Influence of Evaporation, Ground Water, and Uncertainty in the Hydrologic Budget of Lake Lucerne, a Seepage Lake in Polk County, Florida

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Influence of Evaporation, Ground Water, and Uncertainty in the Hydrologic Budget of Lake Lucerne, a Seepage Lake in Polk County, Florida

By T.M. LEE and AMY SWANCAR

Prepared in cooperation with the
Southwest Florida
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CONVERSION FACTORS, VERTICAL DATUM, AND ADDITIONAL ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per day (in/d)	2.54	centimeter per day
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per day per foot [(ft^3/d)/ft]	1.0000	cubic meter per day per meter
million gallons (Mgal)	3,785	cubic meter
calorie per square centimeter per day [(cal/cm^2)/d]	3.69	British thermal unit per square foot per day
calorie per gram (cal/g)	1.80	British thermal unit per pound mass
calorie per gram per degree Celsius [(cal/g)/°C]	1.00	British thermal unit per pound mass per degree Fahrenheit
gram per cubic centimeter (g/cm^3)	0.00112	pound mass per cubic inch
millibar (mb)	0.0145	pound-force per square inch

Temperature conversions for degrees Fahrenheit (°F) and degrees Celsius (°C) follow:

$$°C = 5/9 \times (°F - 32)$$
$$°F = 1.8\ °C + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Additional units used in report:

cm	centimeter
cm/d	centimeter per day
m	meter

NOTE: Inch-pound units were selected for use in this report. An exception to the use of inch-pound units, however, is made in the presentation of data collected for the energy-budget and mass-transfer evaporation methods. The metric unit of langley (calories per square centimeter) is conventionally used to describe the energy terms in an energy-budget analysis (Anderson, 1954; Sturrock, 1985). Temperatures used in the computation of energy terms are in the compatible metric unit of degrees Celsius. The dual units that are conventionally used to describe the components of the mass-transfer evaporation method (Harbeck, 1964; Sturrock, 1985) also are used in this report.

Influence of Evaporation, Ground Water, and Uncertainty in the Hydrologic Budget of Lake Lucerne, a Seepage Lake in Polk County, Florida

By T.M. Lee *and* Amy Swancar

Abstract

Evaporation losses and the interaction of ground water with Lake Lucerne were studied to determine the influence of these two processes on the hydrologic budget of a seepage lake. Lake Lucerne is representative of the numerous seepage lakes of sinkhole origin in the karst terrain of central Florida. Because of permeable surficial deposits, ground-water inflow is the only significant contribution from the surrounding watershed. The lake recharges the underlying Upper Floridan aquifer and, as a result, is susceptible to increased leakage induced by pumping from this aquifer. Ground-water fluxes determined in the study were analyzed to define the proportion of the total lake leakage induced by pumping from the Upper Floridan aquifer. A hydrologic budget is analyzed for the 1-year period from October 1985 to September 1986.

Ground-water inflow and leakage are significant components of the hydrologic budget. Changes in the quantity of either of these fluxes can substantially alter lake stage. Ground-water inflow contributed from 20 to 37 percent of the total annual inflow to the lake. Leakage from the lake accounted for 18 to 23 percent of the total annual outflow. Water withdrawals from the Upper Floridan aquifer increased annual lake leakage by 22 percent over nonpumping conditions. Most of the increase (92 percent) in leakage occurred during April, May, and June 1986, when local citrus irrigation was highest.

For the study year, ground-water inflow and leakage volumes were calculated by flow-net analysis to be equal to 10.5 and 12.6 inches, respectively, of water depth above (or below) the lake surface. These estimates were revised upward on the basis of an analysis of the error in the hydrologic-budget equation. Revised ground-water inflow exceeded annual leakage from the lake. Ground-water inflow rates were increased by 120 percent to 23.6 inches, and leakage was increased by 40 percent to 17.5 inches. Differences between the two estimates probably reflect the uncertainty in the hydraulic conductivity estimates of the porous media around the lake and the unaccounted effect of transient ground-water inflow.

The geometry of the sinkhole complex beneath Lake Lucerne and pumping in the Upper Floridan aquifer are primary controls on ground-water interactions with the lake and, in particular, lake leakage. A numerical ground-water model was used to test the effects of these two factors on ground-water interactions with the lake. Results indicate that the intermediate confining unit below Lake Lucerne has been breached and replaced by materials about two orders of magnitude more conductive. Anisotropy in the surficial aquifer is approximately 100 and controls the depth of the ground-water flow intercepted by the lake. Lake sediments having low permeability may control the distribution of leakage through the lakebed but did not appreciably reduce total leakage rates in these simulations.

Evaporation loss was the major outflow component of the hydrologic budget. Annual lake evaporation determined by the energy-budget method was 57.9 inches, about 8 inches greater than long-term estimates for the region. The greater rate was attributed to drier than normal conditions: rainfall totaled 40.9 inches during the study year, about 10 inches less than the long-term average. Similar annual evaporation rates were determined by the energy-budget method, the simpler mass-transfer method, and by corrected pan evaporation from an onsite pan; however, the probable errors associated with these other two methods were greater than for the energy budget. Weekly energy-budget evaporation rates ranged from 0.04 inch per day in early January 1986 to 0.26 inch per day in early May 1986. The largest monthly energy-budget evaporation rates occurred in April and May 1986, 7.16 and 7.12 inches per month, respectively. Monthly evaporation estimated from corrected pan evaporation generally was within 10 percent of the energy-budget estimate but differed by as much as 35 percent. Daily energy-budget evaporation also was computed for 321 days during the year.

INTRODUCTION

In Florida, the more than 7,700 warm-water lakes form a lake district that is unique to the southern United States. Comparably large lake districts are found only within the formerly glaciated northern States from Minnesota to Maine (Brenner and others, 1990). Many lakes in Florida are under enormous developmental pressures as the population of the State rapidly increases. Lakefront property is highly desirable as homesites, as the density of lakefront development can often attest. Lake basins also are favored sites for cultivation of citrus because lakes tend to moderate winter temperatures and provide accessible irrigation water. Increased development within lake basins and increased demand for freshwater for irrigation, industrial, and municipal supplies can adversely affect the water quality of and water-level fluctuations in many lakes in Florida.

Optimum management of lakes in Florida requires an improved understanding of the influence of lakes on the hydrologic system. Hydrologic budgets that describe the sources and losses of water to lakes are essential to many lake-management decisions, for example, to adopt the best management practices and to evaluate lake-restoration projects. However, many available hydrologic budgets lack the necessary accuracy to define cause and effect clearly when lake levels begin to change.

Uncertainties about evaporation and ground-water fluxes from seepage lakes are major obstacles in the determination of accurate hydrologic budgets. Approximately two-thirds of all lakes in Florida are seepage lakes that lack channelized surface-water inflows or outflows. Overland runoff is minimal because of the high infiltration rate of the sandy soils near these lakes. The principal sources of water to these lakes are rainfall, which can be measured easily, and ground-water inflow. Principal water losses are by evaporation and leakage of lake water to the underlying aquifer. The lack of adequate information on these hydrologic-budget components makes it difficult to distinguish the effects of evaporation, lake leakage, and ground-water withdrawals on lake-level declines.

In 1983 the U.S. Geological Survey, in cooperation with the Southwest Florida Water Management District, began a detailed 5-year study of the hydrologic budget of Lake Lucerne in Polk County, Fla. The study focused on determining the influence of evaporation and ground water in the overall hydrologic budget and also evaluated the uncertainty in each budget component. The study also examined the influence of the geology underlying the lake and water withdrawals from the Upper Floridan aquifer on the ground-water interactions with Lake Lucerne.

Purpose and Scope

This report describes the evaporative losses and ground-water fluxes to Lake Lucerne and the influence of these processes on the hydrologic budget of the lake for the period October 1, 1985, to September 30, 1986. Also described are the effects of ground-water pumping near the lake on ground-water fluxes to Lake Lucerne. The ability to define the importance of evaporative losses and ground-water fluxes on the hydrologic budget of the lake is limited by the accuracy of each component. Therefore, the uncertainty in each budget component is estimated, and its influence on the interpretation of individual budget components is evaluated. The magnitude and seasonality of uncertainty in the final hydrologic budget are examined to provide insight into potentially unaccounted fluxes.

Precipitation and lake-stage components of the hydrologic budget were measured directly on a daily basis. Evaporation and ground-water fluxes were computed indirectly from climatologic and hydrologic variables. In this report, estimates of lake evaporation are computed by the energy-budget method and the simpler mass-transfer method. Evaporation estimates also are compared and contrasted with each other and with those determined by the National Oceanographic and Atmospheric Administration (NOAA) pan-evaporation method. A steady-state numerical ground-water model was used to evaluate qualitatively the influence of geology and pumping from the Upper Floridan aquifer on ground-water interactions with the lake. Ground-water fluxes to and from the lake were estimated by flow-net analysis of head data measured in 36 wells. The uncertainty in each budget component was either computed or estimated from values reported in the literature.

Previous Investigations

Numerous investigations of hydrologic budgets for lakes in Florida have concentrated on understanding the ground-water component of the hydrologic budget of the lake; few, however, have attempted to quantify accurately the evaporation component. Previous budget studies that focused on ground-water fluxes generally are based on one of three approaches. The most common approach treats net ground-water flow (the difference between ground-water inflow and leakage) as the sole unknown term in the hydrologic-budget equation (Clark and others, 1963; Hughes, 1974; Lichtler and others, 1976; Baker and others, 1988; Deevey, 1988). In a variation on this approach, ground-water inflow is estimated by Darcy’s law, leaving leakage to be derived as the residual term (Henderson, 1983; Henderson and others, 1985). When ground-water flow is calculated as a residual of the budget equation, it includes the measurement errors in all other budget terms and, thus, may be inaccurate (Winter, 1981b).

Less frequently, seepage-measuring devices modeled after Lee (1977) have been used to measure directly the flux of water through lakebeds. (The general term “seepage” can describe flow either into or out of a lake.) Point measurements of seepage have been used to estimate ground-water inflow to Lake Conway and Lake Apopka (Fellows and Brezonik, 1980) and Lake Washington (Conner and Belanger, 1981). Leakage (negative seepage) was observed only by Conner and Belanger (1981) but was not quantified. In both studies, ground-water inflow was presented as a fraction of the total inflow to the hydrologic budget of each lake. Finally, trend analysis has been used to establish indirectly a relation between lake stage and such hydrologic variables as local ground-water levels and ground-water pumping rates (Geraghty and Miller, Inc., 1980; Henderson and Lopez, 1989).

In each of these studies, evaporation was computed from NOAA pan-evaporation data (Farnsworth and others, 1982). Because evaporation-pan measurements overestimate lake evaporation, pan-correction factors are available to estimate the annual average evaporation in Florida (Farnsworth and others, 1982). In previous studies, evaporation estimates have been made for periods as short as 7 days (Lichtler and others, 1976) or 1 month (Hughes, 1974; Hammett and others, 1981; Deevey, 1988) to as long as 1 year (Clark and others, 1963). The validity of lake evaporation estimates derived from pan evaporation for periods less than 1 year is highly questionable (Winter, 1981b). However, few alternative estimates of short-term lake evaporation exist for Florida.

Of the two common, theoretically based techniques for computing lake evaporation losses, the energy-budget method and the mass-transfer method, only the mass-transfer method has been used in previous investigations in Florida. Pride and others (1966) used a mass-transfer method to determine monthly evaporation losses from Lake Helene in central Florida. The accuracy of the evaporation estimates in their study, however, cannot be determined, as the assumptions used in the method, instrumentation, and data were not reported. Bartholic and others (1978) determined evaporation from Orange Lake in north-central Florida over one 24-hour period by using a third method—the eddy-correlation technique.

The most common means of estimating short-term evaporation in Florida lakes is monthly pan evaporation corrected by factors developed by Kohler (1954) from the work of Langbein (1951). Langbein

(1951) determined the monthly evaporative loss from Lake Okeechobee in southern Florida by computing it as the residual term to the hydrologic-budget equation for the lake. However, Langbein made no analysis of the potential importance of measurement errors on this residual term. Kohler (1954) subsequently related these losses to a NOAA evaporation pan at Belle Glade, Fla., and developed pan-correction factors for Lake Okeechobee. These monthly pan-correction factors, or coefficients, are commonly used to estimate lake evaporation outside of southern Florida, although the error due to regional differences in climate is rarely considered. In an exception to this rule, Deevey (1988) "normalized" these monthly pan coefficients for use in central and northern Florida by an adjustment based on the long-term average pan evaporation in each region.

None of the studies systematically considered the measurement errors in each budget term in relation to the overall hydrologic budget. Discussion is usually restricted to the importance of measurement errors on the residual term, most often of errors in evaporation on net ground-water flow (Hughes, 1974; Henderson, 1983).

Acknowledgments

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DESCRIPTION OF STUDY AREA

Physical Setting

Lake Lucerne is about 4 miles (mi) northeast of the city of Winter Haven in northern Polk County within the Central Highlands physiographic region of west-central Florida. It lies on the Winter Haven Ridge, one of three ridges that trend northwest to southeast through Polk County (fig. 1) (White, 1970). Lake Lucerne is typical of the many small, nearly circular lakes of sinkhole origin that characterize this region. It has a surface area of approximately 44 acres, a maximum depth of about 22 feet (ft), and an average depth of about 15 ft.

The surrounding drainage basin (fig. 2) is small, 0.26 square mile (mi^2), has no streams, and consists of the lake and a small wetland pond, herein named "Terrie Pond," upgradient from the lake. Lake Lucerne is at an altitude of about 125 ft above sea level, and the highest point in the surrounding basin is about 180 ft above sea level. The lake is several feet higher than four larger lakes that surround it (fig. 2). Except along the lake margin, soils within the basin generally consist of a washed silica sand. As a result, the lake receives minimal surface runoff; precipitation and ground-water inflow are the major sources of water to the lake. Thus, the watershed relevant to the lake is underground. Homesites surround the lake, and most of the land in the basin is used for citrus agriculture.

Climate

The climate of the study area is humid and subtropical. High temperatures and frequent afternoon thundershowers from convective storms characterize the wet summer period from June through September. October through May is generally drier, except for a shorter winter wet season from December through February as a result of frontal storms. Seventy-one years of climatic data for the area are available from the Lake Alfred Agricultural Research and Education Center, a NOAA climate-reporting station 2 mi northwest of Lake Lucerne (fig. 2). Long-term rainfall at the Lake Alfred station averages 50.83 inches per year (in/yr) for the period 1951 to 1980. The average annual air temperature is 71.6 degrees Fahrenheit (°F), and monthly averages range from 59.6 °F in December to 81.9 °F in August (National Oceanic and Atmospheric Administration, 1986).

The monthly rainfall at Lake Lucerne during data collection for this study followed the expected seasonal pattern (fig. 3). However, rainfall was well below normal for May, July, and September 1986. As a result, the total rainfall for the study year (40.88 in.) was substantially less than the long-term average (50.83 in/yr), and the stage in Lake Lucerne and Terrie Pond declined steeply (fig. 4).

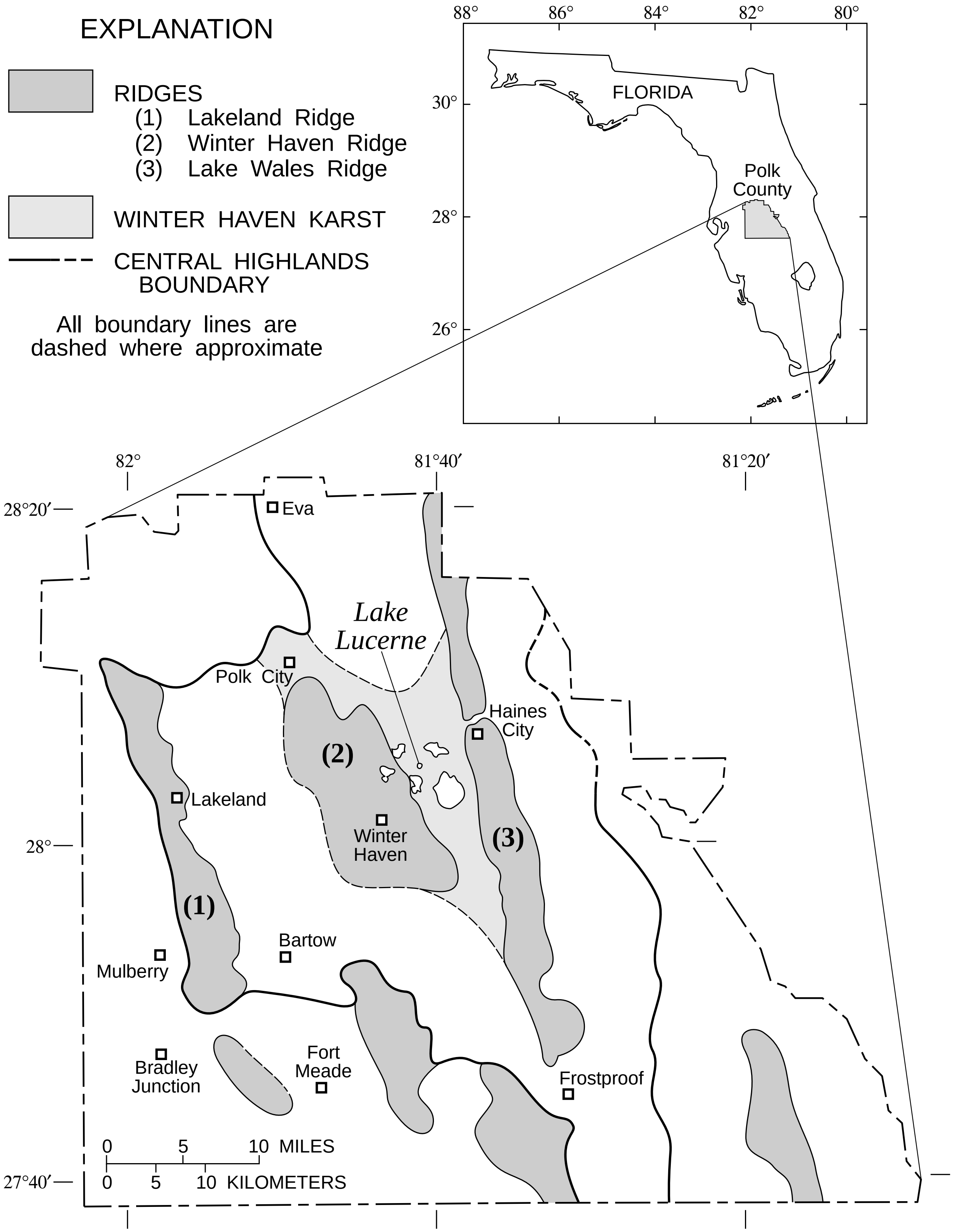

Figure 1. Location of Lake Lucerne and physiographic divisions in Polk County (modified from Lee and others, 1991).

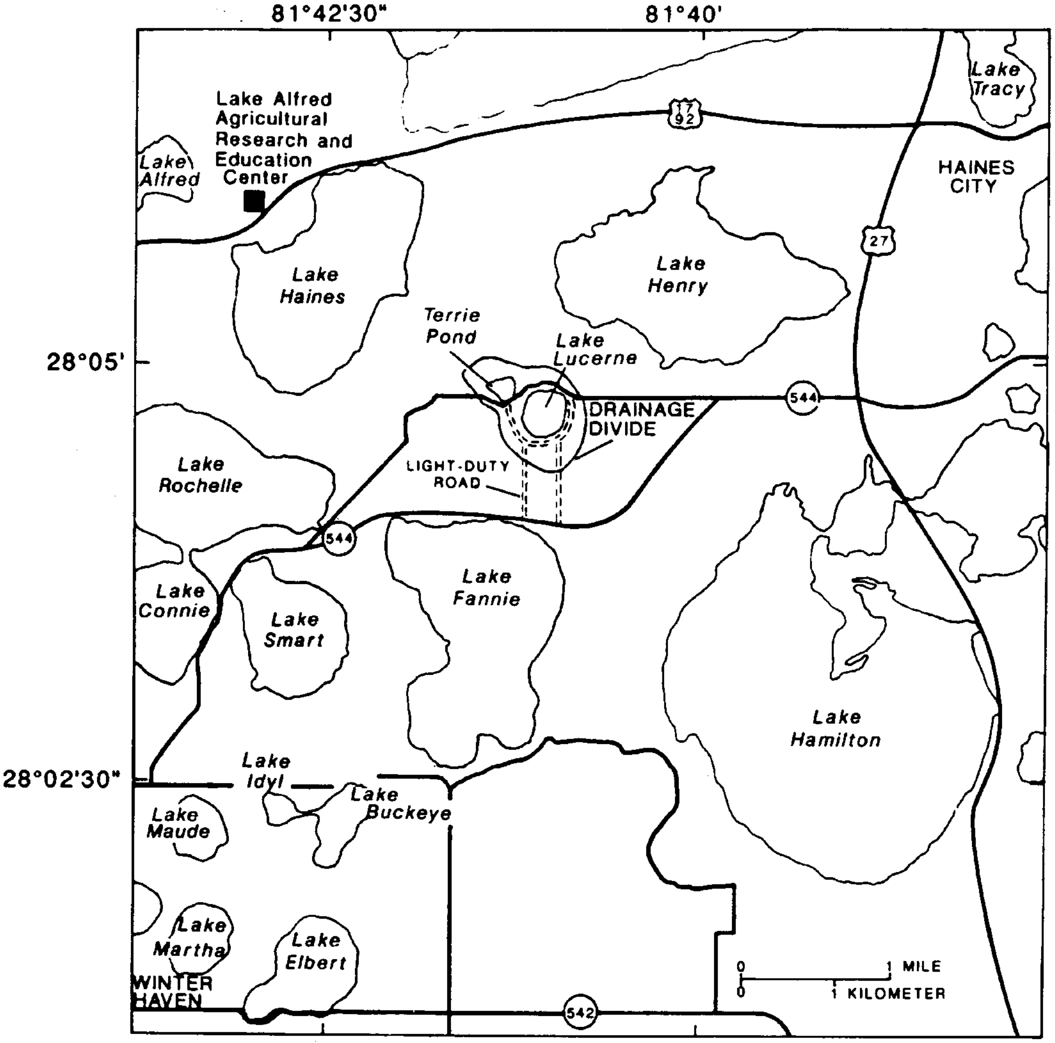

Figure 2. Lakes in the vicinity of the study area (modified from Lee and others, 1991).

Hydrogeologic Setting

The hydrogeologic setting of Lake Lucerne has a significant effect on ground-water interaction with the lake. The geometry and vertical hydraulic conductivity of the confining unit beneath Lake Lucerne, for example, are critical hydrogeologic controls on lake leakage.

The hydrogeologic setting of Lake Lucerne has been described in detail by Lee and others (1991) but is discussed briefly here as background to later sections on the ground-water component of the hydrologic budget. A hydrogeologic section through the basin depicts the geology underlying and surrounding the lake and describes the hydrogeologic units (fig. 5). The locations of the wells whose lithologic logs were used to construct this section are shown in figure 6.

The three hydrogeologic units of interest at Lake Lucerne are, from bottom to top, the Upper Floridan aquifer, the intermediate confining unit, and the surficial aquifer (fig. 5). Because the ground-water flow patterns that influence the lake occur mostly in the shallowest deposits around the lake, the description of the Upper Floridan aquifer here is limited to its two uppermost units, the limestone Ocala Group and the carbonate part (Arcadia Formation) of the overlying Hawthorn Group (fig. 5). The Upper Floridan aquifer constitutes the upper 300 to 400 ft of the Floridan aquifer system in the study area (Miller, 1986). This limestone aquifer is highly transmissive but is confined above by the intermediate confining unit, a thin sequence of clastic material approximately

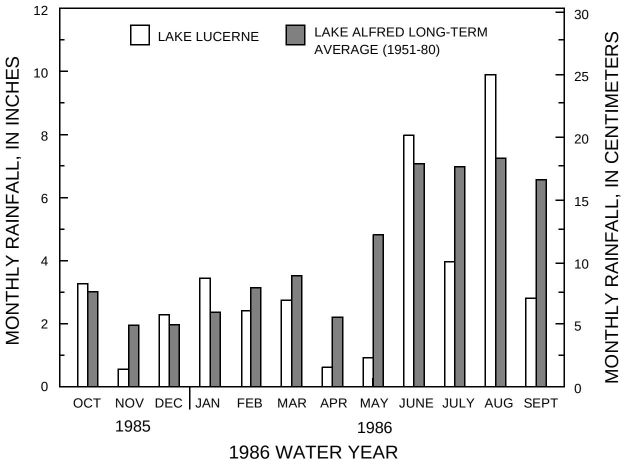

Figure 3. Monthly rainfall at Lake Lucerne for the 1986 water year and the long-term average monthly rainfall at the National Oceanic and Atmospheric Administration climate station at Lake Alfred, 1951–80.

15 ft thick within the Peace River Formation of the Hawthorn Group (Lee and others, 1991) (fig. 5). The low permeability of this intermediate confining unit slows recharge from the surficial aquifer to the Upper Floridan aquifer. The surficial aquifer consists of the surficial deposits of undifferentiated sand and clay overlying the intermediate confining unit. These deposits range in thickness from 50 to 100 ft in the study area and consist of alternating lenses of fine to coarse sand, clay, and clayey sand. The clay content generally increases with depth.

Geologic Framework

The geologic framework beneath Lake Lucerne was interpreted from a marine seismic-reflection survey and indicates the sinkhole origin of the lake basin. The survey was used to map the depth to the contact between the undifferentiated surficial deposits and the clay-rich Hawthorn Group beneath the lake. Variations in the altitude of this contact indicated subsidence and discontinuity of the clay layer beneath the lake as a result of sinkhole development (fig. 7) (Lee and others, 1991). Features indicated by the configuration of this surficial deposit–clay contact are voids, vertical pipes, and pinnacles. The steep-sided walls of the pipe structures probably represent the boundary between the limestone and the subsided overburden. Pinnacles and raised areas between the pipe features probably represent residual limestone that can retain overlying caps of the Hawthorn Group clays (fig. 7).

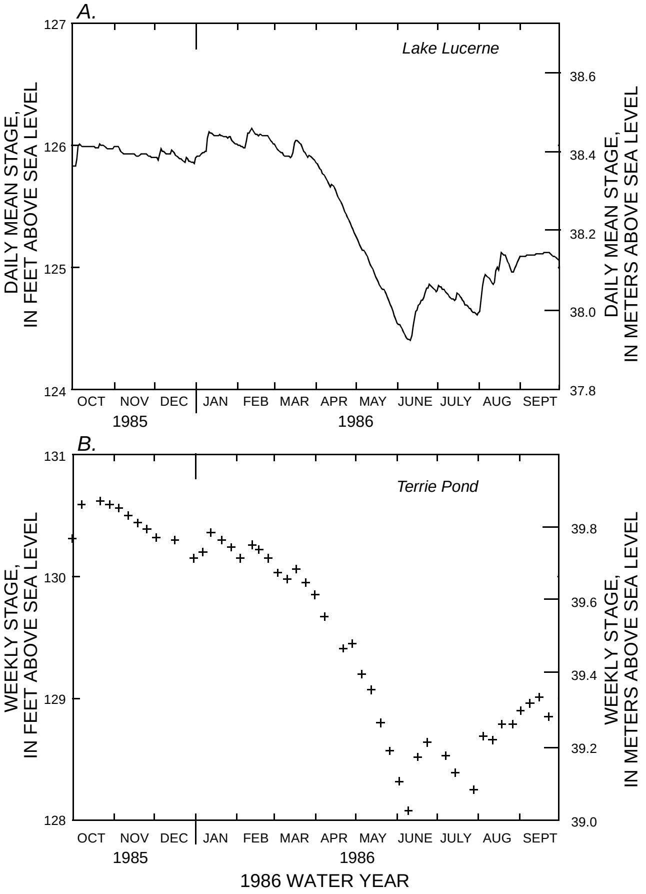

Figure 4. (*A*) Daily mean stage of Lake Lucerne and (*B*) weekly stage of Terrie Pond for the 1986 water year (modified from Lee and others, 1991).

