapor pressure corresponding to the temperature of the water surface, and the wind speed at the lake center. The instrumentation for measuring temperatures upon which the computation of vapor pressure is based was described with the instrumentation used in the energy-budget studies.

Wind measurements. Wind movement was recorded by a three-cup totalizing anemometer mounted on the raft anchored at lake center (fig. 2). The anemometer was constructed to give an electrical signal for every 10 miles (16.1 km) of wind movement. Neither of the two types of recorders used to record these signals operated successfully over any extended length of time. As a result of recorder malfunction, much of the wind record has been discredited, and this report is based largely upon wind records computed from the totalizer-dial readings that were made at the times of instrument inspection.

The totalizing anemometers used are simple instruments which proved to be quite reliable. Occasional icing of the anemometer cups caused by spray, sleet, or freezing rain resulted in small losses of record. In addition, the dial counters failed twice.

During springtime periods when the instrument raft was removed from the lake for short periods following ice breakup, the anemometers were operated on the bank on the access area.

At the beginning of the Pretty Lake study, the anemometer was installed with its cups 1.73 meters (5.64 ft) above the water surface. A second anemometer was later installed at the 2.00-meter (6.56-ft) level. Simultaneous readings of the two instruments were made in order to correlate the data from the two different levels.

EVAPORATION PANS

Pan-evaporation data used in the study of Pretty Lake are from the pan operated by the U.S. Weather Bureau in Kendallville, Ind., a site about 9 miles (14 kilometers) south of Pretty Lake. This installation is shown in an earlier report of Indiana lakes (Perry and Corbett, 1956, p. 51). The station normally is operated for the 7-month summer period April through October. Figures of daily pan evaporation are listed in the U.S. Weather Bureau's monthly publication, "Climatological Data," for Indiana. Copies of the original observer's notes were made available for the Pretty Lake study. At times it was necessary to supplement with records from other pan stations operated by the Weather Bureau.

ENERGY-BUDGET STUDIES

Estimation of evaporation by budgeting energy terms is a practice that dates back about 50 years. An excellent review and explanation of the method is presented in the reports describing studies on Lake Mead (Anderson and others, 1950 p. 38–49) and Lake Hefner (Anderson, 1952). The budget, as used in the study of Pretty Lake, is written to equate the net sum of energy into and out of the lake to changes in stored energy, as

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{ts} + Q_v - Q_e - Q_h - Q_w = Q_x, \quad (1)$$

where Q_s=incoming solar radiation,
Q_r=reflected solar radiation,
Q_a=incoming long-wave radiation,
Q_{ar}=reflected long-wave radiation,
Q_{bs}=long-wave radiation from the water,
Q_v=net energy advected into the lake,
Q_e=energy used for evaporation,
Q_h=energy conducted from the water as sensible heat,
Q_w=energy advected by evaporating water, and
Q_x=increase in stored energy.

INSTRUMENT RECORDS

Solar radiation. Data from the Eppley pyrheliometer were complete, except for short periods when record was lost owing to power failure or malfunction of the recorder or integrator. Much of the record lost was estimated from the record of a bimetallic pyrheliometer. The bimetallic instrument, which was mounted on the raft at the center of the lake, was owned by Indiana University and was maintained at Pretty Lake as part of a biological study conducted by the university. Other short periods of missing pyrheliometer data were filled in by estimates based upon tabulated values of clear-sky radiation and records of hours of sunshine at the U.S. Weather Bureau station at Fort Wayne.

Figure 10 is a time graph of solar-radiation (Q_s) values recorded at Pretty Lake during 1963, 1964, and 1965. The many short lines of varying length represent the average values computed for the periods between integrator readings.

Reflected solar radiation (Q_r) was estimated as a part of the mean Q_s for the energy-budget periods according to the graph developed by Koberg (1964, fig. 36).

Long-wave radiation. Three different flat-plate radiometers were used in the study of Pretty Lake. The durations of their periods of use are listed in table 1. As processing of the 1963 data was completed in mid-1964, it became obvious that the results were unreasonable and that the measured values of long-wave radiation seemed to be too large. Consequently, the instrument change in October of 1964 was preceded by careful calibration checks throughout the range of instrument 263. Then instruments 245 and 263 were operated side by side for 16 days. Finally, when instrument 245 was removed, it was subjected to extensive laboratory calibration.

The laboratory studies of flat-plate radiometer 245 showed that the radiometer errors were caused by electrical potentials being generated by thermocouple action within a voltage divider that had been installed

TABLE 1.—*Periods of use for flat-plate radiometers at Pretty Lake*

Instrument serial No.	From	To
500	Apr. 5, 1963	Nov. 21, 1963
245	Nov. 22, 1963	Oct. 14, 1964
263	Sept. 28, 1964	Sept. 22, 1965

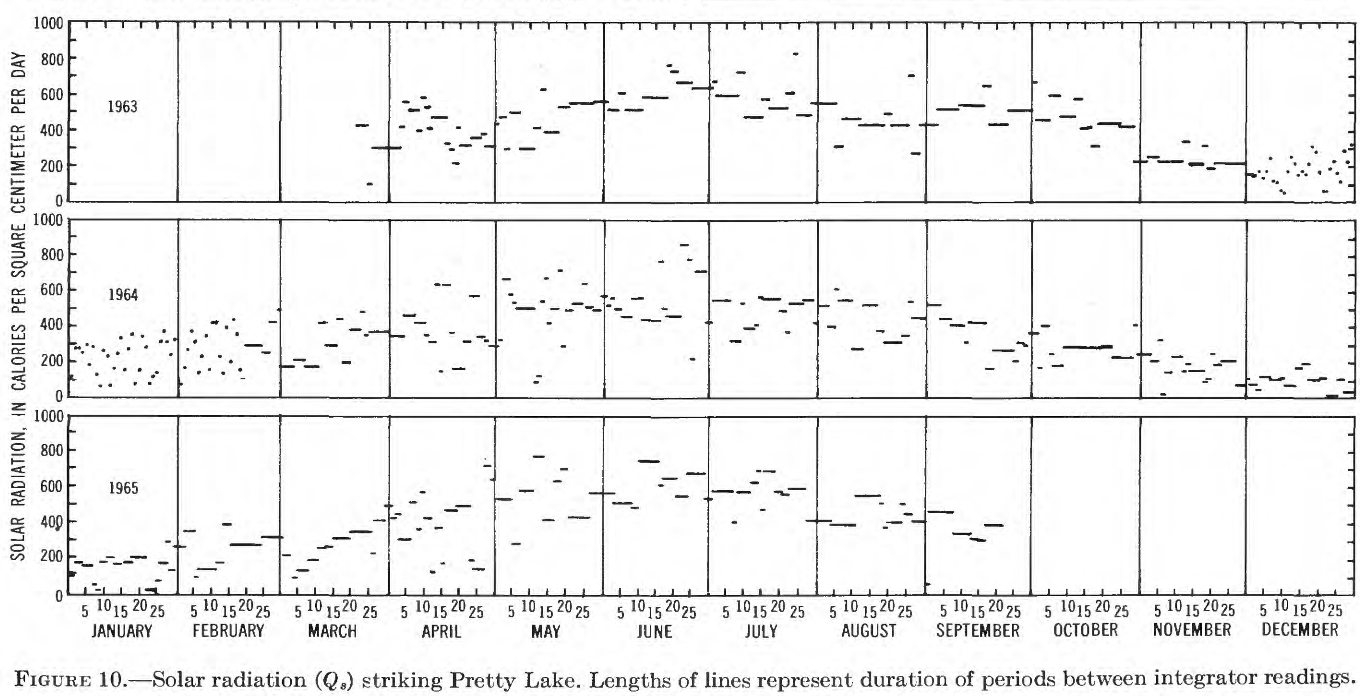

FIGURE 10.—Solar radiation (Q_s) striking Pretty Lake. Lengths of lines represent duration of periods between integrator readings.

in the radiometer. The field and laboratory studies found that the sizes of these errors were largely functions of wind conditions. An effective correction procedure was devised, and the corrections were applied to the 1964 records from flat-plate radiometer 245.

When instrument 500 was removed, the calibration problem had not yet been discovered, so that the sensing element was refinished without first making calibration. It was reasoned, but later proved erroneous, that it might be possible to apply the corrections developed for instrument 245 to the records obtained from instrument 500.

Figure 11 is a plot of the measured long-wave radiation from the records of the three radiometers against values of long-wave radiation estimated by the Koberg (1964) method. Short arrows indicate the values

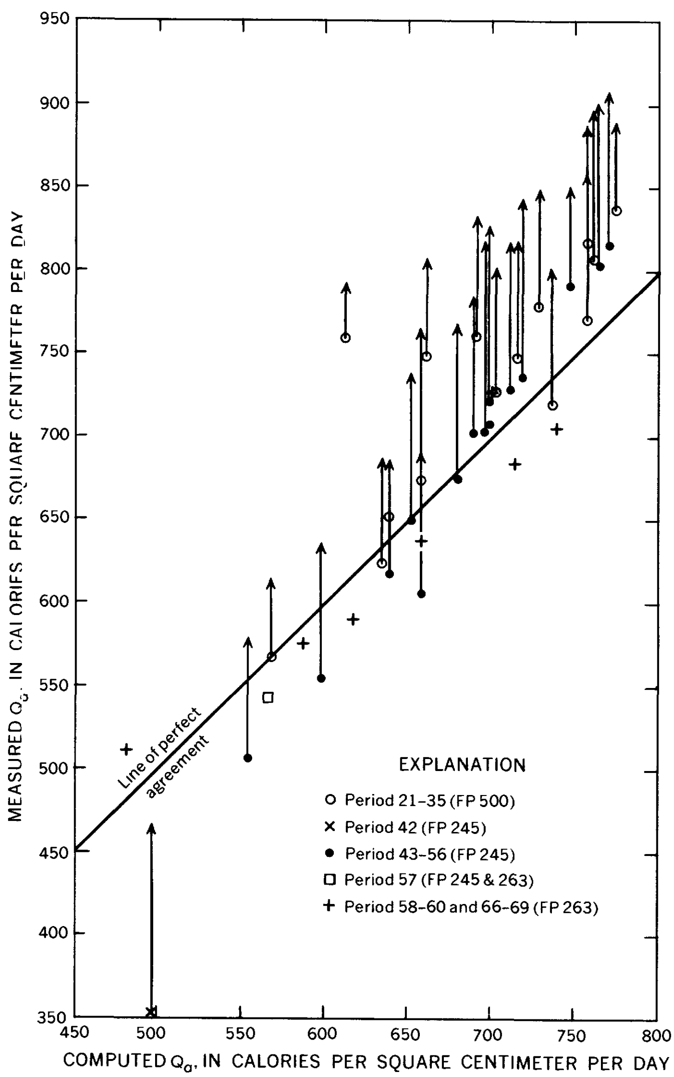

FIGURE 11.—Relation of long-wave radiation (Q_a) as measured by flat-plate (FP) radiometers and as computed by the Koberg method. Arrows point to places where uncorrected data would have plotted.

before corrections of the data from flat-plate radiometers 500 and 245. As indicated by the pattern of the plot in figure 11 and by the summary of averages in table 2, it appears that the data from flat-plate radiometer 263 and the corrected data from flat-plate radiometer 245 agree quite well with the long-wave radiation values computed by the Koberg method. On the other hand, the correction developed for flat-plate radiometer 245 did not seem to work well in correcting data for 1963 from flat-plate radiometer 500. Measured values differ from the computed values by 7 percent or more in 47 percent of the periods. This wide scatter of the individual periods and the average difference of 5.6 percent supported the conclusion that the correction of the 1963 data was not good enough. Consequently, values of Q_a used in the energy-budget computations for 1963 were those computed by the Koberg method. A computed value of Q_a also was used for period 42 because the large deviation from the rest of the data cannot be explained.

The values of long-wave radiation used in the energy-budget computation are graphed in figure 12. The pattern of figure 12 illustrates how well the seasonal patterns of long-wave radiation agree with each other from year to year.

Reflected long-wave radiation, Q_{ar}, was estimated to be 3.0 percent of the measured or computed incoming radiation, Q_a.

Air temperature and vapor pressure. Long-wave radiation from the water surface (Q_{bs}) was determined, as a function of the average surface temperature over the computation period, from the record of the raft-mounted thermograph. The Stefan-Boltzman law was used, with an emissivity of 0.97 (Anderson, 1952, p. 97). Figure 13 is a time plot of the daily mean temperatures recorded at the center of Pretty Lake. The figure has scales to enable the reader to estimate values of Q_{bs}.

Records of wet-bulb and dry-bulb temperatures were computed largely from the integrator records of the recorder connected to the psychrometer described earlier. Except for minor difficulties caused by integrator failure or by broken thermocouple leads, the records were quite complete. It was difficult to evaluate the

TABLE 2.—*Summary of data from flat-plate radiometers*

Instrument serial No.	Energy-budget periods included	Number of days	Average measured Q_a (cal cm^{-2} day^{-1})	Average computed Q_a (cal cm^{-2} day^{-1})	Difference, measured from computed (percent)
500	21–35	199.0	[1] 722	684	+5.6
245	43–56	185.2	[1] 708	698	+1.4
263	58–60, 66–69	198.8	659	674	−1.3

[1] Corrected.

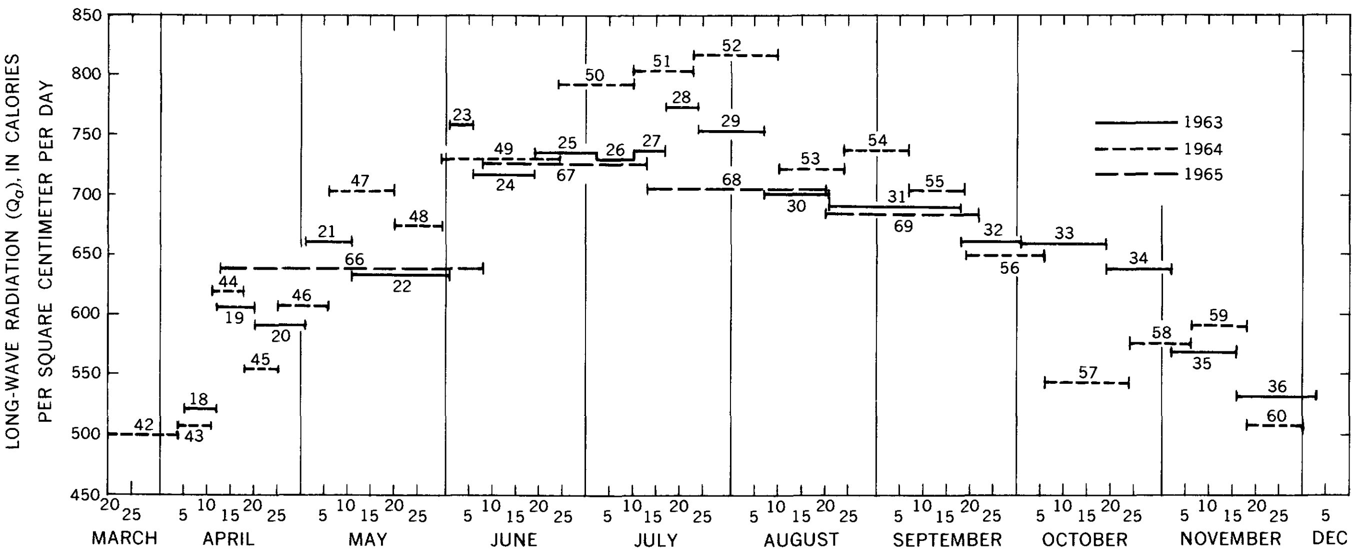

FIGURE 12.—Long-wave radiation (Q_a) measured at Pretty Lake for open-water energy-budget periods (identified by numbers).

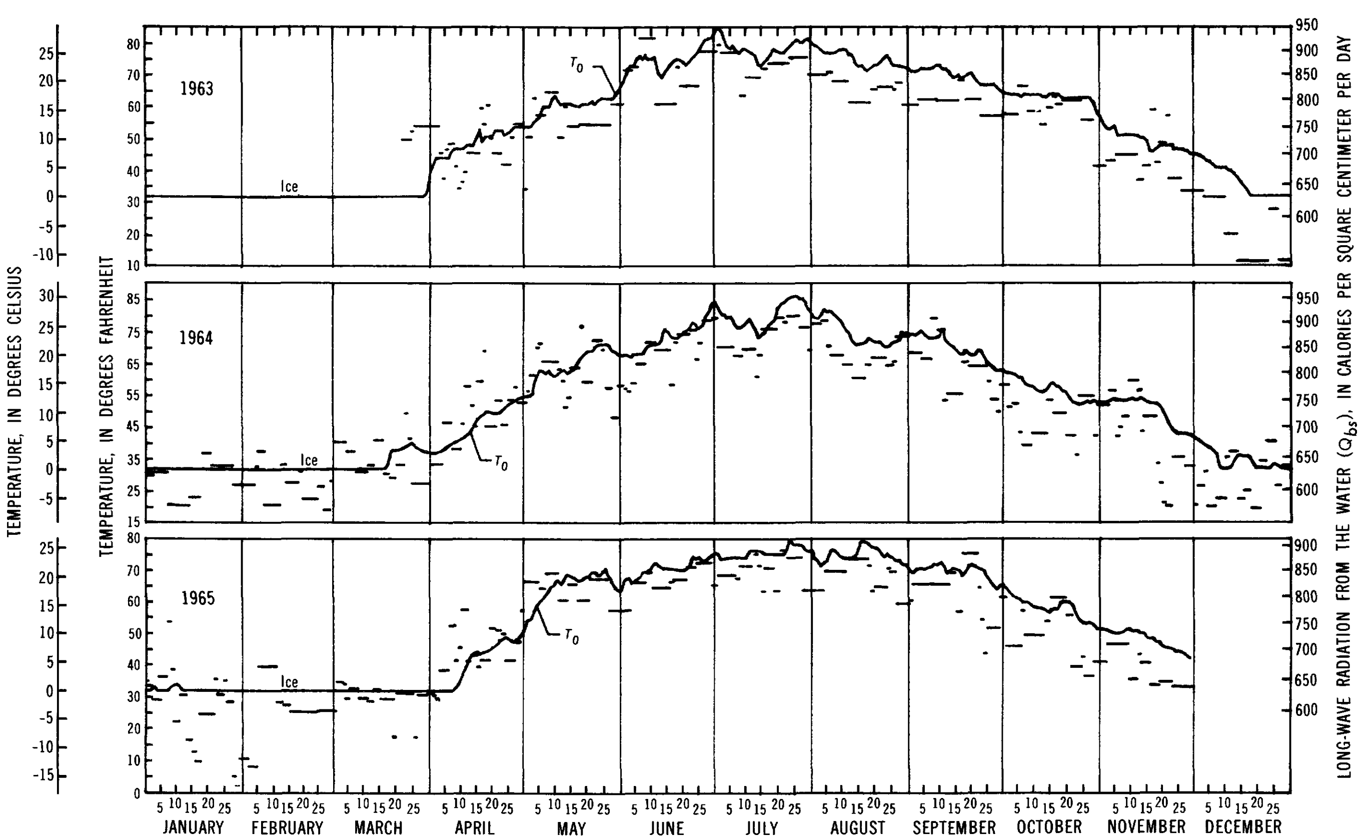

FIGURE 13.—Air and water-surface temperature records for Pretty Lake. Air temperatures are shown by lines representing duration of periods between integrator readings. Values of Q_{bs}. correspond to water-surface temperature (T_o).

effect of freezing upon the wet-bulb temperature record. Consequently, most vapor-pressure records for periods when air temperature was below freezing or when equipment failed were estimated from published dewpoint temperatures by the U.S. Weather Bureau at Fort Wayne.

As indicated by the temperature and vapor-pressure records in figure 14, values of air vapor pressure (e_a) often were computed from temperatures averaged over several days. Errors could be expected to result from this type of computation because the relationship between temperature and vapor pressure is not linear. On the other hand, the errors are small and the cost of additional accuracy afforded by more frequent integrator readings or hand reduction of the recorder chart could not be justified. If future studies of this type are to attain greater accuracy by use of more frequent data readings, the results will have to be achieved by the use of automatic recording that can be machine processed.

In checking the data computations, values of e_a were computed from even longer term average temperatures than were used in the original data computations. The method produced results that checked the original computations generally within 0.3 millibar. Errors caused by the shorter term averaging probably are even less, owing to the smaller temperature ranges over the shorter periods.

Values of saturation vapor pressure at the temperature of the water surface (e_0) were selected from tables of the saturation vapor pressure of water, as functions of daily mean temperatures computed from records of the thermograph on the raft in the center of the lake. The few days of record loss immediately following each spring ice breakup was filled in by interpolating between thermistor-thermometer readings made every 3 or 4 days. Records of e_0 are shown in figure 14.

Advected energy. Volume and temperature records for rainfall, inflow, and outflow were used to compute advected energy (Q_v). Computations were made using the base temperature of 0° C and considering heat inflow as positive. Temperature-volume products were computed for the rainfall from each storm and for inflow and outflow over periods of a week or less. Summations

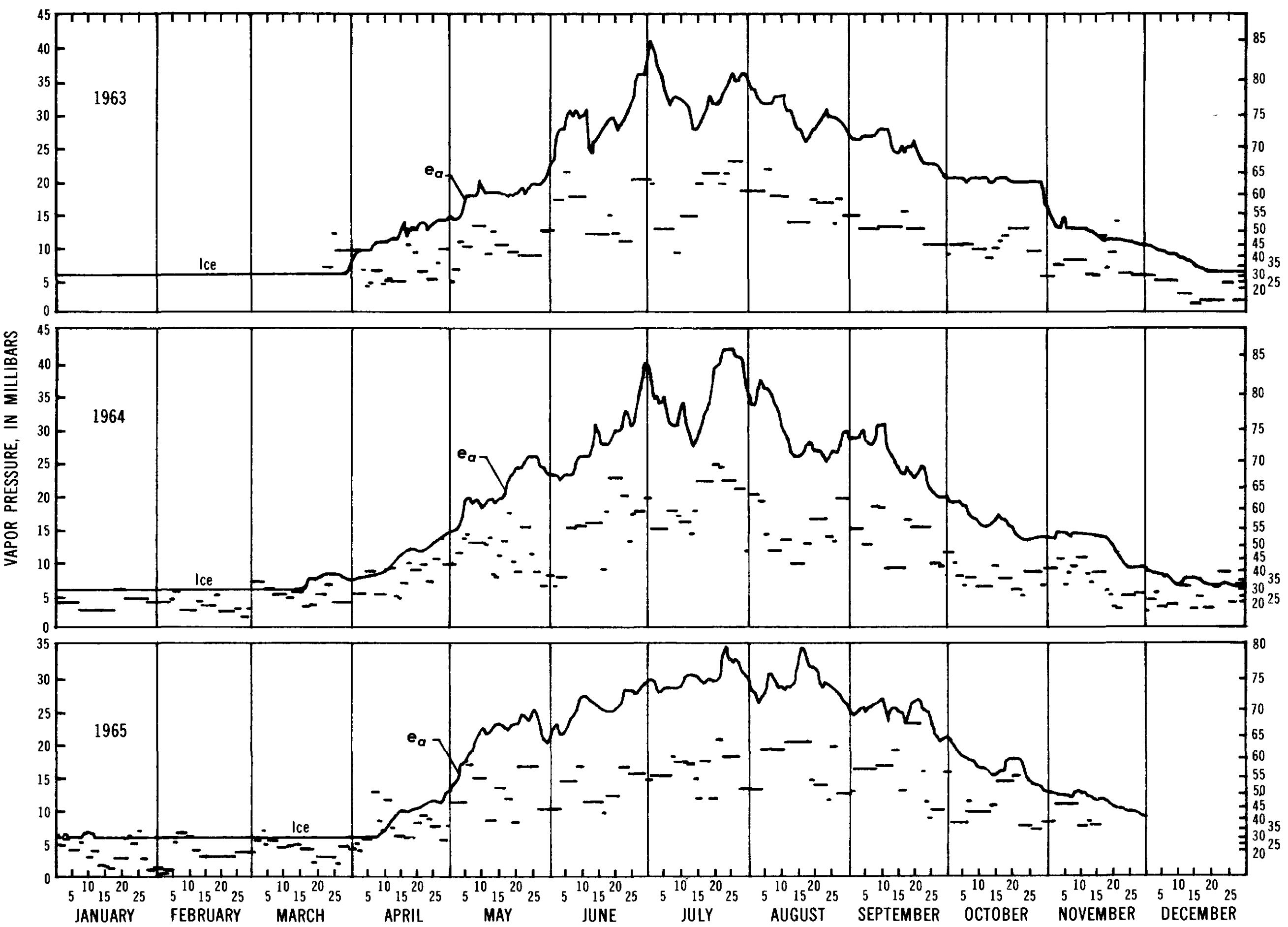

FIGURE 14.—Pretty Lake vapor-pressure records. Values of e_a are shown by lines representing duration of periods between integrator readings.

of temperature-volume products over a computation period were divided by length of the period, surface area of the lake, and a units-conversion factor to yield values of Q_v in calories per square centimeter per day. These values generally were positive and small. The volumes of inflow and outflow were small, and often their effects tended to negate each other. Sizable Q_v values resulted from heavy summer rains. The maximum of 24 cal cm^{-2} day^{-1} for any one energy-budget period occurred during a short period in July 1963, when 3.5 inches (8.9 cm) of precipitation fell during a 7-day period.