The solution features below Lake Lucerne are characteristic of the cover-subsidence-type sinkholes described by Sinclair and others (1985). This is the most prevalent type of sinkhole in the region of west-central Florida that includes Lake Lucerne. In the formation of cover-subsidence-type sinkholes, a cavity is dissolved in the limestone, whereas a relatively thick overburden is suspended above the cavity by a thin clay confining unit. The confining unit collapses before the horizontal dimension of the cavity becomes large, and the unconsolidated sand and clay of the surficial deposits stream down into the cavity. As dissolution of the limestone continues, accelerated by the vertical movement of water, surficial deposits gradually channel into the vertical solution feature in a process referred to as “piping” (Sinclair and others, 1985).

The collapse of surficial deposits of unconsolidated sand and clay into solution cavities in the underlying limestone is considered to be the origin

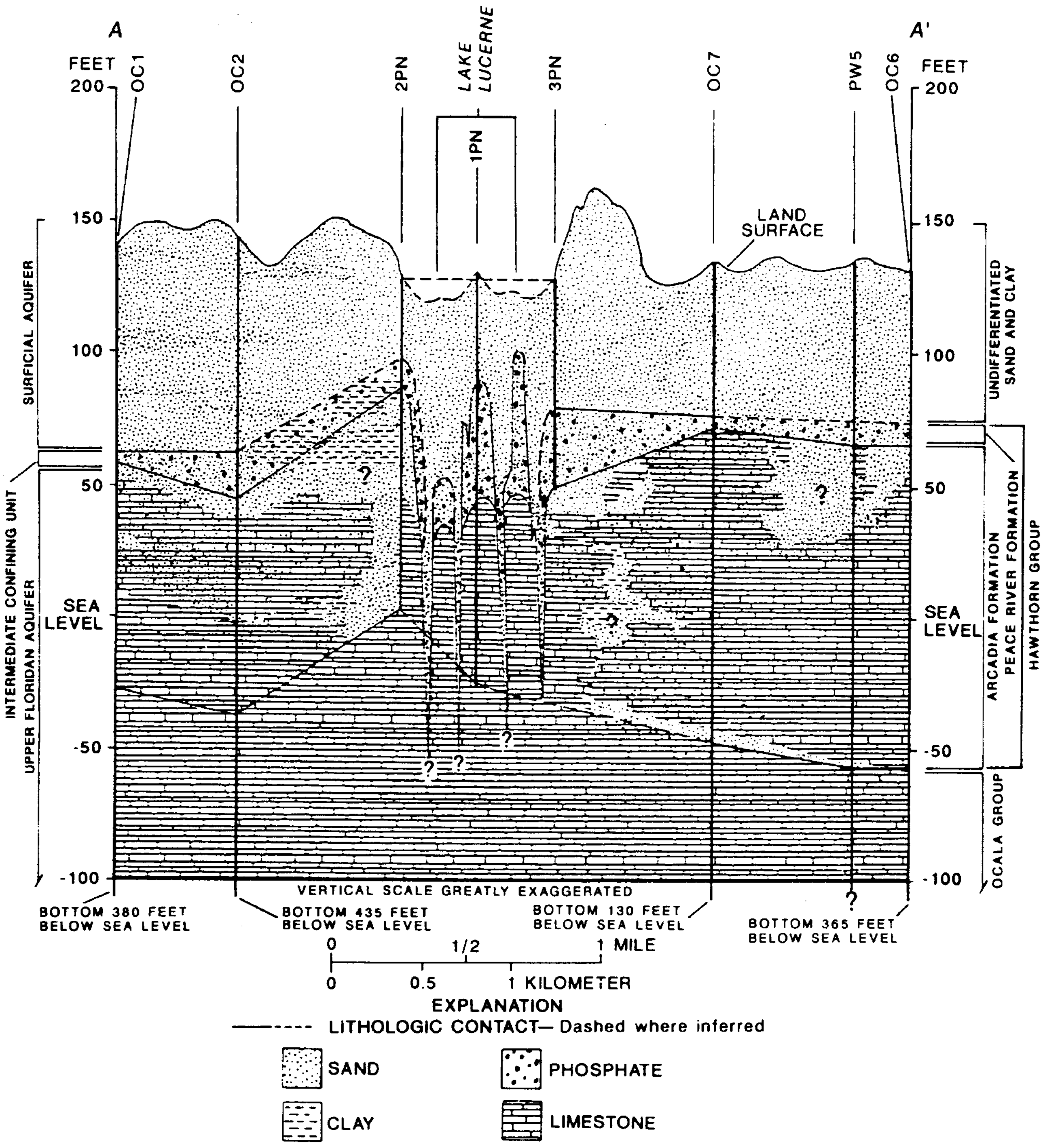

Figure 5. Hydrogeologic section of the study area (modified from Lee and others, 1991).

of the numerous small, circular lake basins in Florida (White, 1958). If the material infilling these cavities is of sufficiently low permeability, the resultant topographic depression will hold water. Large, irregularly shaped lakes can form when several sinkholes develop in close enough proximity to merge (Beck and others, 1984). The similarity between the bathymetric contours of the lake bottom and those of the solution features in the underlying limestone supports the conclusion that the Lake Lucerne basin developed as a sinkhole complex (fig. 7).

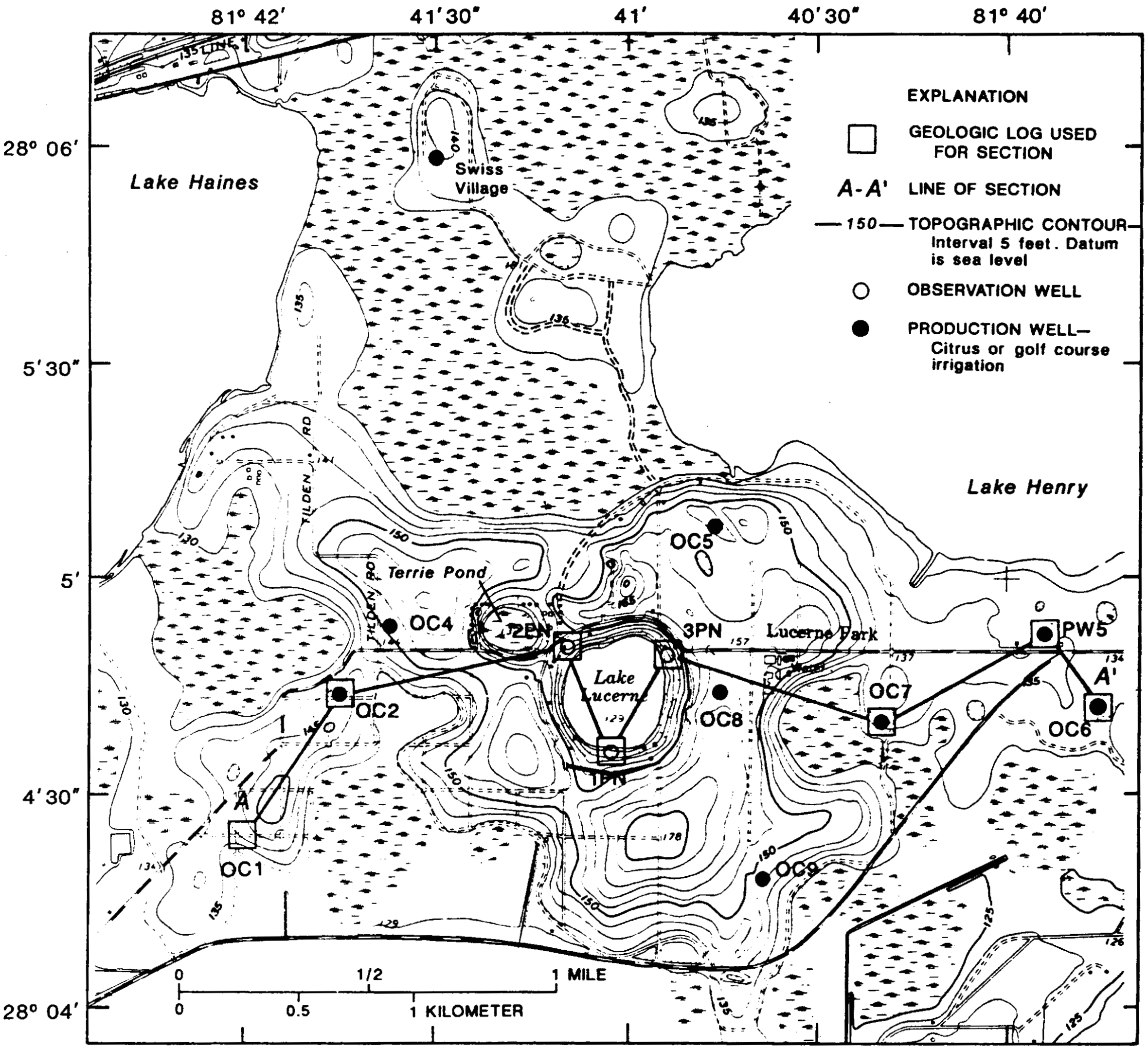

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Figure 6. Locations of wells whose logs were used to construct the hydrogeologic section (modified from Lee and others, 1991).

Ground-Water Flow Patterns

Ground-water flow patterns around Lake Lucerne were determined from contour maps of the water table in the surrounding surficial aquifer and from the vertical head distribution near the lake. The altitude of the water table and vertical head distribution around Lake Lucerne were measured in a network of 36 observation wells. Head also was measured in the surficial aquifer beneath the center of the lake. A well at the center of the lake was finished 8 ft below the lake bottom in clayey sand (fig. 8). Lee and others (1991) present a thorough discussion of the ground-water monitoring network and well-construction characteristics.

Ground-water flow patterns, determined from the configuration of the water table, indicate that the surficial aquifer around the lake is not part of a larger regional flow system. Instead, the lake and the surrounding surficial aquifer usually are isolated in a “closed” ground-water basin coincident with the topographic drainage basin. A ground-water divide in the aquifer generally coincided with the topographic drainage divide for the basin, and the water table around Lake Lucerne generally conforms to topographic contours. As a result, ground water in the surficial aquifer generally flowed in a centripetal pattern toward the lake. The configurations of the water table around Lake Lucerne for the dry (May 1986) and wet (October 1985) seasonal conditions for

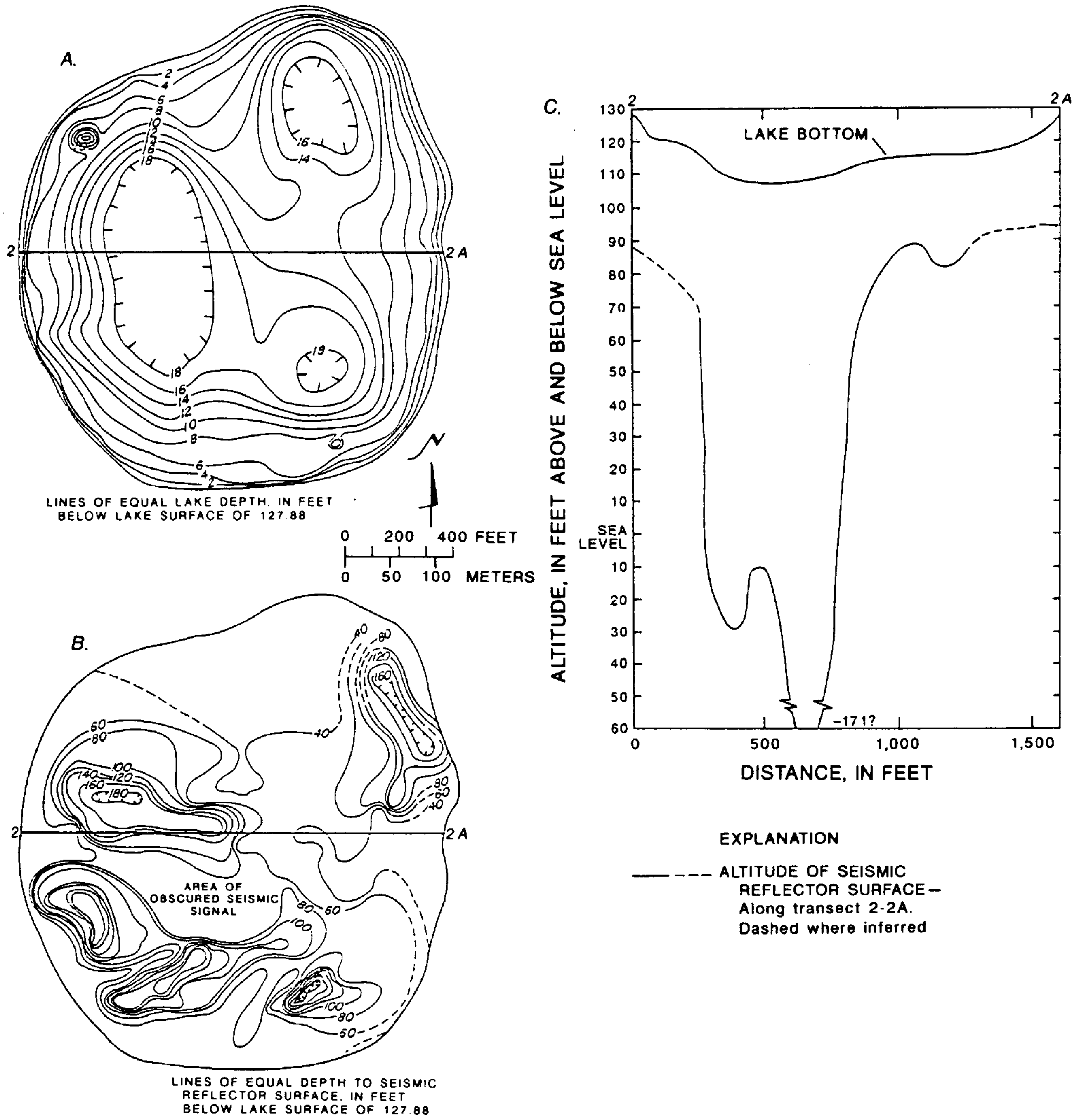

Figure 7. (*A*) Bathymetric and (*B*) seismic-reflection contours and (*C*) cross section of Lake Lucerne (modified from Lee and others, 1991).

the 1986 water year are shown in figure 9. The month of highest water-table altitude (October 1985) lagged behind the highest rainfall months of June and August 1985. The altitude of the water table in the surrounding basin never exceeded the lake stage by more than about 8 ft (fig. 9). The topography of the basin is shown in figure 6.

The surficial aquifer is approximately 45 to 55 ft thick around Lake Lucerne; however, the entire thickness of the aquifer does not contribute inflow to the lake. As lateral flow converges at the lake, it divides into upward and downward flowing components. The upward flow component contributes ground-water inflow to the lake. The downward

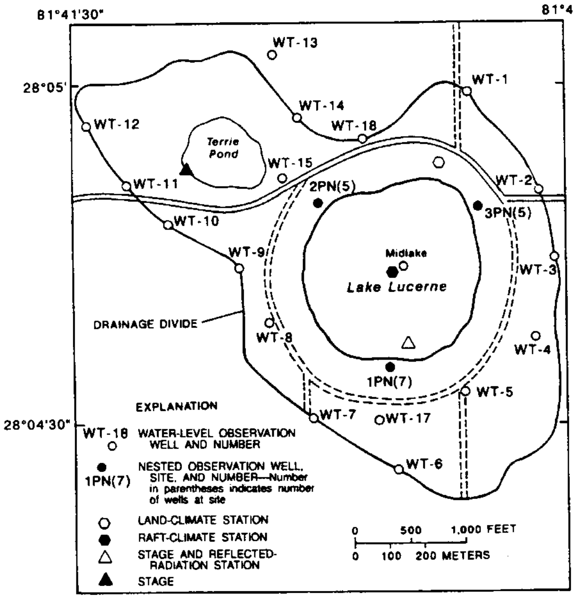

Figure 8. Data-collection sites in the Lake Lucerne study area (modified from Lee and others, 1991).

component flows beneath the lake and recharges the Upper Floridan aquifer through the breaches in the confining unit beneath the lake (Lee and others, 1991). At each of the nested well sites, the highest head most often occurred in the well at the 20-ft depth (see wells 1PN-20 and 2PN-20 in figs. 10 and 11, respectively), and head decreased in the wells above and below this depth. Thus, as an approximation, it can be considered that upward flow in the surficial aquifer above this depth generally contributed ground-water inflow to the lake, whereas downward flow below this depth did not (figs. 10 and 11).

Occasionally, downward head gradients occurred at all depths in the surficial aquifer, as indicated by measurements in the nested wells. The downward head gradients reflected downward flow and minimal lateral inflow to the lake (fig. 12). This downward flow pattern was short lived and usually resulted from rapid recharge to the surficial aquifer during the early part of the summer wet season. Downward head gradients also occurred at sites 1PN and 3PN during a dry period between January and March 1985 when rainfall was below normal, when water levels in the surficial aquifer were declining rapidly, and when a substantial drawdown of the water levels in the Upper Floridan aquifer was occurring (Lee and others, 1991).

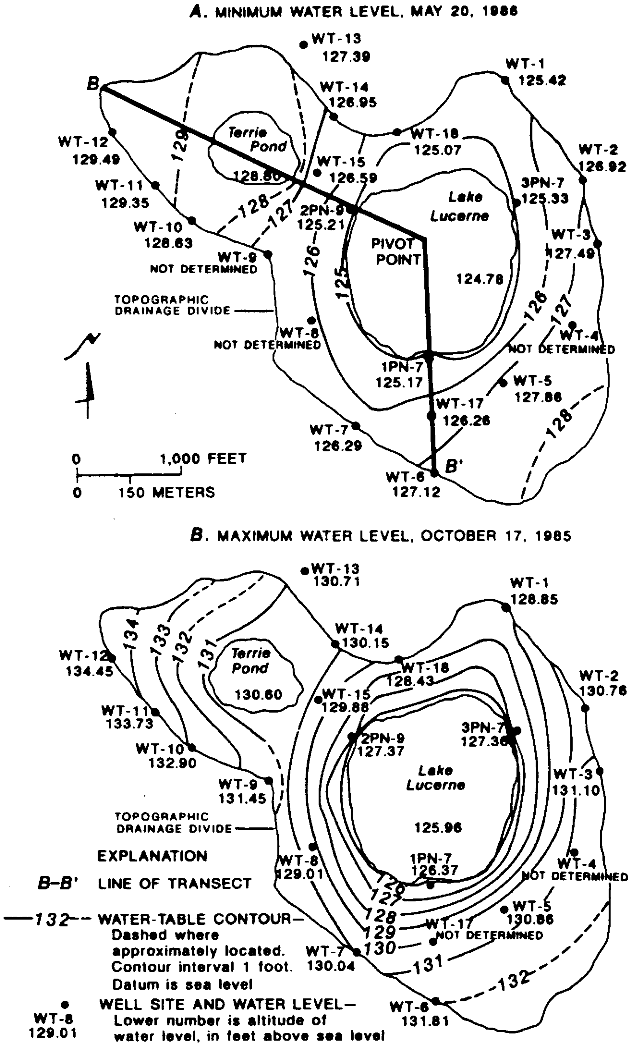

Figure 9. Configuration of the water table in the Lake Lucerne area based on (*A*) the minimum and (*B*) the maximum recorded water levels during the 1986 water year (modified from Lee and others, 1991).

Leakage through deeper regions of the lakebed flows downward toward the Upper Floridan aquifer. Leakage is indicated by the downward head difference between the lake and the midlake well (figs. 10 and 11). This vertical head distribution and the fact that radial flow in the surficial aquifer converges at Lake Lucerne indicate that the sinkhole complex beneath the lake is the preferential path for recharge to the Upper Floridan aquifer. Focused recharge below the lake supports the interpretation (based on the seismic-reflection survey) that the confining unit below the lake has been replaced by more permeable sands and clays and that the Upper Floridan aquifer is less confined below the lake than elsewhere in the surrounding basin.

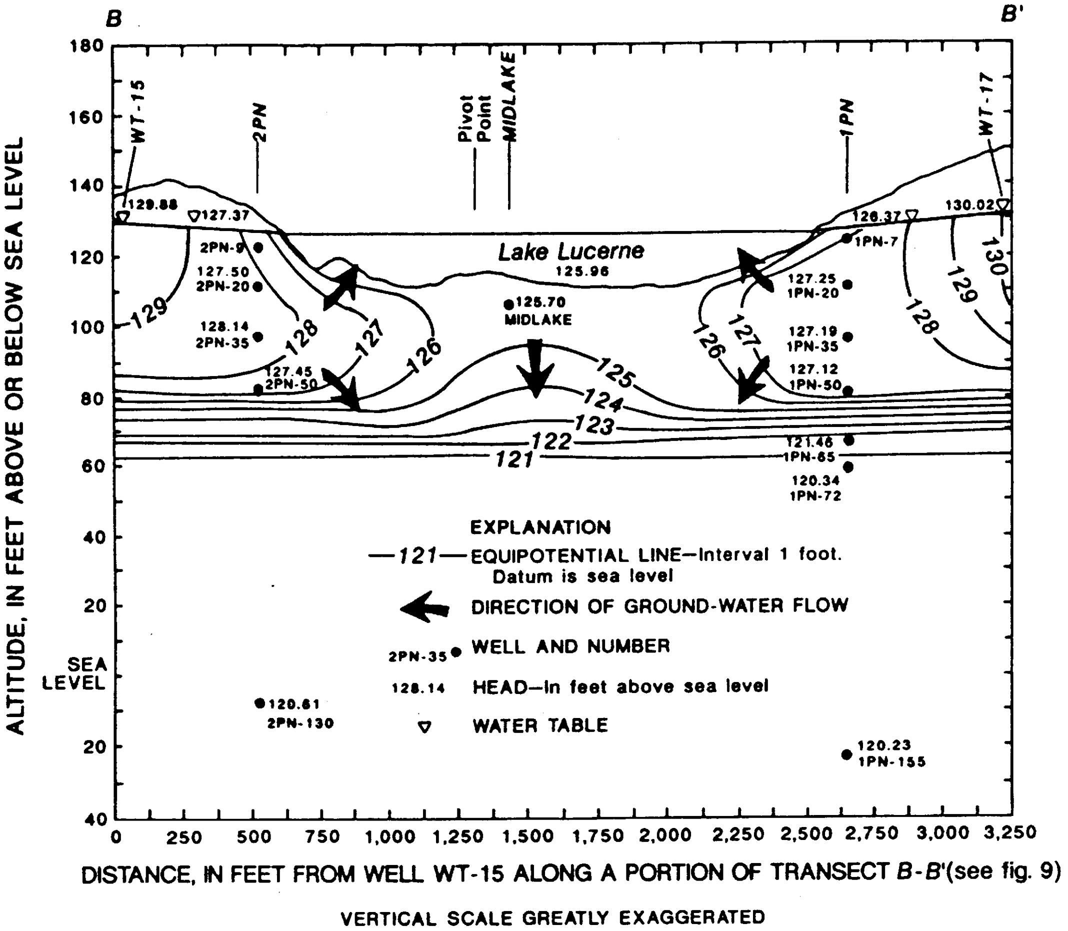

Figure 10. Vertical distribution of head during high water-level conditions, October 17, 1985 (modified from Lee and others, 1991).

Further evidence of substantial recharge to the Upper Floridan aquifer beneath Lake Lucerne is indicated by the head measurements in the midlake well, which were always substantially lower than heads measured at the same altitude in the three nested well locations. This head difference increased when the head in the Floridan aquifer was drawn down by pumping, as is the case in figure 11. Correlation analysis also indicated that head in the midlake well was more highly correlated to the head in the Upper Floridan aquifer than any other wells in the surficial aquifer near the lake (Lee and others, 1991).

Generally, the head distribution around the lake changed less in response to climate than it did to pumping from the Upper Floridan aquifer. Although the water table generally responded slowly to rainfall, the head in the Upper Floridan aquifer underwent large seasonal drawdowns as a result of pumping from citrus irrigation wells in and around the basin (Lee and others, 1991). Drawdown in the Upper Floridan aquifer approximately doubled the downward head gradient beneath the lake in May 1986, compared with October 1985, increasing the potential for lake leakage as well as recharge from the surficial aquifer to the Upper Floridan aquifer (figs. 10 and 11). The hydrograph for well 2PN-130 shows the rapid water-level declines caused by pumping (fig. 13). As a result, during the 1986 water year, downward head differences between the lake and the Upper Floridan aquifer were at a minimum during the late summer and fall (minimum monthly average value of 5.05 ft, September 1986). Maximum downward head differences occurred in the dry spring months from March to early June of 1986, when irrigation pumping was at a maximum (maximum monthly average value of 12.50 ft, May 1986). The approximate seasonal variation of the head in the Upper Floridan aquifer without the local effects of pumping was estimated by connecting the highest points in the hydrograph into a smooth curve (fig. 13).

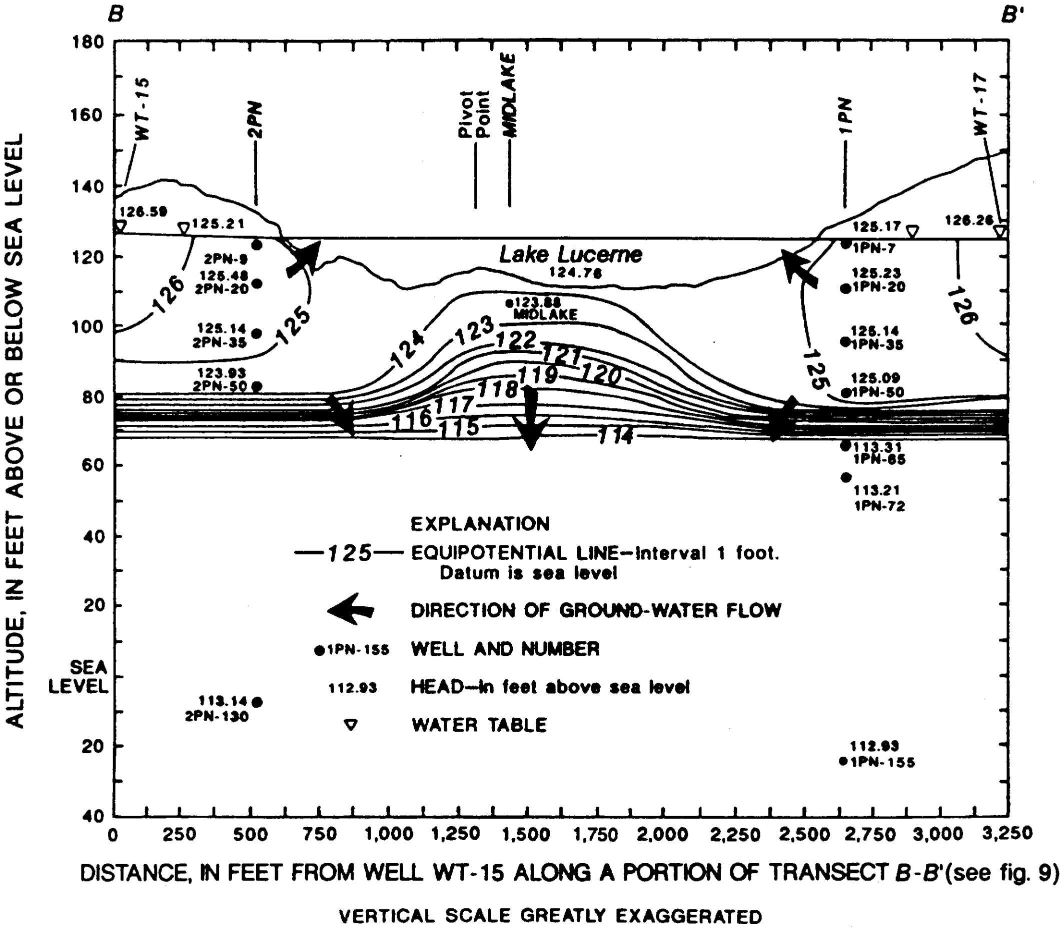

Figure 11. Vertical distribution of head during low water-level conditions, May 20, 1986 (modified from Lee and others, 1991).