CHANGES IN ENERGY STORAGE

Temperature-survey data were used to compute the mean temperature in each of the 2.5-foot (0.76-m) horizontal layers sampled. All readings were weighted equally except those made in the dredged setbacks (T21, T22, and T23), which were weighted at one-third of the value of measurements in the main lake body. The energy in each layer, measured above a base of 0° C, was computed as the product of temperature and volume of the layer. Finally, average storage in calories per square centimeter was computed as the sum of the individual layers divided by the surface area of the lake. Changes in the stored energy between any two surveys, divided by the length of the period, yielded the term Q_x in calories per square centimeter per day.

Volumes used in the computation of energy storage were computed from a capacity table developed from the data of the survey made to construct the map in figure 2. Volumes between the 5-foot (1.52-m) depth contours were computed using the average-end-area formula. The average-end-area formula is generally known to yield results that are too large in cases where there is a considerable difference between the areas of the two ends of the solid whose volume is being computed. In addition, it is believed that errors in the Pretty Lake capacity table may result from uneven shape within the shallow area that lies above the 5-foot (1.52-m) depth-contour line.

Computation of evaporation would not be affected by errors in the capacity table during those periods when there is little or no change in heat storage. The greatest error could be expected during periods of rapid heating in the spring.

It is obvious that reliable values of Q_x can be computed only between two accurate measurements of energy storage. Consequently, solutions of the energy-budget formula are limited to those periods between major temperature surveys. Solutions of the energy-budget formula for short periods by use of data from a single vertical were not attempted. Unlike the vapor-pressure and Q_{bs} terms, the energy-storage computation cannot tolerate even a 0.2°C error in average lake temperature. Such an error would result in an error of 155 cal cm^{-2} (calories per square centimeter) in energy-storage computation. The effect would be magnified to unacceptable proportion if the data were to be used over short periods of 2 or 3 days.

INTERRELATION OF Q_e, Q_h, AND Q_w AND THE BOWEN RATIO

The three remaining terms of the energy-budget equation, Q_e, Q_h, and Q_w, have been defined as functions of the evaporation rate (E_{EB}). Energy used in evaporation is simply defined as

$$Q_e = \rho E_{EB} L \qquad (2)$$

where ρ is density and L is latent heat of vaporization. Using metric units within the water temperature range found in Pretty Lake, density is considered to be unity. Latent heat is determined, as a function of temperature, from a physics handbook. The energy advected by the evaporating water is expressed as

$$Q_w = \rho c E_{EB}(T_e - T_b) \qquad (3)$$

where c is specific heat, T_e is temperature of the evaporated water, and T_b is a base temperature. In this case, c is taken to be unity, T_e is presumed to be equal to the surface temperature of the lake (T_0), and T_b is assumed to be 0°C, the same as the base used for computation of Q_v. Conducted sensible heat was estimated as a function of Q_e by use of the Bowen ratio (Bowen, 1926), R, as

$$Q_h = RQ_e \qquad (4)$$

The Bowen ratio is computed by the formula

$$R = \frac{\gamma(T_0 - T_a)P_a}{(e_0 - e_a)1{,}000}. \qquad (5)$$

Here γ is a coefficient equal to about 0.61 in the units used, and P_a is atmospheric pressure in millibars. In the study of Pretty Lake, the values of temperature and vapor pressure used to compute the Bowen ratio were those determined by the instrumentation described earlier. Koberg (1958, p. 23) has determined that the overland data are sufficiently accurate for estimating the Bowen ratio for the lake. Ratios used in the evaporation computation were computed from equation 5 by use of average temperatures and vapor pressures for the energy-budget computation periods. Diurnal or other short-term changes of the type described by Webb (1960) were not believed to be significant in the climate that prevails in the Pretty Lake region. However, the observed conditions were similar to those that Anderson (1952, p. 106–109) has cited in his extensive discussion of the eccentricities of the Bowen ratio. With a few exceptions, the ratio varies from −0.1 to +0.4. During 57 percent of the open-water periods, the ratio was between 0 and 0.2. High Bowen ratios occurred most frequently in the fall, when evaporation rates decreased and the cool autumn air caused a higher proportion of the energy transfer to take place as sensible heat. Negative ratios occasionally occurred in the spring under stable atmospheric conditions within the boundary layer.

Equations 1, 2, 3, and 4 can be combined to form an equation to compute the energy-budget evaporation rate for any period between thermal surveys. This equation has the form

$$E_{EB}=\frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x}{L(1+R)+T_0}. \quad (6)$$

When the energy terms are in units of calories per square centimeter per day and latent heat and temperature are in gram-calorie-centimeter-degree Celsius units, evaporation rates will be in grams per square centimeter per day or centimeters per day.

When the Bowen ratio is large and negative, the denominator in equation 6 is small, and small differences or errors in the numerator can cause large differences in the estimated Q_h. There is even the possibility that the equation may become indeterminate. When large negative Bowen ratios occur, the possible error may be avoided by use of an alternate method of estimating Q_h. Use is made of the mass-transfer equation for estimating evaporation in the form

$$E_{MT}=N\,u_2\,(e_0-e_a), \quad (11)$$

where N is a coefficient and u_2 is wind speed measured 2 meters (6.56 ft) above the water surface. From equations 4, 5 and 11 it is possible to estimate conducted energy as

$$Q_h=\frac{0.61(T_0-T_a)LNu_2(e_0-e_a)P_a}{1{,}000(e_0-e_a)}, \quad (7)$$

which may be substituted into the energy-budget equation to give

$$E_{EB}=\frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_x-0.61LNu_2(T_0-T_a)P_a}{1{,}000(L+T_0)}. \quad (8)$$

RESULTS OF ENERGY-BUDGET STUDIES

Computations of evaporation by the energy-budget method for 1963, 1964, and 1965 open-water periods are listed in table 3. All periods except 43 and 44 were solved for E_{EB} according to equation 6. Values of Q_e, Q_h, and Q_w were then computed using equations 2, 3 and 4. Owing to errors in rounding to whole numbers the sum of the 10 energy terms is not always exactly zero.

Periods 43 and 44 had Bowen ratios that were near enough to −1 to make the term $L(1+R)+T_0$ very small. Such small values created an unacceptable condition. For instance, in period 43 the six terms in the numerator of equation 6 total zero. Consequently, evaporation computed for this period would be zero. However, with $L(1+R)+T_0$ equal to 35, the computed evaporation is very sensitive to small changes in the numerator. An energy subtotal of 15 cal cm^{-2} day^{-1} in the numerator would have raised the computed evaporation from 0 to 0.43 cm day^{-1}.

Table 3 lists values of E_{EB} for periods 43 and 44 that were computed according to equation 8. The Q_h term was estimated from equation 7 by use of the terms listed in table 4. The values of Q_e and Q_w listed in table 3 for periods 43 and 44 were computed from equations 2 and 3 in the same manner as for the other periods.

Evaporation rates and amounts computed by the energy-budget method are shown graphically and further summarized in figures 30 and 31 and in tables 20 and 21 in a later section of this report.

In the evaporation studies on Lake Mead, Koberg (1958, p. 29) estimated errors in evaporation caused by errors in the different terms of the energy-budget equation. Volume, inflow, and outflow differences would make the values of such estimates for Pretty Lake slightly different; however, as in Lake Mead, the principal sources of error in evaporation are errors in the Q_h term caused by errors in the Bowen ratio, and errors in the Q_x term caused by errors in the thermal surveys and in the capacity table. Unfortunately, large errors in the Bowen ratio occur most often in the spring at the time changes in stored energy are the greatest. Consequently, a larger error is to be expected in the computed evaporation values early in the spring than for those from later in the season. For example, table 3 shows low evaporation rates that are highly variable during April and May. It is possible that much of the scatter in the data result from errors in the Q_h and Q_x terms. Values of Q_x obviously are more accurate for longer computation periods than they are for shorter periods.

SEDIMENT HEATING EFFECTS

The computations here described have followed the form of most previous evaporation studies that used the energy-balance approach. Heat-storage terms have included only the water content of the lake, and heat-exchange terms have included only the factors at the

TABLE 3.—*Summary of energy-budget terms and evaporation computation for open-water periods, 1963–65*

[Q values given in calories per square centimeter per day]

Period													Bowen ratio R	Evaporation	
No.	Length (days)	Dates	Q_s	Q_r	Q_a	Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w		Centimeters per day	Centimeters per period
		1963													
18	7.0	Apr. 5–12	485	33	522	16	709	−1	154	72	21	1	0.298	0.121	0.85
19	8.0	12–20	396	30	606	18	728	2	205	25	−3	0	−.113	.043	.34
20	10.9	20–May 1	339	27	592	18	747	−4	68	50	17	1	.336	.084	.92
21	10.0	May 1–11	419	31	663	20	779	−1	236	15	−1	0	−.039	.026	.26
22	21.0	11–June 1	512	35	635	19	801	1	35	202	50	6	.249	.344	7.22
23	5.4	June 1–6	557	36	757	23	871	6	341	45	2	2	.041	.078	.42
24	13.1	6–19	582	36	716	21	872	7	−16	346	32	14	.094	.593	7.73
25	13.0	19–July 2	663	39	736	22	908	0	99	286	32	13	.111	.492	6.38
26	7.6	July 2–10	648	39	729	22	908	0	−82	435	35	19	.080	.748	5.71
27	7.4	10–17	507	34	737	22	884	24	57	233	29	10	.125	.399	2.93
28	7.0	17–24	557	36	775	23	898	9	116	233	25	10	.105	.401	2.82
29	13.9	24–Aug. 7	513	35	757	23	910	12	−8	265	45	12	.171	.455	6.32
30	14.1	Aug. 7–21	449	32	703	21	880	0	−76	227	58	9	.256	.390	5.50
31	27.5	21–Sept. 18	395	30	691	21	863	1	−30	161	37	6	.228	.275	7.57
32	13.1	Sept. 18–Oct. 1	331	26	661	20	832	2	−95	167	38	6	.231	.285	3.74
33	17.9	Oct. 1–19	314	25	658	20	811	0	−27	124	16	4	.129	.211	3.78
34	14.0	19–Nov. 2	199	18	638	19	795	1	−134	109	28	3	.254	.186	2.60
35	14.0	Nov. 2–16	164	16	569	17	735	1	−184	101	47	2	.461	.172	2.41
36	17.1	16–Dec. 3	188	18	532	16	708	2	−111	60	30	1	.495	.102	1.74
Record season.	242.0	Apr. 5–Dec. 3												.286	69.24
		1964													
42	14.9	Mar. 20–Apr. 4	359	28	497	15	662	4	2	97	56	1	.579	.163	2.43
43	7.0	Apr. 4–11	443	32	507	15	673	2	232	31	−31	0	−.949	[1].052	[1].36
44	7.1	11–18	464	32	619	19	706	0	379	111	−165	1	−1.296	[1].187	[1]1.33
45	6.9	18–25	313	26	555	17	729	2	129	−25	−5	0	.193	−.043	−.30
46	11.1	25–May 6	429	31	608	18	770	−4	207	8	−1	0	−.122	.013	.14
47	14.0	May 6–20	478	33	703	21	809	0	130	181	1	5	.008	.309	4.34
48	9.9	20–30	549	36	675	20	849	3	−8	276	45	10	.163	.471	4.64
49	25.1	30–June 24	535	35	729	22	860	8	67	248	31	9	.125	.424	10.66
50	16.0	June 24–July 10	547	35	792	24	910	4	42	283	36	13	.127	.487	7.78
51	12.9	July 10–23	496	33	804	24	906	5	64	238	29	11	.122	.409	5.27
52	18.0	23–Aug. 10	546	36	816	24	929	0	−43	355	44	17	.124	.611	11.02
53	14.0	Aug. 10–24	383	28	721	22	863	12	−75	227	42	9	.185	.389	5.45
54	14.0	24–Sept. 7	473	33	737	22	871	2	8	240	28	9	.118	.412	5.77
55	12.0	Sept. 7–19	376	28	704	21	859	4	−71	203	36	8	.180	.347	4.17
56	17.2	19–Oct. 6	319	26	650	20	813	1	−129	187	47	6	.249	.320	5.49
57	17.8	Oct. 6–24	280	24	544	16	766	0	−134	106	43	2	.404	.181	3.23
58	12.8	24–Nov. 6	279	24	576	17	745	1	26	41	2	1	.041	.070	.90
59	11.9	Nov. 6–18	184	18	591	18	748	1	−42	29	4	1	.130	.050	.59
60	12.0	18–30	165	16	512	15	702	1	−331	150	124	2	.828	.253	3.03
Record season.	254.6	Mar. 20–Nov. 30												.300	76.30
		1965													
66	56.1	Apr. 13–June 8	500	34	638	19	786	0	126	158	10	4	.065	.269	15.09
67	30.0	June 8–July 8	628	38	726	22	867	3	48	332	37	13	.110	.569	17.04
68	43.0	July 8–Aug. 20	532	35	706	21	886	9	33	233	30	10	.128	.399	17.16
69	33.0	Aug. 20–Sept. 22	396	30	684	21	858	9	−33	175	31	7	.176	.300	9.91
Record season.	162.1	Apr. 13–Sept. 22												.365	59.20

[1] Periods 43 and 44 computed using alternate energy budget.

TABLE 4.—*Estimated energy conducted as sensible heat* (Q_h), *according to equation 7 and assuming* N=*0.0060*

Period	43	44
u_2 mile hr^{-1}	7.73	11.89
T_0-T_a ° C	−1.9	−6.5
Q_h cal cm^{-2} day^{-1}	−31	−165

surface, plus inflow and outflow. Energy advected through the bottom sediments or stored by the sediments has been ignored.

Compared with the effects of radiation, the flow of geothermal heat through the lake bottom is believed to be negligibly small (Anderson and others, 1950, p. 42). The radiation heating of bottom material has been shown to be significant in the case of a mudflat that is alternately exposed and flooded (Ayres, 1965). However, in the case of shallow waters of a lake of constant area, the sediments are creating much the same effect as would a deep-water column. Radiant energy is absorbed by the bottom in the shallow water and then is conducted back to the water. On a unit-area basis the effect of radiant heating of the shallow-water sediments probably can be ignored, except on a diurnal basis.

The sediment below the lake bottom influences the energy system by absorbing heat from the water during warm seasons and releasing it as the lake cools. Generally it has been believed that the role the sediment played in the heat budget was small, and obviously the annual net change is zero. Heat storage in the sediment is difficult to measure, and its short-term effects have not been believed to be important enough to warrant investigation. A limited amount of sediment-temperature data is available from the studies on Pretty Lake, so that the effect of sediment heating upon evaporation can be discussed on a rough basis.

A probe containing thermocouples at 1-foot (0.30-m) intervals to a depth of 17.5 feet (5.33 m) below the lake bottom was placed in Pretty Lake 82 feet (25 m) below the instrument raft in late 1963. Temperatures sensed by the thermocouples were recorded on the instrument raft. Equipment-operation problems caused loss of records from some of the sensors at different times, but enough data were collected to construct the temperature lines in figure 15. The lower part of the figure is a graph of heat storage within the 17.5-foot (5.33-m) layer, assuming heat capacity of the sediment to be 1.00 cal cm^{-3}°C^{-1} (calorie per cubic centimeter per degree Celsius).

One of the very few reported previous studies of the heat budget of lake sediment was made on Lake Mendota, Wis., in the years 1916–21 (Birge and others, 1928). Birge and Juday used a probe which had an electrical-resistance thermometer in its point and which was driven into the lake bottom. Over 200 profiles of sediment temperatures were made at four selected stations beneath water ranging in depth from 8 to 23.5 meters (26 to 77 ft).

The Lake Mendota study showed that the upper 5 meters (16.4 ft) of sediment had a total annual budget involving the exchange of about 3,000 cal cm^{-2} beneath 8 meters (26 ft) of water, 2,200 cal cm^{-2} beneath 12 meters (39 ft) of water, and 1,100 cal cm^{-2} beneath 18 and 23.5 meters (59 and 77 ft) of water. The annual heat budget for the entire lake was computed to involve the average exchange of about 2,000 cal cm^{-2} with the sediment. In each of the data-collection sites, the top meter of sediment accounted for about 50 percent of the annual budget, and the second meter accounted for about 25 percent.

Data from the two deepest Lake Mendota stations are similar to the Pretty Lake data represented in

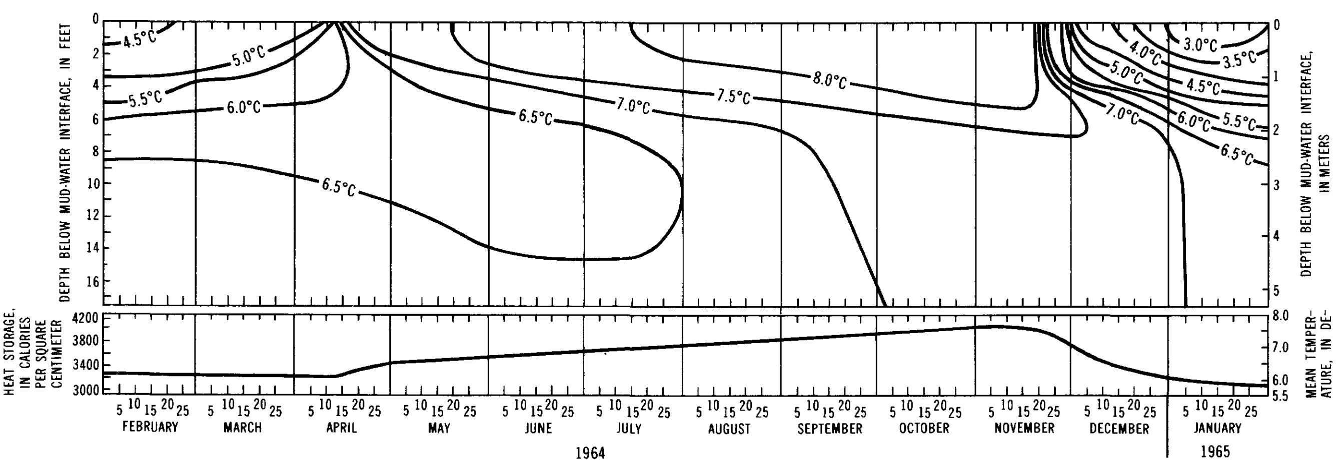

FIGURE 15.—Yearly temperature and heat-storage pattern in the upper 17.5 feet (5.33 m) of sediment below 82 feet (25 m) of water near the center of Pretty Lake. Heat storage is computed above a base of 0°C, assuming heat capacity to be 1.00 calorie per cubic centimeter per degree Celsius.

figure 15. Lake Mendota has about the same maximum depth as Pretty Lake, and its average depth is only about 4 meters (13 ft) greater, but Lake Mendota's area is about 50 times greater than that of Pretty Lake. Therefore, the greater wind fetch at Lake Mendota causes it to stratify later and to have a deeper thermocline than is found in Pretty Lake. The result is a greater range of hypolimnetic temperature and a higher mean annual temperature in the hypolimnion, which in turn causes higher mean sediment temperature and a greater total annual heat budget of the sediment. The annual heat budget of about 800 cal cm^{-2} for Pretty Lake deep-water sediment differs from the Lake Mendota budget in direct proportion to differences in the range of hypolimnetic temperature.

A simple expression for total heat transfer through a plane subjected to a sinusoidal temperature stress of amplitude T_m and period p_m is given by the equation

$$Q_m = sT_m\sqrt{\frac{2p_m}{\pi\beta}} \tag{9}$$

where Q_m is heat flow per unit area, s is thermal conductivity, and β is thermal diffusivity (Ingersoll and others, 1954, p. 50). It is recognized that the thermal stress on the Pretty Lake bottom is not truly sinusoidal, but it is possible, without going through the complex Fourier analysis used by March (Birge and others, 1928), to determine from the data and equation 9 that the thermal diffusivity of Pretty Lake is about the same as the value of 0.00325 cm^2 sec^{-1} (square centimeters per second) computed for Lake Mendota.

Values of Q_m for different depths in Pretty Lake were computed by use of T_m values from the thermal-survey data. The Q_m values were then weighted according to the size of the bottom area they represented in order to compute the mean annual heat budget for the lake, which was found to be about 2,000 cal cm^{-2}. Judging from the similarity of figure 15 and several similar plots of Lake Mendota data, the annual change in heat storage in Pretty Lake sediments can be represented by a curve similar to the one in figure 15, but having an amplitude about 2½ times as great (fig. 16). The slope of figure 16 represents the rate at which absorption of heat energy into the lake sediment is influencing the lake's energy budget as it is used to compute evaporation. During May, June, and July, it is estimated that the net energy available for evaporation is about 17 cal cm^{-2} day^{-1} less than the quantities shown in table 3. In late November, when the lake is cooling rapidly, the bottom sediments are releasing more than 30 cal cm^{-2} day^{-1}.

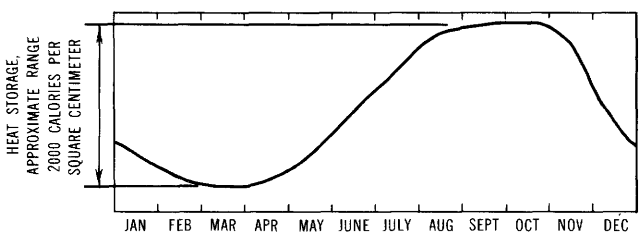

FIGURE 16—Estimated annual cycle of average heat storage in the upper 5 meters (16.4 ft) of Pretty Lake sediment.

Corrections for the sediment heat storage in the energy-budget evaporation terms were estimated from figure 16. During the early summer warmup the heat entering the sediment is equivalent to a reduction in computed evaporation of about 0.025 cm day^{-1}. Generally this reduction is about a 5-percent correction. The cooling corrections in the fall periods increased the computed evaporation about 0.03 cm day^{-1}, which is more than 50 percent for a period like number 59.

Sediment-heating corrections made for Pretty Lake are not considered to be accurate enough for use in the subsequent sections of this report, such as in the calibration of mass transfer. Sediment temperatures from two shallower stations are needed for a reasonably accurate computation of the budget. The assumed heat capacity of 1 cal $gram^{-1}$ $°C^{-1}$ (calorie per gram per degree Celsins) which was used in these computations and in the Lake Mendota computations probably is too large. However, the sediment-heating factor is sometimes significant, and undoubtedly it will receive further consideration in other evaporation studies that utilize the energy-budget technique.

MASS-TRANSFER STUDIES

The mass-transfer method of evaporation computation is widely used. Bibliographies prepared by the U.S. Geological Survey (Robinson and Johnson, 1961) and Utah State University (Christiansen and Lauritzen, 1963) make numerous references to the use of the method within the United States. Papers by Budyko (1948) and by Braslavskii and Vikulina (1954) present lengthy bibliographies that are indicative of the use of the method within the Soviet Union. For an excellent description of the theory and a discussion of the development of the method, the reader is referred to the reports of the Lake Mead study (Anderson and others, 1950) and of the Lake Hefner study (Marciano and Harbeck, 1952) and to the thesis of Al-Barrak (1964) that summarizes many of the present forms of the mass-transfer method as it is used to estimate evaporation and evapotranspiration.

Equations for estimating evaporation by the mass-transfer method take the form

$$E_{MT} = f(u_z)(e_0 - e_a), \tag{10}$$

where

u_z=windspeed at some height z above the water surface,

e_0=saturation vapor pressure calculated from the temperature of the water surface, and

e_a=vapor pressure of the air.

Various forms of the equation use different multiplier constants and different functions of wind speed based upon area, season, lake size, temperature and other factors.

The study of Pretty Lake assumed the mass-transfer relationship to be in the form developed in the Lake Hefner study (Marciano and Harbeck, 1952) as

$$E_{MT}=Nu_2(e_0-e_a), \quad (11)$$

which is the same equation used with equations 4 and 5 to estimate Q_h in the previous section. Here, N is a constant for a specific lake, and u_2 is the average wind speed measured 2 meters (6.56 ft) above the water surface. Harbeck, realizing that the mass-transfer coefficient, N, summarizes many variables such as wind and vapor profiles and wave heights, has made an empirical relationship[1] $N=0.00859/A^{0.05}$ between the constant and the surface area, A, of the body of water to which it applies (Harbeck, 1962, fig. 31). The constant N can be only roughly related to lake size, for it also is affected by local peculiarities, topography, and point of wind measurement. One purpose of the Pretty Lake study was to determine the mass-transfer coefficient and to compare the Pretty Lake coefficient with those of other lakes or with a coefficient of 0.00661 predicted by Harbeck's surface-area method.

INSTRUMENT RECORDS

Vapor pressure. The mass-transfer study made use of the same vapor-pressure data that were used in the energy-budget study for estimating the Bowen ratio. Figure 14 includes the values of e_0 and e_a, and the difference $e=e_0-e_a$ is represented linearly by the separation of the two plots on the figure.

The difference between average values of e_0 and e_a over the energy-budget periods were used in the calibration of N and in the computation of evaporation. Values of (e_0-e_a) for the energy-budget periods are listed in table 5.

Wind record. Records from the anemometer dial readings were supplemented by the recorder-chart records when it was necessary to interpolate between dial readings for special study purposes. An approximate correction was applied to the springtime bank-measured values to make them more nearly equivalent to the rest of the records.

[1] This form assumes that equation 11 will have E_{MT} in centimeters per day, u_2 in miles per hour, and e_0 and e_a in millibars. Surface area A is in acres.

Anemometer height correction. Records from the 1.73-meter (5.68 ft) anemometers were adjusted to make them equivalent to the windspeed at 2.0 meters (6.56 ft) (u_2). The correction factor to be applied to the 1.73-meter (5.68 ft) records was determined by comparing the average windspeed between consecutive dial readings for the two anemometers.

Four sets of data that seemed to be affected by anemometer icing or stalling were disregarded, and the remaining 85 pairs of data were equally weighted to define a regression line

$$u_{2.0}=1.032\ u_{1.73}+0.118, \quad (12)$$

which had a standard error of 0.275 miles per hour (0.123 m per second). Upon testing the significance of the slope and intercept, it was found that the slope of 1.032 was significantly different from unity but that the intercept of the ordinate was not significantly different from zero. Restricting the regression line to make it pass through the origin, a line was constructed by least squares that defined the relation

$$u_{2.0}=1.046u_{1.73}$$

All $u_{1.73}$ data were corrected to 2-meter (6.56-ft) data by multiplying them by the constant 1.046. Figure 17 is a time plot of values of $u_{2.0}$ computed between dial readings of the anemometers. Average values of $u_{2.0}$ over the energy-budget periods are tabulated in table 5.

MASS-TRANSFER COEFFICIENT FROM ENERGY-BUDGET CALIBRATION

Assuming that evaporation can be computed as the product of the three terms in equation 11, the constant N for a particular lake can be defined as the slope of a straight line of calibration relating the product $u(e_0-e_a)$ to some independent measure of evaporation. It is common practice to use energy-budget data as the independent measure. Figure 18 is a plot of the products of u and (e_0-e_a) values listed in table 5 against the evaporation values computed from the energy-budget studies. Figure 18A shows rates of evaporation and figure 18B shows total amounts of evaporation during the computation periods. A symbol n represents the number of days in a computation period.

If N, as expressed in equation 11, is a constant, a straight line fitted to figure 18 must pass through the origin. There is a physical basis to support such an assumption. At the time when wind is calm or when there is no driving force of the vapor pressure difference $(e_0-e_a=0)$, turbulent exchange of vapor between the lake surface and the air is negligibly small. Likewise, the vapor exchange by simple molecular diffusion also would be small enough to be negligible.

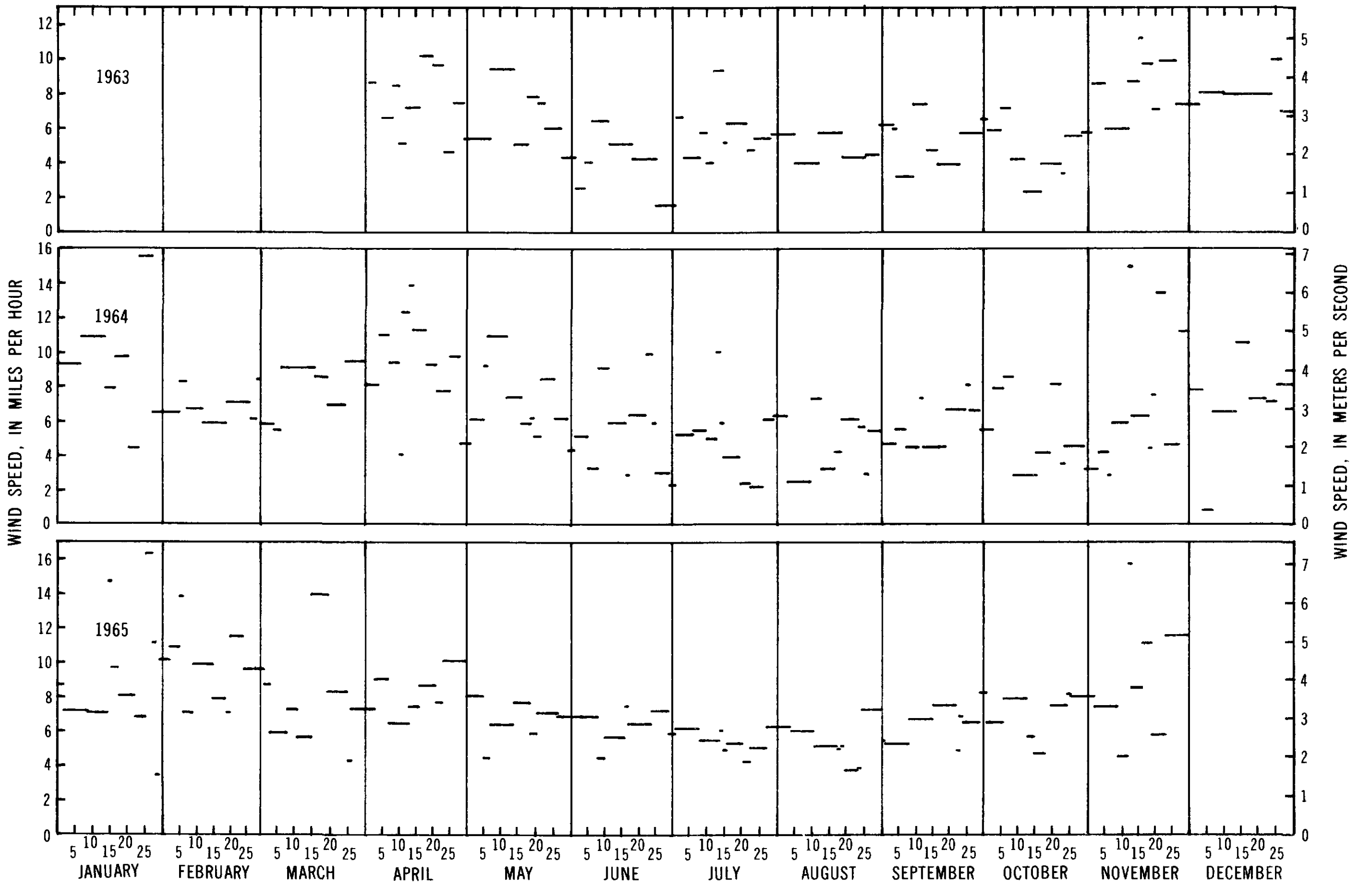

FIGURE 17.—Wind speeds. Length of lines represent duration of periods between integrator readings.

Several techniques were used in the attempt to determine the proper fit of a relation line to figure 18. Lines were fitted to the rate plot (fig. 18*A*) by standard least-squares technique and by using weighting factors for each period proportional to the period lengths. Weighting factors are a way of accounting for the greater accuracy of the longer energy-budget periods. Lines also were fitted to figure 18*B* for what is, in effect, a double-weighted regression. The results showed very little difference between the weighted and unweighted lines fitted to figure 18*A* but gave the weighted lines fitted to figure 18*B* flatter slopes and intercepts nearer to the origin.

Limitations of regression analysis must be remembered in interpreting the fitting of the regression lines, which assumes that the dependent variable is normally distributed about the true regression line and has constant variance throughout the range of the independent variable.

Tests of the lines fitted to figure 18 do not unanimously support the assumption of an origin intercept, but it is believed that the springtime errors in the short periods have biased greatly the data points near the origin of figure 18*A*.

Several techniques exist to determine the slopes of straight lines that are fitted to figure 18 and that will satisfy equation 11. A simple ratio technique would define a line passing through the origin and through the means of the two variables on figure 18*A*. The ratio also can be weighted to account for varying lengths of the computation periods to define a line that would have the same slope as would a simple ratio computed for figure 18*B*. Values of N computed for each period can be averaged, or they can be weighted according to period length or amount of evaporation. Regression techniques also may be used to fit unweighted, weighted, and double-weighted lines passing through the origin with slopes that will minimize the squares of the deviations of the dependent variable.

Figure 19 represents the slopes of straight lines passing through the origin and fitted by different methods. The 95-percent confidence limits computed for the regression fits give some idea of the expected error. The ratio techniques give greater consideration to the short low-rate values, whereas the double-weighted regression is influenced most by the longer periods of 1965 and by the high-rate periods. Even the ratio-estimated slopes lie within the confidence

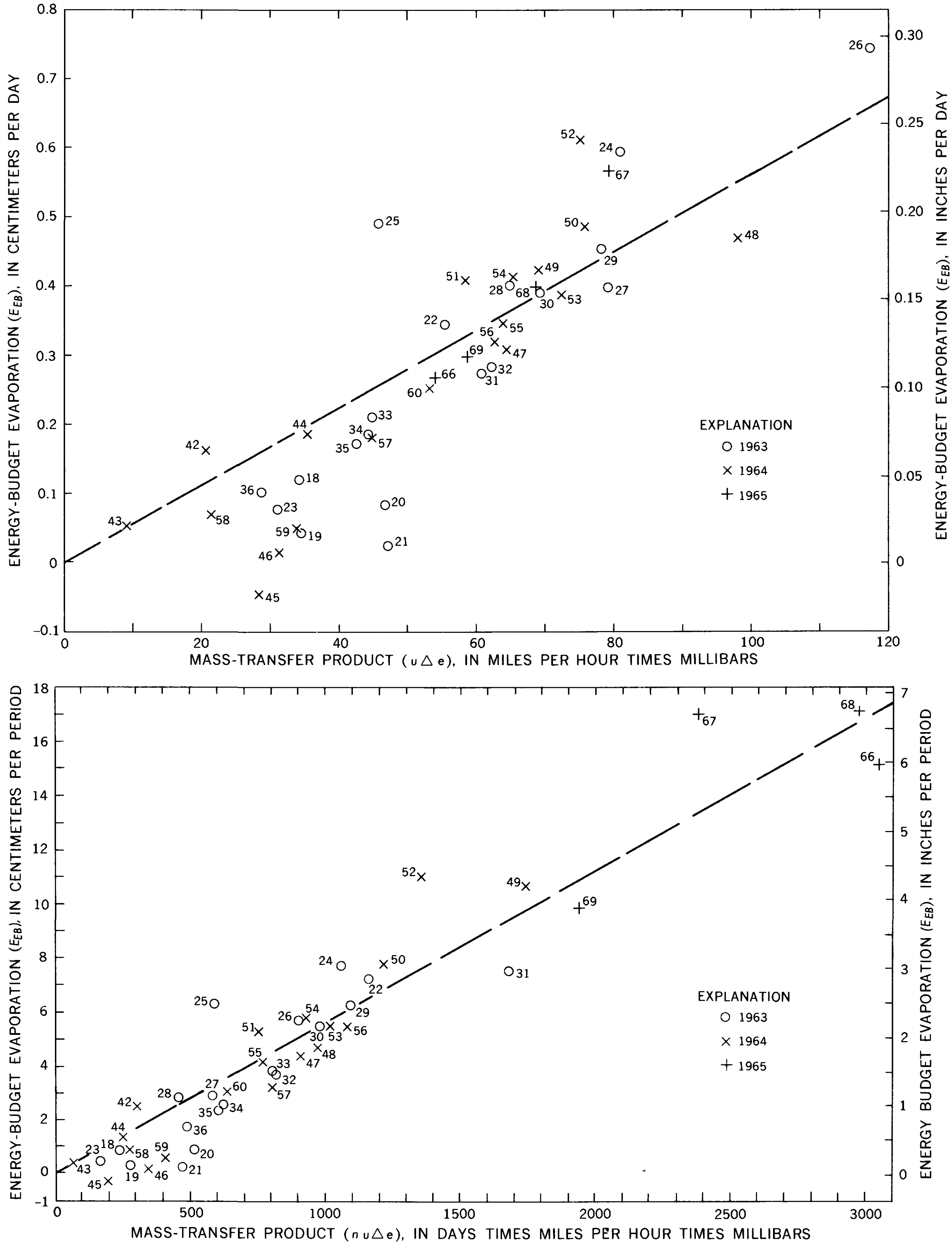

FIGURE 18.—Relation of the mass-transfer product to evaporation measured by the energy-budget method. *A* (upper), Using evaporation rates. *B* (lower), Using amounts of evaporation per period. Dashed lines are at a slope of 0.00560.

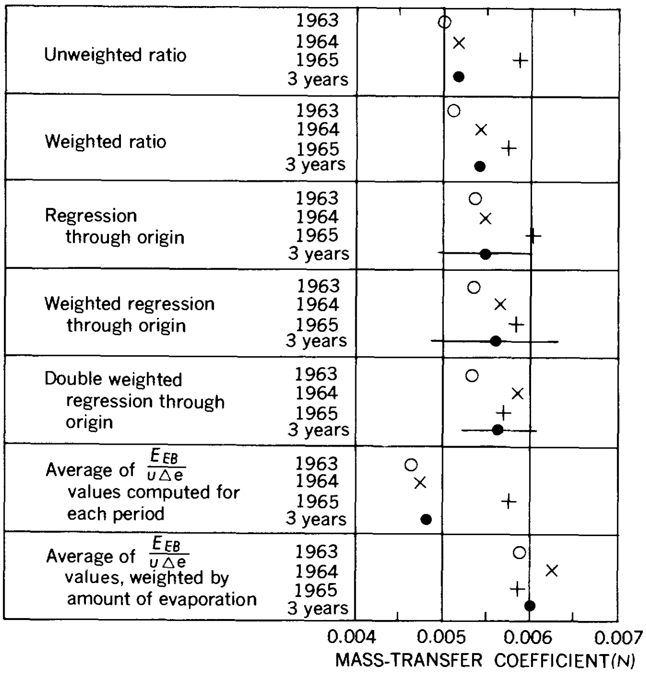

FIGURE 19.—Mass-transfer coefficients determined by different methods. Lines drawn through some symbols represent 95-percent confidence limits.

intervals of the slopes of the unweighted and weighted regressions through the origin.

Visual inspection of figure 18, especially of the rate plot, may give reason to suspect the validity of an assumed straight-line function. A curved line, logarithmic, parabolic, or second degree, might seem to be better, especially if it is restricted to pass through the origin. However, in consideration of the origin of the data and the errors contained in the low-rate energy-budget computation, a curved line is not believed to be a better representation of the mass-transfer function than is the straight line. Further discussion of this problem is in a later section of this report.

Considering the various coefficients computed by different methods, the relation

$$E_{\mathrm{MT}}=0.00560\ u_{2.0}(e_0-e_a) \qquad (14)$$

was selected to compute mass-transfer evaporation.[2] The mass-transfer coefficient in equation 14 is 15 percent less than the coefficient of 0.00661 preducted by Harbeck's (1962, fig. 31)method.

[2] The constant N, here expressed as 0.00560 with E in centimeters per day and $u_{2.0}$ in miles per hour, would be 0.0125 with E in centimeters per day and $u_{2.0}$ in meters per second, and would be 0.00220 with E in inches per day and $u_{2.0}$ in miles per hour. Vapor pressure is in millibars.

COMPUTATION OF EVAPORATION BY MASS TRANSFER

Evaporation rates and quantities were computed for the energy-budget periods by use of equation 14. Table 5 lists the terms of the computation. Evaporation rates and amounts computed by the mass-transfer method are shown graphically and further summarized in figures 30 and 31 and in tables 20 and 21 in a later section of this report.

Accuracy of the mass-transfer data is difficult to estimate because there is no absolutely accurate control. Often the judgment of the investigator provides the most tangible estimate of accuracy.

The regression analyses of the calibration data indicated standard errors about the line fitted to figure 18*A* of about 0.08 cm day^{-1}. The estimated confidence interval at the origin spread 0.04 cm day^{-1}

TABLE 5.—*Summary of mass-transfer terms for open-water periods, 1963–65*

Period			$u_{2.0}$ miles per hour	e_0-e_a (mb)	Evaporation	
No.	Length (days)	Dates			Centimeters per day	Centimeters per period
		1963				
18	7.0	Apr. 5–12	6.92	5.0	0.193	1.36
19	8.0	12–20	8.70	4.0	.196	1.57
20	10.9	20–May 1	7.15	6.6	.265	2.89
21	10.0	May 1–11	7.80	6.1	.267	2.67
22	21.0	11–June 1	6.23	8.9	.310	6.51
23	5.4	June 1–6	3.57	8.7	.174	.95
24	13.1	6–19	5.79	14.0	.454	5.92
25	13.0	19–July 2	2.65	17.3	.256	3.33
26	7.6	July 2–10	5.43	21.7	.660	5.04
27	7.4	10–17	5.93	13.4	.445	3.27
28	7.0	17–24	5.72	11.4	.365	2.57
29	13.9	24–Aug. 7	5.77	13.6	.440	6.10
30	14.1	Aug. 7–21	5.04	13.8	.390	5.49
31	27.5	Sept. 18	4.85	12.6	.342	9.42
32	13.1	Sept. 18–Oct. 1	5.26	11.9	.351	4.60
33	17.9	Oct. 1–19	4.41	10.2	.252	4.51
34	14.0	19–Nov. 2	5.13	8.7	.250	3.49
35	14.0	Nov. 2–16	7.54	5.7	.241	3.38
36	17.1	16–Dec. 3	8.29	3.5	.162	2.77
Record season.	242.0	Apr. 5–Dec. 3			.313	75.84
		1964				
42	14.9	Mar. 20–Apr. 4	6.68	3.1	.116	1.73
43	7.0	Apr. 4–11	7.73	1.2	.052	.36
44	7.1	11–18	11.89	3.0	.200	1.42
45	6.9	18–25	8.41	3.4	.160	1.10
46	11.1	25–May 6	7.14	4.4	.176	1.94
47	14.0	May 6–20	8.50	7.6	.362	5.08
48	9.9	20–30	6.87	14.3	.550	5.42
49	25.1	30–June 24	6.01	11.5	.387	9.73
50	16.0	June 24–July 10	4.36	17.4	.425	6.79
51	12.9	July 10–23	4.44	13.2	.328	4.23
52	18.0	23–Aug. 10	3.89	19.3	.421	7.58
53	14.0	Aug. 10–24	5.30	13.7	.407	5.69
54	14.0	24–Sept. 7	5.16	12.7	.367	5.14
55	12.0	Sept. 7–19	4.82	13.3	.359	4.31
56	17.2	19–Oct. 6	6.77	9.3	.353	6.05
57	17.8	Oct. 6–24	5.10	8.8	.253	4.50
58	12.8	24–Nov. 6	4.05	5.3	.120	1.54
59	11.9	Nov. 6–18	6.65	5.1	.192	2.28
60	12.0	18–30	8.76	6.1	.300	3.58
Record season.	254.6	Mar. 20–Nov. 30			.308	78.47
		1965				
66	56.1	Apr. 13–June 8	7.53	7.2	.304	17.03
67	30.0	June 8–July 8	6.10	13.0	.444	13.29
68	43.0	July 8–Aug. 20	5.39	12.8	.386	16.62
69	33.0	Aug. 20–Sept. 22	5.99	9.8	.329	10.85
Record season.	162.1	Apr. 13–Sept. 22			.357	57.79

on either side of the regression line. Relative standard error of the slope of the regression line through the origin is about 6 percent.

Standard error about the line fitted to figure 18*B* was 1.37 cm (0.54 inch) per period, and the confidence interval at the origin spread 0.70 cm (0.28 inch) on either side of the line. The slope of the regression line fitted through the origin of figure 18*B* had a standard error of 7 percent.

All of these statistics were computed under the assumption that all the error in the calibration fit was contained in the energy-budget control. They are reasonable estimates of the validity of the calibration, but they give little specific information regarding the individual errors in the two different methods.

Consideration of the errors in the individual vapor-pressure and wind terms tells a little about the accuracy of the mass-transfer method. Comparison of the two anemometers indicates that average windspeed is being measured with an accuracy of about 2 percent. The difference (e_0-e_a) is believed to be within about 0.3 millibar at lower temperatures and within about 0.8 millibar at the highest lake temperatures. Percentage error varies from a minimum at the higher evaporation rate to a large number when Δe is small. However, low vapor-pressure difference often was a result of a calm damp day, so that evaporation rate estimates for these days contain only small absolute errors.

The errors in the mass-transfer computations for the days with low evaporation rates generally are smaller than the errors in the energy-budget evaporation for similar days.

WATER-BUDGET STUDIES

The water-budget technique for measuring evaporation from a lake makes use of common hydrographic techniques of measuring stage, precipitation, and streamflow. The formula for computation simply equates the total inflow to the sum of the total outflow and change of storage, or

$$I+I_p+G=E_{WB}+O+\Delta S \qquad (15)$$

where

I=surface inflow,
I_p=precipitation falling on lake,
G=net underground seepage, considered positive for inflow,
E_{WB}=evaporation,
O=surface outflow, and
ΔS=net change of storage, considered positive for increase.

In order to compute evaporation, it is necessary directly to measure or somehow to determine all the other factors. The ground-water seepage term cannot be directly measured, so that in preliminary computations it is combined with evaporation as $(E-G)$, a difference designated as ΔH. Equation 15 then may be rewritten as

$$\Delta H=E-G=I+I_p-O-\Delta S \qquad (16)$$

where it is seen that the ΔH term may be described as the fall in stage, corrected for inflow, outflow, and precipitation, if all other terms are reduced to change per unit area of water surface. Further analysis of the water budget requires an additional means of defining evaporation or seepage in order to understand completely all the terms of the water budget.

INSTRUMENT RECORDS

The records of inflow, outflow, and precipitation used in the water-budget studies were the same records used in the computation of the advected-energy term of the energy-budget studies.

The small volume of water moving into, and out of Pretty Lake reduced the requirement of accuracy in the computation of the data for the Q_v term of the energy budget. In the water budget, it is necessary that the errors of the measurements be reduced to a minimum to maintain accuracy.

Surface inflow and outflow. Records of streamflow into and out of the lake were computed by standard Geological Survey methods (Corbett and others, 1943). Gage-height records of the water-stage recorders were applied to ratings defined by current-meter or volumetric measurements. Figures 20 and 21 illustrate the magnitude and variability of the flow.

Daily streamflows for the inlet station have been published by the U.S. Geological Survey in the series "Surface Water Records of Indiana." These records have been rated as poor, meaning that daily discharges generally are more than 15 percent in error. This estimate of large error is due to the very low flow, which normally is computed to the nearest 0.01 cfs (cubic foot per second); a change or error in stage reading of 0.01 foot can result in a 20-percent change or error in the daily discharge. Over several days the errors of the daily measurements would tend to compensate one another, and errors in the volumes of inflow used in the water-budget computations would be more in the order of 5 percent instead of greater than 15 percent.

The outlet station, which also is weir controlled, has the same problems of rating sensitivity at low flows as has the inlet station. Whereas the inlet station used a V-notch weir, the outlet had a wider weir and most probably had about twice as much error in the computed outflow values.