Hydrologic-Budget Approach

The hydrologic-budget approach provides the basis for determining the relative importance of evaporation and ground-water fluxes to Lake Lucerne. In this section the hydrologic-budget approach is discussed, along with the approach for estimating error in computed budget components, such as evaporation and ground water. Error estimates are an important part of any hydrologic-budget equation because they indicate how well individual hydrologic fluxes are understood and measured. They also provide a measure of reliability or accuracy of the hydrologic budget as a predictive tool.

Because Lake Lucerne is a seepage lake and receives negligible overland flow, the hydrologic-budget equation can be stated simply:

$$\Delta S \pm e_S = P \pm e_P - E \pm e_E + GI \pm e_{GI} - GO \pm e_{GO} \quad (1)$$

where

ΔS is the change in lake storage or volume for the period of interest,
P is direct precipitation to the lake,
E is evaporation from the lake surface,
GI is ground-water inflow to the lake,
GO is leakage outflow from the lake, and
e_i is the standard deviation or confidence limits around each measured term *i*.

This standard deviation is considered to be the uncertainty or error in each term *i*. The unit of volume for each term is the equivalent depth, in feet, over the lake surface.

Measured terms (for example, *P*) have an associated error depending on the method of

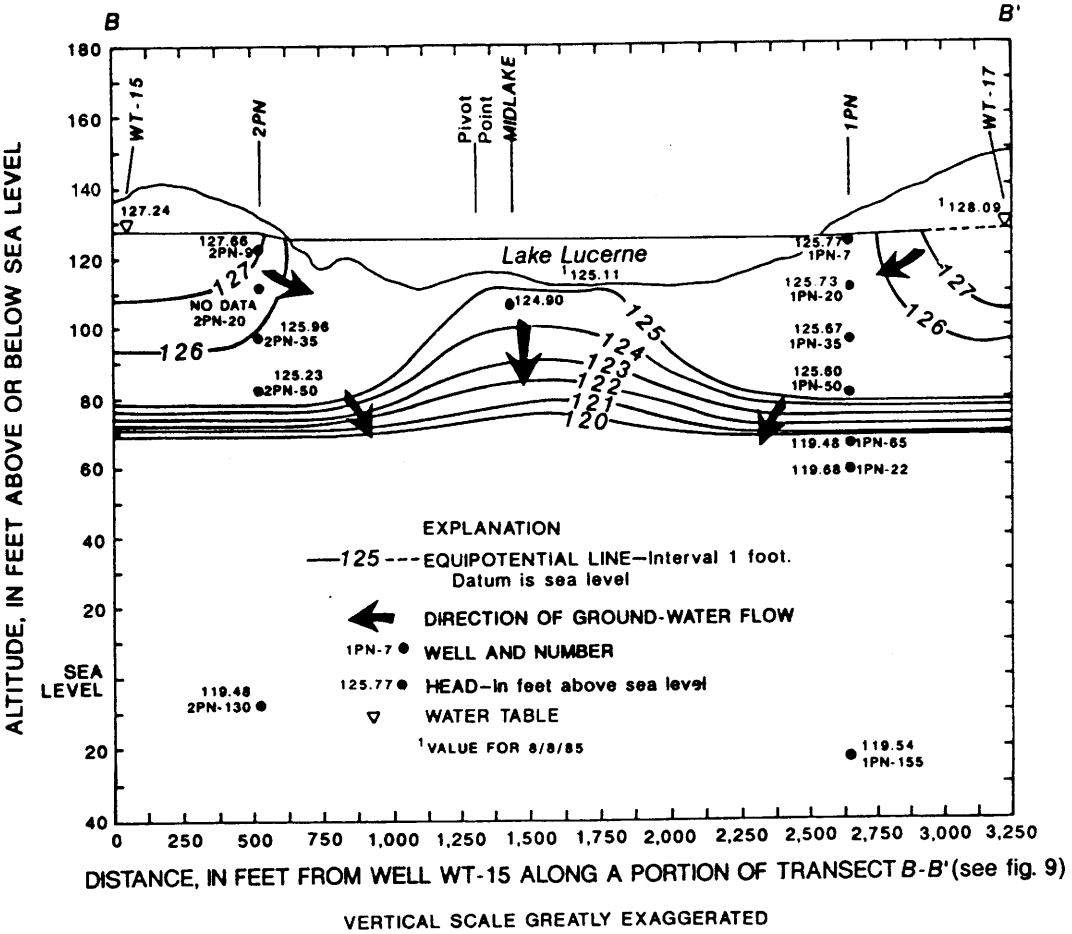

Figure 12. Vertical distribution of head showing downward head gradient conditions, August 6, 1985 (modified from Lee and others, 1991).

measurement. Budget terms that are calculated from more than one measured variable accumulate the errors in the measured terms. If a term is derived as the sum or difference of other measured terms, error is the sum of the variances in the measured terms (Ramette, 1981; Winter, 1981b; LaBaugh, 1985). For example, if a residual term R is calculated as

$$R \pm e_R = A \pm e_A + B \pm e_B + C \pm e_C \qquad (2)$$

in which A, B, and C are measured quantities with associated errors e_A, e_B, and e_C, respectively, e_R is calculated as

$$e_R = \sqrt{e_A^2 + e_B^2 + e_C^2} \qquad (3)$$

and the error in R is independent of the measured values of A, B, and C.

The standard deviation around each measurement was not determined as a part of this study. Instead, the percentage error ascribed in the literature to various methods was used to define the confidence limits around measured values. Equation 3 becomes

$$e_R = \sqrt{(\%e_A \bullet A)^2 + (\%e_B \bullet B)^2 + (\%e_C \bullet C)^2} \qquad (4)$$

where $\%e_i$ is the percentage error (expressed fractionally) attributed to the average measurement of component i for a given method. Winter (1981b) used this approach to compare the errors in net ground-water flow terms derived as residual terms to the hydrologic-budget equation.

Alternately, if a term is calculated by the multiplication or division of other measured terms, as in

$$R \pm e_R = (A \pm e_A)\,[(B \pm e_B)/(C \pm e_C)] \qquad (5)$$

then

$$\%e_R = \sqrt{(\%e_A)^2 + (\%e_B)^2 + (\%e_C)^2} \qquad (6)$$

It is important to note that these calculated errors represent the maximum probable error in the computed term. This approach is based on the assumption that the measurement of each hydrologic-budget component is independent of other components and that no intercorrelations or covariances exist between measurement errors (Winter, 1981b; LaBaugh and Winter, 1984).

EVAPORATION

Numerous lakes and intense solar radiation make lake evaporation an important hydrologic process in Florida. The occurrence of a large, natural lake district at a subtropical latitude is an unusual geographic feature that Florida shares only with the country of China. Because of its low latitude, Florida has the highest annual evaporation of any State east of the Mississippi River (Farnsworth and others, 1982). It also is the warmest State in the Nation and has the smallest seasonal range in air temperatures (about 30 °F) around warm annual mean temperatures. The annual mean air temperature ranges from the upper 60's in north Florida to the middle 70's in southern Florida, excluding the Florida Keys, which average nearly 78 °F (Heath and Conover, 1981). Water temperatures are correspondingly warm. Lakes in Florida never freeze, and because they tend to be shallow, most are well mixed and do not thermally stratify for long periods (Brenner and others, 1990).

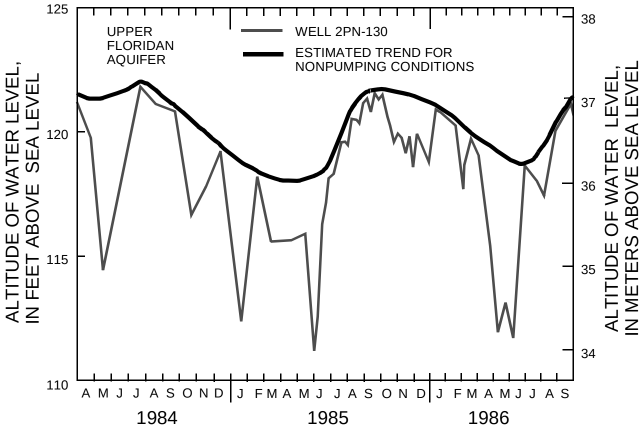

Figure 13. Water levels in well 2PN-130 from April 1984 through September 1986 and the estimated trend in water levels for nonpumping conditions.

In this section, lake evaporation is computed by three different methods, the energy-budget method, mass-transfer method, and pan-evaporation method. These three techniques vary considerably in their complexity and reported accuracy. The energy-budget method is the most accurate of the three methods, but it also is the most complicated. It provides the evaporation estimate used in the hydrologic budget. The mass-transfer method also is presented and compared with the energy-budget method as a simpler but less accurate alternative. Finally, pan evaporation, the most widely used index of lake evaporation, is compared with the two theoretically based evaporation methods. The possible error in each method is also discussed.

Energy-Budget Method

An energy budget accounts for all fluxes of energy into and out of a system, such as a lake. The energy budget is considered to be the most accurate method for measuring evaporation from lakes for periods of a week or longer (Winter, 1981b). It also is a complex method that is costly and manpower intensive; therefore, the method is used infrequently.

Theory and Equations

When the energy-budget method is applied to a system, the energy used for evaporation is calculated as the residual energy after all other energy fluxes are summed. The volume of water evaporated is calculated by dividing the residual energy used for evaporation by the latent heat of evaporation and the density of water. The general form of the energy-budget equation is

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_w - Q_h - Q_e = Q_x \qquad (7)$$

where

Q_s is incident shortwave solar radiation,
Q_r is reflected shortwave solar radiation,
Q_a is incident longwave radiation from the atmosphere,

Q_{ar} is reflected longwave radiation,

Q_{bs} is longwave radiation emitted by the lake,

Q_v is net energy advected by streamflow, ground water, and precipitation,

Q_w is energy advected by evaporating water,

Q_h is energy conducted and convected from the lake to the atmosphere as sensible heat,

Q_e is energy used for evaporation, and

Q_x is change in stored energy.

The energy flux units used in this study are metric units of calories per square centimeter per day. Metric units are conventionally used in studies of energy-budget and mass-transfer evaporation. Therefore, fundamental equations are presented in metric units and metric units are used for calculation purposes in this study (see app. A and B). Final evaporation results in this section, however, are presented in inch-pound units to be consistent with the inch-pound units used in the remainder of the report.

The terms Q_s, Q_r, Q_a, Q_{ar}, Q_{bs}, Q_v , and Q_x were all measured directly. Three other types of energy flux—conduction of heat through the lake bottom, heating due to chemical and biological processes, and the conversion of kinetic energy to heat energy—are assumed to be negligible (Anderson, 1954). The instrumentation used to measure energy fluxes and the resulting energy values are discussed in detail by Lee and others (1991). Briefly, three radiometers were used to measure incident and reflected shortwave radiation (Q_s and Q_r) and incident longwave radiation (Q_a). One longwave radiometer, positioned facing downward toward the lake surface, was used to measure the sum of reflected (Q_{ar}) and backscattered (Q_{bs}) longwave radiation from the lake.

Advected heat (Q_v) enters lakes from rainfall, surface-water, and ground-water inflow, and it leaves through surface-water and ground-water outflow. Q_v may be a difficult component to measure accurately in a lake or reservoir with large surface-water inflow and outflow, and the error in this measurement can be a limiting factor to successful application of the energy-budget method. Rainfall is assumed to be the only source of advected heat to Lake Lucerne. Advected heat from ground water is assumed to be negligible for this study. Advected heat energy from rainfall is calculated from the daily rainfall amount and the average wet-bulb temperature.

The change in stored energy (Q_x) is an important component of the energy budget because the large specific heat capacity of water allows even a small lake to store and exchange large amounts of heat energy. Stored heat was computed from weekly thermal surveys of the lake. Each thermal survey consisted of vertical temperature measurements at 1-ft intervals taken at six sites on the lake. The time interval between successive thermal surveys is the thermal survey period. In addition, a string of thermocouples on a midlake raft measured the water temperature at 1-ft depth intervals. The thermocouple string provided a continuous record of lake temperatures from which daily heat content values were calculated. A strong correlation ($R = 0.99$) between the average thermal survey temperatures and the temperatures measured by the thermocouples at each depth supported the use of thermocouple data to compute total heat content of the lake on a daily and weekly basis.

In previous energy-budget studies the thermal survey period between manual thermal surveys defined the shortest time period for which evaporation could be calculated, often 7-day periods or longer. In this study, because of the high correlation of the thermocouple measurements with the thermal survey data, it was possible to calculate stored heat and evaporation on a daily basis for 321 days. During periods when daily thermocouple readings were missing, only weekly evaporation computations were made. The total stored heat and daily average change in stored heat for each thermal survey period and daily total stored heat and change in stored heat from the thermocouple string measurements are shown in figures A1 and A2 of appendix A.

Three components of the energy budget—the energy advected by evaporating water (Q_w), the energy conducted to the atmosphere as sensible heat (Q_h), and the energy used for evaporation (Q_e)—were not measured directly but were calculated by using the following relations.

Energy advected by evaporating water can be computed as

$$Q_w = c\rho E_{EB} \, (T_0 - T_b) \qquad (8)$$

where

c is specific heat of water [1 calorie per gram per degree Celsius (cal/g/°C)];

ρ is density of evaporating water [1 gram per cubic centimeter (g/cm^3)];

E_{EB} is volume of evaporating water by the energy-budget method, in cubic centimeters per square centimeter per day;

T_0 is water-surface temperature, in degrees Celsius; and

T_b is reference base temperature (0 °C).

The energy used for evaporation (Q_e) also can be expressed as

$$Q_e = \rho E_{EB} L \qquad (9)$$

where

L is latent heat of vaporization, in calories per gram.

Q_h and Q_e are combined by using a theoretical relation derived by Bowen (1926). The Bowen ratio (BR) is the ratio of sensible heat (Q_h) to the heat energy used for evaporation (Q_e):

$$BR = Q_h / Q_e \qquad (10)$$

As neither Q_h nor Q_e can be measured directly, the Bowen ratio has been widely used in evaporation studies. The ratio can be calculated as

$$BR = 0.00061P(T_0 - T_a)/(e_0 - e_a) \qquad (11)$$

where

P is barometric pressure, in millibars;

T_0 is water-surface temperature, in degrees Celsius;

T_a is air temperature at 2 m above the lake, in degrees Celsius;

e_0 is saturation vapor pressure at the water-surface temperature, in millibars; and

e_a is vapor pressure at 2 m above the lake, in millibars.

By placing the three components that were not measured directly (Q_w, Q_h, and Q_e) on one side of equation 7, substituting relations 9, 10, and 11, and solving for E_{EB}, the final energy-budget equation used in this study is produced:

$$E_{EB} = \frac{Q_s - Q_r + Q_a + Q_{ar} - Q_{bs} + Q_v - Q_x}{L(1 + BR) + T_0} \qquad (12)$$

The results of the energy-budget calculation by thermal survey periods are summarized in appendix A. Thermal survey periods range from 5 to 9 days in length; 72 percent are 7 days in length.

Energy-Budget Evaporation Rates

The energy-budget evaporation rates calculated for each thermal survey period, and for 321 days when daily measurements of stored heat were available, are shown in figures 14 and 15. The total evaporation for the 52-week period of record from October 1, 1985, to September 30, 1986 (1986 water year), was 57.87 in. The highest daily average rate of evaporation calculated by thermal survey period was 0.264 inches per day (in/d) between April 29 and May 5, 1986, and also between May 27 and June 2, 1986; a total of 1.85 in. for each week. The lowest rate was 0.040 in/d between December 31, 1985, and January 6, 1986; a total of 0.28 in. for the week.

Annual lake evaporation derived by the energy-budget method was 8 to 10 in. greater than the estimated long-term average evaporation at Lake Lucerne. Annual “shallow” lake evaporation published by NOAA, based on pan-evaporation data, ranged from 48 to 50 in/yr for the period 1946 to 1955 (Kohler and others, 1955). The average for the period 1956 through 1970 was 48 in/yr (Farnsworth and others, 1982). Increased solar radiation during the drought that coincided with the study period is probably responsible for the increase in evaporation rates.

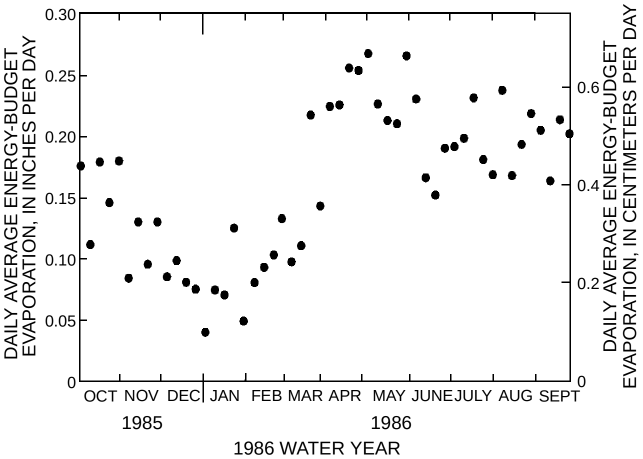

Figure 14. Daily average energy-budget evaporation at Lake Lucerne by thermal survey period for the 1986 water year.

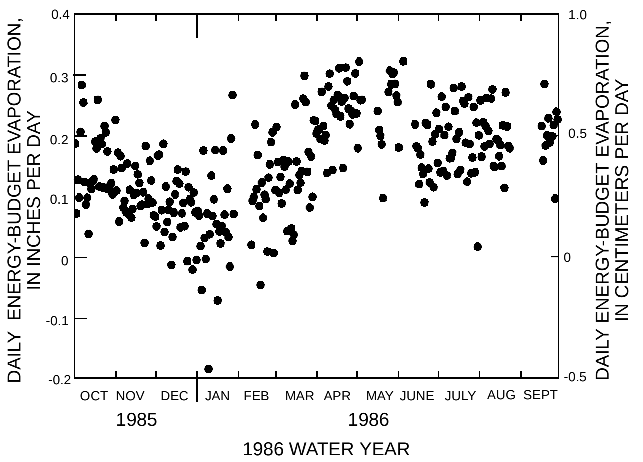

Figure 15. Daily energy-budget evaporation at Lake Lucerne for 321 days of the 1986 water year.

Comparison of Thermal Survey Period and Daily Evaporation Estimates

Daily evaporation estimates closely agreed with the results by thermal survey period (figs. 14 and 15). To compare the evaporation estimates computed for different time periods, daily evaporation rates were averaged to compute an equivalent evaporation estimate by thermal survey period. All the components in the energy budget, except for stored heat and the Bowen ratio, were calculated by averaging daily estimates over each thermal survey period. The correlation between evaporation rates computed by these two different approaches was very good (0.94), the standard error of estimate being 0.02 in/d.

The largest differences between daily and thermal survey estimates occurred during periods of low evaporation in the winter. For periods when the evaporation rate was less than 0.138 in/d, average differences, expressed as the relative percent difference between daily and thermal survey calculations, were 25 percent. When the evaporation rate was greater than 0.138 in/d, the average relative percent difference was 5 percent.

Use of the Bowen ratio in developing equation 12 has been recognized as a source of uncertainty in the energy-budget method (Anderson, 1954). When evaporation rates are high, the Bowen ratio functions as a small correction factor. When evaporation is low, the Bowen ratio can cause instability in the energy-budget equation, which results in unrealistic evaporation estimates. Instability in the equation occurs when the temperature gradient ($T_0 - T_a$) is negative (when the average lake-surface temperature is lower than the average air temperature) or when the vapor pressure gradient ($e_0 - e_a$) approaches zero. Plots of the daily vapor pressure and temperature gradients in figure 16 show that these conditions occurred during the winter months from November to March.

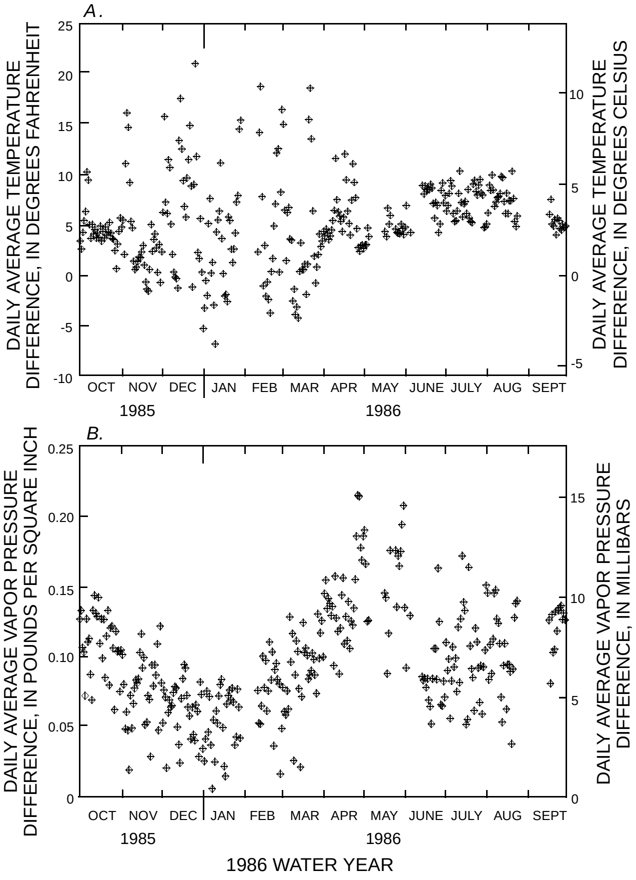

Figure 16. (*A*) Daily average temperature difference and (*B*) vapor pressure difference between the surface of Lake Lucerne and 2 meters above the lake surface for the 1986 water year.

The effect of small or inverted temperature and vapor pressure gradients on the Bowen ratio can be seen in the plot of daily Bowen ratios (fig. 17). The validity of this ratio is questionable if it is less than –1.0 or greater than 1. When this occurs, normally acceptable errors in daily measurements of temperature and vapor pressure result in unrealistic evaporation estimates. One example of the effect of a Bowen ratio outside this range on the energy budget occurred on January 10, 1986, when the Bowen ratio was –1.32. The use of this value in the energy budget resulted in a highly unlikely negative evaporation (condensation) rate of –0.461 in/d.

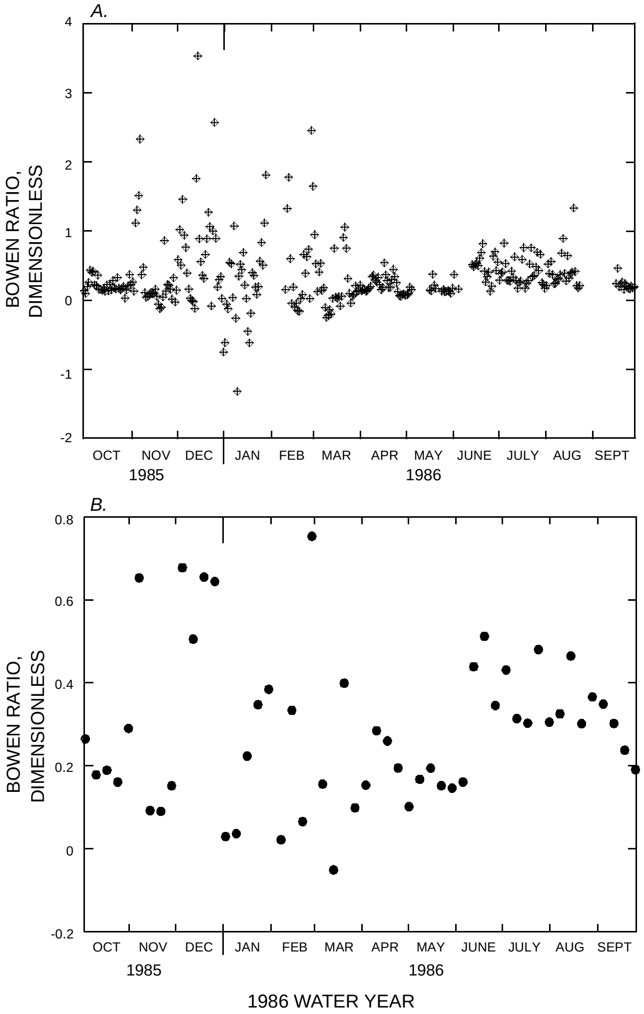

Figure 17. (*A*) Daily average Bowen ratios and (*B*) average Bowen ratios by thermal survey period for the 1986 water year.

At Lake Lucerne, Bowen ratios outside of the range –1.0 to +1.0 occurred on 21 days, a total of 5.8 percent of the record. All but one of these occurrences were between November and March. When evaporation was calculated over longer time periods, such as the thermal survey periods, the averaging of daily values generally resulted in Bowen ratios within the acceptable range (fig. 17). On a thermal survey basis, there was only one small negative Bowen ratio, and there were no negative values for evaporation.

Energy-Budget Error Analysis

Error associated with energy-budget evaporation rates is primarily a function of instrument precision and the adequacy of data estimation methods for periods of missing record. Instrument errors were determined from either instrument specifications of the manufacturer or from field or office calibrations. Errors in data estimates were quantified as the standard errors of the linear regression relations used to estimate values for periods of missing record. These standard errors were always greater than instrument errors alone because of the imperfect linear relation between variables. The instrumentation used for this study and the data estimation methods are described by Lee and others (1991).

The weighted average error for a measured component is calculated for a given time interval as follows:

$$\text{Weighted average error} = \frac{\Sigma(e_i n_i)}{n_T} \qquad (13)$$

where

e_i is type *i* error, in measured units;
n_i is number of days of type *i* error; and
n_T is total number of days.

After a weighted average error was calculated for each energy-budget component, the errors were combined to produce an error in computed evaporation. The algebraic manipulation of each component in equation 12 determined the way the errors were combined (Ramette, 1981).

The weighted average error of each energy-budget component was calculated for the 1-yr study period. The greatest relative error occurred in the Q_x term (60.7 percent). Lake-water temperature measurements were accurate to ±0.1 °C, resulting in an error of less than 0.5 percent in the total stored heat for the lake. However, this error can be large in comparison with the change in stored heat (Q_x) between thermal surveys. The Bowen ratio also is subject to large errors because it too is a function of the difference between absolute measurements of temperature and vapor pressure (eq. 10). Relative errors for the remaining components of the energy budget generally were less than 5 percent (see app. A).

The error in the total evaporation for the study period is 16.4 percent. Without estimated data, the error would be 13.6 percent, and if all the data were estimated, the error could be as great as 24.9 percent. Evaporation errors also were calculated by month (table 1). In general, errors were greatest relative to evaporation when evaporation rates were least, which was during the winter months from November to March. This primarily reflects the large relative error associated with making measurements of the smaller energy components that contribute to evaporation during these months. Large relative errors also occurred when the errors contained in data estimates were much greater than measurement errors.

Table 1. Monthly energy-budget evaporation rates and errors, October 1985 through September 1986

Year and month	Monthly evaporation (inches)	Relative error (percent)
1985:		
October	4.70	27.1
November	3.49	27.6
December	2.65	22.8
1986:		
January	2.29	27.1
February	2.56	20.0
March	4.32	15.6
April	7.16	16.2
May	7.12	19.1
June	5.63	12.8
July	6.04	13.4
August	6.08	13.5
September	5.83	15.7

Sensitivity Analysis

To determine which errors have the greatest effect on energy-budget evaporation, a simple sensitivity analysis was performed using the thermal survey period data. The results of this analysis indicate which components require the most attention during data collection for seepage lakes in Florida.

Each component of the energy budget was varied from 50 percent less to 50 percent more than the original value, and the evaporation for each thermal survey period was then recalculated. The results are shown in figure 18 as change in calculated evaporation expressed as a percentage of the original evaporation.