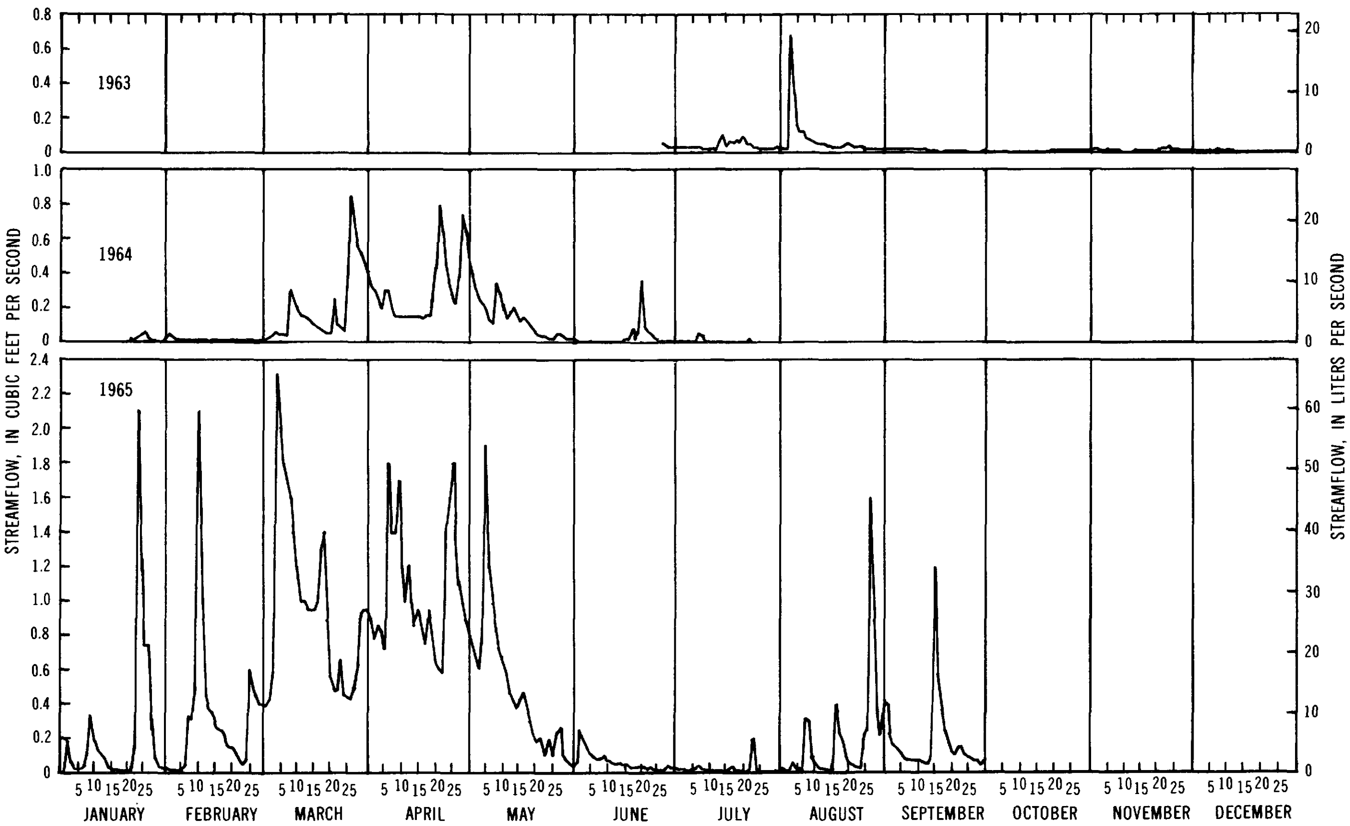

FIGURE 20.—Discharge of Pretty Lake inlet.

Lake stage. Figure 22 illustrates on a small scale the variations in the stage of Pretty Lake. The pattern shows a rise with each rain followed by a slow fall in stage caused by outflow and evaporation. The instrumentation section of this report describes the limitations of the two recorders used to measure stage. Although the recorder operating at 1:1 ratio was readable to the nearest 0.001 foot (0.03 cm) the accuracy of such a float-operated instrument probably is not within the limits of readability. Conservative estimates of the error in the change-of-storage term indicate that the value over one computation period was within 0.02 foot (0.6 cm) during the 1963 season and was within 0.01 foot (0.3 cm) during 1964 and 1965.

Precipitation. The values used in the precipitation terms of the Pretty Lake water budget were selected from the records of the two recording rain gages, the nonrecording gage, and the stage gage (fig. 23). It was not unusual for differences among the gages to be more than 15 percent. The differences resulted from areal differences in the precipitation and from catch errors of the unshielded gages. Unless the chart indicated poor operation of the recorder, the lake stage gage generally was considered to be the most reliable measurer of the average precipitation falling directly upon the lake.

The topography around the lake is flat enough to prevent large amounts of ungaged surface runoff from running into the lake. A good deal of the water falling along the shoreline soaked directly into the grass-covered fields and lawns or was caught by the many small closed basins. Runoff which did reach the lake was measured by the stage recorder and was treated in computation the same as was precipitation. In a few cases, it was possible to separate overland ungaged flow into the lake after the rain had ceased to fall. Such instances were the result of rainfall of 1.5 inches (3.8 cm) or more.

BALANCING THE WATER BUDGET (SEEPAGE CORRECTION)

The values of individual terms of the water budget for the three years of study are presented in table 6. The table is arranged to solve for ΔH in centimeters per day for the same periods that were used in the energy-budget computations and in the mass-transfer calibration.

Values of evaporation computed by the water-budget method (E_{WB}) would be expected to plot with the same kind of mass-transfer calibration as did the energy-budget values used in figure 18, if it is assumed that the water budget was accurate. A certain amount of information also can be gotten from a plot of the corrected fall in stage, ΔH, against the mass-transfer product,

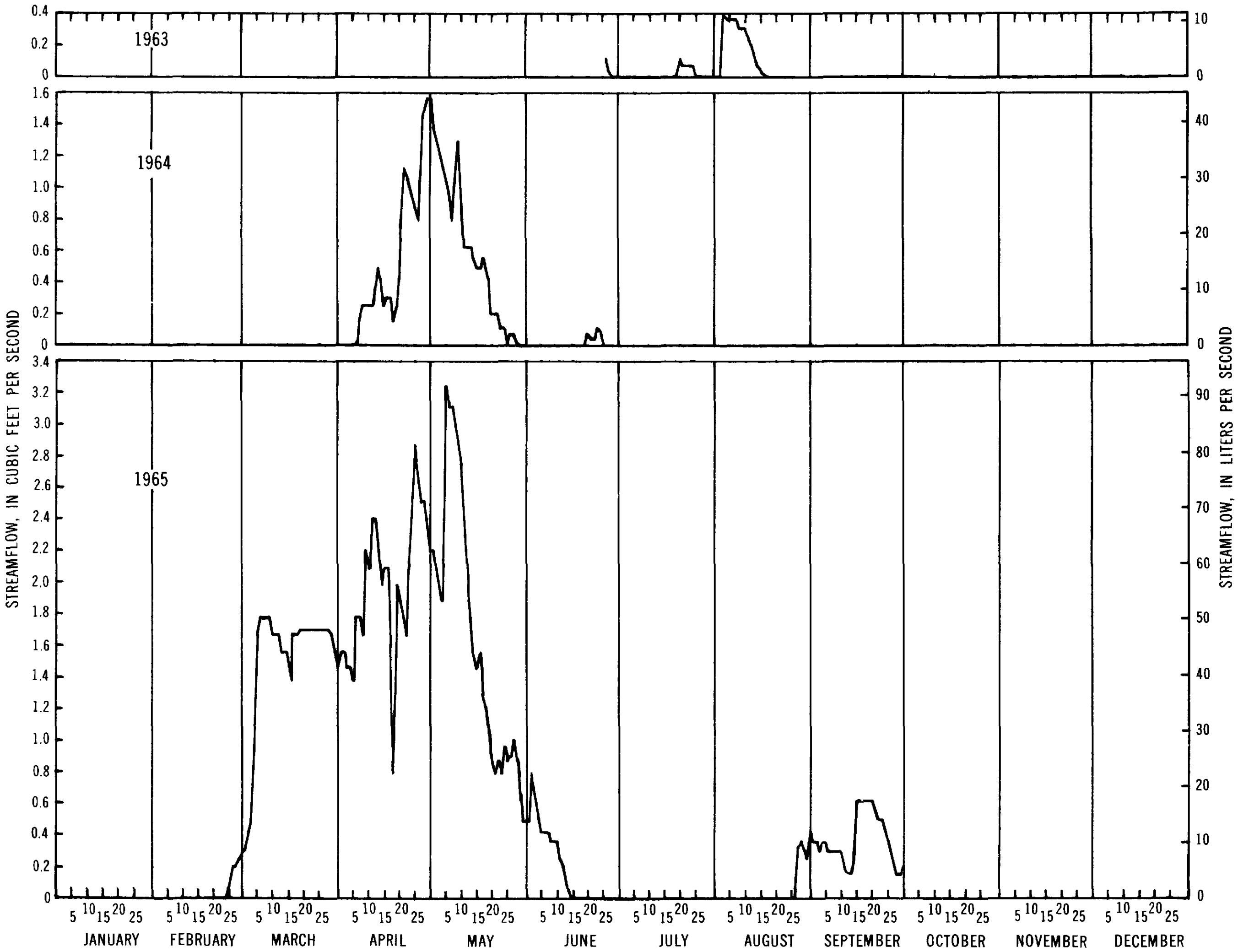

FIGURE 21.—Pretty Lake outflow.

$u\Delta e$ (Langbein and others, 1951). Such a plot for the three years of study is shown in figure 24, which shows both rate and amount-per-period scales. The line shown in figure 24 is drawn with the slope defined in the mass-transfer calibration (eq 14). If the seepage, G, were zero or negligibly small, a line fitted to the points in figure 24 would be nearly identical to the line shown and definitely would pass through the origin.

Most of the data points on the figure agree well with the relation line shown. The fit is as good as the fit of the energy-budget data. However, a group of data points (Nos. 42–48, 66, and 69) seem to define a separate line approximately parallel to the relation line shown but intersecting the ordinate axis somewhere below the origin. Rather than being a part of the total set of data, these points seem to be part of a separate population. Undoubtedly they describe periods when the fall in stage, ΔH, is influenced by seepage as well as by evaporation. This conclusion is further supported by the coincidence of the periods represented by these points with the times of moderate, heavy, or frequent rainfall. The vertical distance between the point position and the line is the measure of the rate or amount of seepage during the period represented by the point.

The differences of the deviations of the several points indicate that the seepage rate is variable between and within the periods. A better analysis of variability is provided by breaking the data periods into subperiods representing fewer days. The mass-transfer and water-budget data are easily arranged for such analyses.

Figure 25 is a plot of the subperiod data for periods 42 through 48 in 1964 and for all the periods in 1965. It is estimated that the error for each subperiod may be 0.2 cm (0.08 inch), which is 0.03 to 0.2 cm day^{-1} for the 1- to 7-day-long subperiods. The seepage estimates based upon the deviations of the subperiod points from the line are plotted as a function of time in the seepage plot of

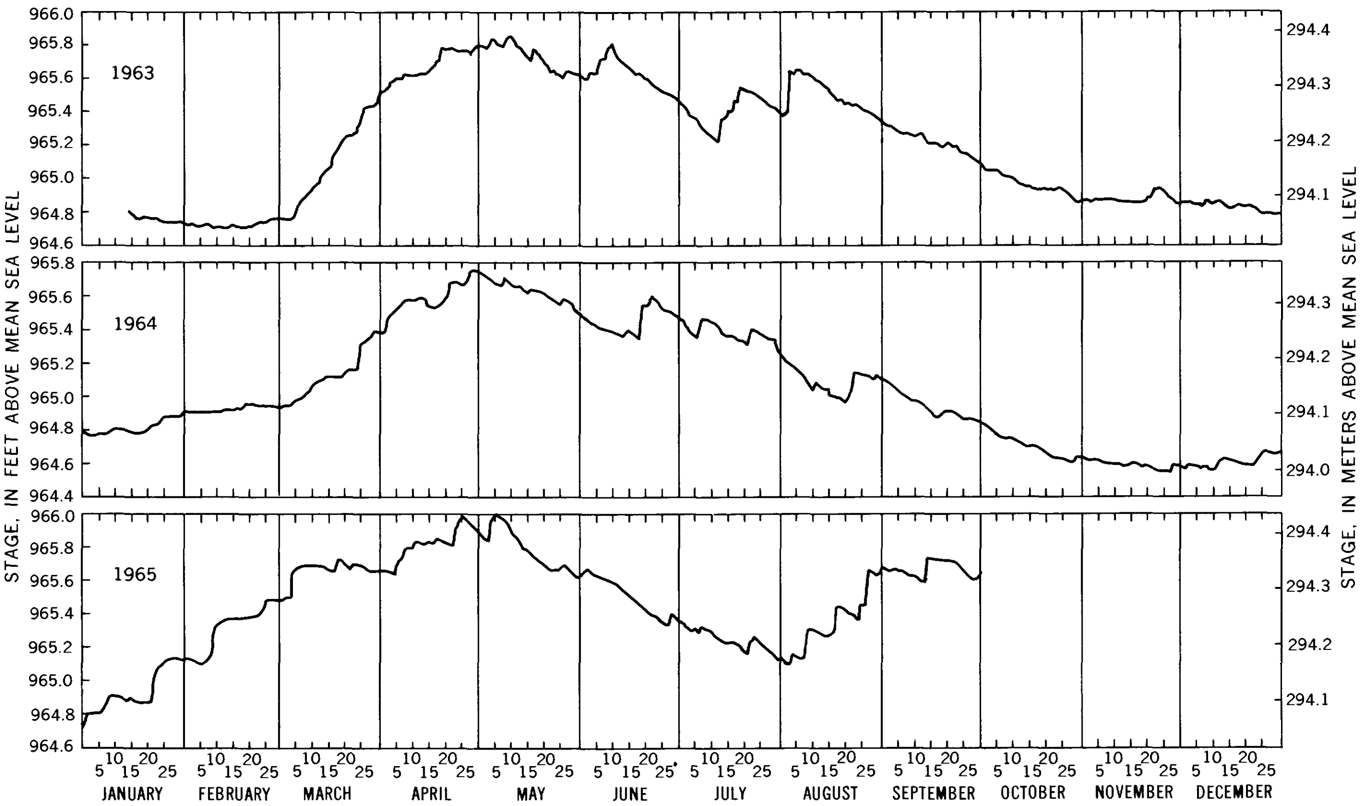

FIGURE 22.—Pretty Lake stage, 1963–65.

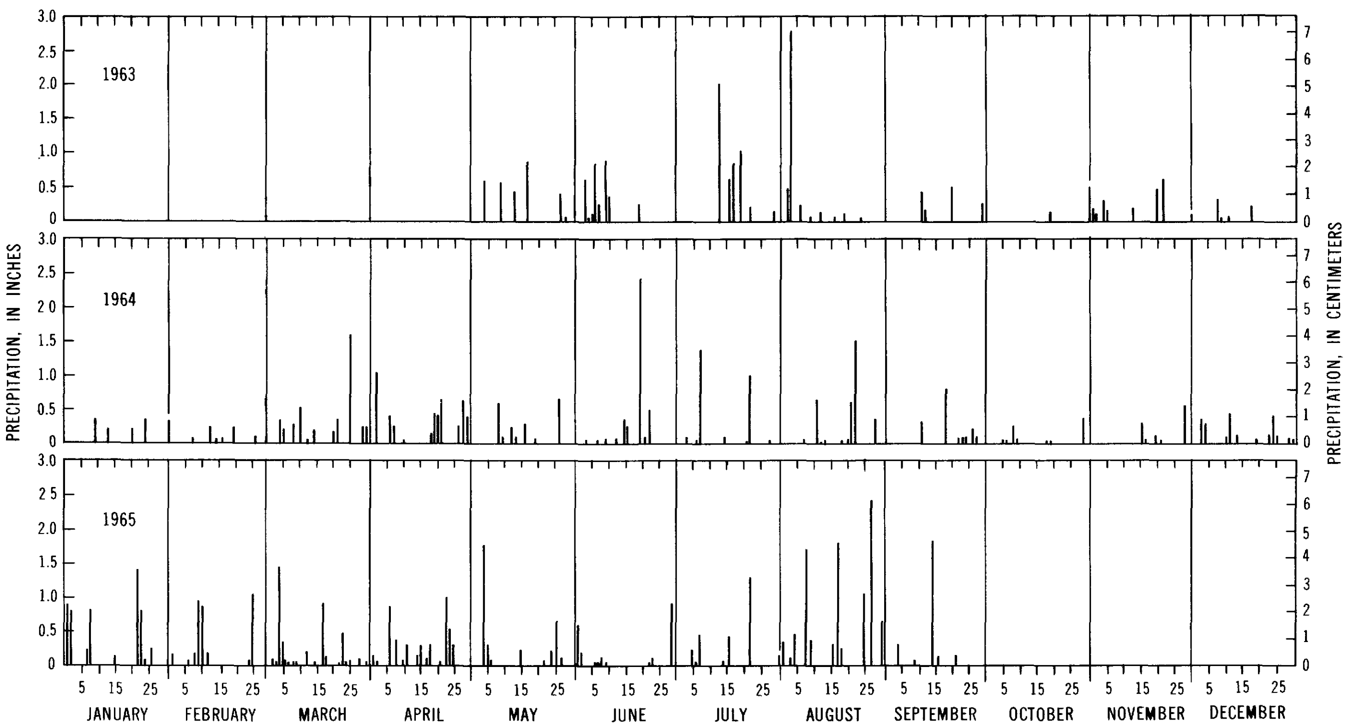

FIGURE 23.—Daily precipitation measured at Pretty Lake.

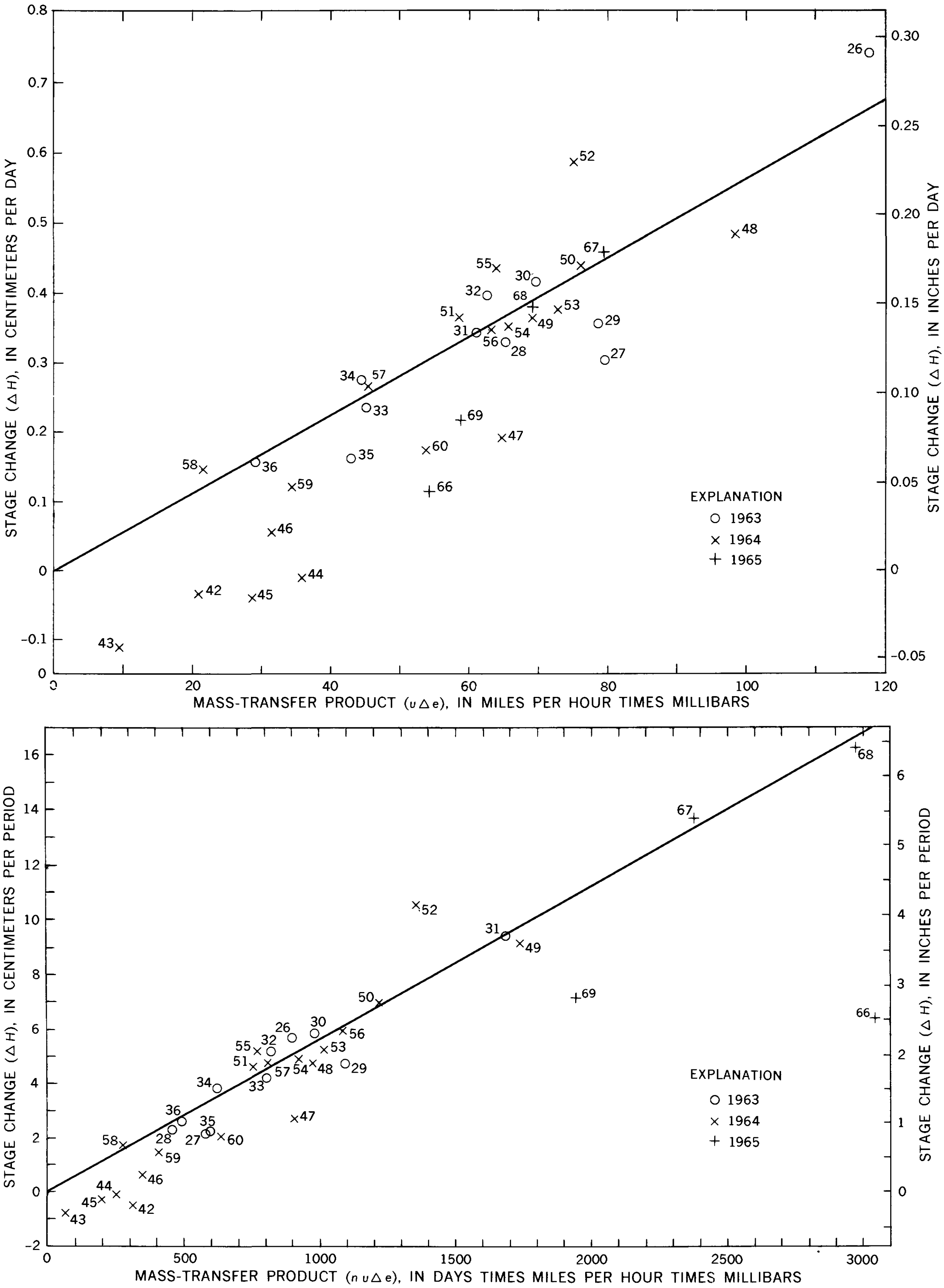

FIGURE 24.—Relation of corrected stage change to the mass-transfer product by energy-budget periods. The line shown has the slope determined by the calibration plot of figure 18.

TABLE 6.—*Summary of water-budget terms for Pretty Lake open-water periods, 1963–65*

Period			Precipitation and overland runoff (cm)	Inlet inflow (cm)	Outflow (cm)	Storage change (cm)	Thermal expansion (cm)	ΔH	
No.	Length (days)	Dates						Centimeters per period	Centimeters per day
		1963							
26	7.6	July 2–10	0	0.07	0	−5.49	0.12	5.68	0.743
27	7.4	10–17	8.66	.10	0	6.40	−.15	2.21	.301
28	7.0	17–24	3.07	.12	0.13	.91	.15	2.30	.327
29	13.9	24–Aug. 7	9.12	.53	.59	4.27	−.03	4.76	.343
30	14.1	Aug. 7–21	.86	.22	.55	−5.49	−.18	5.84	.414
31	27.5	21–Sept. 18	1.42	.17	0	−7.92	−.12	9.39	.341
32	13.1	Sept. 18–Oct. 1	1.68	.03	0	−3.66	−.18	5.19	.396
33	17.9	Oct. 1–19	.28	0	0	−3.96	−.06	4.18	.233
34	14.0	19–Nov. 2	1.88	.05	0	−2.13	−.24	3.82	.273
35	14.0	Nov. 2–16	1.55	.04	0	−.91	−.24	2.26	.161
36	17.1	16–Dec. 3	2.79	.07	0	.15	−.09	2.62	.154
Record season.	153.6	July 2–Dec. 3						48.25	
		1964							
42	14.9	Mar. 20–Apr. 4	[1] 8.92	1.72	0	11.13	0	−.49	−.033
43	7.0	Apr. 4–11	1.70	.47	.34	2.65	.03	−.79	−.113
44	7.1	11–18	.38	.34	.77	.15	.12	−.08	−.011
45	6.9	18–25	3.45	1.02	1.66	3.14	.06	−.27	−.039
46	11.1	25–May 6	3.23	1.34	4.41	−.21	.24	.61	.055
47	14.0	May 6–20	3.23	.73	3.12	−1.62	.24	2.70	.192
48	9.9	20–30	1.47	.11	.27	−3.44	0	4.75	.482
49	25.1	30–June 24	9.60	.27	.10	.94	.27	9.10	.362
50	16.0	June 24–July 10	3.86	.03	.01	−2.96	.12	6.96	.436
51	12.9	July 10–23	2.82	.01	0	−1.68	.15	4.66	.362
52	18.0	23–Aug. 10	.20	0	0	−10.49	−.12	10.57	.586
53	14.0	Aug. 10–24	7.52	0	0	2.16	−.12	5.24	.374
54	14.0	24–Sept. 7	.94	0	0	−3.93	.03	4.90	.350
55	12.0	Sept. 7–19	2.87	0	0	−2.47	−.15	5.19	.432
56	17.2	19–Oct. 6	1.80	0	0	−4.45	−.30	5.95	.347
57	17.8	Oct. 6–24	.86	0	0	−4.11	−.24	4.73	.265
58	12.8	24–Nov. 6	.99	0	0	−.85	.03	1.87	.146
59	11.9	Nov. 6–18	.86	0	0	−.61	−.03	1.44	.121
60	12.0	18–30	1.90	0	0	−.37	−.21	2.06	.172
Record season.	254.6	Mar. 20–Nov. 30						69.10	
		1965							
66	56.1	Apr. 13–June 8	[1] 17.70	10.94	29.79	−6.89	.64	6.38	.114
67	30.0	June 8–July 8	4.78	.43	.49	−8.72	.25	13.69	.457
68	43.0	July 8–Aug. 20	18.59	.88	0	3.47	.25	16.25	.378
69	33.0	Aug. 20–Sept. 22	[1] 16.64	2.91	3.32	8.87	−.20	7.16	.217
Record season.	162.1	Apr. 13–Sept. 22						43.48	

[1] Includes obvious overland runoff.

figure 26, which also illustrates the time duration of the numbered periods and letter-designated subperiods.

A line (long dashes) appears in figure 26 as an estimate of the changing rate of seepage as defined by the periods and subperiods. A rapidly fluctuating line also is shown as an estimate of the manner in which the seepage rate probably fluctuates with each rain and with dry periods of several days. The many depressions in the flat sandy land around the lake are responsible for rapid and frequent changes in the ground-water gradient which controls the rate of seepage into Pretty Lake. Although the rapidly fluctuating curves lack absolute accuracy and bases in data, they are a reasonable estimate of the real phenomenon.

EVAPORATION FROM THE WATER BUDGET

The water budget is a poor means of evaporation estimation unless the seepage rate is determined independently, is known to be constant, or is known to be zero. As it was used on Pretty Lake, the water budget is more of an estimator of seepage than an estimator of evaporation because evaporation already has been estimated by other methods. A line might have been fitted to figure 24 that satisfied the data and intercepted the ordinate in such a way as to define a high N and a constant seepage of about 0.2 cm day^{-1}. The scatter about the line would not have been much greater than the scatter about the mass-transfer calibration based

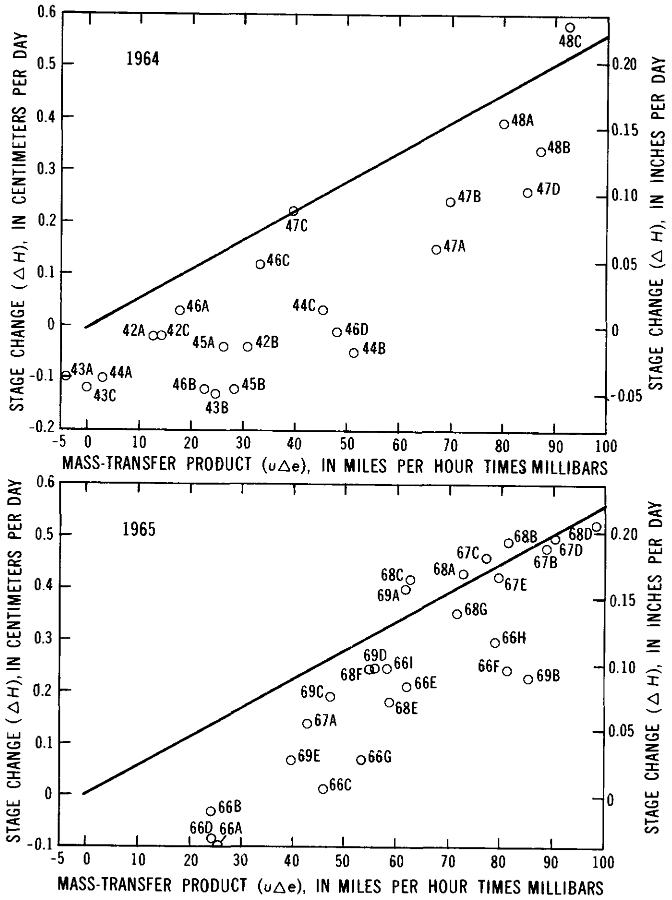

FIGURE 25.—Relation of corrected stage change to the mass-transfer product by subperiods during 1964 and 1965. The lines shown have the slope determined by the calibration plot of figure 18.

upon the energy-budget data. The seasonal bias found in the water-budget term, ΔH, must be removed in order to properly calibrate the mass-transfer equation. Although the energy-budget data contain larger errors in each period than do the water-budget data, it can be assumed that the errors are more random and that bias is not so likely to result.

It is common practice to use lake-stage data to determine an N value from a regression line fitted to a plot similar to figures 24 and 25. Use of this method often produces an N value considerably larger than would have been estimated by Harbeck's (1962, fig. 31) method. It is possible that many lakes could be affected by high inflow-seepage rates during periods of low evaporation, much the same as was Pretty Lake.

The method of determining seepage rate dictates that total evaporation computed by the water budget will agree closely with the evaporation measured by mass-transfer or energy-budget methods. Table 7 lists the seepage estimates by energy-budget periods and gives the computed values of E_{WB}. Evaporation rates and amounts computed by the water-budget method are shown graphically and are further summarized in figures 30 and 31 and in tables 20 and 21 in a later section of this report.

EVAPORATION-PAN STUDIES

It has long been a practice to attempt to estimate lake evaporation from records of evaporation measured in a small pan. One standard pan used within the United States is the class-A pan. The pan is metal, 4 feet (1.22 m) in diameter and 1 foot (0.30 m) deep, and is set on wood planks above the ground. The weaknesses in its performance in duplicating lake evaporation are well known. The principal criticisms concern distortions of the temperatures and wind regime, considerable increase in the values of evaporation, and instability of reduction coefficients. Nevertheless, the class-A pan has been the basis for records for a long time, and its advantages of simple installation, easy service, and moderate cost undoubtedly will encourage its use for a long time in the future.

Excellent discussions of research and interpretative work that have been done to improve the effectiveness of pan records are contained in U.S. Weather Bureau (USWB) Research Paper 38 (Kohler and others, 1955), USWB Technical Paper 37 (Kohler and others, 1959), and the Geological Survey reports on the Lake Hefner (Kohler, 1952) and Lake Mead (Kohler and others, 1958) studies.

KENDALLVILLE STATION DATA

Pan studies were not a principal part of the Pretty Lake project, but some insight can be gained from the consideration of records from a nearby evaporation pan. The U.S. Weather Bureau maintains a class-A pan in Kendallville, Ind., at a site about 9 miles (14

TABLE 7.—*Corrections for seepage applied to water budget, and water-budget evaporation*

Period	Seepage (centimeters per day)	E_{WB}	
		Centimeters per day	Centimeters per period
26–36	0	(1)	(1)
42	.16	0.13	1.94
43	.18	.07	.49
44	.21	.20	1.42
45	.20	.16	1.10
46	.15	.21	2.32
47	.13	.32	4.49
48	.06	.54	5.32
49–60	0	(1)	(1)
66	.19	.30	16.83
67	0	.46	13.69
68	0	.38	16.25
69	.11	.33	10.90

[1] Use ΔH, table 6.

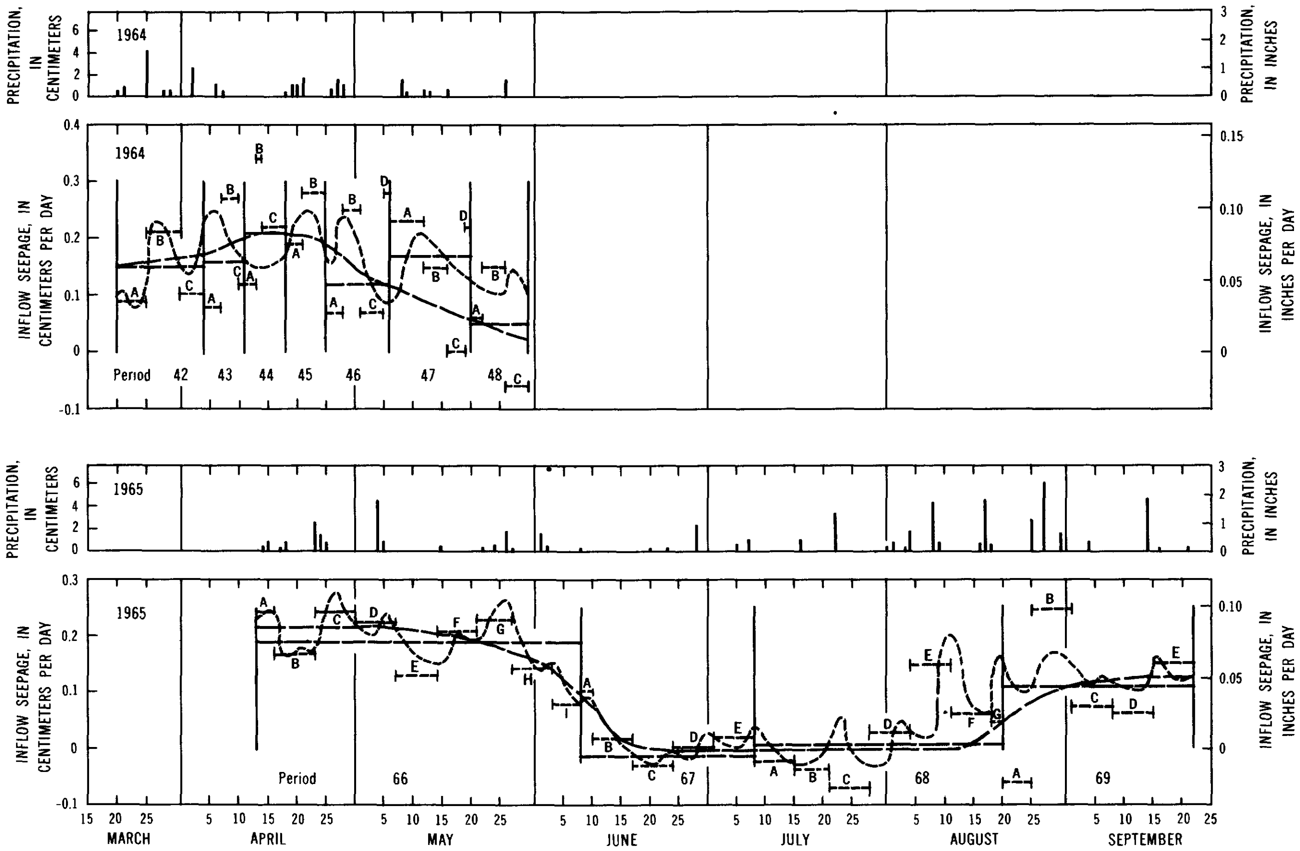

FIGURE 26.—Seepage during 1964 and 1965 open-water periods, showing precipitation and duration of subperiods. Horizontal dashed lines represent measured values by periods and subperiods. Curved lines are estimates of long-term and short-term variations in seepage.

km) south of Pretty Lake. The station is operated by a lay observer who makes daily readings of air temperature and precipitation the year round and who reads pan evaporation and wind passage over the pan daily during the summer months. The station would have to be classified as nonstandard, in the strictest sense, owing to trees in the vicinity, grass growing around the pan, and irregularities of cleaning and maintenance. However, the irregularities in the maintenance and location of this station probably are of no greater consequence than those found in many other stations.

Records from the Kendallville evaporation station are published in the Climatological Data series for Indiana. Those records for the 3 years of the Pretty Lake study are repeated in table 8.

Another Weather Bureau pan station is located at the Purdue University experiment station near Culver, Ind. This location is about 70 miles (112 km) east-southeast of Pretty Lake. Records for the station are published, and those for the period of the Pretty Lake study are repeated in table 9.

Both the Kendallville and Culver pan records are missing several days' readings. For short periods of a day or two, one record has been used to estimate evaporation at the other pan, or estimates have been made using computed pan evaporation techniques, which will be explained in the following paragraphs.

Nationwide evaporation patterns are described in USWB Technical Paper 37 (Kohler and others, 1959). The following factors for the Pretty Lake location were obtained from the five plates in that report:

- Average annual pan evaporation is 42 inches (107 cm).
- Average annual lake evaporation is 31.5 inches (80 cm.)
- Average annual pan coefficient is 76 percent.
- Average annual May–October lake evaporation is 82 percent of annual lake evaporation. This is equal to 26 inches (66 cm).
- Standard deviation of annual pan evaporation is 2.4 inches (6 cm).

It is an easy, common practice to multiply the daily evaporations from a pan by a coefficient in order to estimate lake evaporation. For northeastern Indiana, such estimates might be made by multiplying pan evaporation values listed in table 8 by the 0.76 annual co-

TABLE 8.—*Daily evaporation, in inches, from U.S. Weather Bureau class-A pan at Kendallville, Ind.*

[Values are for the 24 hours ending at 4 p.m. on the date shown]

Day of month	1963							1964					1965				
	Apr.	May	June	July	Aug.	Sept.	Oct.	June	July	Aug.	Sept.	Oct.	May	June	July	Aug.	Sept.
1	------	0.06	0.22	0.24	0.20	(1)	0.17	------	0.30	0.20	0.16	0.14	------	0.29	------	0.08	0.19
2	0.18	.19	.21	.34	.19	0.29	24	------	.31	.29	.22	.09	------	.10	------	.22	.12
3	.15	.20	.27	.31	[2].15	.10	.20	------	.20	.32	25	.14	------	.21	------	.22	.15
4	.28	.20	.18	.30	.31	.18	.09	------	(1)	.31	.29	.19	------	.25	------	.10	.11
5	.10	.13	.34	.30	.14	.13	.16	------	.59	.30	.22	.13	------	.18	------	.18	(1)
6	.10	.16	.13	.32	.13	.18	.21	------	.25	.28	(1)	.06	------	.21	------	.33	.37
7	.28	.23	.26	.35	.16	.15	.28	------	.34	.30	.45	.07	------	.11	------	.14	.09
8	.11	.34	.18	.18	.21	.09	.15	------	[3].15	.31	[3].25	.08	------	.21	------	.16	.08
9	.14	.28	.27	.33	.13	.16	.15	.30	.24	.20	.21	.03	------	.27	------	.08	.17
10	.13	.21	.24	.34	.17	.23	.16	.34	.22	.18	28	.09	------	.22	------	.11	.13
11	.15	.15	.30	.31	.25	.22	.14	.27	.27	.21.	.13	.10	------	.27	------	.23	.15
12	.14	.20	.28	.34	.12	.12	.15	.25	.20	.19	.18	.08	------	------	------	.25	.11
13	.17	.13	.14	.17	.13	.19	.17	.30	.20	.10	.16	.07	------	------	------	.30	.10
14	.26	.21	.29	.17	.12	.18	.11	.25	.15	.20	.21	.09	------	------	------	.27	.09
15	.10	.17	.18	.32	.17	.24	.12	.12	.16	.16	.15	.09	------	------	------	.27	[2].22
16	.20	.09	.23	.19	.22	.09	.13	.18	.30	.26	.10	.10	------	------	------	.26	[2].11
17	.10	.22	.14	.26	.16	.19	.16	.26	.25	.28	.10	.11	------	------	------	.22	.04
18	.24	.16	.24	.29	.15	.16	.09	.17	.18	.14	.06	.19	------	------	------	.13	.12
19	.13	.22	.27	.27	.10	.22	.04	.29	.22	.22	.05	.08	------	------	------	.17	.20
20	.33	.14	.18	[2].21	.09	.10	.07	.32	.30	.15	.04	.06	------	------	------	.22	.12
21	.20	.23	.25	.32	.20	.05	.09	.14	.19	.13	.14	.14	------	------	------	.16	.16
22	.22	.16	.19	.17	.15	.14	.11	.15	.19	.17	.12	.05	0.23	------	------	.09	.06
23	.08	.11	.25	.20	.21	.13	.13	.39	.24	.20	.36	.07	.24	------	------	.12	.12
24	.08	.18	.33	.32	.11	.15	.13	.38	.27	.15	.15	.09	.20	------	------	.19	.16
25	.14	.21	.26	.19	.20	.17	.11	.23	.21	.20	.10	.13	.19	------	------	.17	.10
26	.14	(1)	.30	.27	.20	.20	.15	.37	.23	.16	.10	.10	.18	------	------	.19	.09
27	.14	.51	.25	.22	.19	.16	.09	.24	.26	.18	.13	.08	.30	------	------	.31	.09
28	.24	.08	.29	.24	.10	.16	.15	.18	.30	.20	.12	.06	.26	------	0.35	.22	.10
29	.17	.11	.26	.26	.09	.14	.11	.30	.27	.16	.10	.09	.16	------	.25	.14	.09
30	.11	.30	.30	.23	.26	.14	.09	.24	.33	.28	.12	.08	;13	------	.20	.11	.03
31	------	.11	------	.22	.10	------	.07	------	.29	.22	------	.05	.19	------	.16	.04	------
Total	[4]4.98	5.69	7.23	8.18	5.11	4.66	4.22	------	7.61	6.65	4.95	2.83	------	------	------	5.68	3.67

[1] Included in next observation.
[2] Estimated (Kohler and others, 1959, fig. 1).
[3] Estimated, based on Culver record.
[4] Total adjusted by Weather Bureau.

TABLE 9.—*Daily evaporation, in inches, from U.S. Weather Bureau class–A pan at Culver Experiment Farm, Ind.*

[Values are for the 24 hours ending at 8 a.m. on the date shown]

Day of month	1963							1964							1965				
	Apr.	May	June	July	Aug.	Sept.	Oct.	May	June	July	Aug.	Sept.	Oct.	Nov.	May	June	July	Aug.	Sept.
1	-------	0.26	(1)	0.31	0.13	0.15	0.18	-------	0.28	0.28	0.16	0.24	0.00	0.11	-------	0.23	0.27	0.10	0.06
2	-------	.14	0.55	.32	-------	.30	.27	0.20	.26	.29	.22	.18	.25	.09	0.47	.16	.28	.07	.23
3	-------	.22	.27	.41	-------	-------	.26	.36	.14	.35	.28	.18	.15	.11	.40	.09	.10	.25	.17
4	-------	.21	.24	.23	.32	.08	.15	.16	.30	.20	.32	.35	.27	.09	.40	.35	.25	.25	.16
5	-------	.22	.25	.27	.26	.08	.07	.20	.33	.32	.34	.33	.14	.10	.32	.31	.20	.11	.08
6	-------	.09	.27	.28	.06	.17	.19	.28	.07	.16	.32	.24	.11	.07	.15	.21	.26	.26	.31
7	-------	.22	.19	.21	.04	.15	.23	.37	.33	.42	.24	.20	.08	.09	.08	.17	[2].17	.32	.14
8	-------	.31	-------	.22	.23	.21	.23	.27	.14	.46	.20	.24	.23	.05	.32	.07	.08	.21	.14
9	-------	.29	-------	.27	.21	.10	.14	.38	.32	.13	.21	.30	.05	.04	.28	[3].25	.27	.18	.16
10	-------	.40	-------	.31	.15	.15	.14	.29	.42	.31	.36	.25	.06	.00	.24	.20	.20	.07	.19
11	-------	.20	-------	.40	.13	.20	.14	.38	.39	.15	.20	.39	.05	.01	.28	.32	.26	.24	.15
12	-------	.17	.41	.36	.21	.36	.12	.14	.31	(1)	.27	.19	.07	.24	.21	.22	.28	.18	.10
13	-------	.22	.19	.43	-------	.12	.17	.11	.18	.41	.23	.19	.08	.31	.27	.43	.28	.27	.12
14	-------	.17	.10	-------	.15	.16	.10	.06	.35	.14	.08	.15	.08	.09	.34	.28	.36	.30	.19
15	0.23	.30	.29	.24	.22	.18	.16	.22	.23	.13	.22	.31	.14	.12	.27	.31	.16	.29	-------
16	.25	.06	.24	-------	.13	.14	.13	.29	.30	.24	.20	.02	.07	.01	.15	.34	.33	.31	.28
17	.08	.21	.24	-------	.22	.15	.16	.33	.10	.26	.25	.09	.08	.05	.33	.22	.45	.54	.03
18	.27	.09	.15	-------	.15	.13	.17	.25	.36	.30	.28	.13	.09	.06	.21	.31	.23	.16	.28
19	.21	.26	.35	-------	.18	.15	.09	.29	.28	.10	.26	.04	.00	.00	.15	.34	.28	[3].20	.17
20	.38	.13	.31	-------	.02	.23	.08	.45	[3].30	.20	.19	.05	.47	-------	.29	.33	.27	.24	.11
21	.19	.22	.27	.26	.17	.11	.09	.25	.22	.27	-------	.31	.13	-------	.35	.38	.27	.22	.24
22	.32	.22	.21	.14	.20	.17	.05	.28	.09	.18	.46	.15	.15	-------	.26	.31	.19	.15	.21
23	.17	.13	.22	.13	.18	.06	.19	.35	.28	.21	-------	.29	.08	-------	.09	.32	.20	.13	-------
24	.07	.15	.32	.27	.15	.13	.13	.38	.45	.27	.16	.38	.06	-------	.33	.23	.22	.17	.19
25	.06	.16	.30	.20	.21	.13	.08	.34	.29	.20	.26	.10	.07	-------	.20	.33	.28	.23	.06
26	.12	.04	.26	-------	.24	.26	.16	.34	.27	.19	.16	.08	.15	-------	.17	.28	.29	.21	.24
27	.16	.62	.29	.26	.21	.01	.18	.23	.31	.25	.19	.22	.14	-------	.17	.31	.28	.51	.06
28	.23	.05	.26	.24	.19	.23	.12	.31	.33	.33	.23	.13	.03	-------	.29	.34	.26	.26	.11
29	.29	.11	.31	.16	.07	.23	.14	.22	.29	.41	.23	.14	.04	-------	.27	.41	.31	.19	.09
30	-------	.14	.24	.32	.14	.14	.07	.23	.34	.33	.19	.13	.07	-------	.19	.17	.25	.14	.16
31	-------	.30	-------	.20	.18	-------	.10	.15	-------	.26	.29	-------	.07	-------	.20	-------	.23	.07	-------
Total	-------	6.31	[4]7.77	[4]8.32	[4]5.26	[4]4.84	4.49	[4]8.58	8.26	7.75	[4]7.48	6.00	3.46	-------	[4]7.94	8.22	7.76	6.83	[4]4.75

[1] Included in next observation.
[2] Estimated (Kohler and others, 1959, fig. 1).
[3] Estimated, based on Kendallville record.
[4] Total adjusted by Weather Bureau.

efficient. These estimates have been made for Pretty Lake to illustrate the way results of such computations differ from the results of other methods of evaporation computation. The estimates, averaged over Pretty Lake energy-budget computation periods, are listed in table 10. They are plotted as a function of time and are further summarized in tables 20 and 21 and in figures 30 and 31 in a later section of this report.

COMPUTED PAN AND LAKE EVAPORATION

As pan data have become widely used as a means of estimating evaporation or evapotranspiration, a demand has developed among data users for more widespread and complete data. Although pan installations are less costly than most other means of evaporation estimation, the stations still are separated by several hundred miles. Often a station will be out of service for part of a year, and at times data are of questionable accuracy. Consequently, hydrologists, agronomists, climatologists, and other interested persons have tried to develop means of estimating evaporation from other variables, such as wind, humidity, and cloud cover, which are more frequently measured. The relationships generally have been highly empirical. In most cases they have used pan data as the control.

TABLE 10.—*Lake evaporation based upon data from Kendallville (K) or Culver (C) pan and average annual coefficient of 0.76, computed by Pretty Lake energy-budget periods*

Period			Pan data used	Pan evaporation		Lake evaporation	
No.	Length (days)	Dates		Centimeters per period	Centimeters per day	Centimeters per period	Centimeters per day
		1963					
18	7.0	Apr. 5-12	K	2.64	0.38	2.01	0.29
19	8.0	12-20	K	3.84	.48	2.91	.36
20	10.9	20-May 1	K	4.09	.37	3.11	.28
21	10.0	May 1-11	K	5.21	.52	3.96	.40
22	21.0	11-June 1	K	9.52	.45	7.24	.34
23	5.4	June 1-6	K	3.12	.57	2.37	.44
24	13.1	6-19	K	7.67	.59	5.83	.45
25	13.0	19-July 2	K	8.76	.68	6.66	.51
26	7.6	July 2-10	K	5.94	.78	4.52	.59
27	7.4	10-17	K	4.67	.64	3.55	.48
28	7.0	17-24	K	4.50	.64	3.42	.49
29	13.9	24-Aug. 7	K	7.42	.53	5.64	.41
30	14.1	Aug. 7-21	K	5.61	.40	4.27	.30
31	27.5	21-Sept. 18	K	11.23	.41	8.53	.31
32	13.1	Sept. 18-Oct. 1	K	5.00	.38	3.80	.29
33	17.9	Oct. 1-19	K	7.01	.39	5.33	.30
34	14.0	19-Nov. 2	K	3.71	.27	2.82	.20
Record season.	210.9	Apr. 5-Nov. 2		99.94	.474	75.97	.360
		1964					
47	14.0	May 6-20	C	9.73	.69	7.39	.53
48	9.9	20-30	C	7.34	.74	5.58	.57
49	25.1	30-June 24	C	16.89	.67	12.83	.51
50	16.0	June 24-July 10	K	10.67	.67	8.11	.51
51	12.9	July 10-23	K	7.09	.55	5.38	.42
52	18.0	23-Aug. 10	K	12.37	.69	9.40	.52
53	14.0	Aug. 10-24	K	6.55	.47	4.98	.36
54	14.0	24-Sept. 7	K	7.59	.54	5.77	.41
55	12.0	Sept. 7-19	K	4.88	.41	3.71	.31
56	17.2	19-Oct. 6	K	5.69	.33	4.32	.25
57	17.8	Oct. 6-24	K	3.73	.21	2.84	.16
58	12.8	24-Nov. 6	C	2.95	.23	2.24	.17
59	11.9	Nov. 6-18	C	2.62	.22	1.99	.17
Record season.	195.6	May 6-Nov. 18		98.10	.501	74.54	.381
		1965					
67	30.0	June 8-July 8	C	20.90	.70	15.88	.53
68	43.0	July 8-Aug. 20	C	27.15	.63	20.63	.48
69	33.0	Aug. 20-Sept. 22	K	11.84	.36	8.99	.27
Record season.	106.0	June 8-Sept. 22		59.89	.565	45.50	.429

Stephens and Stewart (1963) compared nine different methods of estimating pan evaporation and ranked the Weather Bureau method described in USWB Research Paper 38 (Kohler and others, 1955) as the best of the group. Stephens (1965), discussing the work of Lane, emphasized the importance of pan-operating technique and presented additional analysis of data from several parts of the United States.