Terms in the numerator of equation 12 cause a linear increase in the evaporation error, but the slopes vary considerably, depending upon the magnitude of the component and its sign (fig. 18). A change in the sum of reflected and emitted longwave radiation, which is the largest term in the numerator, causes the largest change in the computed evaporation. A 10-percent error in this term causes a 35-percent error in computed evaporation. Errors in incident shortwave and longwave radiation also are important and produce 20- and 30-percent errors in the rate of evaporation, respectively (fig. 18).

Terms that appear in the denominator of equation 12 have a nonlinear relation with computed evaporation. Of these, water-surface temperature is most important because it appears in three places in the denominator: in the Bowen ratio, in the calculation of the latent heat of vaporization, and as a constant. Underestimating the water-surface temperature increases the error of the calculated evaporation more than does overestimation (fig. 18).

Other components of the energy budget have less effect on the error in evaporation at Lake Lucerne. Large errors in smaller components, such as reflected shortwave radiation, advected heat, and stored heat, have little effect. The energy budget is only moderately sensitive to the value of the Bowen ratio; a 10-percent error in the Bowen ratio produces a 2-percent error in the calculated evaporation. Changes in barometric pressure, which was measured at Lake Lucerne (Lee and others, 1991), had an insignificant effect on the calculation of energy-budget evaporation. Barometric pressure varied less than 2 percent of the mean [1,021 millibars (mb)] for the period of record. An average barometric pressure could have been used without adding to the error in the method.

The priorities for measurement accuracy suggested by this analysis should apply to energy-budget calculations for other seepage lakes in central Florida. However, other terms can be of greater importance for lakes in different settings. For example, changes in stored heat will be greater for lakes in temperate climates, and advected heat can be a major source of error for lakes with surface-water inflows and outflows.

Mass-Transfer Method

The mass-transfer method relates evaporation to the processes affecting the removal of water vapor from the boundary layer above the air-water interface at the surface of the lake. As the wind speed over the water surface increases, water vapor is removed from the system more rapidly. This causes the vapor pressure gradient above the lake to increase, thereby increasing evaporation. Thus, evaporation can be directly related to both wind speed and vapor pressure gradient.

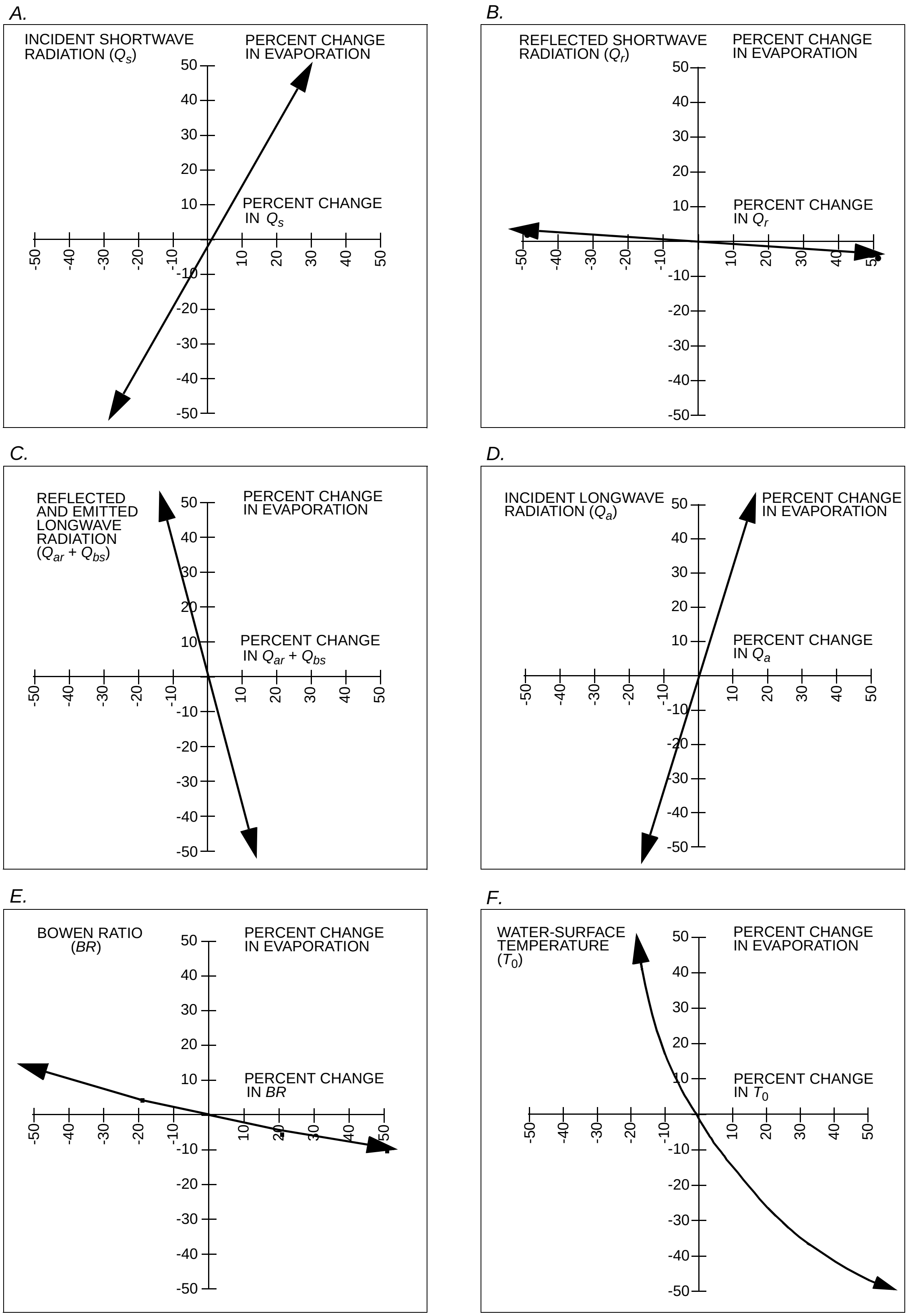

Figure 18. Sensitivity of energy-budget evaporation to errors in (*A*) incident shortwave radiation, (*B*) reflected shortwave radiation, (*C*) reflected and emitted longwave radiation, (*D*) incident longwave radiation, (*E*) Bowen ratio, and (*F*) water-surface temperature.

Theory and Equations

The mass-transfer method was developed during studies of Lake Hefner (Marciano and Harbeck, 1954) and Lake Mead (Harbeck and others, 1958). Reports from these two studies contain theoretical discussions of the boundary layer structure and derive the following general equation for mass transfer:

$$E_{MT} = Nu_2(e_0 - e_a) \qquad (14)$$

where

E_{MT} is evaporation by the mass-transfer method, in centimeters per day;
N is mass-transfer coefficient;
u_2 is daily average wind speed at 2 meters (m) above the lake, in miles per hour;
e_0 is saturation vapor pressure at the water-surface temperature, in millibars; and
e_a is vapor pressure of the air at 2 m above the lake surface, in millibars.

The two vapor pressure measurements also are used for the energy-budget method, so wind speed at 2 m (6.6 ft) above the lake surface was the only additional measurement needed to calculate evaporation by the mass-transfer method.

Mass-Transfer Coefficient

A number of methods have been used to determine *N*, the mass-transfer coefficient. For studies where an energy budget also has been done, the best estimate of *N* is a calibration between the mass-transfer method and the energy-budget method. Energy-budget evaporation is regressed against the mass-transfer product (the product of the wind speed at 2 m (6.6 ft) and the vapor pressure gradient) averaged for a given period, and *N* is estimated as the slope of the best-fit line through the data.

A plot of the relation of energy-budget evaporation to the mass-transfer product for the 52 thermal survey periods is shown in figure 19. Three methods were used to estimate the slope of the line of relation fitted to the data in figure 19. A linear regression through the origin produced a slope (*N*) of 0.0112 and the standard error of estimating energy-budget evaporation with the regression is 0.04 in/d (0.10 cm/d). A ratio of the mean energy-budget evaporation to the mean mass-transfer product for the entire 52 weeks was 0.0114. The mean of the ratios of energy-budget evaporation to the mass-transfer product by thermal survey period was 0.0115. Because there was a less than 3-percent difference between these three estimates, the mean (0.0114) was selected as the final value for *N*.

Comparison of Mass-Transfer and Energy-Budget Evaporation Rates

Pronounced seasonal differences exist between evaporation calculated by the energy-budget and mass-transfer methods. Mass-transfer evaporation was greater than the energy-budget evaporation in the winter and less in the summer. Seasonal differences between the two methods also have been found in other energy- budget and mass-transfer studies (Harbeck and others, 1958; Ficke, 1972). These differences have been attributed to errors in the energy-budget method, the mass-transfer method, or both.

At Lake Mead the seasonal difference between the energy-budget and mass-transfer methods was attributed to the influence of seasonal changes in atmospheric stability on evaporation estimated by the mass-transfer method (Harbeck and others, 1958). The empirically based form of the mass-transfer equation used for this study and for the Lake Mead study (eq. 14) is based on the assumption that atmospheric stability and *N*, the mass-transfer coefficient, are relatively constant. Before an equation of this type is used, however, each set of mass-transfer data should be tested to ensure that this assumption is valid.

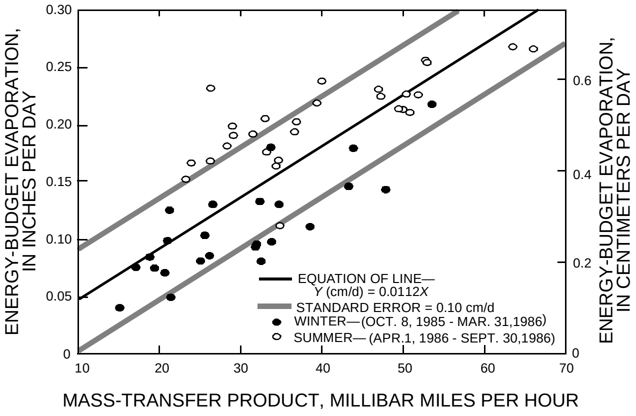

Figure 19. Relation between energy-budget evaporation and the mass-transfer product by thermal survey period.

Stability

A stability parameter, S_{MT}, which is proportional to the Richardson number, can be defined as follows (Harbeck and others, 1958):

$$S_{MT} = (T_h - T_0)/(u_h)^2 \qquad (15)$$

where

T_h is temperature at height h, in degrees Celsius;

T_0 is temperature of the lake surface, in degrees Celsius; and

u_h is wind speed at height h, in miles per hour.

The stability parameter is a measure of buoyant forces (represented by the temperature gradient) relative to the turbulent forces (represented by the wind speed) acting on an airmass. When buoyant forces dominate, S_{MT} is high and the mass-transfer equation underestimates evaporation. When turbulent forces dominate, S_{MT} is low and the mass-transfer equation tends to overestimate evaporation (Rosenberg and others, 1983).

Changes in atmospheric stability at Lake Lucerne explained some of the difference between evaporation computed using the energy-budget and mass-transfer methods. Components of the energy-budget and mass-transfer methods were checked for correlation with the difference between the two methods. The difference was correlated with the stability parameter and the water-surface temperature for data by thermal survey periods. The atmospheric stability parameter (S_{MT}) increases in the summer, when wind speeds and vapor pressure gradients are small and temperatures are high, and decreases in the winter. For the Lake Lucerne data, the stability parameter also was correlated with N (see Harbeck and others, 1958). An alternative mass-transfer equation was developed by adding a correction factor based on the relation between N and the stability parameter to the original mass-transfer equation:

$$E_{MT} = u_2(e_0 - e_a)[-0.0337(S_{MT}) + 0.0074] \qquad (16)$$

where

E_{MT} is mass-transfer evaporation, in centimeters per day;

u_2 is wind speed at 2 m (6.6 ft) above the lake, in miles per hour;

e_0 is saturation vapor pressure at the water-surface temperature, in millibars;

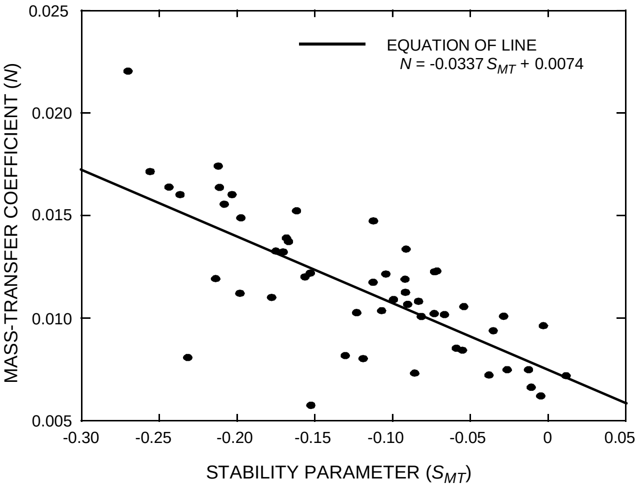

Figure 20. Relation between the mass-transfer coefficient (N) and the stability parameter (S_{MT}) by thermal survey period.

e_a is vapor pressure at 2 m (6.6 ft) above the lake, in millibars; and

S_{MT} is stability parameter

In this equation, N was determined by a linear regression against S_{MT} with a slope equal to –0.0337 and y-intercept equal to 0.0074 (fig. 20). N is no longer a constant but is dependent on stability.

Mass-Transfer Evaporation Rates

The mass-transfer evaporation rates, corrected for atmospheric stability for each thermal survey period, are shown in figure 21. The total evaporation for the 52-week period of record from October 1, 1985, to September 30, 1986 (1986 water year), was 57.39 in. The largest daily average rate of evaporation calculated by thermal survey period was 0.265 in/d between April 22 and 29, 1986; a total of 1.86 in. The smallest rate was 0.047 in/d between December 31, 1985, and January 6, 1986; a total of 0.33 in.

Mass-Transfer Error Analysis

The maximum probable error in the uncorrected mass-transfer estimate of evaporation for the 1-yr period of record was 31 percent when the value of 0.0114 was used for N. The large error in this method is due to the large standard error in determining N from the linear regression of the mass-transfer product with the energy budget (25 percent) and errors in the measurement of vapor pressure gradients (18 percent).

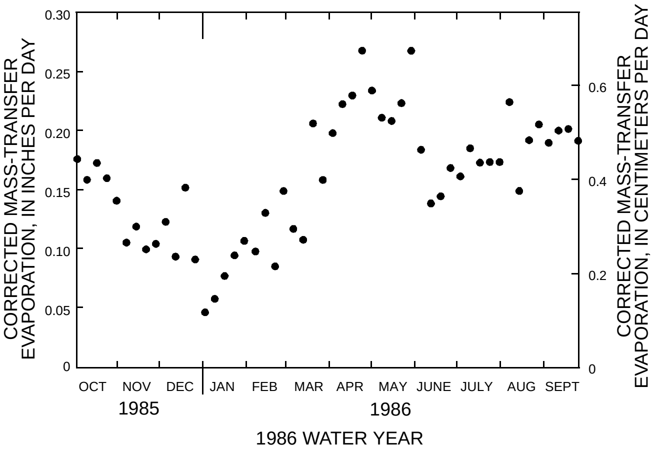

Figure 21. Mass-transfer evaporation rates corrected for atmospheric stability by thermal survey period for the 1986 water year.

Incorporating the effects of atmospheric stability reduced the error in the mass-transfer method by 10 percent. The differences between the energy-budget evaporation and both the corrected and uncorrected mass-transfer evaporation by thermal survey period are shown in figure 22. Improvement in the relation after correction for atmospheric stability is illustrated by the increased balance, or symmetry, of errors throughout the year; however, some seasonal discrepancy is still evident even after stability is accounted for in the mass-transfer equation. These results emphasize the need to test each new set of mass-transfer data for the effects of atmospheric stability. In addition to testing each set of mass-transfer data for the effects of atmospheric stability, future studies also should consider measuring wind speed and vapor pressure at heights other than 2 m (6.6 ft), because stability is height dependent.

Other causes of the differences between the two methods are unclear but are probably related to random errors in measurement in both the energy-budget and mass-transfer methods. Unaccounted energy fluxes, such as heat exchange between the water in Lake Lucerne and the lake sediments, may have contributed slightly to the deviation between the two methods.

By failing to account for heat flux through the bottom of the lake, the energy-budget estimate of evaporation might be lower than actual evaporation in the winter. Bottom sediments can be a source of heat energy to the lake during winter that is not accounted for in the budget. The opposite would be true in the summer, when the lake is relatively warm in comparison with ground water and bottom sediments. Lake-sediment heat flux could contribute to the difference between the methods, but this heat flux is small in relation to the total difference between methods (less than 10 percent for differences greater than 0.0079 in/d), so it cannot be the sole explanation for seasonal trends in residual errors.

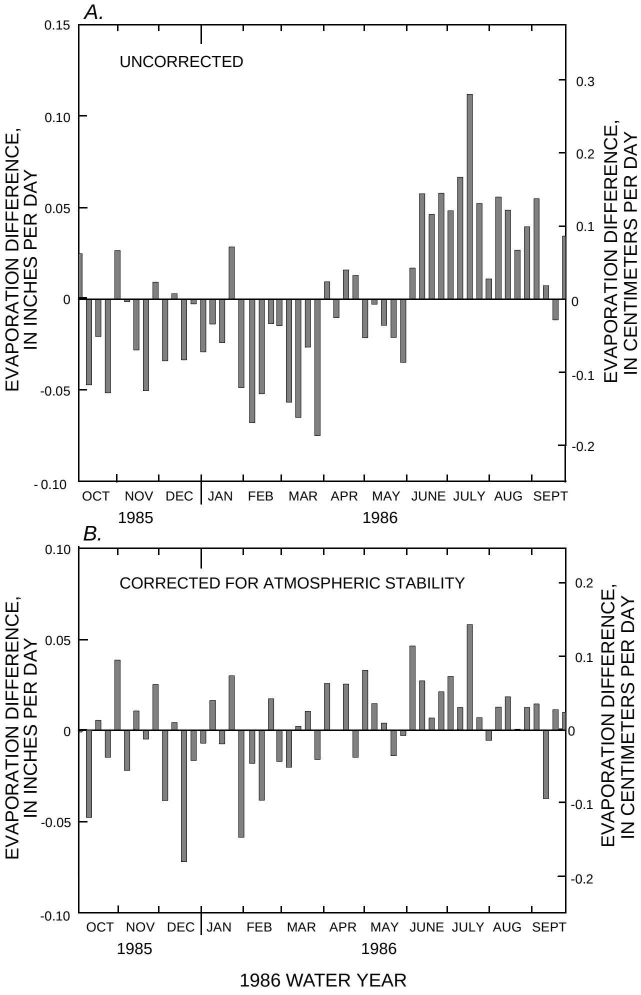

Figure 22. Differences between energy-budget evaporation and (*A*) mass-transfer evaporation (uncorrected), and (*B*) mass-transfer evaporation corrected for atmospheric stability by thermal survey period for the 1986 water year.

Pan-Evaporation Method

National Weather Service (NWS) class A pan-evaporation data are widely used to estimate evaporation and evapotranspiration in the United States. Class A pan evaporation was measured at Lake Lucerne throughout this study to compare with the theoretically based energy-budget and mass-transfer measures of evaporation. The depth of water evaporated, minimum and maximum water temperature, and total wind across the pan were recorded daily by an observer. Pan-evaporation data also are available from a NOAA station about 2 mi northwest of Lake Lucerne at the Lake Alfred Agricultural Research and Education Center (National Oceanic and Atmospheric Administration, 1986) (fig. 2).

Theory and Equations

Pan-evaporation data from the Lake Lucerne and the Lake Alfred pans were analyzed and adjusted to “free water-surface evaporation” (the maximum potential evaporation from a water body) on a monthly basis by using methods originally developed by Kohler and others (1955). A summary of more recent applications of these methods, and national long-term pan-evaporation data, can be found in the report by Farnsworth and others (1982).

Free water-surface evaporation is computed by using these methods to correct for the different heat storage capabilities of the water in the pan and in the lake. Lakes may differ greatly from evaporation pans and from other lakes in their ability to store heat. As a result, evaporation rates for lakes of different volumes can differ even under similar climatic conditions. Before pan evaporation can be directly compared with lake evaporation, differences in heat storage and advection from the two systems must be accounted for. When these effects are removed, a new term, free water-surface evaporation, describes the theoretical evaporation rate from a shallow water body that does not store significant amounts of heat.

A pan coefficient can be used to predict free water-surface evaporation from pan evaporation. The coefficient is calculated as the ratio of free water-surface evaporation to observed pan evaporation:

$$\text{Pan coefficient} = \frac{\text{free water-surface evaporation (inches)}}{\text{pan evaporation(inches)}} \qquad (17)$$

Free water-surface evaporation, which also is used to estimate evapotranspiration, can be calculated from pan-evaporation measurements by using an equation from Kohler and others (1955):

$$FWS_p = 0.70[E_p + 0.00051P\alpha_p(0.37 + 0.0041U_p)(T_0 - T_a)^{0.88}] \qquad (18)$$

where

FWS_p is free water-surface evaporation from a pan, in inches;
E_p is pan evaporation, in inches;
P is barometric pressure, in inches of mercury;
α_p is ratio of advected energy used in evaporation to the total energy advected from the pan;
U_p is wind travel over the pan, in miles per day;
T_0 is average pan water temperature, in degrees Fahrenheit; and
T_a is average air temperature, in degrees Fahrenheit.

This equation is based on the assumption that any energy advected into the lake is balanced by a change in energy storage and that the pan exposure is representative of the lake. Measurements are required for pan evaporation, average wind speed over the pan, average pan water temperature, and average air temperature. Barometric pressure at Lake Lucerne was assumed to be constant at 30.21 in. of mercury. The ratio α_p can be taken from a plot of α_p in relation to water-surface temperature and wind speed (Kohler and others, 1955, fig. 5).

For comparison, the energy-budget evaporation rates can be converted to free water-surface evaporation from a lake (FWS_l) by using a correction factor from Ficke (1972):

$$\begin{aligned} \Delta E &= \alpha_l(Q_x + Q_w - Q_v)/\rho(L) \\ FWS_l &= E_{EB} + \Delta E \end{aligned} \qquad (19)$$

The terms Q_x, Q_w, and Q_v are defined in equation 7. The value of α_l, the ratio of advected energy used in evaporation to the total energy advected from the lake, is taken from a plot of α_l in relation to water temperature and wind speed at 2 m (6.6 ft) above the lake surface (Harbeck, 1964, fig. 2).

Free Water-Surface Evaporation Rates

Monthly free water-surface evaporation calculated from the pan-evaporation data (FWS_p) for Lake Lucerne and Lake Alfred is shown in figure 23.

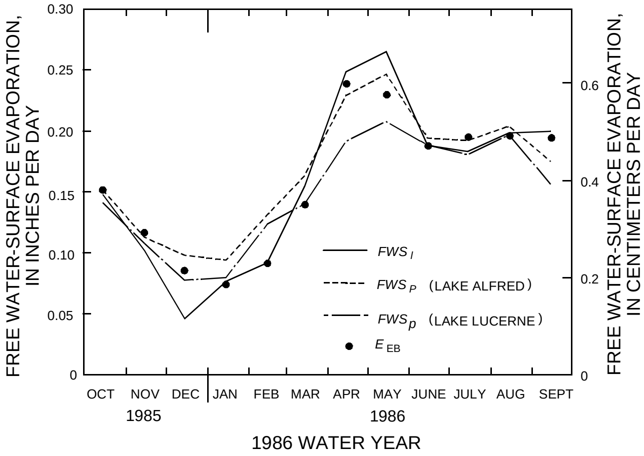

Figure 23. Monthly free water-surface evaporation (FWS_p) calculated from the evaporation pans at Lake Lucerne and at the Lake Alfred National Oceanic and Atmospheric Administration site, and from the corrected energy-budget evaporation (FWS_l) for the 1986 water year. (Energy-budget evaporation rates (E_{EB}) are shown for comparison).

FWS_p at Lake Lucerne ranged from 0.078 in/d in December 1985 to 0.208 in/d in May 1986 and totaled 54.54 in/yr. FWS_p at Lake Alfred ranged from 0.094 in/d in January 1986 to 0.247 in/d in May 1986 and totaled 60.64 in/yr. The pan evaporation is always greater at Lake Alfred than at Lake Lucerne; as a result, the FWS_p is consistently greater. Although the Lake Alfred pan is only about 2 mi away, it is not representative of climatic conditions at Lake Lucerne.

Free water-surface evaporation calculated from energy-budget evaporation at Lake Lucerne (FWS_l) is also shown in figure 23. FWS_l ranged from 0.055 in/d in December 1985 to 0.249 in/d in April 1986 and totaled 58.61 in/yr. Conversion tables for calculating all monthly free water-surface evaporation rates are given in appendix B.

Theoretically, the FWS_p and FWS_l for Lake Lucerne should be nearly equivalent. Although FWS_p and FWS_l agree to within 7 percent on an annual basis, they are dissimilar on a monthly basis. The FWS_p differs from FWS_l by up to 68 percent, and 5 months had deviations greater than 20 percent. Surprisingly, FWS_p is a more accurate predictor of actual lake evaporation on a monthly basis than it is of FWS_l. The FWS_p from Lake Lucerne underestimated actual lake evaporation calculated by the energy budget by 6 percent on an annual basis. The monthly deviation from the energy-budget evaporation ranged from −20 percent in September 1986 to +35 percent in February 1986. Errors were less than 10 percent for all but 3 months.

In general, FWS_p overestimates energy-budget evaporation during the winter months (December through March) and underestimates it in spring (April and May) (fig. 23). During the winter months (December and January), when the lake rapidly loses stored heat, lake evaporation is higher than FWS_p because more energy is available to evaporate water than there would be in a free water surface where no energy is stored. In the spring the opposite is true, and energy that goes into stored heat in a lake is not available for evaporation, as it would be in a free water surface. These effects could be expected to be even greater in more temperate climates.

Pan Coefficients

The best estimate of the pan coefficient for a given lake should be the ratio of the free water-surface evaporation derived from the corrected energy-budget evaporation to the observed pan evaporation (FWS_l/E_p) because energy-budget evaporation is assumed to have the highest accuracy. Because local energy-budget evaporation rates are seldom available, the pan coefficient is usually calculated as the ratio of the free water-surface evaporation derived from the pan data to the observed pan evaporation (FWS_p/E_p) (Farnsworth and others, 1982).

The pan coefficients calculated for this study are listed in table 2. Maps of annual pan coefficients for the continental United States, based on pan-evaporation data from 1956 to 1970, are presented by Farnsworth and others (1982). The pan coefficient for Lake Lucerne interpolated from this map is just over 0.74. Monthly pan coefficients for Lake Okeechobee, Fla., which were calculated from a water budget by Langbein (1951) for the years 1940–46, also are listed. A ratio of the energy-budget evaporation to pan evaporation (E_{EB}/E_p) also was computed for comparison with pan coefficients.

On an annual basis, the pan coefficients calculated by the various methods were similar. The average pan coefficient calculated for the 1986 water year using the Lake Lucerne pan data or the data from Lake Alfred was 0.73. These results agreed well with the long-term annual average coefficient of 0.74 of Farnsworth and others (1982). The pan coefficient derived from the corrected energy-budget evaporation was higher, the average for the year being 0.75. The mean coefficient for Lake Okeechobee was 0.81, but unlike the Lake Alfred data, the results were not directly comparable with the Lake Lucerne results because they did not cover the same time period.

Table 2. Monthly and annual pan coefficients for Lake Lucerne for the 1986 water year

[FWS_l, free water-surface evaporation from lake; FWS_p, free water-surface evaporation from pan; E_p, pan evaporation; E_{EB}, energy-budget evaporation]

Year and month	FWS_p/E_p	FWS_p/E_p (Lake Alfred)	FWS_l/E_p	E_{EB}/E_p	Langbein (1951) 1940–46
1985:					
October	0.74	0.73	0.77	0.79	0.76
November	.72	.72	.68	.72	.71
December	.70	.72	.42	.69	.83
1986:					
January	.70	.71	.67	.64	.77
February	.77	.74	.57	.50	.69
March	.72	.74	.79	.71	.73
April	.74	.74	.96	.92	.84
May	.72	.73	.92	.86	.82
June	.76	.74	.76	.73	.85
July	.75	.74	.76	.75	.91
August	.76	.75	.76	.75	.91
September	.75	.75	.95	.95	.85
Annual mean	.73	.73	.75	.75	.81

Larger differences appeared among pan coefficients when they were calculated on a monthly basis. The range of the Lake Lucerne pan coefficient was from 0.70 to 0.77. This was slightly larger than the range of the pan coefficient at Lake Alfred, 0.71 to 0.75. Both the Lake Lucerne and Lake Alfred pan coefficients varied less from month to month in comparison with the ratios derived from corrected (0.42 to 0.96) or uncorrected (0.50 to 0.92) energy-budget evaporation.

Theoretically, pan coefficients calculate free water-surface evaporation rather than lake evaporation because heat storage is not accounted for. Nevertheless, the results of this study indicate that pan-evaporation data corrected to free water-surface evaporation were similar to actual lake evaporation at Lake Lucerne and might be a reasonable predictor for periods of at least a month. Annual FWS_p was about 6 percent less than the annual energy-budget evaporation at Lake Lucerne during the 1986 water year. Errors in estimates of lake evaporation based on FWS_p data on a monthly basis were generally less than 10 percent but were as large as 35 percent. Larger errors occurred during periods of high or low rates of evaporation or periods of rapid change in lake temperature.

Evaporation Summary

The energy-budget method was used to obtain the most accurate available measurement of evaporation at Lake Lucerne. The total energy-budget evaporation calculated on a thermal survey basis for 52 weeks from October 1, 1985, to September 30, 1986, was 57.87 in. This was greater than the long-term average evaporation for the area but probably was a result of drier than average conditions during the study year. The largest evaporation rate was 0.264 in/d between April 29 and May 5, 1986. The smallest was 0.040 in/d between December 31, 1985, and January 6, 1986 (fig. 14 and app. A). The error for the energy-budget method for the 52-week period of record was 16.4 percent.

Daily energy-budget evaporation rates were computed by using daily changes in stored heat and were averaged and compared with the thermal survey evaporation rates. These two estimates generally agreed closely except for periods of low evaporation, when unrealistic values for the Bowen ratio were a limiting factor in the use of daily values. When data were averaged over weekly thermal survey periods, these effects were minimized.

The total mass-transfer evaporation with a correction for atmospheric stability for the 1986 water year was 57.39 in. The largest evaporation rate was 0.265 in/d between April 22 and April 28, 1986. The smallest was 0.047 in/d between December 31, 1985, and January 6, 1986 (fig. 21).

The error in the uncorrected mass-transfer estimate of evaporation for the 1-yr study period was 31 percent when a value of 0.0114 was used for N. The large error in this method is a result of the large errors in determining N from the linear regression with the energy budget (25 percent) and the vapor pressure gradient (18 percent).

Pronounced seasonal differences existed between the energy-budget and the mass-transfer methods, the mass-transfer evaporation being greater than the energy-budget evaporation in the winter and less in the summer. At Lake Lucerne, changes in atmospheric stability explained part of the difference between evaporation computed by using the energy-budget and mass-transfer methods. By incorporating the effects of atmospheric stability, the error in the mass-transfer method was reduced to 21 percent.

FWS_p at Lake Lucerne totaled 54.53 in. for the 1986 water year and ranged from 0.078 in/d in December 1985 to 0.208 in/d in May 1986. FWS_p at the Lake Alfred NOAA station totaled 60.65 in. and ranged from 0.094 in/d in January 1986 to 0.247 in/d in May 1986. FWS_l from Lake Lucerne totaled 58.59 in. and ranged from 0.055 in/d in December 1985 to 0.249 in/d in April 1986. The FWS_p at Lake Lucerne underestimated actual lake evaporation calculated from the energy-budget method by 6 percent on an annual basis, and the monthly deviation from the energy-budget evaporation ranged from –20 percent in September 1986 to +35 percent in February 1986. Deviations were less than 10 percent for all but 3 months. The FWS_p deviated from FWS_l by up to 68 percent on a monthly basis, an annual deviation being 7 percent. Five months had deviations greater than 20 percent.

On an annual basis, the pan coefficients calculated by the various methods were similar. The average pan coefficient calculated for the 1986 water year using the Lake Lucerne pan data or the data from Lake Alfred was 0.73. These results agreed well with the long-term annual average coefficient of 0.74 of Farnsworth and others (1982). The pan coefficient derived from the corrected energy-budget evaporation was higher, an average for the year being 0.75. Differences of as much as 68 percent appeared among pan coefficients when they were calculated on a monthly basis.

Within the study period, pan-evaporation data, corrected to free water-surface evaporation, were reasonable predictors of monthly lake evaporation measured by the energy-budget method. The largest discrepancies between pan evaporation and energy-budget evaporation occurred during periods of high or low rates of evaporation or periods of rapid change in lake temperature.

GROUND WATER

Understanding lake and ground-water interaction is critical to understanding the hydrologic budget of seepage lakes such as Lake Lucerne. In this section the analysis of the ground-water fluxes to Lake Lucerne is undertaken in two parts. The first, a qualitative analysis based on numerical modeling, improves the conceptual and physical understanding of ground-water interactions with the lake and defines the physical constraints needed to quantify ground-water fluxes. In the second part, ground-water fluxes are quantified using flow-net analysis, and the potential errors in these estimates are discussed.

Numerical Simulation of Ground-Water and Lake Interactions

Ground-water flow simulations that are described in this section were used to refine the interpretation of the hydrogeologic setting of Lake Lucerne. This interpretation was based largely on point observations of the geology and head distribution around the lake and, consequently, could not completely describe the small-scale flow patterns that control ground-water exchange with the lake, particularly in the large sublake region. In this region, geophysical data provided indirect evidence of the geometry of the sinkhole complex beneath the lake, and the heads in the midlake well provided physical evidence of probable flow patterns. Simulation results indicated the possible distribution of ground-water inflow to and leakage from Lake Lucerne under high and low water-level conditions by interpolating heads in the areas between the field observations. Modeling results also provided insight into the factors controlling ground-water interactions with Lake Lucerne as well as other sinkhole-type lakes.

Modeling Approach

Three simulated cases were used to test the influence of the geologic framework of the lake on the ground-water and lake interactions. In the first case, cover-subsidence-type sinkholes were simulated in the sublake region. The geometry of the sinkholes was based upon the seismic survey. In the second and third cases, ground-water flow simulations were used to test the degree of anisotropy in the surficial aquifer and the possible influence of low-permeability lake sediments on lake and ground-water interactions, respectively. For each of these cases, simulations also were made to test the possible influence of the head in the Upper Floridan aquifer on ground-water and lake interactions. A low-head condition in the Upper Floridan aquifer, representative of drawdown due to pumping, was simulated for steady-state conditions and compared with results for higher head conditions. The two conditions were used to demonstrate the potential range of influence of the head in the Upper Floridan aquifer on ground-water interactions with Lake Lucerne.

Ground-water flow at Lake Lucerne was simulated using a steady-state, finite-difference, ground-water model (McDonald and Harbaugh, 1984). Two-dimensional ground-water flow was simulated along a cross section through the lake basin using a single model layer of unit width. To minimize the flow that occurs through the plane of the cross section, the model cross section was aligned along stream lines that enter the lake. This transect is shown on figure 9. The finite-difference grid for the ground-water basin along this transect had varied spacing and is shown in figure 24. The model was used to simulate flow patterns only within the surficial aquifer and the intermediate confining unit.

The hydrogeologic framework represented in the model incorporates the sublake geology interpreted from the seismic-reflection survey and the local geology shown in the hydrogeologic section (fig. 5). Adjacent to the lake, the surficial deposits overlie the intermediate confining unit. Beneath the lake, however, the surficial deposits make irregular contact with the intermediate confining unit or, where this unit is absent, with the Upper Floridan aquifer. In keeping with field observations, organic lake sediments are modeled only in the deepest regions of the lake bottom.

The boundary conditions that define the modeled ground-water flow system occur within the surficial aquifer and in the Upper Floridan aquifer, just below the intermediate confining unit. Because of the large transmissivity of the Upper Floridan aquifer, recharge from the surficial aquifer could be assumed to have little effect on the head in this aquifer. Consequently, the Upper Floridan aquifer is simulated along the base of the modeled flow system as a specified-head boundary. Because the lateral model boundaries were coincident with the ground-water and topographic drainage divides, these were specified as no-flow boundaries. The top of the flow system, which consists of the water table, Lake Lucerne, and Terrie Pond, also was modeled as a specified-head boundary condition.

Franke and others (1984) discussed the effects of using two constant-head boundaries (a particular case of the specified-head boundary) and two no-flow boundaries when modeling head distributions and flow rates within a confined, two-dimensional flow system. They showed that modeled head distributions are insensitive to the chosen values of hydraulic conductivity used (although sensitive to the contrast in hydraulic conductivity between units) but that modeled flows do increase proportionately to this value. For this reason, head distributions modeled at Lake Lucerne are presumed to be influenced only by the relative magnitude of the hydraulic conductivity and the anisotropy in different geologic units. Fortunately, the contrast of hydraulic conductivity between units is often more accurately represented in models than is the actual value of each unit. The quantity of flow entering the system from the specified-head boundary along the water table depends only upon the specified head imposed at the lower model boundary and the distribution of hydraulic conductivities within the model.

The hydraulic characteristics of the surficial aquifer and intermediate confining unit were defined as follows. The horizontal hydraulic conductivity (K_h) was estimated to be 8 feet per day (ft/d) in the upper part of the surficial aquifer and 2 ft/d in the lower part of the surficial aquifer. The vertical hydraulic conductivity (K_v) in the intermediate confining unit was estimated to be 0.0001 ft/d (Lee and others, 1991). The K_v of the lake sediments was varied between 0.0002 and 0.005 ft/d. Anisotropy in the surficial aquifer, or the ratio of K_h to K_v, was set initially to 100 and changed in subsequent simulations to 10 and 1,000. The model could accommodate only one value of anisotropy for the entire model cross section. Therefore, K_h within the intermediate confining unit was selected to produce the desired K_v value of 0.0001 ft/d when divided by the anisotropy.

Munter and Anderson (1981) defended this simplification in flow systems similar to Lake Lucerne. Their simulations showed that K_h in formations through which the flow is predominantly vertical makes negligible difference in the rate of ground-water flux to the lake. Instead, they found that vertical seepage was sensitive to K_v (the quotient of K_h and anisotropy). This same assumption was used to model the K_v in the lake sediments, as flow through both the confining unit and the lake sediments was predominantly vertical.

Two seasonal extremes in the heads in the surrounding aquifers were simulated by imposing different specified-head conditions along the upper and lower model boundaries. High water-level conditions were modeled for both the surficial and the Upper Floridan aquifers using head conditions observed on October 17, 1985 (figs. 9*B* and 10). The head in the Upper Floridan aquifer in well 1PN-155 was 120.23 ft above sea level, and the downward head difference between the lake and this aquifer was 5.73 ft. The high water-level condition generally is representative of the basin between August and

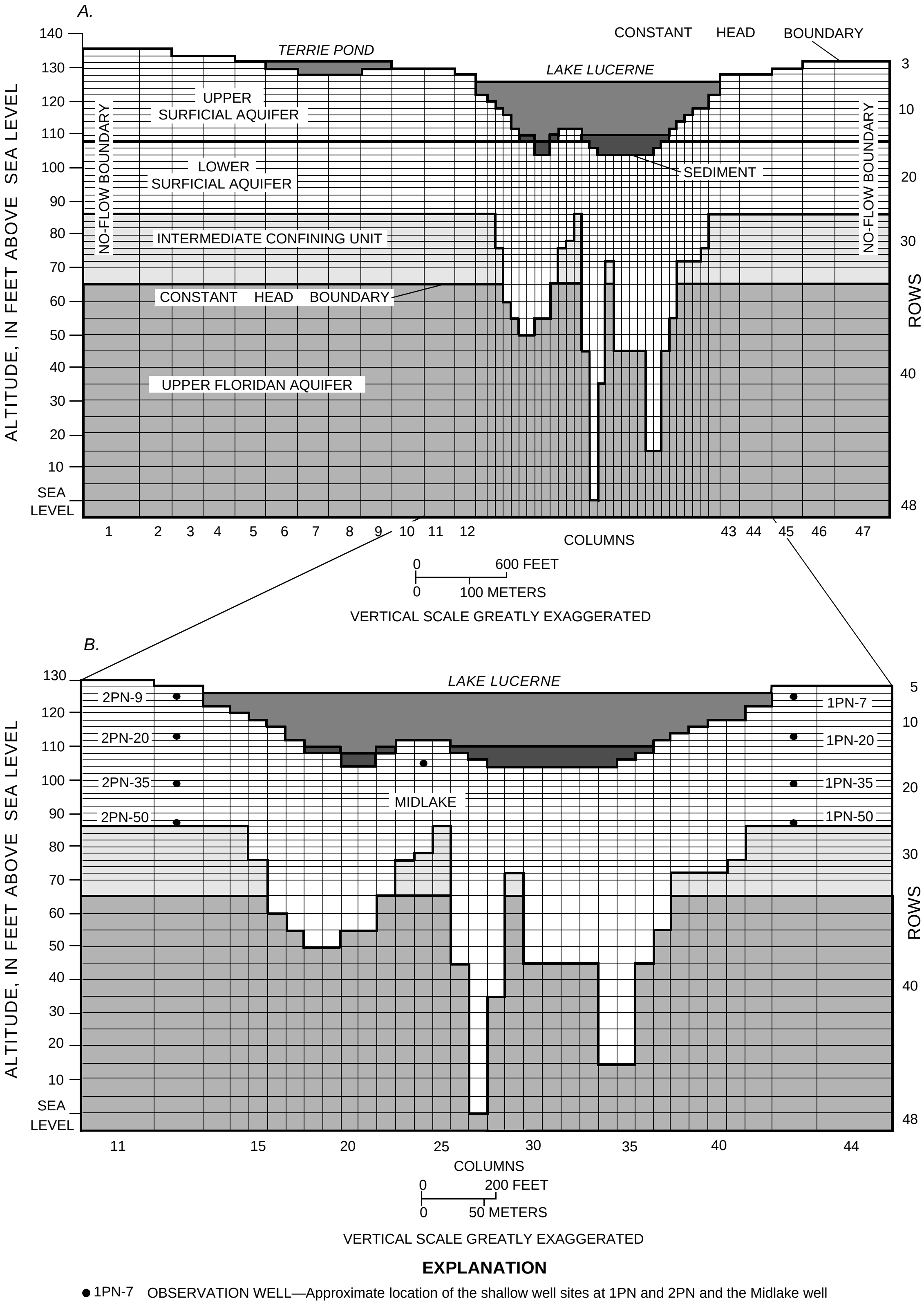

Figure 24. Layout of model grid for (*A*) numerical ground-water simulation and (*B*) enlarged model area around Lake Lucerne showing approximate locations of wells at sites 1PN and 2PN.

February. During these months of the 1986 water year, heads in the Upper Floridan aquifer were high and ranged from 118 to 121 ft above sea level.

The low water-level condition was simulated using head conditions observed in the surficial and Upper Floridan aquifers on May 20, 1986. The water-table configuration for this date is shown in figures 9*A* and 11. The head in the Upper Floridan aquifer was 112.93 ft above sea level, and the downward head difference between the lake and Upper Floridan aquifer was 11.85 ft. This low water-level condition was characteristic of the driest months of the year: April, May, and early June. Heads were below 115 ft above sea level for 60 days (16 percent) of the 1986 water year due to irrigation pumping. These days occurred continuously during April, May, and June of 1986, with a minimum head of 109.96 ft above sea level occurring on May 30.

Comparisons between observed and modeled head distributions were used to evaluate the realism of the hydrogeologic setting simulated by the model. Model simulations that compared well with observed heads were used to improve parameter estimates used in the flow-net analyses. These parameters were depth of the ground-water inflow component and area of leakage through the lake bottom.

Although neither water-level condition was, in fact, steady state, the high water-level simulation most closely approximated steady state, as this condition persisted for nearly 7 months of the year. Therefore, simulated heads should resemble heads observed in the field. In contrast, extremely low heads in the Upper Floridan aquifer existed for a period of approximately 2 months during the 1986 water year and were preceded and followed by weeks in which the head in the Upper Floridan aquifer was higher, but fluctuating. For this reason, steady-state results might overpredict the effects of the low water-level conditions.

Effect of Intermediate Confining Unit Below the Lake

The geometry of the intermediate confining unit beneath Lake Lucerne is one of the most important geologic factors controlling the lake and ground-water interaction. Figure 25 compares the results of simulations with a continuous confining unit beneath the lake and with the confining unit geometry inferred from the seismic-reflection survey. Both simulations are for the seasonally high water-level condition. Model parameters for the two simulations are identical except that, in the simulation shown in figure 25*B*, the lower surficial deposits (K_h = 2 ft/d) replace the confining unit in areas below the lake and extend downward into the Upper Floridan aquifer. Lake sediments are omitted in these simulations.

Because the general pattern of ground-water flow in the basin at high water-level conditions was similar for all simulations (fig. 26), figures hereafter show only the enlarged area of interest shown in figure 25. As seen in figure 26, ground water in the surficial aquifer moves laterally from the flow boundary at the basin drainage divides toward the lake, as well as downward. Due to vertical head gradients, recharge occurring farthest from the lake probably leaks across the confining unit before reaching the lake. Closer to the lake, flow in the upper part of the surficial aquifer can be intercepted by the lake, while the remainder bypasses the lake and flows downward toward the Upper Floridan aquifer.

With a continuous confining unit beneath the lake, the model predicts upward flow at all depths within the surficial aquifer adjacent to the lake (fig. 25*A*). The extensive upward flow around the lake results in only minimal leakage through a small percentage (17 percent) of the lake bottom (expressed as a percentage of the lakebed length along the cross section). Leakage is not predicted to occur at the location of the midlake well (fig. 25*A*). Instead, a large downward head difference occurs across the intermediate confining unit below the lake.

Alternately, the simulation shown in figure 25*B* indicates that horizontal flow near the lake diverges into upward and downward flow. A flow divide occurs at both sides of the lake at a depth of about 16 ft below the lake level or between the depths of the 20- and 35-ft-deep wells at sites 1PN and 2PN. The area of the lake bottom that receives ground-water inflow has decreased significantly, and leakage occurs from approximately 74 percent of the lake bottom. The model more closely predicts the heads observed in the lower part of the surficial aquifer and also closely predicts the head observed in the midlake well (125.63 and 125.70 ft above sea level, predicted and observed, respectively).

The contrasts between simulations, with and without a continuous confining unit, increase for the low water-level condition. With the confining unit intact, the model predicts weak, upward head gradients in the surficial aquifer adjacent to the lake

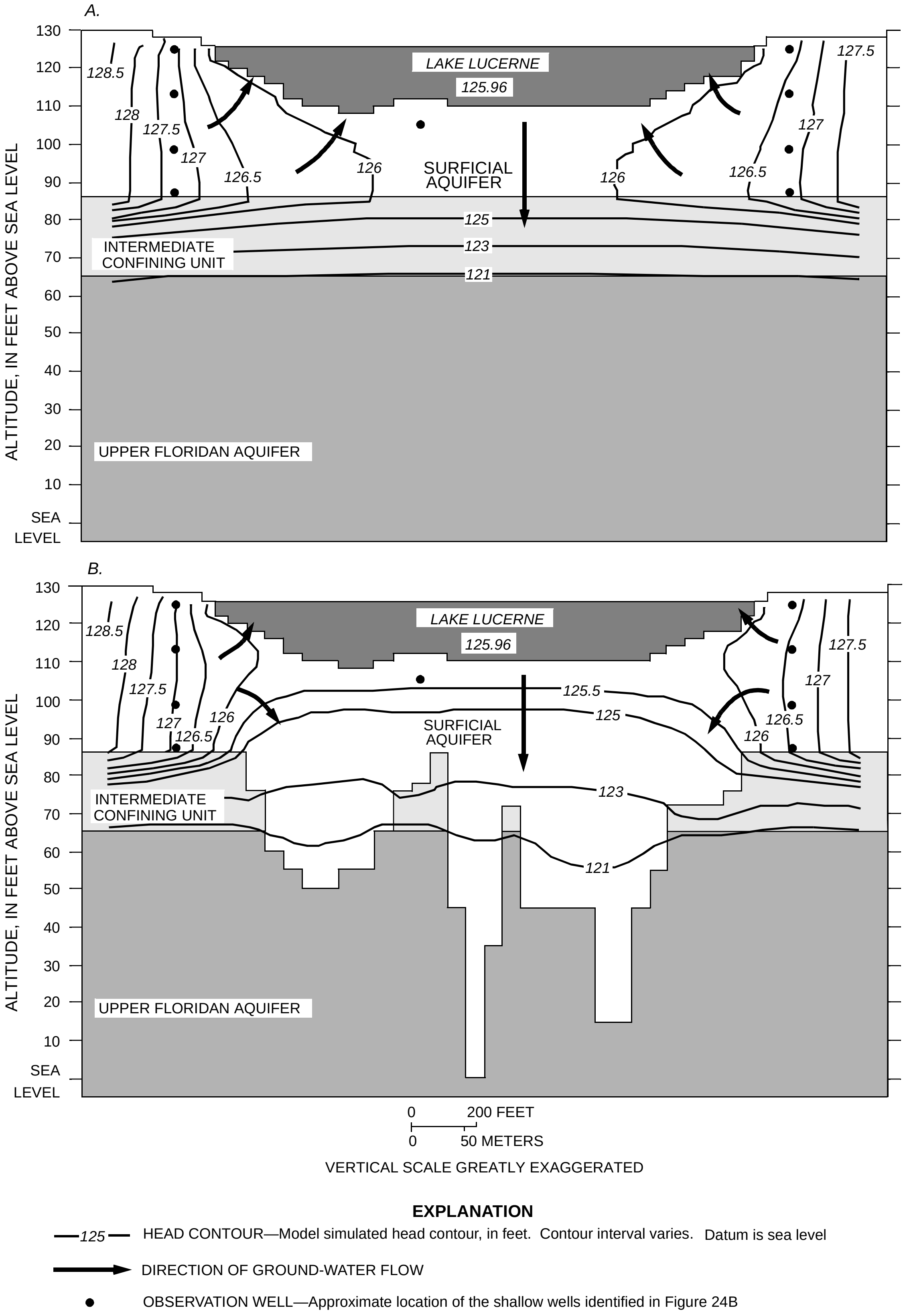

Figure 25. Simulated vertical head distribution for high water-level conditions with (*A*) a continuous confining unit beneath Lake Lucerne and (*B*) a breached confining unit beneath Lake Lucerne.

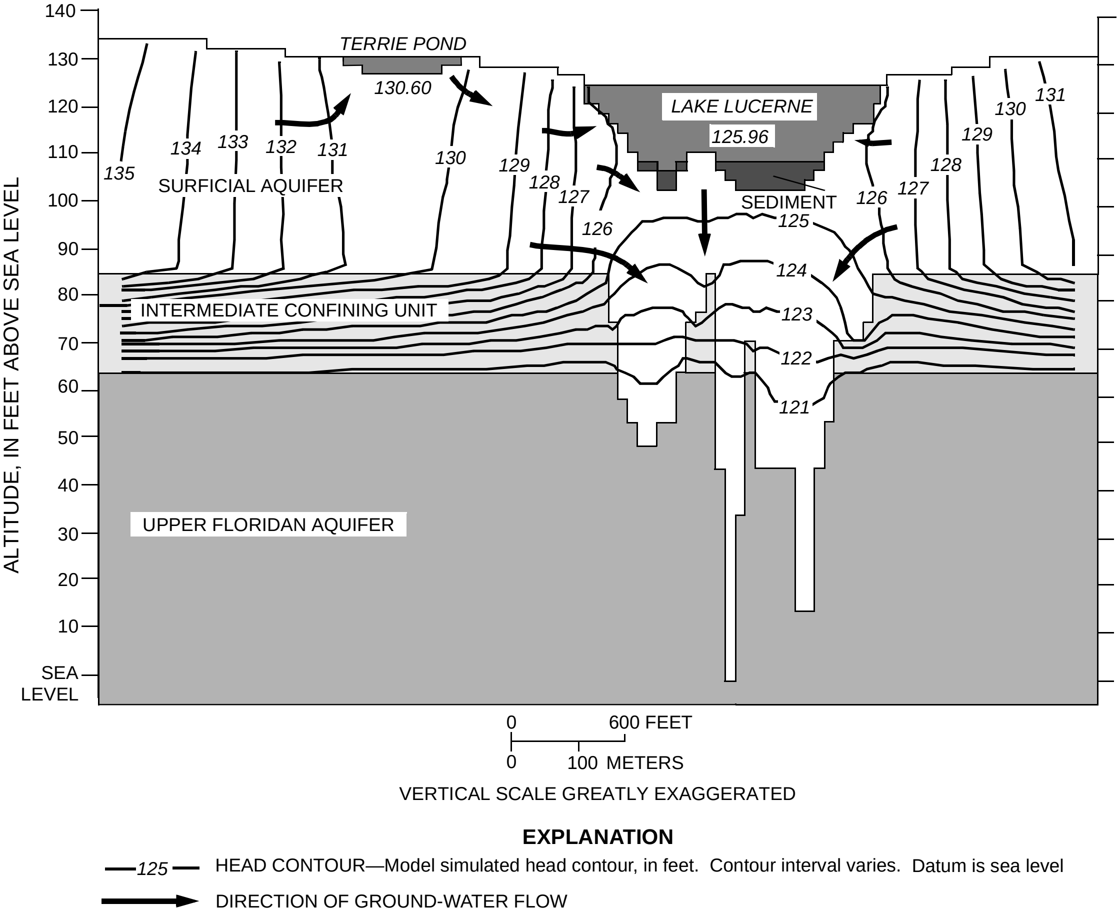

Figure 26. Simulated vertical head distribution for high water-level conditions showing general pattern of ground-water flow in the basin.

(fig. 27*A*). However, the predicted area of leakage increases to nearly half of the lake bottom (47 percent). Leakage occurs at the midlake well, but the predicted head in the midlake well is nearly 1 ft higher than the observed head (124.77 and 123.88 ft above sea level, predicted and observed, respectively) (figs. 27*A* and 11).

With breaches in the confining unit, the predicted head for the midlake well (124.10 ft above sea level) approaches the observed head (123.88 ft above sea level) but is still higher (fig. 27*B*). The similarity between predicted and observed heads indicates that the head distribution below the lake could approach steady state within the duration of the low water-level conditions. The predicted pattern of flow adjacent to the lake also more closely resembles the observed conditions (fig. 27*B*). Leakage dominates the predicted ground-water interactions with Lake Lucerne at extreme low water-level conditions and is predicted to occur through nearly 88 percent of the lake bottom. Ground-water inflow occurs only to a depth of 6 to 8 ft below the lake surface.

The pattern of leakage from Lake Lucerne is strongly dependent on the geometry of the breaches in the confining unit. For example, the presence of even small areas of confining unit between sinkholes redirects flow lines and significantly reduces the leakage that occurs from the nodes in the overlying lakebed (fig. 27*B*). Thus, differences in confining unit geometries below the numerous lakes of sinkhole origin along the Central Highlands Ridge should result in significantly different quantities of leakage under low head conditions in the Upper Floridan aquifer.