Computed pan evaporation and lake evaporation for the 3 years of Pretty Lake study have been determined using the Weather Bureau method (Kohler and others, 1959, fig. 1 and 2) and are listed in table 11. They are shown graphically and are further summarized in figures 30 and 31 and in tables 20 and 21 in a later section of this report. Ratios of the computed lake evaporation to the computed pan evaporation also are shown as computed pan coefficients. The estimates have been computed for the same energy-budget periods used for the other forms of computation. Data observed at Pretty Lake field instruments have been incorporated. Wind speeds observed at 1.73 meters (5.68 ft) above the lake at its center have been used to estimate wind movement at pan height by use of a power law having an exponent of 0.3.

ADVECTION AND ENERGY-STORAGE EFFECTS

In the study of Lake Mead (Kohler and others, 1958, p. 57–59), the influence of advected and stored energy was shown to be an important factor contributing to the difference between pan and lake evaporation. Nordenson (1963) has concluded that these factors are the main cause of the apparently large seasonal variation in the pan coefficient. Whereas the varying effects of energy advected through the sides and bottom of a pan can be computed from meteorological data, the effects of energy advected into or out of a lake, or stored by the lake from season to season, must be determined from field measurements of water volume and temperature.

As they were defined earlier in the energy-budget section of this report, the advected and stored energy are contained in the three terms, Q_v, the net advected energy from precipitation, inflow, and outflow; Q_w, the energy advected by evaporating water; and Q_x, the increase in stored energy. All these represent terms that act upon the lake and not upon the pan. All additional energy from advection or storage will not go directly into evaporation. Part of it will dissipate as increased

TABLE 11.—*Computed pan and lake evaporation by use of U.S. Weather Bureau method with Pretty Lake station data*

[Method from Kohler and others (1959), figs. 1 and 2]

Period			Computed pan evaporation		Computed lake evaporation		Computed pan coefficient
No.	Length (days)	Dates	Centimeters per day	Centimeters per period	Centimeters per day	Centimeters per period	
		1963					
18	7.0	Apr. 5–12	0.33	2.31	0.25	1.75	0.77
19	8.0	12–20	.37	2.96	.25	2.00	.69
20	10.9	20–May 1	.27	2.95	.18	1.96	.67
21	10.0	May 1–11	.51	5.10	.33	3.30	.65
22	21.0	11–June 1	.43	9.02	.33	6.92	.76
23	5.4	June 1–6	.56	3.05	.43	2.34	.77
24	13.1	6–19	.71	9.26	.51	6.65	.71
25	13.0	19–July 2	.69	8.94	.56	7.26	.81
26	7.6	July 2–10	.95	7.26	.64	4.89	.67
27	7.4	10–17	.60	4.41	.42	3.09	.70
28	7.0	17–24	.64	4.51	.46	3.24	.72
29	13.9	24–Aug. 7	.53	7.36	.39	5.41	.74
30	14.1	Aug. 7–21	.41	5.78	.30	4.23	.75
31	27.5	21–Sept. 18	.36	9.91	.27	7.43	.75
32	13.1	Sept. 18–Oct. 1	.33	4.33	.22	2.89	.65
33	17.9	Oct. 1–19	.43	7.71	.24	4.30	.56
34	14.0	19–Nov. 2	.24	3.36	.14	1.96	.58
35	14.0	Nov. 2–16	.18	2.52	.09	1.26	.50
36	17.1	16–Dec. 3	.13	2.22	.08	1.36	.60
Record season.	242.0	Apr. 5–Dec. 3	.426	102.96	.299	72.24	.702
		1964					
42	14.9	Mar. 20–Apr. 4	.13	1.94	.11	1.64	.90
43	7.0	Apr. 4–11	.25	1.75	.22	1.54	.85
44	7.1	11–18	.71	5.03	.44	3.12	.63
45	6.9	18–25	.25	1.72	.17	1.17	.65
46	11.1	25–May 6	.46	5.09	.29	3.21	.64
47	14.0	May 6–20	.58	8.14	.41	5.76	.70
48	9.9	20–30	.65	6.41	.46	4.54	.71
49	25.1	30–June 24	.58	14.58	.42	10.56	.72
50	16.0	June 24–July 10	.65	10.39	.47	7.51	.73
51	12.9	July 10–23	.51	6.57	.39	5.02	.78
52	18.0	23–Aug. 10	.66	11.90	.47	8.47	.71
53	14.0	Aug. 10–24	.44	6.16	.30	4.20	.69
54	14.0	24–Sept. 7	.55	7.71	.38	5.32	.70
55	12.0	Sept. 7–19	.42	5.05	.28	3.37	.67
56	17.2	19–Oct. 6	.30	5.15	.20	3.43	.67
57	17.8	Oct. 6–24	.22	3.92	.17	3.03	.76
58	12.8	24–Nov. 6	.25	3.21	.17	2.18	.65
59	11.9	Nov. 6–18	.23	2.73	.14	1.66	.61
60	12.0	18–30	.10	1.20	.06	.72	.62
Record season.	254.6	Mar. 20–Nov. 30	.427	108.65	.300	76.45	.704
		1965					
66	56.1	Apr. 13–June 8	.47	26.37	.36	20.20	.76
67	30.0	June 8–July 8	.71	21.26	.53	15.87	.75
68	43.0	July 8–Aug. 20	.57	24.51	.43	18.49	.76
69	33.0	Aug. 20–Sept. 22	.36	11.89	.28	9.25	.79
Record season.	162.1	Apr. 13–Sept. 22	.503	84.03	.394	63.81	.759

back radiation and increased sensible heat transfer. Means of estimating α, that part of additional energy that is used in evaporation, are derived and summarized graphically in USWB Research Paper 38 (Kohler and others, 1955, fig. 4). Another method of estimating α, which has been reported by Harbeck (1964), gives veiy similar results (Nordenson, 1965). It is simple to compute

$$\Delta E_L = \frac{\alpha(Q_v - Q_w - Q_x)}{L} \tag{17}$$

where ΔE_L is the effect on lake evaporation and L is the latent heat of vaporization.

Table 12 summarizes the advection and energy-storage influences on Pretty Lake. Energy terms are repeated from the summary in table 3, and heat storage by the sediments is not considered. To illustrate the small effect of advection, a summation of the 1963 and 1964 Q_v and Q_w terms was made that showed that the two terms account for about a 1 cm (0.4 inch) decrease in evaporation during the year. The large negative total shown for 1965 is the result of an incomplete record for the year, whereby the energy storage at the end of the period of record is considerably higher than it was at the beginning of the season. On an annual basis the sum of the energy-storage term is always very nearly zero.

When only part of the season is considered, the storage term plays an important role in the amount of evaporation from Pretty Lake. Energy storage makes it impossible to use pan data alone to measure evaporation from a deep lake on any other than a complete season's basis.

Evaporation rates and amounts based upon class-A and computed pan data and corrected for advection and energy storage are shown and further summarized in figures 30 and 31 and in tables 20 and 21 in a later section of this report.

Energy advected through the sides and bottom of a class-A pan is accounted for by the pan coefficient. The coefficient of 0.76 used for class-A pan data is only a seasonal average. Advection rates vary through the year, and the corrections made by class-A pan coefficients should vary in much the same manner as do the computed coefficients in table 11. Techniques are available for computing variable pan coefficients (Kohler and others, 1955, p. 16), but they require data on pan-water temperature. Water temperature data were not available for the class-A pans that were used to compute Pretty Lake evaporation; therefore, only the average coefficient can be used.

WINTERTIME EVAPORATION AND ENERGY BUDGET

Evaporation from lakes and reservoirs is very slow during ice-covered periods. Many pan studies and hydrologic studies consider the wintertime evaporation to be zero. There are some factors about wintertime records, however, that merit further discussion. Obviously, evaporation from a deep lake does not stop at the same time a pan on the bank freezes over. Then too, for the completeness of hydrologic records and so-called annual averages, the wintertime accounts of budgeted water and energy at least should be estimated.

OBSERVED WINTER CONDITIONS

During the period of the Pretty Lake evaporation study, a variety of ice conditions was observed. Prior to the spring breakup in March of 1963, the lake was covered with a heavy layer of ice, more than 2 feet (0.6 m) thick. Covers of ice observed during the other two winters of study were not nearly so heavy.

The freezeup in 1963 was rapid and produced a passable ice cover in just a few days of very cold weather. By contrast, the freezeup in December 1964 and January 1965 was a month-long seesaw between open water and ice cover. A few cold days would cause a thin ice cover to form, which then would be removed on a warmer windy day.

Snow cover on the lake was not always the same as on surrounding land. The flat surface of the ice could cause light, windblown snow to pile up along one shore. At other times heavy snow would uniformly blanket the lake. The snow cover at times would melt and refreeze as ice cover. The runoff of snowmelt water from the surrounding land would sometimes flow out onto the ice cover or flow under it along the shorelines. Sublimation

TABLE 12.—*Advection and storage corrections for pan-based evaporation data*

No.	Period: Length (days)	Period: Dates	Q_v $\left(\frac{cal}{cm^2\,day}\right)$	Q_w $\left(\frac{cal}{cm^2\,day}\right)$	Q_x $\left(\frac{cal}{cm^2\,day}\right)$	α	Evaporation effect ΔE: Centimeters per day	Evaporation effect ΔE: Centimeters per period
		1963						
18	7.0	Apr. 5–12	−1	1	154	0.42	−0.112	−0.78
19	8.0	12–20	2	0	205	.46	−.160	−1.28
20	10.9	20–May 1	−4	1	68	.47	−.059	−.64
21	10.0	May 1–11	−1	0	236	.52	−.211	−2.11
22	21.0	11–June 1	1	6	35	.52	−.036	−.75
23	5.4	June 1–6	6	2	341	.52	−.300	−1.63
24	13.1	6–19	7	14	−16	.58	.009	.12
25	13.0	19–July 2	0	13	99	.51	−.098	−1.27
26	7.6	July 2–10	0	19	−82	.60	.065	.50
27	7.4	10–17	24	10	57	.60	−.044	−.32
28	7.0	17–24	9	10	116	.61	−.122	−.86
29	13.9	24–Aug. 7	12	12	−8	.62	.008	.11
30	14.1	Aug. 7–21	0	9	−76	.57	.065	.92
31	27.5	21–Sept. 18	1	6	−30	.55	.024	.66
32	13.1	Sept. 18–Oct. 1	2	6	−95	.53	.082	1.08
33	17.9	Oct. 1–19	0	4	−27	.49	.019	.34
34	14.0	19–Nov. 2	1	3	−134	.49	.111	1.55
35	14.0	Nov. 2–16	1	2	−184	.45	.141	1.98
36	17.1	16–Dec. 3	2	1	−111	.43	.082	1.40
Record season	242.0	Apr. 5–Dec. 3						−.98
		1964						
42	14.9	Mar. 20–Apr. 4	4	1	2	.35	.001	.01
43	7.0	Apr. 4–11	2	0	232	.38	−.149	−1.04
44	7.1	11–18	0	1	379	.45	−.292	−2.07
45	6.9	18–25	2	0	129	.46	−.100	−.69
46	11.1	25–May 6	−4	0	207	.50	−.180	−1.99
47	14.0	May 6–20	0	5	130	.56	−.129	−1.81
48	9.9	20–30	3	10	−8	.58	.001	.01
49	25.1	30–June 24	8	9	67	.58	−.067	−1.68
50	16.0	June 24–July 10	4	13	42	.58	−.051	−.81
51	12.9	July 10–23	5	11	64	.58	−.069	−.89
52	18.0	23–Aug. 10	0	17	−43	.59	.026	.47
53	14.0	Aug. 10–24	12	9	−75	.56	.075	1.05
54	14.0	24–Sept. 7	2	9	8	.56	−.014	−.20
55	12.0	Sept. 7–19	4	8	−71	.55	.063	.76
56	17.2	19–Oct. 6	1	6	−129	.54	.114	1.96
57	17.8	Oct. 6–24	0	2	−134	.46	.104	1.85
58	12.8	24–Nov. 6	1	1	26	.42	−.019	−.24
59	11.9	Nov. 6–18	1	1	−42	.49	.035	.42
60	12.0	18–30	1	2	−331	.44	.248	2.97
Record season	254.6	Mar. 20–Nov. 30						−1.92
		1965						
66	56.1	Apr. 13–June 8	0	4	126	.52	−.116	−6.51
67	30.0	June 8–July 8	3	13	48	.58	−.058	−1.74
68	43.0	July 8–Aug. 20	9	10	33	.58	−.034	−1.46
69	33.0	Aug. 20–Sept. 22	9	7	−33	.57	.034	1.12
Record season	162.1	Apr. 13–Sept. 22						−8.59

of the snow and ice and evaporation of the melt waters were the two forms of water loss to the atmosphere.

APPLICATION OF OPEN-WATER EVAPORATION METHODS TO WINTER CONDITIONS

The methods that have been described and used for the estimation of evaporation during open-water periods have limited winter use. Data previously listed estimate the evaporation during the periods between the first open-water thermal survey in the spring and the last open-water survey in the fall. The following sections are intended to fill in the remaining open-water records for the times just before freezing and just after breakup and will at least estimate conditions for times when the lake was ice covered.

LIMITED PAN SEASON

Evaporation pans generally freeze earlier than the lakes, owing to their smaller volume and greater exposure. In the spring, they generally are not set up as soon as the lakes break up. If they are set up early in the spring, their records are influenced by the few days of late freezing that often occur in the spring.

The Weather Bureau methods of computing pan and lake evaporation can be applied to the early and late periods as a means of estimating evaporation. Table 13 lists the Pretty Lake evaporation estimates made to extend the listing in table 11 to include the entire open-water season. It is obvious that evaporation rates during these periods are small and that they are only small parts of the seasons' totals. Values of E_L cannot be computed for these periods because thermal survey data are not available.

The pan methods used to estimate open-water evaporation seem to have no application in estimating the amount of evaporation and sublimation during the periods of ice cover.

TABLE 13.—*Computed wintertime pan and lake evaporation for open-water periods that were not included in table 11*

Period			Computed pan evaporation		Computed lake evaporation		Computed pan coefficient
No.	Length (days)	Dates	Centimeters per day	Centimeters per period	Centimeters per day	Centimeters per period	
17b	6.6	Mar. 30–Apr. 5, 1963	0.37	2.44	0.25	1.65	0.69
37a	14.4	Dec. 3–17, 1963	.06	.86	.05	.72	.80
41b	3.6	Mar. 17–20, 1964	.19	.68	.13	.47	.67
61a	8.5	Nov. 30–Dec. 8, 1964	.05	.42	.01	.08	.25
61c	8.0	Dec. 12–19, 1964	.13	1.04	.09	.72	.70
61e	3.0	25–27, 1964	.06	.18	.05	.15	.80
61g	0.5	Jan. 2, 1965	.05	.02	.03	.02	.50
62a	1.5	2–3, 1965	.13	.20	.09	.14	.70
62c	4.0	8–11, 1965	.18	.72	.10	.40	.57
65b	5.4	Apr. 8–13, 1965	.22	1.19	.17	.92	.76

WATER-BUDGET APPLICATION

The applications of the water-budget technique in computing lake evaporation are much the same during the winter as they are in warmer seasons, but there are limitations that reduce accuracy. Precipitation in the form of snowfall is not measured accurately by rain gages. Overland runoff from snowmelt is large because of frozen ground, and the timing is hard to judge from weather records. The stage record, which generally was excellent during the open-water periods, may suffer from shoreline effect on the ice sheet. Except for those times when streamflow is zero, inflow and outflow records suffer loss of accuracy caused by ice effect. During a wet winter, as 1964–65, inflow and outflow were large, meaning that a 15-percent error in flow measurement can greatly affect computed evaporation values. Undoubtedly seepage influence is significant, especially when a wet winter follows a wet autumn. Table 14 shows wintertime data similar to the

TABLE 14.—*Wintertime water-budget terms*

Period			Lake condition	Precipitation and overland runoff (cm)	Inlet inflow (cm)	Outflow (cm)	Storage change (cm)	ΔH	
No.	Length (days)	Dates						Centimeters per period	Centimeters per day
37a	14.4	Dec. 3–17, 1963	Open	1.37	0.03	0	−1.04	2.44	0.169
37b	13.5	18–31, 1963	Ice	.23	0	0	−1.04	1.27	.094
38	18.0	31, 1963–Jan. 18, 1964	Ice	[1] 1.07	0	0	.15	.92	.051
39	20.1	Jan. 18–Feb. 7, 1964	Ice	[1] 3.15	.12	0	3.11	.16	.008
40	22.0	Feb. 7–29, 1964	Ice	1.32	.07	0	.76	.63	.029
41a	16.4	29–Mar. 16, 1964	Ice	4.04	.57	0	5.55	−.94	−.057
41b	3.6	Mar. 17–20, 1964	Open	.43	.07	0	.18	.32	.090
61	33.0	Nov. 30, 1964–Jan. 2, 1965	40 percent ice	[1] 9.80	.03	0	7.53	2.30	.070
62	26.2	Jan. 2–28, 1965	79 percent ice	[1] 9.70	2.16	0	10.39	1.47	.056
63	33.9	28–Mar. 3, 1965	Ice	[1] 9.80	3.40	.56	11.34	1.30	.038
64	23.0	Mar. 3–26, 1965	Ice	[1] 8.56	8.23	12.20	5.39	−.80	−.035
65a	12.4	26–Apr. 7, 1965	Ice	[1] 3.00	3.76	6.52	1.40	−1.16	−.093
65b	5.4	Apr. 8–13, 1965	Open	[1] 2.49	2.27	3.83	3.02	−2.09	−.386

[1] Includes obvious overland runoff.

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open-water data listed in table 6. The data are summarized by energy-budget periods. Negative values of ΔH listed for several periods indicate inflow seepage or incorrect estimates of ungaged overland runoff.

MASS-TRANSFER METHOD

The mass-transfer method previously was described as the best means of computing evaporation for periods having low evaporation rates. Although the relation given in equation 11 applies to wintertime conditions, the terms are neither so easily evaluated nor so accurate as those for open-water conditions.

In a discussion of wintertime evaporation problems, Williams (1961) points out that surface roughness is different under ice and snow conditions than it is for open water. Consequently, the N term for Pretty Lake, which was given as 0.00560 in equation 14, might be altered significantly when the lake is covered by ice or snow.

It is difficult to measure ice temperature at the surface to determine the term e_0. At night or on a cold overcast day, the temperature of the ice surface will be the same as or a little colder than the air temperature because of evaporative cooling. On a clear day, radiant heating will warm the ice, but obviously the temperature of the ice or of the overlying thin film of water will not exceed 0°C. Figure 27 is a representation of diurnal changes in ice temperature under different conditions. The vapor pressure of ice does not vary much with temperature, so that large errors in e_0 are not likely to result from improper estimates of ice temperature. However, the vapor-pressure difference, e_0-e_a, is small in winter, and small changes in either e_0 or e_a cause a sizable percentage change in the difference and in the evaporation estimate. Figure 28 illustrates the air vapor pressure, e_a, computed as the over-water equivalent to dewpoint values published for the U.S. Weather Bureau station at Fort Wayne. The figure also shows the probable range of e_0 between the over-ice vapor pressure at Pretty Lake air temperatures and the freezing-point pressure of 6.11 millibars.

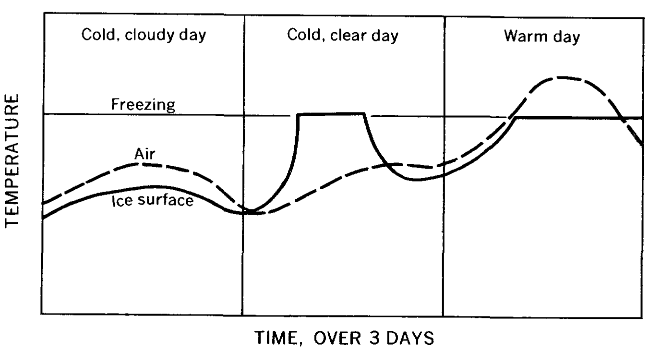

FIGURE 27.—Diurnal fluctuation of air and ice-surface temperatures over a cold, cloudy day; a cold, clear day; and a warm day.

Table 15 presents wintertime mass-transfer data similar to those shown in table 5. Average values of e_0 have been computed as the average of the two extremes of e_0 illustrated in figure 28. Estimates of evaporation listed in table 15 assume the mass-transfer constant, N, to be the same as the N used for open-water conditions.

Figure 29 shows wintertime data analogous to figures 24 and 25. Considering the many weaknesses in the data, there is surprising agreement of the plotted points with the mass-transfer relationship defined by the open-water energy budget. The deviation of the several points to the right of the line could be explained as seepage, ungaged overland runoff, or overestimation of e_0. It is possible also that the slope of the mass-transfer relation for winter might properly be different from the 0.0056 defined for open water. Undoubtedly, the late-winter periods (Nos. 41, 64, and 65) are influenced by seepage at about the same rates as previously defined for their following periods, Nos. 42 and 66 (fig. 26).

WINTER ENERGY BUDGET

The energy-budget method is unlike the mass-transfer and the water-budget methods in that it cannot be used even as a gross estimator of winter evaporation. Some of the wintertime energy parameters can be estimated or measured in much the same way as can the summertime data. However, the reflected solar radiation, Q_r, and the conducted energy, Q_h, present difficult problems.

Table 16 has been constructed as part of an attempt to present a complete annual energy budget for Pretty Lake. Radiation data, Q_s and Q_a, were derived from the same type of pyrheliometer, flat plate–radiometer, and Koberg-method records that were used for the open-water records. They should be equally reliable.

TABLE 15.—*Summary of wintertime mass-transfer terms for Pretty Lake, with evaporation computed by equation 14*

Period			Lake condition	$u_{2.0}$ (mph)	e_0-e_a (mb)	Evaporation	
No.	Length (days)	Dates				Centimeters per day	Centimeters per period
17b	6.6	Mar. 30–Apr. 5, 1963	Open	11.0	−0.2	−0.012	−0.08
37a	14.4	Dec. 3–17, 1963	do	8.09	4.7	.213	3.07
37b	13.5	18–31, 1963	Ice	8.10	2.0	.091	1.23
38	18.0	31, 1963–Jan. 18, 1964.	Ice	9.72	1.6	.087	1.57
39	20.1	Jan. 18–Feb. 7, 1964	Ice	8.68	.7	.034	.68
40	22.0	Feb. 7–29, 1964	Ice	6.65	1.9	.071	1.56
41a	16.4	29–Mar. 6, 1964	Ice	7.80	−.1	−.004	−.06
41b	3.6	Mar. 17–20, 1964	Open	8.69	4.4	.214	.76
61	33.0	Nov. 30, 1964–Jan. 2, 1965.	40 percent ice.	7.28	1.93	.078	2.58
62	26.2	Jan. 2–28, 1965	79 percent ice.	8.85	1.25	.062	1.62
63	33.9	28–Mar. 3, 1965	Ice	9.22	1.57	.081	2.74
64	23.0	Mar. 3–26, 1965	Ice	8.36	1.22	.057	1.31
65a	12.4	26–Apr. 7, 1965	Ice	7.27	.11	.004	.05
65b	5.4	Apr. 8–13, 1965	Open	5.91	−1.55	−.052	−.28

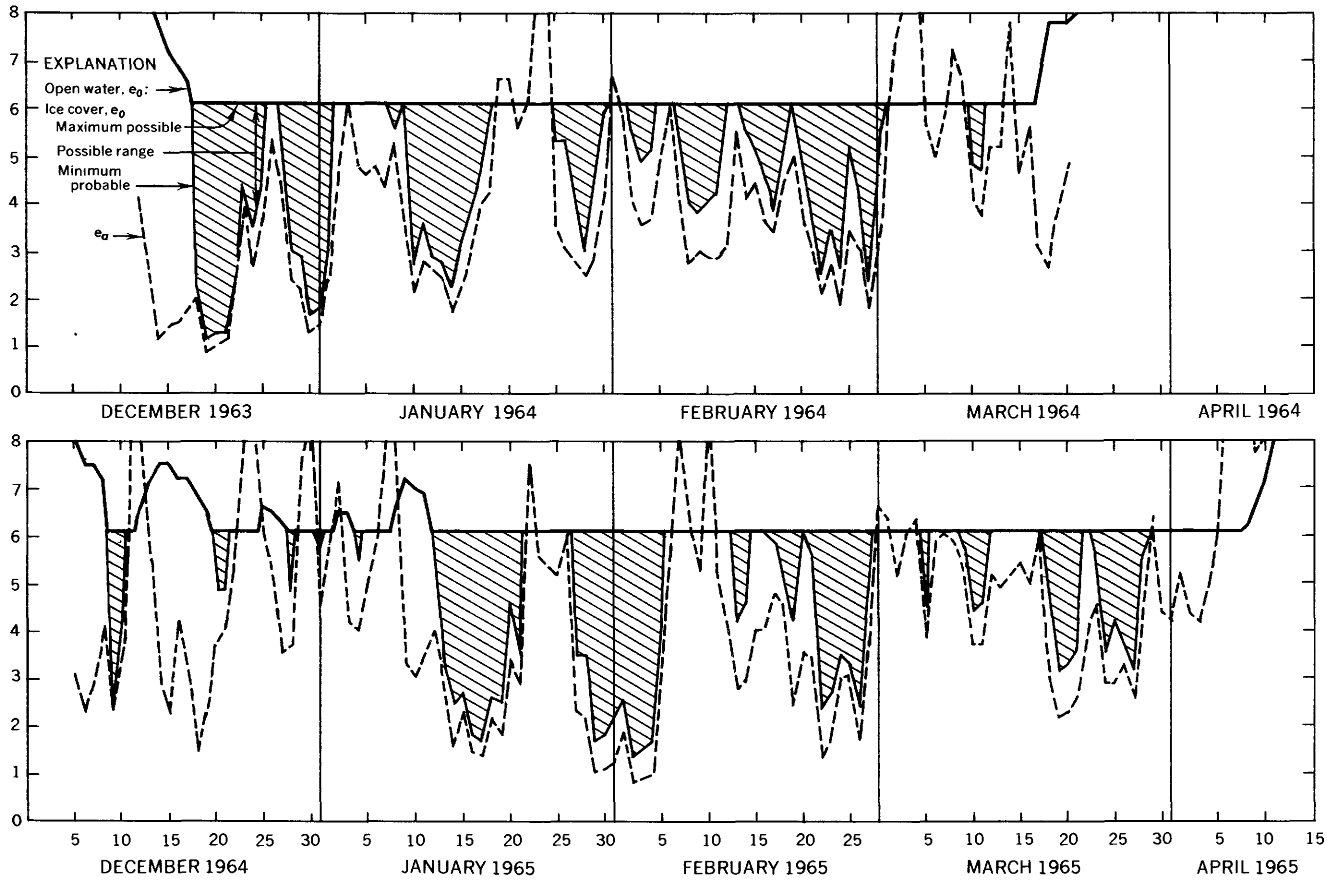

FIGURE 28.—Wintertime air vapor pressure and probable range of lake-surface vapor pressure for Pretty Lake.