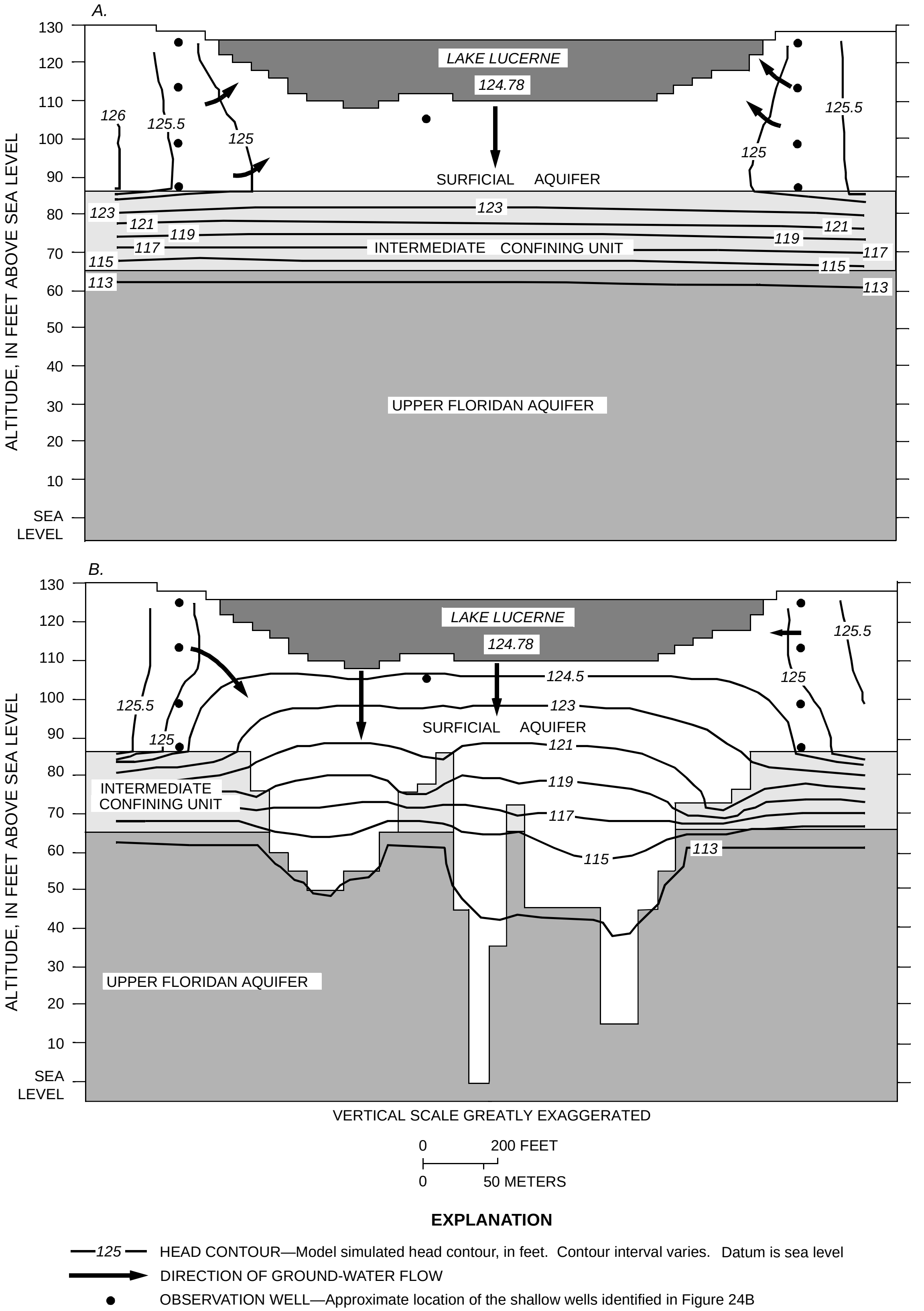

Figure 27. Simulated vertical head distribution for low water-level conditions with (*A*) a continuous confining unit beneath Lake Lucerne and (*B*) a breached confining unit beneath Lake Lucerne.

Effect of Anisotropy in the Surficial Aquifer

The anisotropy of the surficial aquifer has a major effect on the amount of ground-water inflow intercepted by the lakebed and on the rate of lake leakage. Reliable estimates of anisotropy determined from field investigations, however, are rare, and none exists for the surficial aquifer around Lake Lucerne. As a result, anisotropy is often estimated during the process of calibrating a model to reproduce observed head distributions. Anisotropy values reported in both field and modeling investigations generally range from 10 to 1,000 (Winter, 1976).

Simulation results for three values of anisotropy at Lake Lucerne are shown in figure 28 for the high water-level condition. The predicted areas of ground-water inflow and leakage across the lakebed and the rates of inflow and leakage for the three values of anisotropy considered are summarized in table 3.

Increasing anisotropy in the surficial aquifer causes a more pronounced divergence between upward flow into the lake and downward flow toward the Upper Floridan aquifer. When anisotropy is 10, little vertical variation in head occurs in the surficial aquifer near the lake, and the flow divides that were observed at sites 1PN and 2PN were not reproduced (fig. 28*A*). When anisotropy is increased to either 100 or 1,000, distinct flow divides occur near the lake (figs. 28*B* and 28*C*). When anisotropy is increased from 100 to 1,000, the upward flow component is distributed farther beneath the lake (fig. 28*C*). Thus, increasing anisotropy increases the area of the lakebed that receives ground-water inflow and decreases both the area and the rate of leakage.

The area of the lakebed that receives inflow increases with increasing anisotropy, however, there is little change in the magnitude of predicted inflows (table 3). This result follows from the fact that variations in model anisotropy do not affect the K_h value in the surficial aquifer. As the majority of the ground-water inflow occurs along horizontal flow lines near the lakeshore, anisotropy has little effect on the magnitude of ground-water inflow.

Increasing anisotropy has a dual effect on leakage. It decreases both the area of the lakebed that leaks and the rate of leakage by decreasing K_v. Greater anisotropy also increases the vertical head drop in the surficial aquifer below the flow divide. As a result, when anisotropy is 1,000, heads predicted for the lower part of the surficial aquifer (wells 1PN-50 and 2PN-50) are much lower than observed. Whereas changes in anisotropy did not significantly alter the predicted head in the midlake well, increasing anisotropy from 10 to 1,000 reduced total leakage rates by three orders of magnitude from 19.4 to 0.06 cubic feet per day per foot [$(ft^3/d)/ft$] (table 3).

Simulation results for the three anisotropy values suggest that anisotropy on the order of 100 is appropriate for the surficial aquifer surrounding Lake Lucerne. An anisotropy of 10 does not simulate the vertical flow divide in the surficial aquifer. The higher value of 1,000 results in too much vertical head loss and an unlikely low leakage rate. Anisotropy equal to 100 most closely approximates the vertical head distribution near the lake and, therefore, is considered most representative of the surficial aquifer around Lake Lucerne.

This value also agrees closely with the anisotropy reported for surficial sand deposits in northwest Hillsborough County, approximately 50 mi west of Lake Lucerne (Sinclair, 1974). For a noncohesive, “clean, well-sorted, fine to very fine quartz sand” with a combined silt and clay content ranging from 0.9 to 4.7 percent, the respective anisotropies ranged from 1 to 37. (Anisotropy was computed from reported vertical and horizontal coefficients of permeability.) At Lake Lucerne, grain sizes were determined in split-spoon samples collected at 5-ft intervals at a test hole at site 1PN. The combined silt and clay content in the surficial deposits ranged from 4.5 to 24.8 percent by weight. The higher percentages of silt and clay in the surficial deposits at Lake Lucerne support anisotropy values on the order of 37 or greater.

Effect of Lake Sediments

Lake sediments could play a major role in regulating the ground-water interaction with sinkhole-type lakes, yet few data exist to describe sediment hydraulic characteristics. Frequently, sediment K_h values are assumed to be several orders of magnitude less than the K_h value in the surrounding aquifer (Winter, 1976; Munter and Anderson, 1981). Such low permeabilities below lakes in recharge settings could act as an important confining unit to impede vertical leakage from the lake. Lake sediments preferentially accumulate in the deepest regions of the lakebed. At Lake Lucerne, depressions in the bathymetry overlie sinkhole features in the underlying limestone. Therefore, sediments could inhibit lake leakage that would otherwise be facilitated by breaches in the underlying confining unit.

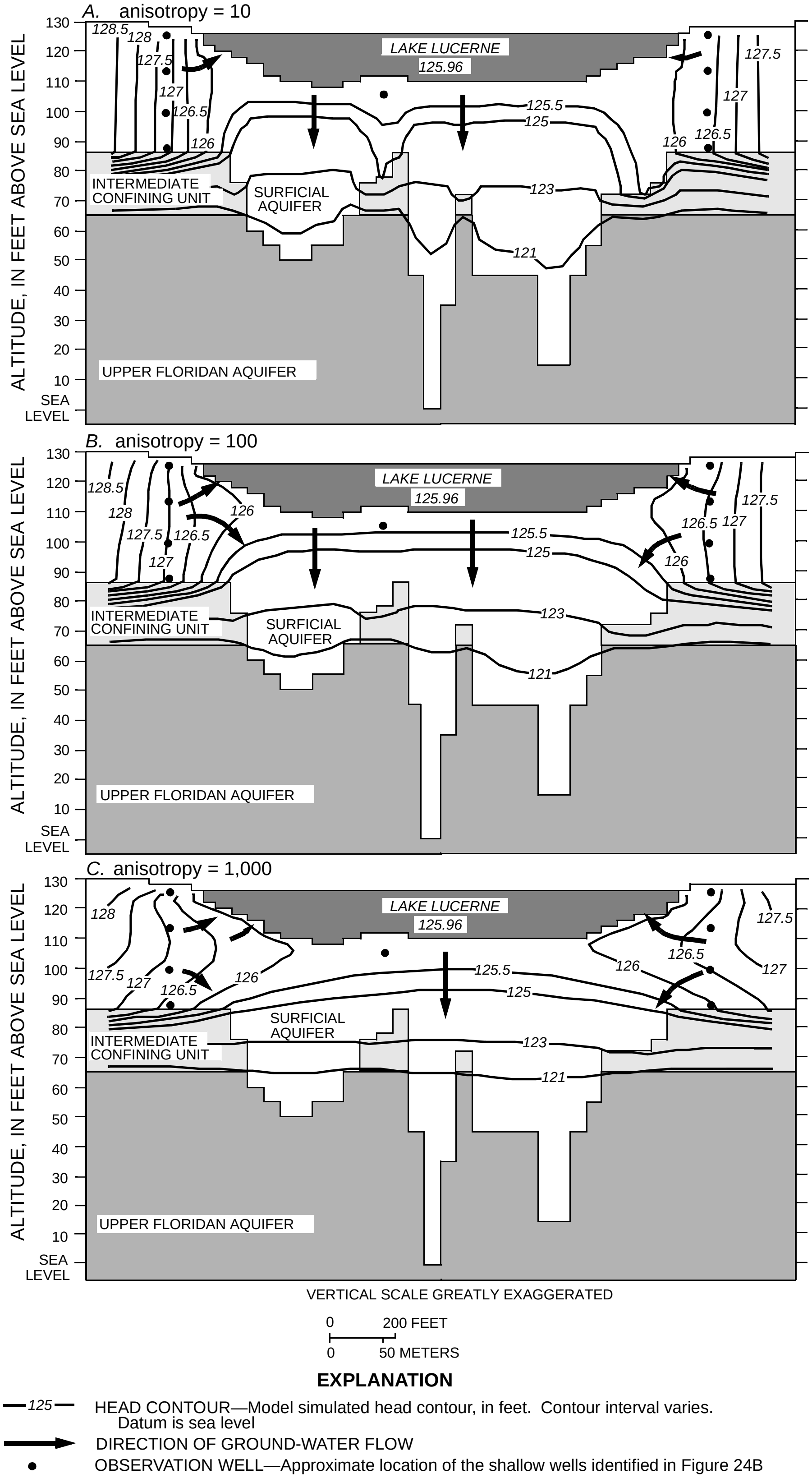

Figure 28. Simulated vertical head distribution for high water-level conditions with anisotropy equal to (*A*) 10, (*B*) 100, and (*C*) 1,000.

Table 3. Predicted ground-water inflow and leakage rates and areas for three modeled values of anisotropy at high water-level conditions

Parameter	Anisotropy		
	10	100	1,000
Percent inflow[1]	12	26	53
Percent leakage[1]	88	74	47
Depth of inflow (feet)	8–10	8–12	16
Inflow rate (cubic feet per day per foot)	2.76	2.20	1.70
Leakage rate (cubic feet per day per foot)	19.4	1.80	.06

[1] Percentage of the cross-section projection of lakebed (length 1,475 ft) experiencing either ground-water inflow or leakage.

To explore the potential influence of lake sediments on ground-water interactions at Lake Lucerne, three simulations were performed with h_{sed} equal to 25, 10, and 1 percent of the K_h of the lower part of the surficial aquifer. Using an anisotropy of 100, the resulting v_{sed} values ranged from 0.005 to 0.0002 ft/d. The spatial distribution of lake sediments used in the simulations is shown in figure 29. Sediments were modeled only in the deeper regions of the lake, and no sediments were modeled at the location of the midlake well. Sediment thickness in Lake Lucerne is unknown; however, a maximum sediment thickness of 6 ft was assumed. All other model parameters were kept as previously stated, with anisotropy equal to 100. The modeling results also reflect the assumptions that the lake-water surface is a constant-head boundary and that steady-state conditions exist.

The simulation results for the three v_{sed} values are shown in figure 29 for the high water-level conditions and in figure 30 for the low water-level conditions. Predicted ground-water inflow and leakage rates are summarized in table 4, along with the predicted heads at the midlake well.

The inclusion of lake sediments in this steady-state model had a negligible effect on the vertical head distribution in the surficial aquifer adjacent to the lake, or on the magnitude of ground-water inflow to the lake (table 4). Lake sediments also made a negligible difference in the area of the lakebed experiencing inflow relative to leakage. For example, the change from no sediments to sediments with the lowest v_{sed} increased the area of leakage from 1,100 ft (expressed as a length along the model cross section) to 1,150 ft. Because the area of inflow was nearly constant and because sediments were modeled only along the deeper parts of the lakebed, inflow rates at the shallower depths were not significantly altered by the presence of sediments at either high or low water-level conditions (table 4).

Decreasing h_{sed} increased the downward head gradient across the sediments. Vertical head gradients also increased across the lakebed in areas where sediments were absent (figs. 29 and 30). For example, the head predicted in the midlake well declined slightly from 125.49 to 125.28 ft above sea level when h_{sed} was decreased from 0.005 to 0.0002 ft/d. The increased downward head gradient across the lakebed where sediments are absent increases leakage in these areas and decreases it in the areas with sediments.

The increased leakage through “bare” areas of the deeper lakebed is apparent in the leakage rates summarized in table 4. Reducing h_{sed} from 0.002 to 0.0002 ft/d only decreased the predicted leakage from 1.53 to 1.15 ft^3/d under the high water-level conditions and from 3.74 to 3.03 ft^3/d under the low water-level conditions (table 4). Reducing v_{sed} from 0.005 to 0.0002 ft/d under high water-level conditions increased leakage through nodes without lake sediments from 40 to 84 percent of the total. Because of this effect, none of the simulations significantly reduced the total leakage rate over simulations in which sediments were absent (table 3).

The effect of the sediments in these simulations in which lake stage is held constant is to decrease the leakage through the deeper areas of the lakebed where sediments are present and to increase it in areas where the sediments are either thin or absent. This effect can be seen in the shape of the potentiometric contours beneath the lake. These contours are convex below sediments and concave around the midlake well, where sediments are absent. The concave potentiometric lines indicate a recharge mound at the lakebed. This recharge mound becomes more pronounced as the v_{sed} is reduced and as water levels go from high to low conditions. Flow lines exiting the lakebed where the sediments are absent eventually converge farther below the lakebed and move toward the openings in the confining unit (fig. 30*C*). For a system with predominantly vertical flow, some estimate of the true v_{sed} could be determined by comparing predicted and observed vertical head gradients across a sediment lens. This comparison, however, would require several midlake wells to be finished in the surficial aquifer below the sediment lens. The midlake well at Lake Lucerne was in an area with a thin sediment

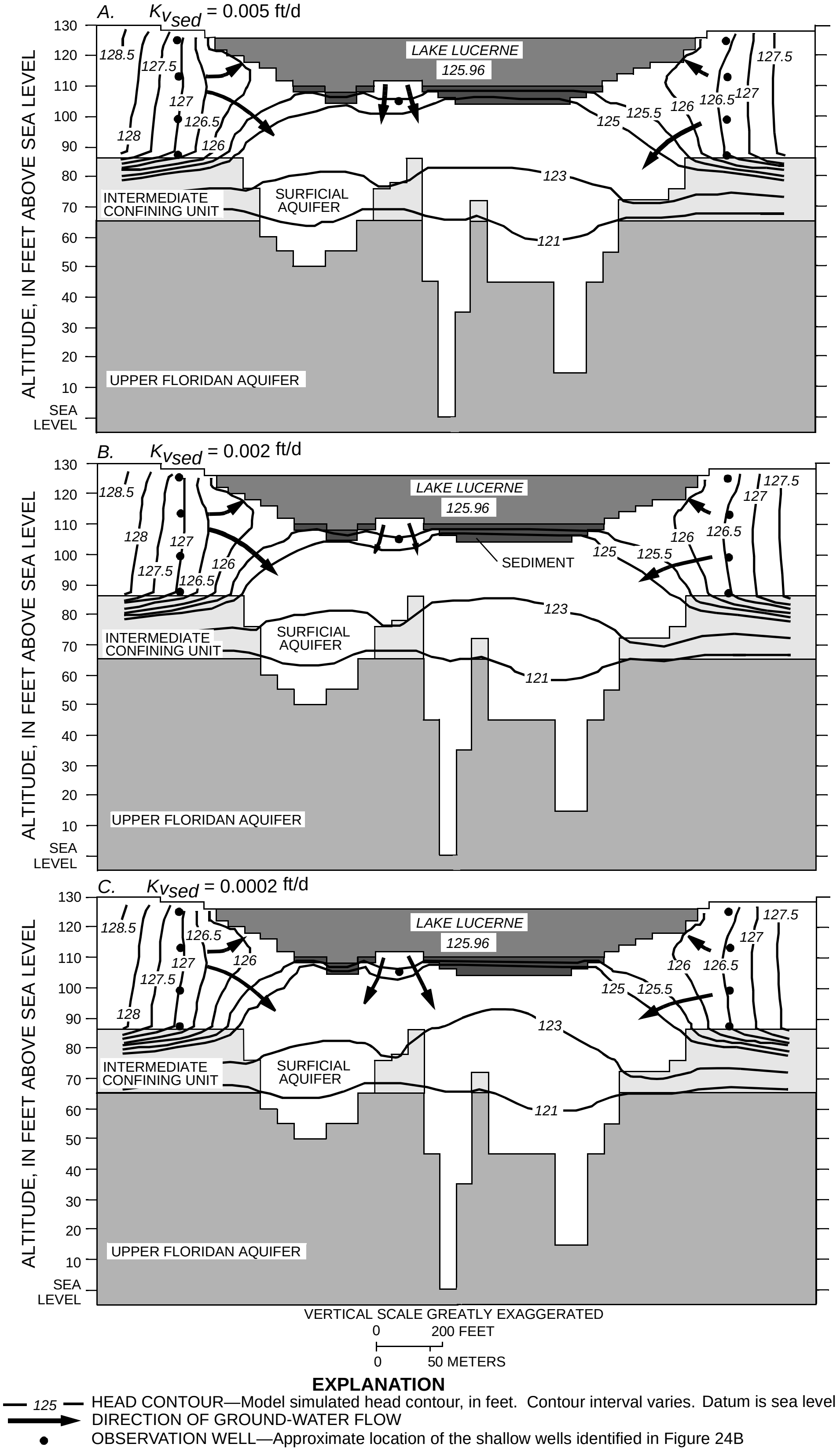

Figure 29. Simulated vertical head distribution for high water-level conditions with vertical hydraulic conductivity of the sediment, $K_{v_{sed}}$, equal to (*A*) 0.005, (*B*) 0.002, and (*C*) 0.0002 foot per day.

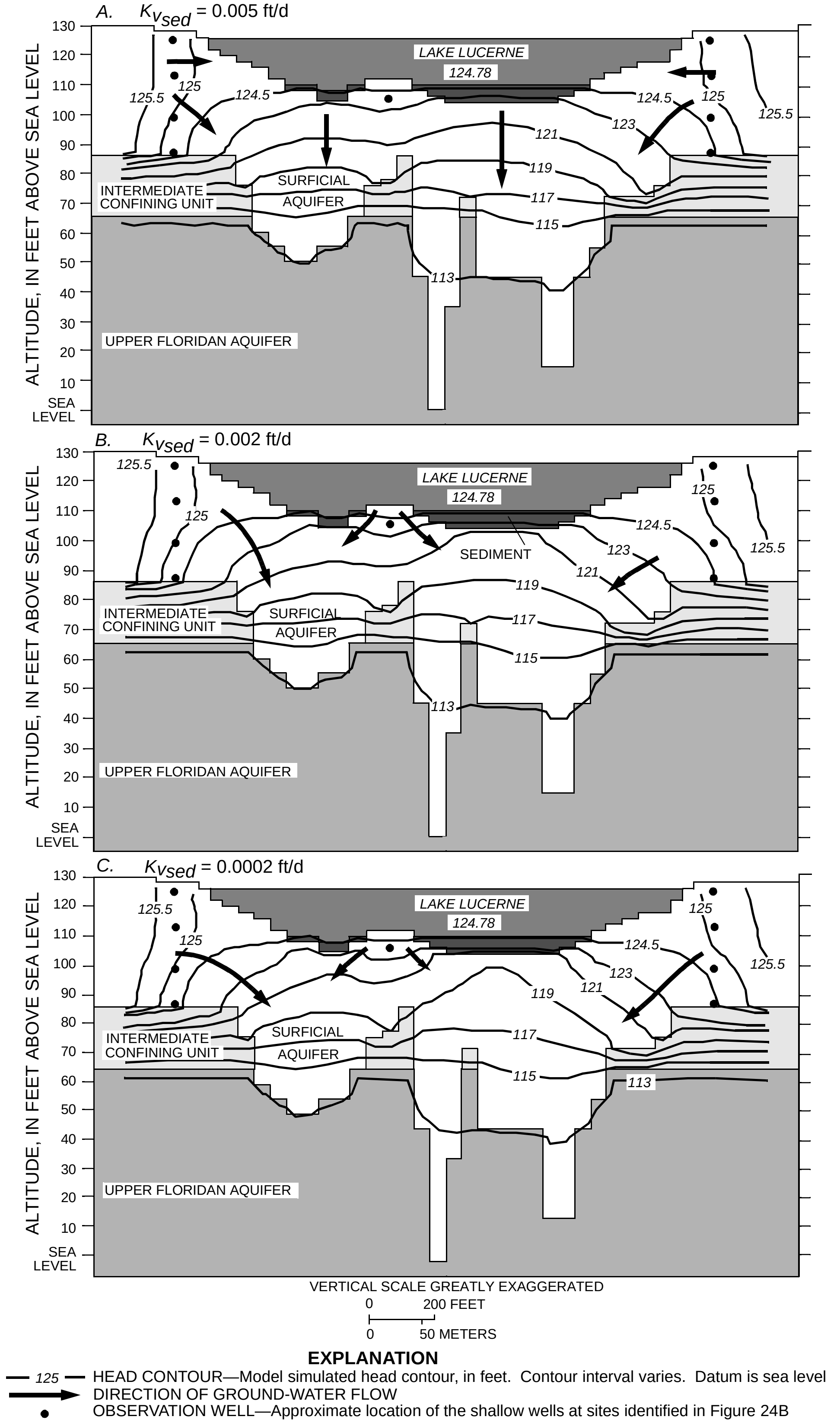

Figure 30. Simulated vertical head distribution for low water-level conditions with vertical hydraulic conductivity of the sediment, $K_{v_{sed}}$, equal to (*A*) 0.005, (*B*) 0.002, and (*C*) 0.0002 foot per day.

layer and, as such, was not a sensitive indicator of the potential v_{sed} at Lake Lucerne. Despite this fact, heads predicted in the midlake well did respond slightly to changes in v_{sed} and were closest to the observed head for both high and low head conditions when v_{sed} was the highest (0.005 ft/d).

Table 4. Predicted ground-water inflow and leakage rates for three $K_{v_{sed}}$ values under high and low water-level conditions and heads for the midlake well

[$K_{v_{sed}}$, vertical hydraulic conductivity of lake sediments]

Parameter	$K_{v_{sed}}$, (in feet per day)		
	0.005	0.002	0.0002
High water level:			
Ground-water inflow[1]	2.15	2.13	2.08
Leakage[1]	1.53	1.37	1.15
Percent leakage through nodes with sediments	60	44	16
Low water level:			
Ground-water inflow[1]	.67	.65	.62
Leakage[1]	3.74	3.42	3.03
Percent leakage through nodes with sediments	53	38	13
Midlake-well heads:			
High water level[2]	125.49	125.40	125.28
Low water level[2]	123.79	123.60	123.35

[1] Computed by multiplying discharge rate by the fraction of the total lakebed area represented by the model cross section, in cubic feet per day per foot.

[2] Observed midlake-well head equals 125.70 for high and 123.88 for low water-level conditions.

Limitations of Two-Dimensional Model

Modeling ground-water flow patterns along a cross section through Lake Lucerne provided a simple and useful tool for testing the influence of the hydrogeologic setting on ground-water interactions with the lake. Regardless of the hydrogeologic framework or hydraulic properties used, however, two-dimensional model simulations of ground-water flow did not duplicate the extent and magnitude of the upward head gradients that were consistently observed in the nested observation wells near Lake Lucerne at sites 1PN and 2PN.

This discrepancy is most likely due to the limitations of using a two-dimensional model instead of a three-dimensional model to simulate ground-water flow around the lake. Winter (1978) compares ground-water flow patterns simulated around a hypothetical circular lake using a two-dimensional and a three-dimensional, steady-state model. For a given hypothetical lake setting, upward head gradients near the margin of the lake were larger and distributed farther beneath the lake for a cross-section projection taken from the three-dimensional simulation than for the same cross-section projection simulated with a two-dimensional model. Also, if “outseepage” or leakage was predicted in the two-dimensional analysis, much less or no outseepage was predicted in the three-dimensional simulation. For lakes that showed outseepage in both two-dimensional and three-dimensional results, the area of the outseepage was reduced in the three-dimensional results over the two-dimensional results.

These conclusions are partly intuitive if the primary assumption of a two-dimensional model is considered, namely, symmetry along the *y*-axis. When applied to a nearly circular lake such as Lake Lucerne, or the hypothetical lake modeled by Winter (1978), a two-dimensional, cross-section model lacks the capability to simulate the radial pattern of flow lines that converge inward toward the center of the lake. Therefore, the reinforcing effect of this crowding, or convergence, of flow lines along the perimeter of the lakebed is not accounted for in the head distribution predicted by the two-dimensional model. The result is an underprediction of the magnitude of the lateral and upward head gradients that cause ground-water inflow to Lake Lucerne.

The cross-section model also might underpredict the vertical hydraulic conductivity below the lake. By using the same parameters as the two-dimensional model, a three-dimensional model would tend to decrease both the predicted downward head gradient below the lake and the area of leakage. Thus, the vertical hydraulic conductivity below Lake Lucerne would probably have to be increased in the three-dimensional model in order to reproduce observed heads in the midlake well.

Summary of Modeling Results

Numerical modeling results generally support the initial interpretation of the hydrogeologic setting of Lake Lucerne. Although the model is used primarily as a qualitative tool, it simulates with reasonable accuracy the head distribution around Lake Lucerne at high and low water-level conditions, especially if the differences between the two- and three-dimensional approach, just mentioned, are taken into account. The model confirms the presence of breaches in the confining unit below the lake. These breaches are required to reproduce the flow divide in the surficial aquifer near the lake and to simulate heads observed in the midlake well.