Dorsey (1940, p. 491–494) cites reports concluding that infrared absorptivity and emissivity for ice and snow are about the same as for water. Consequently, for table 16, Q_{ar} has been estimated as 3 percent of Q_a, and Q_{bs} has been computed using the Stefan-Boltzman law and 0.97 emissivity. The same technique has been used to estimate T_0 as was used to estimate e_0 in the mass-transfer estimates for ice conditions. In the range of computation, a 1-degree error in estimating T_0 results in an error of about 9 cal cm^{-2} day^{-1} (calorie per square centimeter per day) in Q_{bs}.

Changes in energy storage, Q_x, listed in table 16 were computed from wintertime thermal surveys. The latent heat of freezing entered the computations in that the ice was considered to be at an effective temperature of −79.7°C. The sediment heat storage was not considered in the construction of table 16.

The 0°C base temperature used in computation causes the advected-energy terms, Q_v and Q_w, listed in table 16 to be small. Negative values of Q_v result from computing values of snowfall energy advection by multiplying water-equivalent volume by an effective temperature of −79.7°C, or colder.

Values of Q_e listed in table 16 were computed as the product of the E_{MT} values listed in table 15 and the latent heat of vaporization or sublimation. Latent heat of sublimation of ice was considered to be 679 calories per gram, or greater.

Conducted energy has been estimated for open-water conditions by use of the Bowen ratio (eq 4, 5, 6, 7, and 8). Serious doubts arise when the use of this ratio is considered for winter conditions, for which the thermal conductivity of ice is different from that of water. Williams (1961) reports that reliable wintertime Bowen ratios can be computed but warns that serious errors can result from the very small values of ΔT and Δe. The method used to estimate T_0 values for the Pretty Lake ice could cause errors of several hundred percent in the Bowen ratio. Very little confidence should be placed in the Q_h values listed in table 16.

Snow and ice reflect considerably larger proportions of the solar radiation than does a water surface. Data from wintertime flights over snow-covered regions in Wisconsin (Kung and others, 1964) list numerous instances when the ratio Q_r/Q_s (albedo) is more than 50 percent. Field studies by Lyubomirova (1962)

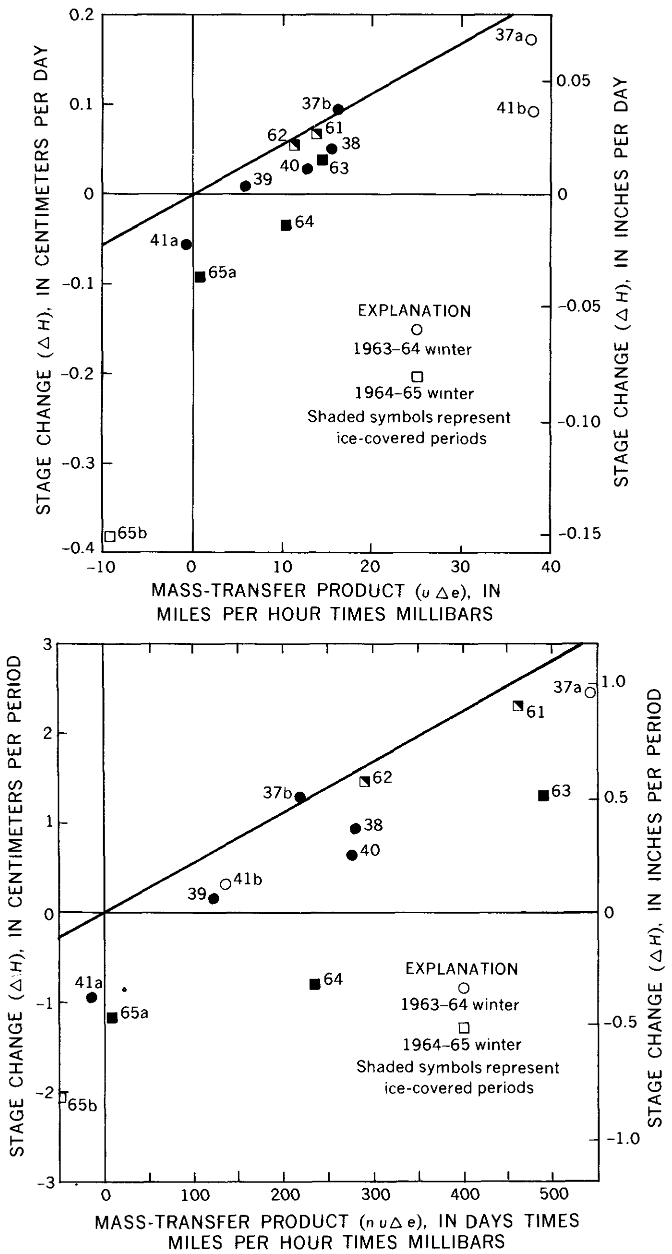

FIGURE 29.—Wintertime relation of the mass-transfer product, $u\Delta e$, and the water budget, as indicated by the corrected stage change, ΔH. The lines shown represent the open-water mass-transfer relation.

related the angle of incidence to albedo and showed albedo ranging from 30.7 to 58.4 percent for dry ice, and from 24.0 to 35.3 percent for wet ice, as the angle of incidence increased from 0 to 80 degrees. In an energy budget of a lake, about all that can be said about the magnitude of the Q_r term is that it is large and highly variable.

The data in table 16 are present only to illustrate the probable magnitude of some of the winter energy terms. If values of Q_r were estimated based upon information in the literature, the totals of $(Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_x - Q_e - Q_h - Q_w)$ in table 16 would be large negative numbers for many periods. These obviously are wrong and illustrate well the probable error in the other terms.

COMPARISON OF RESULTS

This report has been organized to demonstrate the common techniques used in an evaporation study. It also shows the dependence of one method upon another and the uses of the same data by different methods (table 17). Energy budget data were considered to be the prime independent measure of evaporation and were used to calibrate the mass-transfer constant, N. Mass-transfer data, obtained by use of the energy-budget–calibrated N, were used to define seepage effects in the water budget.

No absolutely correct evaporation data are available for evaluating the results of the several computation methods discussed in the earlier sections of this report. The energy-budget and pan methods produce independent data, but the mass-transfer and water-budget methods each rely on some other method to get a complete answer. Evaluation of the results, therefore, consists of comparing the evaporation data computed by the different methods. Where differences occur among the various results, an attempt must be made to explain them and to evaluate which answers are most nearly correct.

RESULTS SUMMARIZED

Tables 18 and 19 summarize evaporation data for summer and winter periods; the results are shown on an amount-per-period basis. Evaporation rates for each open-water period, as computed by different methods, are shown by the evaporation hydrograph (fig. 30).

Seasonal totals and averages shown in table 10 are hard to compare on a year-by-year basis, or even among methods, because the season lengths are different. Table 20 is presented to summarize similar results for all three years of study. The bar graph of figure 31 also compares totals but is broken down to permit use of some of the shorter term data.

CHARACTERISTICS OF RESULTS FROM INDIVIDUAL METHODS

Energy budget. Evaporation rates computed by the energy-budget method generally are lower than rates computed by other methods (except uncorrected pan and water-budget) during the springtime and autumn periods. This characteristic is shown clearly by the hydrograph of figure 30 and by the summary bar graph (fig. 31) for 31 autumn days in 1963 and 47 springtime days in 1964. All these periods of low energy-budget

TABLE 16.—*Estimated terms for wintertime energy budget*

[Q values given in calories per square centimeter per day]

Period			Ice cover (percent)	Q_s	Q_a	Q_{ar}	Q_{bs}	Q_v	Q_x	Q_e	Q_h	Q_w
No.	Length (days)	Dates										
37	27.9	Dec. 3–31, 1963	48	178	382	11	629	−3	−185	93	110	0
38	18.0	31, 1963–Jan. 18, 1964	100	220	343	10	611	−2	−19	61	40	0
39	20.1	Jan 18–Feb. 7, 1964	100	223	470	14	624	0	76	20	−16	0
40	22.0	Feb. 7–29, 1964	100	290	418	13	612	−5	−20	48	27	0
41	20.0	29–Mar. 20, 1964	82	255	521	16	635	−7	102	24	−28	0
61	33.0	Nov. 30, 1964–Jan. 2, 1965	40	102	532	16	642	−4	−89	48	44	0
62	26.2	Jan. 2–28, 1965	79	149	499	15	593	−8	−31	36	−33	0
63	33.9	28–Mar. 3, 1965	100	256	463	14	608	−8	23	54	−29	0
64	23.0	Mar. 3–26, 1965	100	258	569	17	621	−12	6	41	−19	0
65	17.8	26–Apr. 13, 1965	70	409	541	16	636	0	208	−7	−33	0

TABLE 17.—*Summary of data requirements for different evaporation computation methods*

Data required	Energy budget	Mass transfer	Water budget	Class-A pan	Corrected class-A pan	Computed pan	Corrected computed pan
Inflow volume	X		X		X		X
Outflow volume	X		X		X		X
Lake stage	[1] X		X		X		X
Precipitation	X		X				
Surface temperature	X	X					
Radiation	X					X	X
Temperature structure	X		[1] X		X		X
Inflow and outflow temperatures	X				X		X
Air temperature and vapor pressure	X	X				X	X
Wind	[2] X	X				X	X
Class-A pan and rain gage				X	X		
Independent measure of evaporation		X	X				

[1] Low accuracy requirement.

[2] Only when Bowen ratio questionable.

evaporation occurred when the evaporation rate was less than about 0.35 cm day^{-1}.

Energy-budget evaporation rates are higher than those determined by other methods during the two highest rate periods in 1963, during several of the highest rate periods (nos. 50, 51, 52, and 54) in 1964, and during the highest rate period in 1965. All these periods having high energy-budget evaporation rates are during June, July, and August. All have evaporation rates of more than 0.4 cm day $^{-1}$.

The record-season totals in table 20 and the 160-day totals in table 20 show that long-term total evaporation computed by the energy budget is near the mean of evaporation amounts computed by other methods. The 160-day totals for the energy-budget method (table 20) are within 3 percent of the mean, and the record-season

TABLE 18.—*Pretty Lake evaporation as computed by different methods for open-water periods, 1963–1965*

Period			Evaporation (cm)						
No. or season	Length	Dates	Energy budget	Mass transfer	Water budget	Class-A pan	Corrected [1] class-A pan	Computed pan	Corrected [1] computed pan
		1963							
18	7.0	Apr. 5–12	0.85	1.36		2.01	1.23	1.75	0.97
19	8.0	12–20	.34	1.57		2.91	1.63	2.00	.72
20	10.9	20–May 1	.92	2.89		3.11	2.47	1.96	1.32
21	10.0	May 1–11	.26	2.67		3.96	1.85	3.30	1.19
22	21.0	11–June 1	7.22	6.51		7.24	6.49	6.92	6.17
23	5.4	June 1–6	.42	.95		2.37	.74	2.34	.71
24	13.1	6–19	7.73	5.92		5.83	5.95	6.65	6.77
25	13.0	19–July 2	6.38	3.33		6.66	5.39	7.26	5.99
26	7.6	July 2–10	5.71	5.04	5.68	4.52	5.02	4.89	5.39
27	7.4	10–17	2.93	3.27	2.21	3.55	3.23	3.09	2.77
28	7.0	17–24	2.82	2.57	2.30	3.42	2.56	3.24	2.38
29	13.9	24–Aug. 7	6.32	6.10	4.76	5.64	5.75	5.41	5.52
30	14.1	Aug. 7–21	5.50	5.49	5.84	4.27	5.19	4.23	5.15
31	27.5	21–Sept. 18	7.57	9.42	9.39	8.53	9.19	7.43	8.09
32	13.1	Sept. 18–Oct. 1	3.74	4.60	5.19	3.80	4.88	2.89	3.97
33	17.9	Oct. 1–19	3.78	4.51	4.18	5.33	5.67	4.30	4.64
34	14.0	19–Nov. 2	2.60	3.49	3.82	2.82	4.37	1.96	3.51
35	14.0	Nov. 2–16	2.41	3.38	2.26			1.26	3.24
36	17.1	16–Dec. 3	1.74	2.77	2.62			1.36	2.76
Principal season.	242.0	Apr. 5–Dec. 3	[2] 69.24	[2] 75.84				[2] 72.24	[2] 71.26

See footnotes at end of table.

TABLE 18.—*Pretty Lake evaporation as computed by different methods for open-water periods, 1963–1965*—Continued

Period			Evaporation (cm)						
No. or season	Length	Dates	Energy budget	Mass transfer	Water budget	Class-A pan	Corrected [1] class-A pan	Computed pan	Corrected [1] computed pan
		1963—Continued							
Water-budget season.	153.6	July 2–Dec. 3	45.12	50.64	48.25			40.06	47.42
Class-A pan season.	210.9	Apr. 5–Nov. 2	65.09	69.69		75.97	71.61	69.62	65.26
Season average (cm/day).			.286	.313	.314	.360	.340	.299	.294
		1964							
42	14.9	Mar. 20–Apr. 4	2.43	1.73	[3] 1.94			1.64	1.65
43	7.0	Apr. 4–11	.36	.36	[3] .49			1.54	.50
44	7.1	11–18	1.33	1.42	[3] 1.42			3.12	1.05
45	6.9	18–25	–.30	1.10	[3] 1.10			1.17	.48
46	11.1	25–May 6	.14	1.94	[3] 2.32			3.21	1.22
47	14.0	May 6–20	4.34	5.08	[3] 4.49	7.39	5.58	5.76	3.95
48	9.9	20–30	4.64	5.42	[3] 5.32	5.58	5.59	4.54	4.55
49	25.1	30–June 24	10.66	9.73	9.10	12.83	11.15	10.56	8.88
50	16.0	June 24–July 10	7.78	6.79	6.96	8.11	7.30	7.51	6.70
51	12.9	July 10–23	5.27	4.23	4.66	5.38	4.49	5.02	4.13
52	18.0	23–Aug. 10	11.02	7.58	10.57	9.40	9.87	8.47	8.94
53	14.0	Aug. 10–24	5.45	5.69	5.24	4.98	6.03	4.20	5.25
54	14.0	24–Sept. 7	5.77	5.14	4.90	5.77	5.57	5.32	5.12
55	12.0	Sept. 7–19	4.17	4.31	5.19	3.71	4.47	3.37	4.13
56	17.2	19–Oct. 6	5.49	6.05	5.95	4.32	6.28	3.43	5.39
57	17.8	Oct. 6–24	3.23	4.50	4.73	2.84	4.69	3.03	4.88
58	12.8	24–Nov. 6	.90	1.54	1.87	2.24	2.00	2.18	1.94
59	11.9	Nov. 6–18	.59	2.28	1.44	1.99	2.41	1.66	2.08
60	12.0	18–30	3.03	3.58	2.06			.72	3.69
Principal season.	254.6	Mar. 20–Nov. 30	[2] 76.30	[2] 78.47	[2] 79.75			[2] 76.45	[2] 74.53
Class-A pan season.	195.6	May 6–Nov. 18	69.31	68.34	70.42	74.54	75.43	65.05	65.94
Season average (cm/day).			.300	.308	.313	.381	.386	.300	.293
		1965							
66	56.1	Apr. 13–June 8	15.09	17.03	[3] 16.83			20.20	13.69
67	30.0	June 8–July 8	17.04	13.29	13.69	15.88	14.14	15.87	14.13
68	43.0	July 8–Aug. 20	17.16	16.62	16.25	20.63	19.17	18.49	17.03
69	33.0	Aug. 20–Sept. 22	9.91	10.85	[3] 10.90	8.99	10.11	9.25	10.37
Principal season.	162.1	Apr. 13–Sept. 22	[2] 59.20	[2] 57.79	[2] 57.67			[2] 63.81	[2] 55.22
Class-A pan season.	106.0	June 8–Sept. 22	44.11	40.76	40.84	45.50	43.42	43.61	41.53
Season average (cm/day).			.365	.357	.356	.429	.410	.394	.341

[1] Corrected for advection and energy-storage effects in the lake. Not corrected for advection effects on class-A pan.

[2] Total used in computing season average.

[3] Corrected for seepage. See tables 6 and 7.

totals (table 18) are within 6 percent of the mean in 1963, within 2 percent in 1964, and within 4.2 percent in 1965. The 160-day totals (table 20) for energy-budget data agree with the data from other methods, which showed the 1964 and 1965 totals as being within about 1 cm (0.4 inch) of each other and the 1963 totals as being 3 to 6 cm (1.2 to 2.4 inches) less.

Evaporation hydrographs (fig. 30) for 1963 and 1964 show significant differences between years in springtime evaporation patterns. Rates for periods 21 and 22 are considerably less than rates for periods 47 and 48. The energy-budget data (table 3) show that May 1963 had less solar and long-wave radiation than did May 1964 and that the lake warmed later in 1963 than in 1964.

TABLE 19.—*Pretty Lake evaporation as computed by different methods for wintertime periods, 1963–65*

Period			Lake condition	Evaporation, in centimeters		
No.	Length (days)	Dates		Mass transfer	Water budget ΔH	Computed pan
17b	6.6	Mar. 30–Apr. 5, 1963	Open	−0.08	----------	1.65
37a	14.4	Dec. 3–17, 1963	do	3.07	2.44	.72
37b	13.5	Dec. 18–31, 1963	Ice	1.23	1.27	----------
38	18.0	Dec. 31, 1963–Jan. 18, 1964.	do	1.57	.92	----------
39	20.1	Jan. 18–Fep. 7, 1964	do	.68	.16	----------
40	22.0	Feb. 7–29, 1964	do	1.56	.63	----------
41a	16.4	Feb. 29–Mar. 16, 1964	do	−.06	[1] −.94	----------
41b	3.6	Mar. 17–20, 1964	Open	.76	[1] .32	.47
61	33.0	Nov. 30, 1964–Jan. 2, 1965.	40 percent ice.	2.58	2.30	[2] .97
62	26.2	Jan. 2–28, 1965	79 percent ice.	1.62	1.47	[2] .54
63	33.9	Jan. 28–Mar. 3, 1965	Ice	2.74	1.30	----------
64	23.0	Mar. 3–26, 1965	do	1.31	[1] −.80	----------
65a	12.4	Mar. 26–Apr. 7, 1965	do	.05	[1] −1.16	----------
65b	5.4	Apr. 8–13, 1965	Open	−.28	[1] −2.09	.92

[1] Probably influenced by seepage.
[2] Total for open-water subperiods only.

TABLE 20.—*Summary of Pretty Lake evaporation, as computed by different methods, for similar periods during 1963–65*

	1963	1964	1965
Periods	19–31	44–55	66–69
Dates	Apr. 12–Sept. 18	Apr. 11–Sept. 19	Apr. 13–Sept. 22
Number of days	158.9	161.0	162.1
Energy budget:			
Evaporation ... cm	54.1	60.3	59.2
Evaporation ... cm day⁻¹	.34	.37	.36
Mass transfer:			
Evaporation ... cm	55.7	58.4	57.8
Evaporation ... cm day⁻¹	.35	.36	.36
Water budget:			
Evaporation ... cm	----------	61.3	57.7
Evaporation ... cm day⁻¹	----------	.38	.36
Class-A pan, uncorrected:			
Evaporation ... cm	62.0	----------	----------
Evaporation ... cm day⁻¹	.39	----------	----------
Class-A pan, corrected:			
Evaporation ... cm	55.5	----------	----------
Evaporation ... cm day⁻¹	.35	----------	----------
Computed pan, uncorrected:			
Evaporation ... cm	58.7	62.2	63.8
Evaporation ... cm day⁻¹	.37	.39	.39
Computed pan, corrected:			
Evaporation ... cm	52.2	54.4	55.2
Evaporation ... cm day⁻¹	.33	.34	.34
Average of methods, uncorrected values excluded:			
Evaporation ... cm	54.4	58.6	57.5
Evaporation ... cm day⁻¹	.34	.36	.35

Earlier discussions of the energy-budget method suggested that there could be serious errors in the Q_x terms caused by errors in the capacity table of the lake. Capacity-table errors would have produced results that either are too high in the spring and too low in the fall or too low in the spring and too high in the fall. Pretty Lake data show energy-budget evaporation rates that are smaller than answers from other methods in both the spring and fall. These data seem to rule out the possibility of significant errors in the capacity table. Corrections to the class-A and computed pan evaporation data used the same Q_x values as did the energy budget. These results also support the conclusion that capacity-table errors are small.

Heat storage in the sediments also would be expected to produce E_{EB} values that are too high in the spring and early summer and too low in the fall (fig. 16). None of the energy-budget data for Pretty Lake have been corrected for sediment heating because available data are not considered to be accurate enough. Such corrections, which probably do not exceed 0.03 cm day^{-1}, would produce better agreement among the results of the different methods in the fall, but they would not increase the E_{EB} values to the rates found by other methods. In the springtime, they only would worsen the already poor agreement. It also is possible that both capacity-table errors and sediment-heating effects exist and tend to compensate each other.

The year-to-year consistency in the seasonal differences between E_{EB} rates and evaporation rates computed by other methods suggests that there are biasing factors in the methods. They could be in the energy-budget method of computation, in the instrument records, in the mass-transfer theory or calibration, in the seepage effect, or in some other phenomenon. Several sources of error probably exist.

During the springtime periods (Nos. 18–21, 45, 46), when energy-budget rates are lower than other results, the E_{EB} data cannot be considered to be so accurate as those from other methods. In other cases such as periods 23 and 24, when one of two sequential periods is lower and the other is higher than data from other methods, it seems that an error in Q_X values could have come from inaccuracies in the thermal survey. By majority rule, it appears that E_{EB} data in the fall tend to be about 0.05 cm day^{-1} too low.

Winter energy budgets are useless for computing evaporation because radiation reflectivity from ice is not know, Q_X is greatly dependent upon accurate ice-thickness measurements, and the Bowen-ratio concept is questionable.

Mass transfer. Evaporation rates computed by the mass-transfer method were within the ranges of rates computed by other methods during about three-fourths of the computation periods (fig. 30). They tended to be higher than rates from other methods during April, May, and November and to be lower than other rates during June and July. The periods when mass-transfer rates were higher than others had evaporation rates of less than 0.35 cm day^{-1}, and those when E_{MT} rates were lower than others had rates greater than 0.35 cm day^{-1}.