The simulated flow divide in the surficial aquifer indicates the area of the lakebed that receives lateral ground-water inflow and the area that loses water by vertical leakage. The shape of this flow divide is most accurately simulated when anisotropy in the surficial aquifer is on the order of 100. With this anisotropy value, the depth (or thickness) of ground-water inflow is about 18 ft for the high water-level condition and about 10 ft for the low water-level condition.

At the high water-level condition, leakage occurs from areas of the lakebed that are below an altitude of 114 ft above sea level. At low water-level conditions, the area of leakage increases to the area below about 118 ft above sea level. These levels correspond to the areas below the 14-ft and 10-ft contours on the bathymetric map, respectively (fig. 7). The predicted upward head gradients associated with the flow divide in the two-dimensional simulations were never as large as the observed gradients. This effect is most likely the result of representing three-dimensional flow in two dimensions.

Lake sediments, even of low hydraulic conductivity, did not significantly inhibit the simulated leakage loss from Lake Lucerne. Though no definitive conclusions can be drawn about the value of v_{sed} for Lake Lucerne, the influence of lake sediments appears to depend on their distribution in the lakebed. If sediment-filled depressions in the lakebed are separated by elevated areas that are bare or thinly covered, then substantial leakage can occur from these elevated areas. This result indicates that leakage might be greater from sinkhole-type lakes with an irregular morphometry formed by multiple, discontinuous “pools” than from lakes with a more regular shape in which sediments are uniformly thick. Alternately, if lake sediments are not significantly less conductive than the adjacent aquifer, then leakage might be somewhat evenly distributed across the lakebed.

Results from the ground-water flow model provide information helpful for calculating ground-water fluxes to Lake Lucerne using less complex analytical methods. Ground-water inflow can be computed by an areal flow-net analysis if the inflow is predominantly along horizontal flow lines and the depth of inflow is known. Leakage, as a steady, one-dimensional flow phenomenon, can be computed using Darcy’s law. These methods were selected for ground-water flux calculations at Lake Lucerne because they are relatively simple, they rely on the actual head distribution observed in the field, and they can be applied to any specific time period for which observations are available.

Modeling results support the use of these methods in several ways. First, they support the conclusion that ground-water inflow to Lake Lucerne follows predominantly horizontal flow lines and, therefore, can be calculated by an areal flow-net analysis. Despite the complex sublake geology, the model indicates that lake leakage is primarily vertical and, thus, can be calculated by a one-dimensional flow equation. These simplifications provide the basis for the calculations of ground-water fluxes in the following section. Other model results are used to support assumptions about the depth of the ground-water inflow component and the area of leakage.

Quantification of Ground-Water Fluxes

Ground-Water Inflow

An areal flow-net analysis was used to estimate the ground-water inflow to Lake Lucerne. A flow-net analysis is a graphical solution technique to the LaPlace equation describing steady, two-dimensional, ground-water flow in a homogeneous, isotropic aquifer. A thorough discussion of the approach was given by Davis and De Wiest (1966, p. 189–198).

Flow-Net Assumptions

The use of an areal flow-net analysis is appropriate under a set of limiting conditions or assumptions, namely, that (1) ground-water flow is two dimensional; (2) hydraulic head, or its derivative normal to the flow region boundary, is known along the entire flow system boundary; (3) ground-water flow is steady, that is, no changes in ground-water storage occur with time; (4) Darcy’s law is valid for the flow region (Reynolds number, $R_e \leqq 1$); and (5) the effective depth of the horizontal flow component is known.

If the above conditions are met, the LaPlace equation can then be solved graphically, and ground-water discharge can be computed using a form of Darcy’s law:

$$Q = mK_h HD/n \qquad (20)$$

where

Q is total discharge of the considered flow region, in cubic feet per second;

m is the number of stream tubes within a flow region;

K_h is the horizontal hydraulic conductivity in the surficial aquifer, in feet per day;

H is the total head drop across the considered flow region, in feet;

D is the effective depth of the horizontal flow intercepted by the lake, in feet; and

n is the number of equipotential drops along the considered flow region.

If 1-ft contour intervals are used to describe the water-table altitude, then H is equal to n, and the equation reduces to

$$Q = mK_h D \qquad (21)$$

The horizontal flow component contributing inflow to the lake is assumed to be bounded above and below by no-flow boundaries. In reality, near the margin of the lake, near-vertical flow lines converge and terminate along a seepage face in the water table adjacent to the lake, as well as along the lakebed. In this analysis, however, vertical flow near the lake is ignored. All of the water that flows horizontally toward the lake at some distance away from the lake margin is assumed to discharge ultimately into the lake. This analysis ignores potential losses of ground water due to evapotranspiration in the water table near the edge of the lake.

The flow system is bounded laterally by no-flow boundaries that are generally coincident with the basin drainage divide. In the northwestern corner of the basin, however, this boundary is defined by the stage of Terrie Pond (fig. 9).

The effective depth (D) of the ground-water inflow intercepted by a lake greatly influences the magnitude of calculated flows to lakes but is difficult to accurately define. Like Lake Lucerne, many lakes partially penetrate the surficial aquifer and intercept only a fraction of the total horizontal flow. The fraction of flow intercepted depends upon such hydrogeologic factors as lake and aquifer geometry (Winter and Pfannkuch, 1984), the distribution of anisotropy and hydraulic conductivity in the ground-water basin (Winter, 1976), and the configuration of the water table (Munter and Anderson, 1981; Winter, 1981a, 1983).

At Lake Lucerne, D is estimated to be the saturated thickness of the surficial aquifer above the vertical flow divides at sites 1PN, 2PN, and 3PN. The monthly average depth for these three sites ranged from 6 to 26 ft and was determined from plots of the cross-section head distribution around the lake. When head gradients were downward at all depths in the surficial aquifer, D was estimated to be 6 ft. The annual average value of D calculated by this method was equal to 16 ft.

By using this annual average value of D, the steady-state inflow to Lake Lucerne was calculated for the period between October 1985 and September 1986. The average annual water-table configuration used for this analysis was the mean of the 12 monthly average water levels for this period (fig. 31*A*). Because seasonal rises and declines in the water table around Lake Lucerne are nearly equal (thus, the annual average change in aquifer storage is approximately zero), this average is a good approximation of steady-state conditions in the ground-water basin. A single representative value of horizontal hydraulic conductivity (K_h) of 8 ft/d was used in all of the flow-net calculations.

Flow nets also were used to calculate monthly average rates of ground-water inflow to Lake Lucerne. This analysis assumes no substantial change in aquifer storage and steady flow conditions for each month. Steady-state conditions are closely approximated in most months, as the monthly change in water-table altitude is often small in relation to the saturated thickness of the aquifer. In addition, the time required to establish steady flow rates in the porous surficial deposits is expected to be significantly less than a month.

The most significant departure from steady-state conditions occurred during June 1986, when a transient recharge mound was detected in the water table near the lake. A similar recharge mound was detected in the water table during the summer of 1985 for the 3-week period July 25 to August 13, 1985 (Lee and others, 1991). A comparison of the flow nets for June 1986 and the preceding month of May shows that the number of stream tubes increases dramatically in June as a result of the steep head gradients associated with the recharge mounds (fig. 31*B* and 31*C*). The depth of the inflow component, however, is much smaller for June, as the transient recharge mounds caused a downward head gradient to occur between all depths in the nested observation wells.

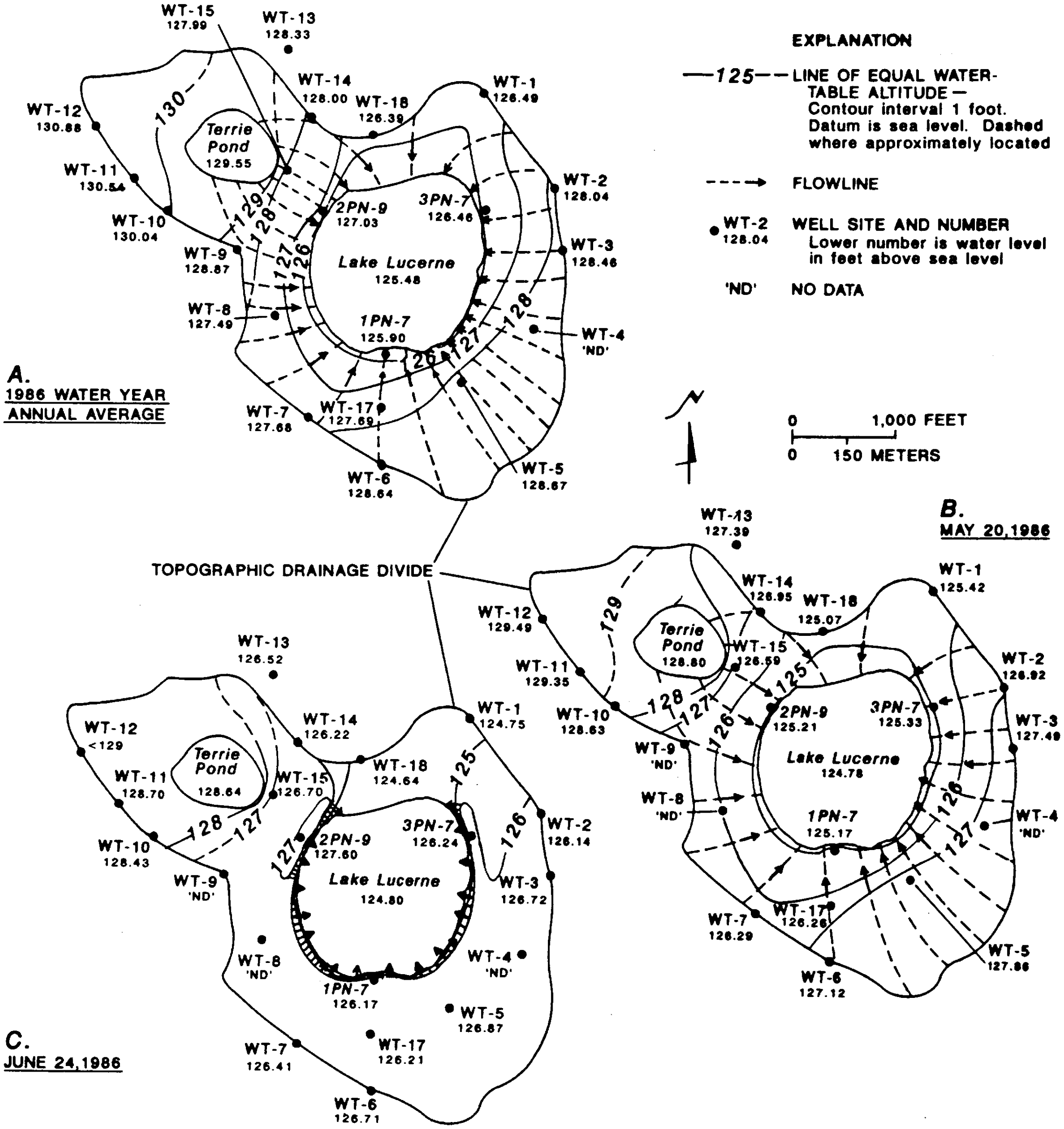

Figure 31. Flow-net diagrams (*A*) for the 1986 water year annual average, (*B*) for May 20, 1986, and (*C*) for June 24, 1986, water-table configurations.

To compute the ground-water inflow during June by flow-net analysis, four assumptions were made: (1) a water-table mound coincided with the contour of the lake in the area of site 2PN (fig. 31*C*), (2) a flow divide existed in the center of this mound with a head value equal to the head measured in well 2PN-9, (3) the mound persisted unchanged for the month of June, and (4) *D* was equal to 6 ft. The results of calculations for June indicate that transient recharge mounds can contribute large quantities of ground-water inflow (fig. 32).

Ground-Water Inflow Rates

The average inflow rate for the 1986 water year from the flow-net analysis was 3,900 ft^3/d, or an equivalent annual rise of 0.88 ft (10.5 in.) of depth over the area of the lake (fig. 32). The highest monthly ground-water inflow to Lake Lucerne occurred during October and November 1985. These months had the highest water-table configuration but lagged behind the highest rainfall months of July and August 1985. Ground-water inflow decreased steadily after October to an annual minimum in March (fig. 32).

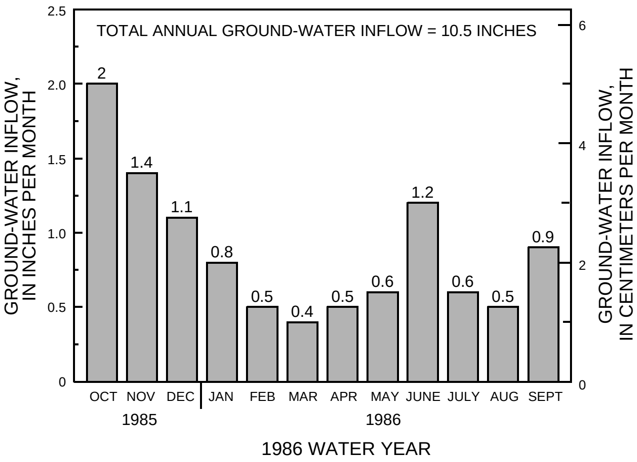

Figure 32. Monthly and total annual ground-water inflow to Lake Lucerne for the 1986 water year.

Ground-water inflow to Lake Lucerne increased slightly between March and May, even though the water table surrounding the lake declined steadily. Inflow increased slightly during these months because the lake stage declined faster than the surrounding water table, which increased the water-table gradient toward the lake (fig. 32). Transient recharge mounds caused a twofold increase in ground-water inflow in June compared with May (fig. 32). The absence of a steady increase in the inflow rate between July and September 1986 probably resulted from the abnormally low precipitation during these months and the timelag between rainfall and recharge to the surficial aquifer. As a result, inflow in September 1986 is less than half that in the previous October.

Errors in Ground-Water Inflow Rates

Errors in the estimates of the steady-state ground-water inflow to Lake Lucerne resulted from uncertainties in the value of hydraulic conductivity (K_h), hydraulic gradients, and effective depth (*D*). Errors also were introduced due to departures from steady-state flow conditions. Transient recharge mounds represent one such unsteady contribution of ground-water inflow. Similar recharge mounds were not observed later in the summer, regardless of the magnitude of later rainfall events. This could indicate less recharge to the water table and the potential for overland flow from the area immediately concentric to the lake during prolonged or high-intensity storms. Alternately, recharge to the water table could be followed by a rapid pulse of transient ground-water inflow. For example, Lichtler and others (1976) described transient ground-water inflows in their study of Lake Johio in central Florida. The unsteady inflow contribution that they estimated from a 75-ft-wide strip around the lake, however, was insignificant compared with total ground-water inflow.

The total error in the ground-water inflow can be computed using equation 6. Estimates of the uncertainty in each of the inflow variables are made in order to quantify the possible error in the inflow values. The error in the inflow is dominated by the large uncertainty in K_h. The standard error of estimate for hydraulic conductivities can be expected to be 100 percent of the estimated value or even higher (Winter, 1981b). Assumed errors of 25 percent for the effective depth and hydraulic gradient (number of stream tubes) estimates contribute only moderately to the total error. By use of equation 6, the error in the estimate of annual average ground-water inflow is computed to be 106 percent:

$$e_Q = \sqrt{(1.00)^2 + (0.25)^2 + (0.25)^2}$$

$$e_Q = 106 \text{ percent}$$

This error indicates annual ground-water inflow could potentially range from a negligible amount to as much as 21.4 in.

Lake Leakage

Unlike ground-water inflow, estimates of leakage from Lake Lucerne cannot reasonably be determined independently of other hydrologic-budget components. This limitation results from the lack of hydrogeologic information in the sublake region. An independent leakage calculation would require a description of the geometry and the hydraulic characteristics of the sublake region, as well as a complete description of the head distribution in the sublake region. Although marine seismic-reflection data have allowed the distribution of geologic materials in the sublake region to be inferred, the hydraulic characteristics of these materials, including lake sediments, remain unknown.

For this analysis, the leakage from Lake Lucerne for a 3-week period was derived from the residual of the hydrologic-budget equation. This estimate of leakage was then used in conjunction with available hydrogeologic data and Darcy's law to calculate a single, spatially integrated value of vertical hydraulic conductivity below the lake (v_{sub}).

With this value of $_{v_{sub}}$, annual and monthly estimates of leakage were computed by using Darcy’s law.

This same general approach has been applied in other studies in Florida (Hughes, 1974; Henderson, 1983; Henderson and others, 1985). These studies, however, gave little regard to the importance of errors in individual budget components on the residual term. Much of this error comes from short-term estimates of lake evaporation derived from pan-evaporation data. The leakage rate derived in this analysis is significantly improved over that of previous analyses by the availability of more accurate short-term estimates of lake evaporation and also by consideration of the errors in the hydrologic budget. In addition, physical information for the flow system at Lake Lucerne provided by field observations and numerical modeling provides the basis for conceptualizing the vertical flow system and for defining the area of leakage outflow.

Flow-Net Assumptions

A simplified flow net was used to calculate the vertical leakage beneath the lake. The flow system was represented as a vertical column, or cylinder. The top of the cylinder was roughly coincident with the lakebed, and the bottom was coincident with the depth of well 1PN-155 in the Upper Floridan aquifer, giving the cylinder a height of 128 ft (fig. 33). The area of the top and bottom of the cylinder is the projected area of the lakebed through which vertical leakage occurs (fig. 33). The vertical flow rate through this cylinder can be computed from a simplified, one-dimensional flow analysis using the following form of Darcy’s law:

$$Q_{GO} = K_{v_{sub}}(dh/dz)A_{proj} \tag{22}$$

where

Q_{GO} is the leakage rate through the lakebed, in cubic feet per day;
$K_{v_{sub}}$ is a spatially averaged value of vertical hydraulic conductivity in the sublake area, in feet per day;
dh/dz is the vertical head gradient between the lakebed and the open interval to well 1PN-155; and
A_{proj} is the projected area of outflow of the lakebed, in square feet.

As an approximation, leakage is assumed to occur through the lakebed below the 12-ft depth contour (a projected area of 917,000 ft^2), or an area equal to 56 percent of the average area of the lake surface. This area also is the mean of the leakage areas predicted by the model for the high and low water-level conditions.

The average vertical head gradients below the lake (dh/dz) were computed on an annual and monthly basis, as well as for the 3-week period when leakage was estimated by using daily lake stage and the predicted daily head in well 1PN-155 (figs. 34 and 35). Daily average heads in well 1PN-155 were predicted from a linear regression between periodic head measurements in well 1PN-155 and continuously recorded heads in the Lake Alfred deep well near Lake Alfred (fig. 2) for the 1986 water year (U.S. Geological Survey, 1986) ($R = 0.99$, standard error (Se) = 0.33 ft). The high correlation between heads at the two locations indicates that irrigation pumping around Lake Lucerne not only controlled heads in the Lake Lucerne wells (Lee and others, 1991), but also largely controlled heads in the Lake Alfred well. Drawdowns in the Lake Alfred well also were considerably smaller than those in well 1PN-155, consistent with moving away from the center of pumping.

Estimation of Sublake Vertical Hydraulic Conductivity

To determine $_{v_{sub}}$, leakage was calculated by solving the hydrologic-budget equation for the 3 weeks from April 15 to May 5, l986 (thermal survey periods 30, 31, and 32 in the energy-budget evaporation analysis). During this time, no rain fell, ground-water inflow to the lake was near minimum, and the downward head gradient beneath the lake was at its maximum.

In the absence of precipitation, the residual term of the hydrologic-budget equation is equal to leakage plus or minus the cumulative error of estimating the lake evaporation, ground-water inflow, and change in lake storage (eq. 1). Therefore, a confidence interval was computed for leakage by adding and subtracting the cumulative error from leakage. The energy-budget evaporation estimate for the 3-week period (0.442 ft) was assumed to have error equal to the mean monthly error for April and May (17.6 percent) (table 1). Ground-water inflow during this period (0.032 ft) is estimated to have an error equal to 106 percent, and change in lake storage (0.51 ft) is estimated to have an error of 5 percent (Winter, 1981b).

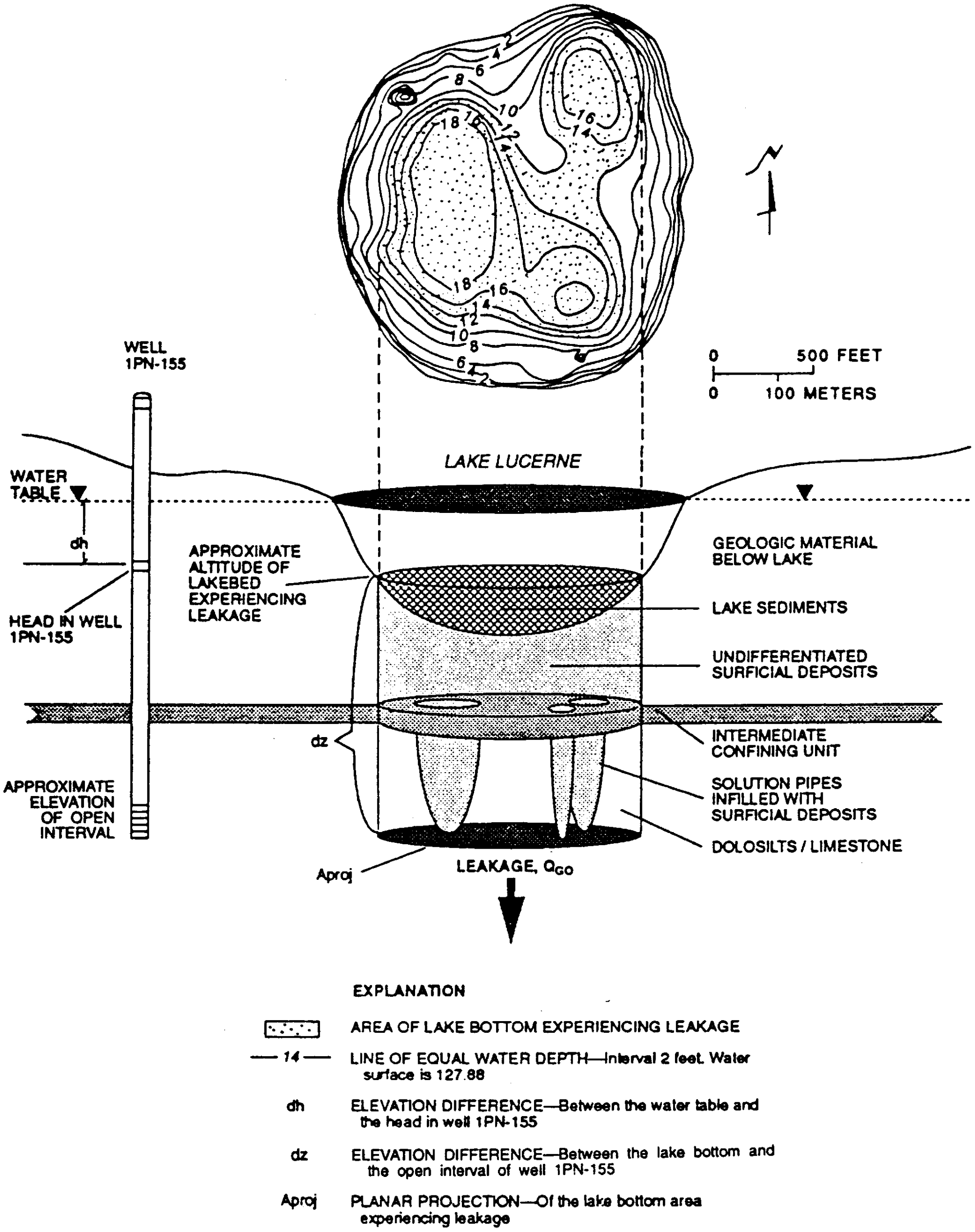

Figure 33. Conceptual model of the leakage from Lake Lucerne.

Although the maximum probable error is large, it does not entirely explain the residual term, and leakage is indicated. Possible leakage losses for the 3-week period fall in the confidence interval from 0.19 ft (2.3 in.) to 0.01 ft (0.12 in.). Kv_{sub} values, calculated by substituting these estimates of leakage into equation 22, fall in a range from 0.17 to 0.01 ft/d, or 0.09±0.08 ft/d. These estimates of v_{sub} are supported by the modeling results in the previous section. Those results could indicate that collapse features below the lake are infilled with sands and clays of the surficial aquifer, which had a K_h ranging from 8 ft/d in the upper part of the surficial aquifer to 2 ft/d in the lower part. Modeling results also could indicate that anisotropy in these deposits was on the order of 100, or that model v_{sub} is approximately 0.08 to 0.02 ft/d, within the 0.17 to 0.01 ft/d interval estimated in this analysis by using Darcy's law. These v_{sub} estimates range from two to three orders of magnitude larger than the confining unit K_v modeled in the region around the lake.

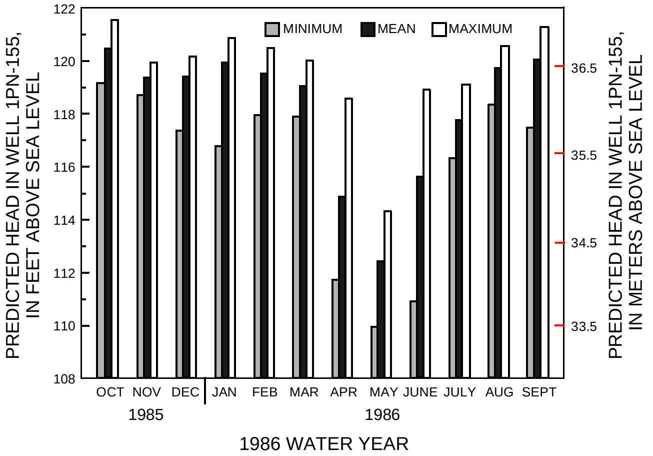

Figure 34. Predicted monthly mean, minimum, and maximum daily values of the head in well 1PN-155 for the 1986 water year.

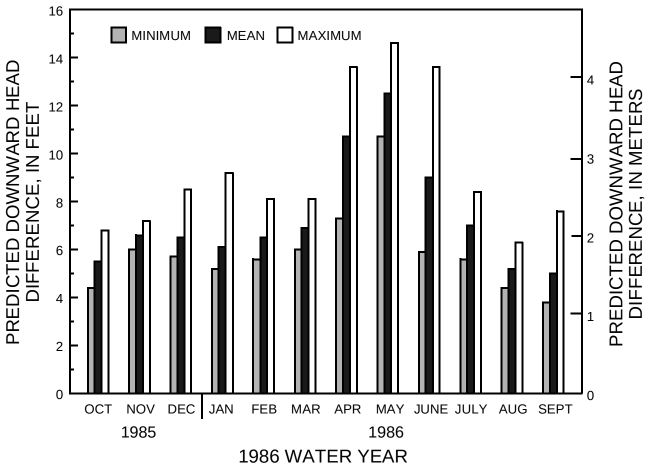

Figure 35. Predicted monthly mean, minimum, and maximum daily values of the downward head difference between Lake Lucerne and well 1PN-155 for the 1986 water year.

Leakage Rates

Monthly average leakage rates from Lake Lucerne were calculated using $K_{v_{sub}}$ = 0.09 ft/d as a representative intermediate value. Leakage area was held constant for all months, allowing leakage to vary only as a function of the vertical head gradient. Thus, monthly leakage rates (fig. 36) are proportional to monthly variations in *dh*/*dz* (fig. 35). Monthly leakage rates were largest in May (1.82 in.) and smallest in September (0.76 in.) (fig. 36). Total annual leakage from the lake, based on the average monthly rates, was 12.6 in.