Two of the computation periods (Nos. 25 and 52) that had mass-transfer evaporation rates considerably lower than rates from other methods also had very low wind velocities (table 5). This phenomenon would support the hypothesis, suggested by some investigators, that the wind-velocity term, u, in the mass-transfer equation should have an exponent of less than 1.0. However, more extensive examination of

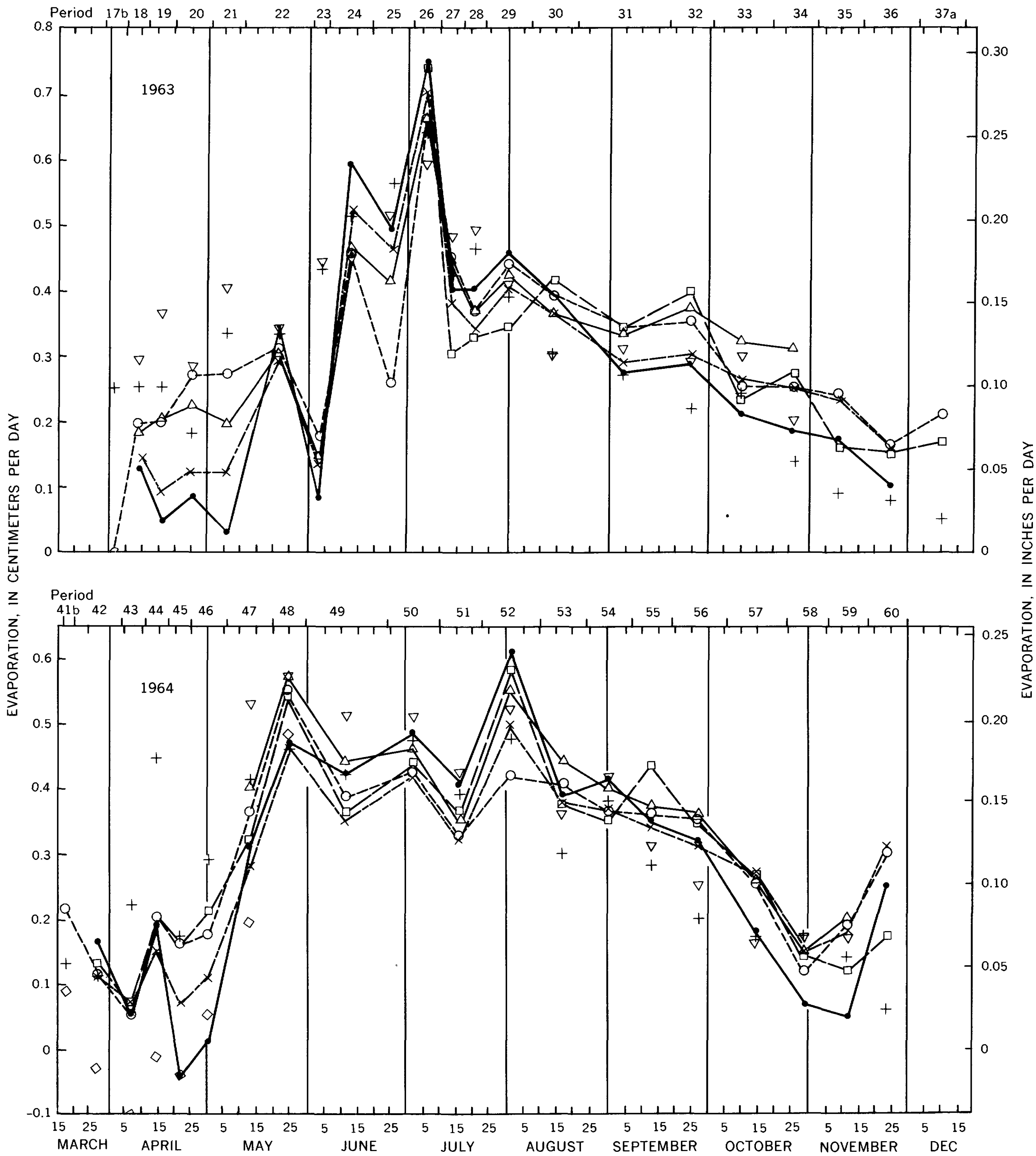

FIGURE 30.—Evaporation rates as computed by different methods for open-water periods, 1963–65. Data points are mean rates for periods shown along tops of hydrographs.

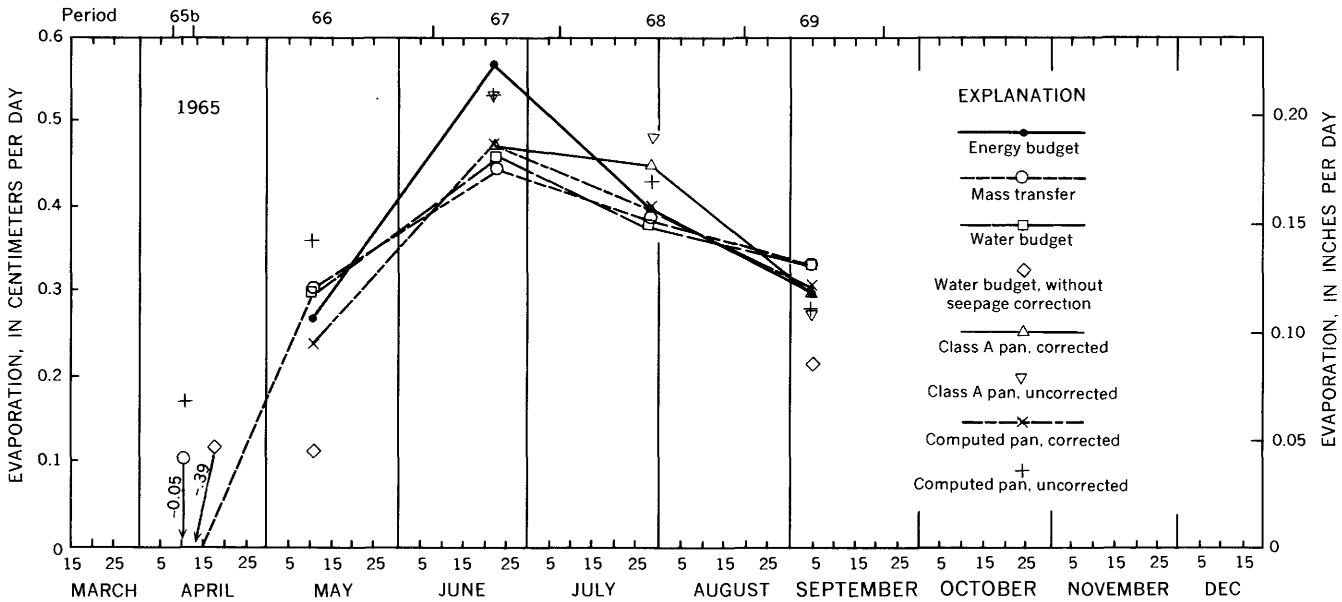

FIGURE 30.—Continued

the data shown in figures 18 and 24 shows that an exponent does not improve the fit of the calibration lines. It is more likely that at very low wind velocities the anemometer cups tended to stall and that the true mean wind velocities for these periods are higher than the data show.

The 160-day data summaries in table 20 show totals of mass-transfer evaporation that are within 3 percent of the several-method means for each year and within 3 percent of the energy-budget totals for each year. The agreement with other method totals for the entire record seasons (table 18) and for shorter summation periods are not so good as the agreement among 160-day totals. These great differences reflect the seasonal differences among the methods.

The Pretty Lake mass-transfer coefficient of 0.00560 (eq 14) is 15 percent less than the 0.00661 predicted by Harbeck's lake-area relation. This 15-percent departure is reasonable, considering the scatter of the data used originally to derive the relationship (Harbeck, 1962, fig. 31). It could, however, mean that some atypical factor affected the Pretty Lake study or that the relationship between N and area developed for the West does not hold for more humid regions.

The coefficient N will not be changed significantly if the discredited energy-budget periods, with E_{EB} rates of less than 0.1 cm day^{-1}, and the periods (nos. 25 and 52) with very low wind velocities are disregarded in the mass-transfer calibration (fig. 18). The scatter among results from different types of calibration computation (fig. 19) would be reduced by ignoring these data.

Similarly, if period 52 and the periods of known or questionable seepage are ignored in figure 24, the data very closely support the N value of 0.00560. The fit of data in either figures 18 or 24 is not improved significantly by use of a fractional exponent of u in the mass-transfer equation.

A seasonal variation in N is suggested by the relationship between energy-budget and mass-transfer values in figure 30. This variation is similar to the phenomenon that Hughes (1967, p. 166–171) found on the Salton Sea. Hughes attributed the variation to errors in the radiation terms of the energy budget. Pretty Lake energy-budget records may be affected by radiation errors or by problems in the Bowen ratio. Also, the closer agreement of water-budget periods (those not affected by seepage) with the mass-transfer data seems to prove that the mass-transfer coefficient is correct and is valid for all seasons.

Mass-transfer data give the most complete winter record of all the methods. The method is well suited to get data during the freezeup and just-thawed periods. Evaporation rates computed for ice-covered periods appear to be reasonable but could have a high percentage of error. The data in table 19 and the plot in figure 29 show differences between the winter mass-transfer and water-budget results, but it is not known if the error is in the mass-transfer coefficient, in the vapor pressure data, or in seepage effect on the water budget.

Water budget. Most of the water-budget evaporation rates shown in figure 30 are within 0.05 cm day^{-1} of the results obtained by other methods. There are no noticeable patterns of variation, other than those mentioned in discussions of the energy-budget and mass-transfer methods. Seepage corrections that have been applied to periods 46–48, 66, and 69 are responsible for

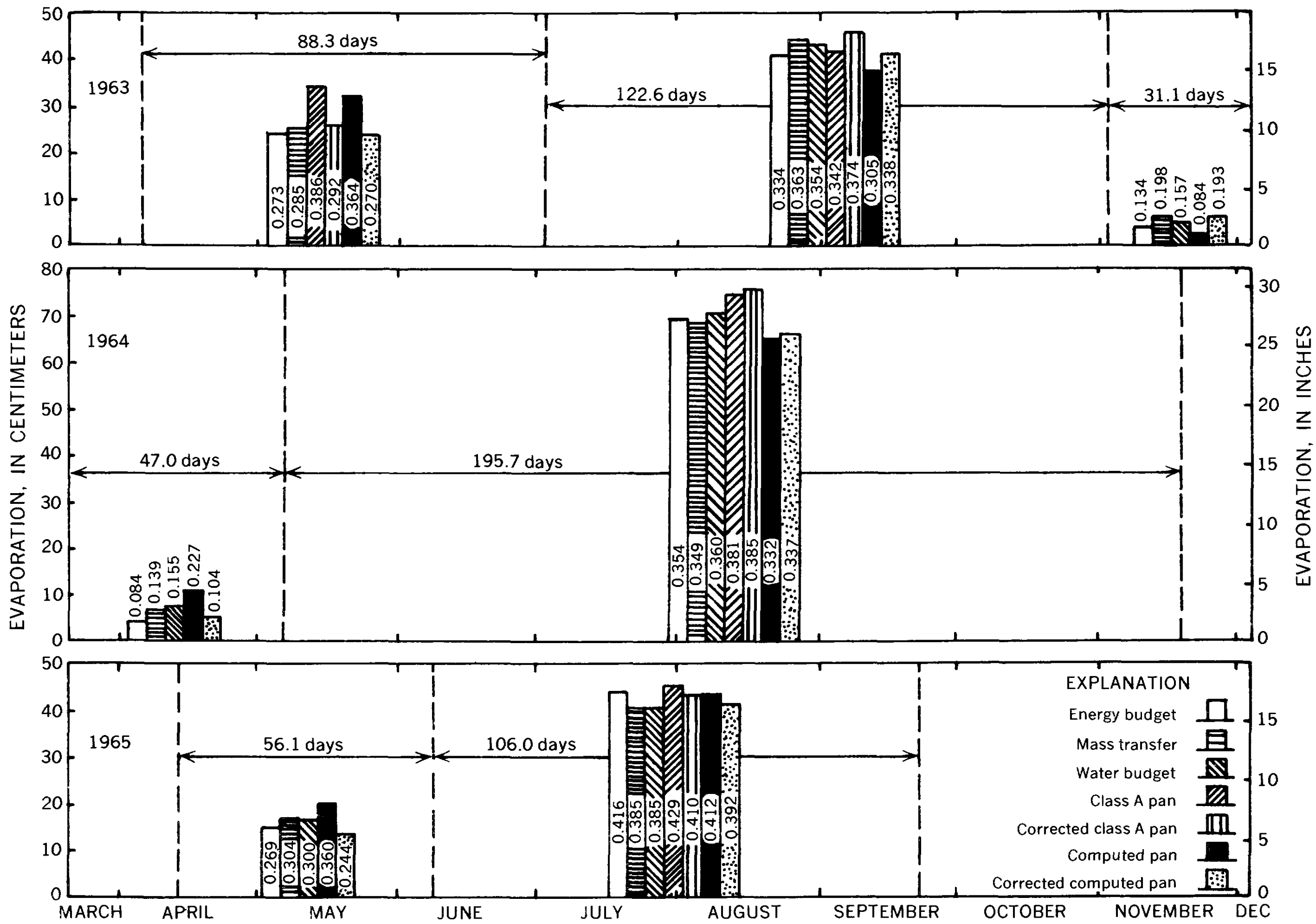

FIGURE 31.—Evaporation results summarized for comparison among different methods.

the very good agreement between E_{MT} and E_{WB} during these periods.

Periods 27, 28, and 29 have E_{WB} values that plot below evaporation rates computed by other methods in figure 30. More than 8 inches (20 cm) of precipitation fell during these periods, and although flow through the inlet was very small, it is possible that these periods were affected by inflow seepage. The position of the E_{WB} point for period 60 in figure 30 also suggests seepage. Only 0.75 inch (1.9 cm) of precipitation fell during this period, but snowmelt or rain on frozen ground could have affected the records.

Tables 18 and 20 show totals of water-budget evaporation that are about 5 percent higher than other method averages for 1964 and nearly the same in 1965. All the water-budget evaporation values in figure 31 are at about the average of evaporation amounts computed by other methods.

Water-budget and mass-transfer data frequently are analyzed by fitting a regression line to a plot similar to figure 24. The intercept of the ordinate axis is considered to be average seepage. The use of such a technique on Pretty Lake data would have produced an inaccurate (too large) N value and would not have shown the variable seepage phenomenon.

The water-budget method offers a good means for estimating wintertime evaporation. It may be the best of all methods because it does not contain estimated values such as mass-transfer coefficients, reflectivity ratios, or pan coefficients, but seepage estimates present a problem. Small amounts of precipitation during periods 37–40 probably did not produce inflow seepage, but most of the other winter periods probably were seepage affected. Assuming a valid mass-transfer technique, figure 29 shows that most of the winter seepage rates, although low, are a high percentage of the evaporation. Evapotranspiration rates are very low during winter periods, so that seepage rates probably are more easily affected by small amounts of precipitation. The data seem to show that times of winter seepage coincide with times of flow through the inlet.

Class-A pan. The evaporation hydrograph (fig. 30) and the bar graph summaries (fig. 31) show that accurate short-term estimates of evaporation cannot be made from class-A pan records without correcting for advection and heat storage. Evaporation estimated from uncorrected class-A pan records are too high in the spring and too low in the fall. On Pretty Lake, where the advected energy is small, full-season estimates of lake evaporation computed from class-A pan records would be reasonably accurate because Q_x terms total zero over a full season. However, the pan data from the Kendallville and Culver pans are limited, and it is not possible to make full season comparisons.

Corrections applied to the class-A pan records use the same values of Q_v, Q_x, and Q_w that were used in the energy-budget computations. They do not allow for advected energy to and from the pan. Although this effect is supposed to be considered in the pan coefficient, it is known to vary with time. Therefore, more error is expected in the pan-based evaporation data for Pretty Lake than in the evaporation results computed by other methods.

Corrected lake evaporation data from class-A pan records are about the same as or slightly greater than those computed by other methods (fig. 30). The tendency for high results from the pan-based data may mean that the average pan coefficient of 0.76 does not fully compensate for advected energy to the pan. Periods 33 and 34 represent some very warm autumn weather, when heat advection to the pan probably affected the pan evaporation considerably. The same type of effect also probably influenced the May and June 1964 records.

Table 20 and figure 31 show good agreement of 1963 and 1965 totals of record-season evaporation computed from the corrected class-A pan compared with other methods. The corrected pan season total is 5 to 7 cm (2.0 to 2.8 inches) greater than totals from other methods for 1964. (See 195.7-day period in fig. 31.) This variation is about equal to the one standard deviation of annual pan evaporation defined in USWB Technical Paper 37 (Kohler and others, 1959, pl. 5).

The differences between uncorrected and corrected pan-based evaporation rates in figure 31 shows more than just the difference between two computation methods. Table 12 shows that the Q_v-Q_w difference does not exceed 19 cal cm^{-2} day^{-1} during any period and is less than 10 cal cm^{-2} day^{-1} during most periods. Therefore, the difference between corrected and uncorrected rates is largely due to the energy storage caused by the slow heating and cooling of the deeper lake water. The difference has considerable hydrologic significance. Lower springtime evaporation rates shown by the corrected data mean that during the midsummer dry period the level of Pretty Lake is about 10 cm (4 inches) higher than it would be if it were not for the effects of energy storage caused by deep water.

The short seasons for which published class-A pan records are available for the Pretty Lake area make it difficult to compare pan-based evaporation data with other results. They also would be a significant detriment in any attempts to estimate annual lake evaporation using only the pan method. None of the records include winter periods, and it is obvious that the class-A pan has no value in computing winter evaporation.

Computed pan-evaporation method. Lake evaporation rates based upon the concept of computed pan evaporation should not be used unless they are corrected for advected and stored energy. Figure 30 shows how the uncorrected computed pan-evaporation gives lake evaporation rates that are too high in the spring and too low in the fall. The 1963 and 1964 totals in table 16 show that the uncorrected method gives a reasonable estimate of annual evaporation. This is because the net Q_x over an entire season is nearly zero and because advected energy to and from Pretty Lake is very small.

The evaporation hydrograph (fig. 30) shows that lake evaporation rates computed from the computed pan method tend to be less than evaporation rates computed by other methods. For most periods, they are within 0.05 cm day^{-1} of rates from other methods. In some of the periods during early summer 1964, the corrected lake evaporation rates determined from computed pan rates were lower than all others.

The data summary of table 20 shows that 160-day lake evaporation totals computed from the corrected computed pan method were 2 to 4 cm (0.8 to 1.6 inches) (4 to 7 percent) below the means of all methods and were the lowest of all totals each year. Totals for the corrected computed pan methods in table 18 and in figure 31 and similarly low, except those for 1963 and early 1963, when energy-budget totals also are very low.

Some explanation of the deviations of lake evaporation data based upon class-A pan records and computed pan methods can be provided by the data in tables 10 and 11. Evaporation from a class-A pan (Kendallville or Culver) was 1.7 cm (0.7 inch) greater than computed pan evaporation during periods 18–34 in 1963, 6.2 cm (2.4 inches) greater during periods 47–59 in 1964, and 2.2 cm (0.9 inch) greater during periods 67–69 in 1965. These follow the same pattern as does lake evaporation computed by the two methods (fig. 31), the class-A pan method giving slightly higher amounts in 1963 and 1965 and considerably higher amounts in 1964. Computed pan coefficients shown in table 11 range from 0.50 to 0.90, the season averages being 0.70 during the two longer record years and 0.76 in 1965. Variations in the computed coefficients are more correct than the constant 0.76 used with the class-A pan because they contain pan-advection factors. By comparison with the results of other methods, it appears that the true annual pan coefficient is somewhere between the 0.70 found by the computed pan and the 0.76 used with the class-A pan.

Wintertime lake evaporation results from the computed pan method that are summarized in table 19 include evaporation for open-water periods only. The data cannot be corrected for heat storage during the times of breakup and freezeup because accurate thermal survey data cannot be obtained. They do agree well with the totals obtained by other methods and cannot be given a very good accuracy rating.

Evaporation maps. Maps in U.S. Weather Bureau Technical Paper 37 (Kohler and others, 1959) show an annual lake evaporation of 31.5 inches (80 cm) and a May–October evaporation of 26 inches (66 cm) for the Pretty Lake location. They show standard deviations of about 2.4 inches (6 cm) in the annual pan evaporation and 2.0 inches (5 cm) in the May–October pan evaporation. These are equivalent to standard deviations of about 2.0 inches (5 cm) in the annual lake evaporation and 1.6 inches (4 cm) in the May–October lake evaporation. Table 21 contains seasonal totals from the Pretty Lake studies for comparison with these values. Corrections for advected energy have been applied to the evaporation-map estimates of annual evaporation in table 21, and corrections for advected and stored energy have been applied to the May–October values. In some cases, estimates have been used in extending the Pretty Lake data to full season or in getting May–October values.

Results shown in table 21 for the various methods of computation have the same types of variation as did the the data that were discussed in earlier paragraphs. In general, the mean evaporation rate computed by the different methods used on Pretty Lake agrees well with the annual and May–October evaporation determined from the published maps. Mass-transfer data agree particularly well (within 2 cm or 0.8 inch) with the map estimates and energy-budget totals agree very well, except for the 1963 annual total, which is affected by the very low spring and autumn values. Class-A pan data tend to be higher and lake evaporation from computed pan data tend to be lower than the map estimates. Corrections for advected and stored energy applied to the pan data are small.

TABLE 21.—*Annual and May–October evaporation from Pretty Lake*

Method of computation	Total annual evaporation (cm)		May-October evaporation (cm)	
	1963	1964	1963	1964
Published map	79	79	64	66
Energy budget	72	79	63	69
Mass transfer	79	81	64	67
Water budget		82		70
Class-A pan	81	88	68	74
Corrected class-A pan	80	87	66	74
Computed pan	75	78	64	64
Corrected computed pan	74	77	62	64

CONCLUSIONS

This study has computed Pretty Lake evaporation by use of five common methods. The following paragraphs are included to summarize and evaluate the methods from the standpoints of cost, ease of operation, and accuracy of results.

In most respects the mass-transfer method proved to be the best means of computing lake evaporation for short periods throughout the year. It is particularly well suited to low evaporation rates and is the only method that provided good springtime records. The method also was superior to others for measuring evaporation just before, during, and just after ice cover. The mass-transfer coefficient, N, for Pretty Lake was computed to be 0.00560, in the units of equation 14, by calibration using the energy-budget records. This coefficient also could have been computed from seasonal records of the class-A pan or computed pan evaporation or from seasonal totals determined from maps based upon pan data (Kohler and others, 1959) simply by dividing the total evaporation by the summation of the products $n\ u\ (e_o - e_a)$ for the season. For lakes with large inflow and outflow, the seasonal totals would have to be corrected for advected energy, but these corrections need not be precise and often can be computed from available weather and streamflow data. A mass-transfer coefficient computed by this method will not be valid for lakes having a variable coefficient, such as that caused by emergent aquatic vegetation. The mass-transfer coefficient for Pretty Lake could not be computed accurately from a water-budget calibration because the seepage rate varies. The coefficient determined for Pretty Lake was 15 percent less than that predicted from lake-area relationships (Harbeck, 1962). Evaporation computation by the mass-transfer method uses simple, reliable, and relatively inexpensive instruments and techniques. With rather simple modifications, these instruments and techniques can be adapted to automatic data processing. Short-term mass-transfer evaporation data were higher than results from other methods for early and late seasons (April, May, and November) with low evaporation rates and lower than results of other methods during periods of high evaporation rates (June and July). The mass-transfer method does not provide good evaporation data during periods of very low wind.

The energy-budget method produces evaporation data that are independent of the other methods. Shorter computation periods provide less accurate results than do longer periods of a month or more. Energy-budget evaporation rates tend to be lower than the results of other methods during the spring and autumn low-rate seasons and higher during the summer high-rate season. These average out, so that the seasonal totals are the same as those computed by other methods, but the springtime and short-term data probably are less reliable than mass-transfer data. Many factors contribute errors to the energy budget; these include instrument records, thermal-survey data, capacity tables, and the Bowen ratio. Of the several methods used in this study, the energy budget is the most expensive. It requires sophisticated equipment, frequent temperature surveys, and complex computations. An integrator device attached to the multipoint analog recorder reduced the amount of time required for data processing, and greater automation is possible by the use of more complex equipment.

The water-budget method is simple and inexpensive to operate, but it depends upon some other measure of evaporation, such as mass-transfer data, in order to compute seepage. During the dryer seasons the water-budget studies of Pretty Lake found a corrected fall in stage that agreed well with the evaporation rates computed by other methods. During wet seasons the water budget was affected by considerable inflow seepage. Because of variable seepage the water budget is not a satisfactory independent evaporation measurement for computing the mass-transfer coefficient.

Standard class-A pan records and computed pan evaporation provide inexpensive lake evaporation data because they rely mainly upon data collected at U.S. Weather Bureau stations, plus less expensive data at the lake. Pan-based evaporation hydrographs are skewed to the left of the hydrographs produced by other methods. The skew is caused by energy-storage effects, which may be corrected, but only if thermal-survey data are available. Corrected lake evaporation data based upon class-A and computed pan evaporation records agree well with other evaporation records through the season. With only simple advected-energy corrections the computed and class-A pan evaporations provide good measures of total yearly lake evaporation. Class-A pan data can provide a better measure of lake evaporation if pan-water temperatures are available. It is difficult to compute complete lake evaporation records from published class-A pan records because data sometimes are missing.

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