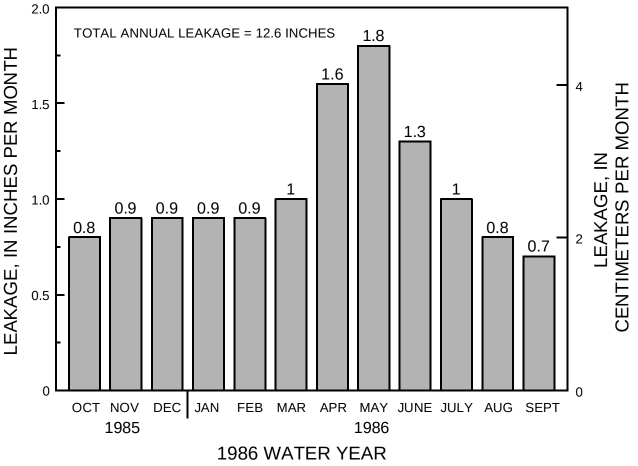

Figure 36. Monthly and total annual leakage from Lake Lucerne for the 1986 water year.

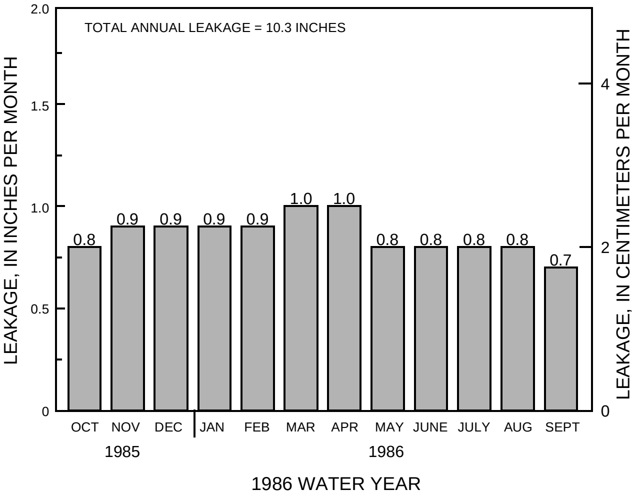

Figure 37. Monthly and total annual leakage from Lake Lucerne under hypothetical, nonpumping conditions for the 1986 water year.

To estimate the effect of ground-water pumping on leakage, a minimum monthly average head of 119 ft above sea level was set in the Upper Floridan aquifer to simulate nonpumping conditions, and leakage rates were recomputed. This criterion is fairly liberal, as daily heads in a given month can fluctuate significantly around this value (fig. 34). This altitude was chosen because it is slightly below the predevelopment potentiometric surface described at Lake Lucerne by Johnston and others (1980). The apparent trend in the potentiometric surface shown in figure 13 generally is above this altitude.

Under hypothetical nonpumping conditions, annual leakage from Lake Lucerne is 10.3 in., or nearly equal to ground-water inflow (fig. 37). The estimated leakage induced by pumping is 2.3 in/yr, or

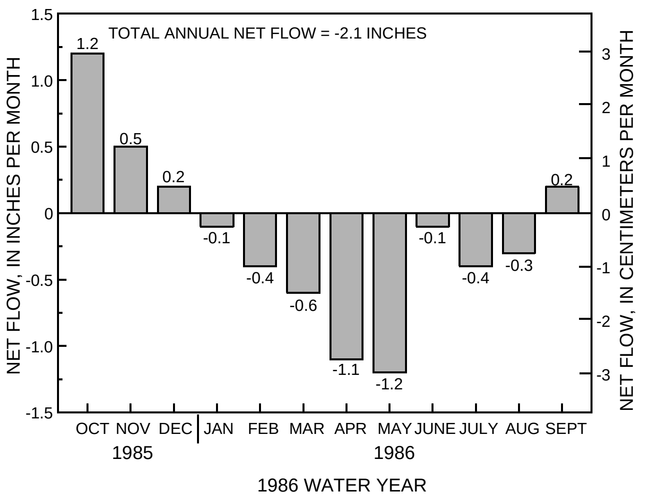

Figure 38. Monthly and total annual net ground-water flow to Lake Lucerne for the 1986 water year.

2.25 million gallons (Mgal). Although this amount can seem small if considered over the entire year, nearly all of this additional leakage (92 percent) occurred during the 3 months of April, May, and June.

With pumping, leakage exceeded ground-water inflow to Lake Lucerne during the 1986 water year by 2.1 in. (fig. 38). Net ground-water flow to Lake Lucerne, defined as ground-water inflow minus leakage, was positive October through December. Net flow then became negative, indicating net outflow, as ground-water inflow declined and leakage increased and reached a minimum value of −1.22 in. in May 1986. Net flow returned to a positive value by September, probably as a result of deficit rainfall during June through September.

Net ground-water flow steadily decreased between March and May despite a small increase in ground-water inflow during these months (fig. 38). The increase in ground-water inflow resulted from an increase in the water-table gradient toward the lake due to the rapidly declining lake stage. During this period, the lake stage declined faster than the surrounding water table for two reasons. The most significant of these was the increase in lake evaporation. Lake evaporation nearly doubled from about 0.08 to 0.12 in/d in March to about 0.24 to 0.28 in/d by early May (fig. 14). The second factor, induced leakage, compounded this loss. For the same period, leakage nearly doubled from 1.00 in. per month in March to 1.8 in. per month in May. The increase in ground-water inflow as a result of the declining lake stage was too small, however, to keep pace with these losses, and the net flow continued to decline (fig. 38).

Errors in Lake Leakage Rates

Errors in leakage estimates result from the errors in estimating v_{sub} (0.09±0.08 ft/d, or 89 percent) and from errors in holding the projected area of outflow constant between months. Modeling results indicate that the projected area of outflow can vary significantly between high and low water-level conditions. The varying depth of the ground-water inflow component (D) also suggests a reciprocal change in the area of outflow. The error in A_{proj} was estimated to be 50 percent. The resulting error in the leakage terms, from equation 6, was estimated to be 102 percent. These errors imply a potential range of annual leakage from a negligible amount to a maximum of 25.6 in.

Summary of Ground-Water Fluxes

Ground-water fluxes to Lake Lucerne were computed for a year that had significantly less rainfall (40.88 in.) than the local long-term average (50.83 in.). Thus, ground-water inflow to Lake Lucerne was possibly well below its long-term average due to reduced recharge to the surficial aquifer. Although the reduction due to drought conditions is not known, reduced ground-water inflow might be an important factor contributing to lake-level declines.

Leakage during the study year also was probably above average due to less recharge and increased irrigation pumping relative to other years. Long-term water levels in the Lake Alfred well indicate that the annual average head in the Upper Floridan aquifer was lower during 1986 than during the previous 4 years. The mean monthly head conditions for April and May 1986 also were below the means for these months in the previous 4 years. A significantly lower annual average head condition occurred during 1981, and average head conditions, lower but similar to 1986, occurred in 1976 and 1977. Therefore, although heads in the Upper Floridan aquifer during the 1986 water year were lower than in recent years, they were within the range of head values recorded between 1976 and 1986.

The drop in the stage of Lake Lucerne due to leakage induced by ground-water pumping during the 1986 water year was estimated to be equal to 2.3 in. This quantity represented approximately a 20-percent increase in the annual leakage from Lake Lucerne compared with hypothetical nonpumping conditions. Ninety-two percent of this increased loss occurred during the months of April, May, and June 1986. In the short term, this recurring annual loss might appear to be compensated for if it is accompanied by average and above average annual rainfall and ground-water inflow. During drought periods, however, the accumulation of induced leakage losses over a succession of years will accelerate the natural decline in lake stage. As a result, the lake might decline well below minimum levels encountered during drought periods prior to pumping. Over the long-term average, induced leakage will result in less lake storage and, in turn, lower lake levels, than existed prior to pumping.

INFLUENCE OF EVAPORATION, GROUND WATER, AND UNCERTAINTY IN THE HYDROLOGIC BUDGET

The hydrologic budget of Lake Lucerne is a statement of the conservation of water mass for the lake: the change in the volume of the lake is equal to the quantity of water added to the lake by rainfall and ground-water inflow minus the water removed from the lake by evaporation and leakage. Measured or computed flux rates for each of these processes allow the true hydrologic budget to be approximated and the relative importance of each of the fluxes to be compared. Monthly rates for each of these fluxes and associated measurement errors are presented in figure 39. The rainfall data are from daily measurements from a standard nonrecording rain gage. Lake storage changes are based on hourly stage data (Lee and others, 1991).

Hydrologic-Budget Results

Precipitation and evaporation are the major components of the hydrologic budget of Lake Lucerne on both a monthly and an annual basis, but ground-water fluxes are significant. Over the entire budget year (October 1, 1985, to September 30, 1986), precipitation was about 10 in. below the long-term average; however, it still composed about 80 percent of the total inflow (precipitation plus ground-water inflow). Ground-water inflow contributed 20 percent of the total annual inflow. On a monthly basis, ground water contributed a more varying amount of the total inflow to the lake, from 5 to 72 percent. It exceeded monthly precipitation only once, in November 1985, and was nearly equal to precipitation in March and April 1986.

Over the year, evaporation accounted for 82 percent of the total outflow (evaporation plus leakage), and lake leakage accounted for 18 percent. For the study year, evaporation was about 8 in. higher than the estimated long-term average for the region. Reduced cloud cover and an associated increase in incoming solar radiation would be expected to increase evaporation during a drought year. Monthly leakage was more consistent than monthly ground-water inflow, varying only from 10 to 30 percent of the total outflow from the lake. Leakage made up the smallest percentage of the outflow in September 1986 and made up the largest percentage of the total outflow in January and February 1986. Leakage rates were highest in May 1986 but represented a smaller percentage of the total outflow because evaporation was also highest in this month.

Pumping increased the relative importance of leakage in the annual budget only moderately (from 15 to 18 percent of the total outflow) but caused a significant increase in certain months. Because evaporation was the dominant outflow, pumping did not translate into a large increase in the total annual outflow, but it did cause a substantial increase in monthly outflows between April and July 1986. Pumping increased the total monthly outflow by 11 percent in May and by 7 and 8 percent, respectively, in April and June. Pumping increased the annual leakage rate by about 20 percent.

The large uncertainty in the ground-water flux terms contributes inaccuracy to the overall budget. The maximum probable errors associated with the ground-water inflow and leakage estimates are large (106 and 102 percent, respectively) and broaden the interpretation of the role of ground water in the hydrologic budget of the lake. Because of these large confidence limits, a smaller probability exists that ground-water inflow could contribute negligibly to the total inflow, or it could contribute as much as 58 percent. Similarly, leakage could potentially range from a negligibly small amount to 53 percent of the annual outflow. The large errors in the ground-water fluxes primarily indicate the uncertainty in the hydraulic conductivity of the geologic materials surrounding and underlying the lake. They do not indicate uncertainty in the overall patterns of ground-water inflow and leakage around the lake, which are based on the head distribution around the lake.

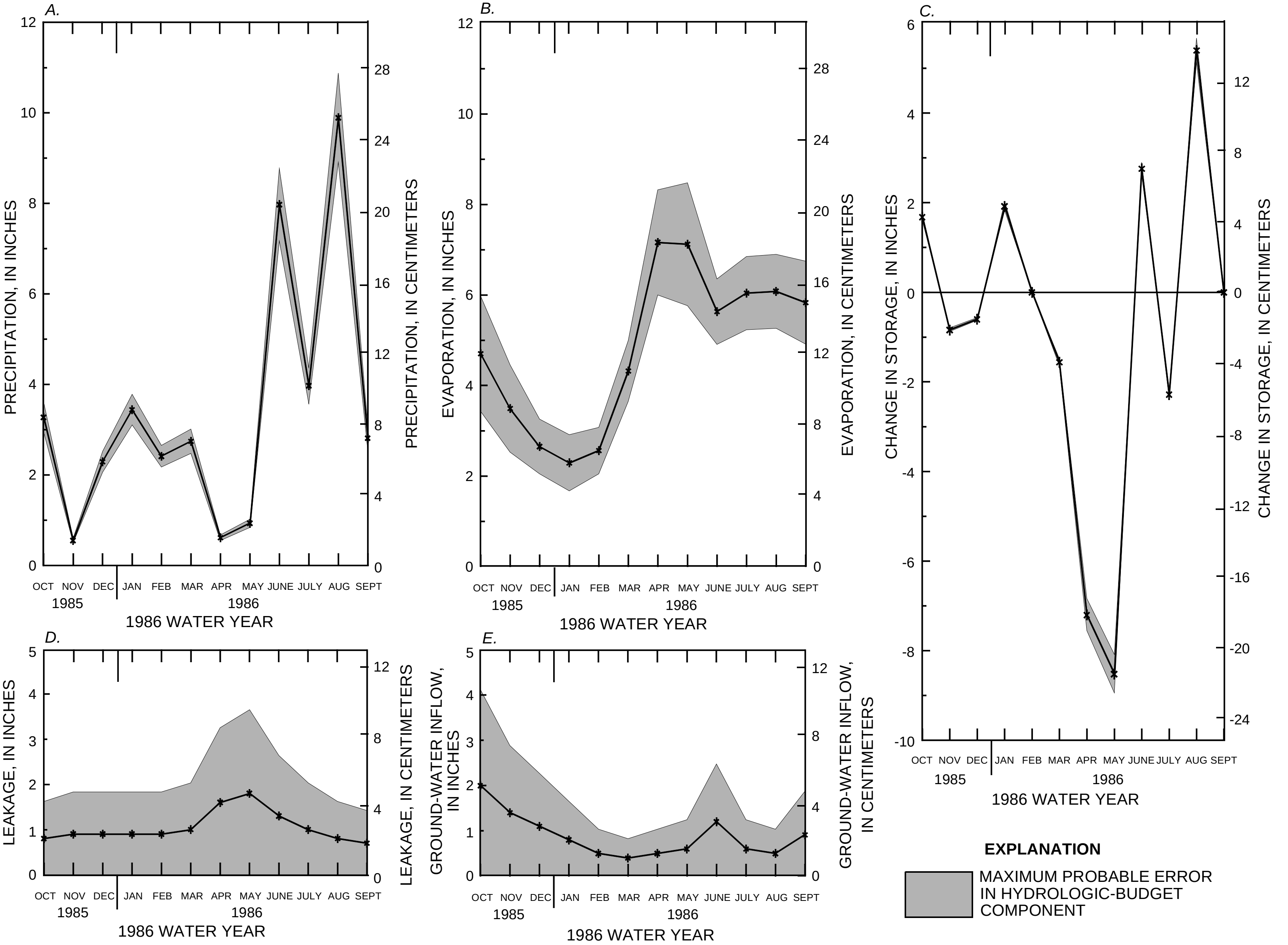

Figure 39. Monthly values of hydrologic-budget components of Lake Lucerne for the 1986 water year: (*A*) precipitation, (*B*) evaporation, (*C*) change in storage, (*D*) leakage, and (*E*) ground-water inflow.

Evaluation of Budget Error

The error in the hydrologic budget is the difference between the observed change in storage and that predicted by the right-hand side of the hydrologic-budget equation (eq. 1). When the annual values for budget terms are put into the right side of equation 1, the predicted annual change in storage is a decline (indicated by a negative sign) of –19.1 in. During this period, however, the measured decline in lake stage was only –9.2 in. The result is an error in the annual hydrologic-budget equation of –9.9 in. Referring to equations 1 and 3,

$$\begin{aligned} ER_{budget,\ annual} &= \Delta S - P + E - GI + GO \\ &= -9.2 - 40.9 + 57.9 - 10.5 + 12.6 = -9.9 \text{ in.} \end{aligned}$$

The annual budget error is much smaller than the probable error in the hydrologic budget, which is computed from the probable measurement errors of terms in the hydrologic budget. Referring to equations 1 and 4,

$$ER_{prob} = \sqrt{(\quad_{\Delta S}\quad)^2 + \quad_{P}\quad{}^2 + (\quad_{E}\quad)^2 + (\quad_{GI}\quad)^2 + (\quad_{GO}\quad)^2}$$

$$\begin{aligned} ER_{prob} &= \sqrt{(0.05 \bullet 9.2)^2 + (0.10 \bullet 40.9)^2 + (0.164 \bullet 57.9)^2 + (1.06 \bullet 10.5)^2 + (1.02 \bullet 12.6)^2} \\ &= \sqrt{(0.21) + (16.7) + (90.2) + (123.9) + (168.4)} \\ &= 20.0 \text{ in.} \end{aligned}$$

The errors in the annual rainfall and change in storage are estimated to be 10 percent and 5 percent, respectively (Winter, 1981b). Error in the annual energy-budget evaporation term is 16.4 percent, and errors in the ground-water inflow and leakage terms are 106 and 102 percent, respectively.

Knowledge of the overall hydrologic budget can provide insight into how well individual terms are quantified. The calculation for probable error indicates that the error in the hydrologic budget is dominated by the error in the ground-water terms. Thus, the budget error term could contain useful information about the ground-water flux terms, but this information must first be extracted from the remaining, randomly distributed error.

To investigate the possibility that the budget error term is not entirely random, a correlation matrix was defined between monthly values of all of the terms in the hydrologic budget and the monthly error term. Only two terms had a correlation with the error of 50 percent or higher: leakage and net ground-water flow. Leakage (*GO*) was linearly correlated with error ($R = 0.70$, probability level = 0.01, $Se = 0.82$ in.). A poor correlation exists between ground-water inflow and error, but because of the correlation with leakage, net ground-water flow (ground-water inflow minus leakage) has the next best correlation with the error term. This correlation is weak and of questionable statistical significance ($R = 0.60$, probability level = 0.04, $Se = 0.90$ in.); however, it does indicate a positive correlation between these two variables.

The weak correlation between monthly budget error and any budget term is not surprising, considering the potentially random nature of the error component. The correlation is significant from a qualitative viewpoint, but the rather poor regression relation prohibits strong quantitative interpretation. Nonetheless, the correlation with leakage does explain 49 percent of the variance in the error term. If the net ground-water flow to Lake Lucerne was computed as the residual term to the hydrologic-budget equation, the influence of this correlation would be incorporated into the result.

To explore the possible physical significance of the budget error term, monthly net ground-water flow was derived as the residual term to the hydrologic-budget equation, and this estimate was regressed against the calculated net ground-water flow. The relatively high correlation between net ground-water flow estimated by these two markedly different methods ($R = 0.83$, probability level = 0.001, $Se = 0.90$ in.) implies that the physical significance of net ground water derived as a budget residual is not overwhelmed by the errors that the term contains (fig. 40). This occurs in spite of the fact that the errors associated with calculating net ground water as a residual term are often larger than estimates of monthly net ground-water flow (table 5).

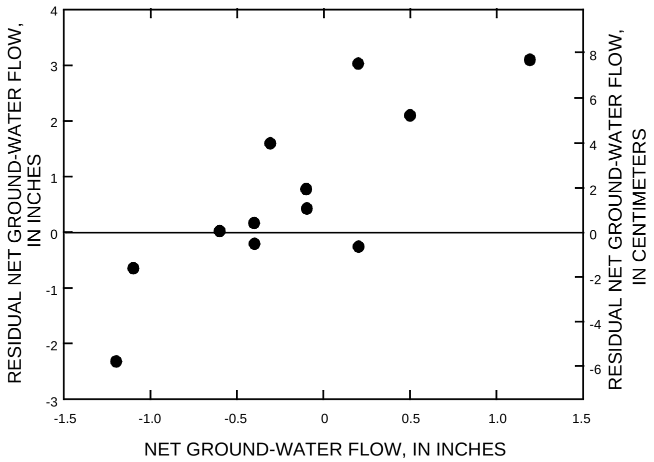

Figure 40. Monthy relation between the residual net ground-water flow and the calculated net ground-water flow to Lake Lucerne for the 1986 water year.

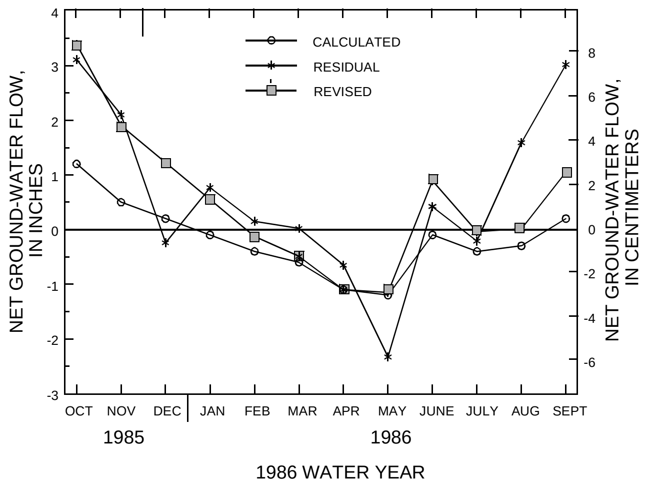

Figure 41. Monthly calculated, residual, and revised net ground-water flow to Lake Lucerne for the 1986 water year.

Table 5. Monthly residual net ground-water flow to Lake Lucerne and the associated error

[*P*, precipitation; e_i , error in term *i*; *E*, evaporation; ΔS, change in storage; *RNGW*, residual net ground-water flow. All values are in inches]

Year and month	*P*	e_P	*E*	e_E	ΔS	$e_{\Delta S}$	*RNGW*	e_{RNGW}
1985:								
October	3.27	0.33	4.70	1.26	1.68	0.08	3.11	1.30
November	.55	.05	3.49	.98	– .84	.04	2.10	.98
December	2.29	.23	2.65	.61	– .60	.03	– .24	.65
1986:								
January	3.44	.34	2.29	.63	1.92	.10	.77	.72
February	2.41	.24	2.56	.51	0	0	.15	.56
March	2.74	.27	4.32	.67	–1.56	.08	.02	.73
April	.61	.06	7.16	1.17	–7.20	.36	– .65	1.22
May	.93	.09	7.12	1.35	–8.52	.43	–2.33	1.42
June	7.97	.80	5.63	.72	2.76	.14	.42	1.08
July	3.97	.40	6.04	.82	–2.28	– .11	– .21	.92
August	9.89	.99	6.08	.82	5.40	.27	1.59	1.31
September	2.81	.28	5.83	.91	0	0	3.02	.95
Total	40.88		57.87		–9.24			

The residual net ground-water term unavoidably includes random errors as well as additional physical information. The fact that a significant part of the budget error is correlated with a physical process, namely leakage (and, thus, net ground-water flow), however, encourages some reevaluation of our independent estimates of ground-water inflow and leakage.

The monthly residual net ground-water flow indicates that both ground-water inflow and leakage rates are greater than those estimated by flow-net analysis. For example, the residual net ground-water flow indicates net inflow occurred in 7 months as opposed to only 4 months using flow-net-derived values (fig. 41). In addition, for most months when the residual net ground-water flow indicated net inflow, this net inflow is greater than the gross ground-water inflow estimated by flow-net analysis (compare table 5 with fig. 32). Thus, these larger residual net inflows cannot be arrived at by simply reducing leakage. Alternatively, the negative residual net flow for May 1986 indicates substantially greater outflow than was estimated by flow-net analysis (fig. 41).

Revised Estimates of Ground-Water Inflow and Leakage

Monthly ground-water inflow and leakage were recomputed on the basis of the relation shown in figure 40 and assuming a simple physical model. Revised ground-water inflow and leakage rates were each defined as the product of the original estimate and some constant coefficient. To determine these coefficients, the monthly residual net flow was regressed against monthly values of *GI* and *GO* by using multiple linear regression. This regression, which was forced through the origin ($R = 0.82$, probability level = 0.004, $Se = 1.0$ in.), predicts a coefficient of 2.2 for ground-water inflow and a coefficient of 1.4 for leakage. The monthly net ground-water flows derived from these revised estimates of ground-water inflow and leakage are shown in figure 41.

Reevaluation of the ground-water inflow and leakage terms on this basis indicates that leakage would increase by about 40 percent over the original estimate (17.5 instead of 12.6 in/yr). Ground-water inflow would more than double, an increase of 120 percent. Ground-water inflow would total 23.6 in/yr, and net ground-water flow would be +6.1 in. The remaining error in the annual hydrologic budget would be greatly reduced, from –9.9 in. to +1.7 in. The monthly budget error also would no longer correlate with terms in the hydrologic budget.

The importance of ground-water inflow to the hydrologic budget is significantly increased using the revised values. As a result, ground-water inflow would contribute about 37 percent of the total annual inflow. Annual leakage increases moderately from 18 to 23 percent of the total outflow, and leakage ranges from 13 to 35 percent of the total monthly outflow. The relative effect of pumping on leakage increases for the revised ground-water fluxes. Pumping would induce an additional 3.2 in/yr of leakage instead of the original estimate of 2.3 in/yr.

These revised estimates also have substantial uncertainty, as there is a substantial standard error in the regression relation between the net flows derived from flow-net analysis and those derived as a residual to the hydrologic-budget equation. At the least, this relation implies that the flow-net estimates of the ground-water fluxes are too low. A more conservative conclusion might be that ground-water fluxes lie within the bounds defined by the two estimates.

Differences between the two estimates of ground-water inflow and leakage could be explained easily by the large uncertainty in the estimates of K_h and Kv_{sub}. The use of a constant coefficient to *GI* and *GO* is analogous to a constant increase in a nonvarying value such as hydraulic conductivity. The effect of other time-varying factors that influence ground-water inflow and leakage (for example, transient inflows, the number of stream tubes, estimated depth of ground-water inflow, and area of leakage) would not be expected to be improved by a constant correction factor. In addition, the error in these terms is considered to be less than that in the hydraulic conductivity.

The justification for reinterpreting ground-water fluxes on the basis of the hydrologic-budget equation is founded on the conclusion that the budget error is not completely random, but instead is significantly correlated with the estimate of ground-water leakage and net ground-water flow. This correlation supports the other lines of evidence that indicate part of the budget error could be associated with systematic error (bias) in estimates of ground-water fluxes. The outcome of the analysis indicates that, although still second in importance to direct precipitation and evaporation, ground-water fluxes probably are more important to the hydrologic budget of Lake Lucerne than first determined. Leakage is estimated to have contributed about 23 percent of the total outflow from Lake Lucerne, and ground-water inflow about 37 percent of the total inflow to the lake during the period of study.

SUMMARY AND CONCLUSIONS

Constructing descriptive hydrologic budgets of lakes requires better estimates of short-term evaporative losses and the ground-water interactions with lakes. This is particularly true for the many seepage lakes in Florida for which leakage and evaporation are the only water losses from the lake. Understanding both of these processes also is a critical step toward determining the added influence of leakage induced by pumping from the underlying Upper Floridan aquifer.

In a hydrologic budget computed for the 1-yr period from October 1, 1985, through September 30, 1986, evaporation was the dominant outflow from Lake Lucerne on both a monthly and an annual basis. Annual evaporation computed by the energy-budget method was 57.87 in. and was nearly equal to the estimate of 57.39 in. from the simpler, theoretically based mass-transfer method. The annual energy-budget estimate had the smallest maximum probable error, 16.4 percent, and was the most accurate method. This error was considerably less than the error in the annual mass-transfer estimate (31 percent), even when the effects of atmospheric stability were accounted for (21 percent). Evaporation for this 52-week period was higher than the long-term average (estimated from pan evaporation), probably as a result of the climatological conditions that resulted in the drought. The annual rainfall of 40.88 in. for the study period was about 10 in. below the long-term average.

The energy-budget method provided the most accurate short-term estimates of evaporation. Short-term evaporation estimates were made for daily, weekly, and monthly time periods. April had the highest monthly evaporation rate (7.16 in.) and January had the lowest (2.29 in.). Errors in energy-budget evaporation ranged from 12.8 percent to 27.6 percent of monthly values.

Daily evaporation rates calculated by the energy-budget method were affected by unrealistic Bowen ratios for 21 days, or 5.8 percent of the period of record. This occurred mostly during the winter months of the study, when evaporation rates were low. Evaporation rates for the remaining days were expected to have a maximum probable error higher than the annual error because of the higher errors in defining daily climatic conditions.

Pronounced seasonal differences existed between the energy-budget and mass-transfer methods, primarily as a result of the effects of atmospheric stability on the mass-transfer method. As a result, the mass-transfer evaporation overpredicted the energy-budget evaporation in the winter and underpredicted it in the summer. At Lake Lucerne, accounting for the effects of atmospheric stability in the mass-transfer method reduced the error in the annual evaporation.

Free water-surface evaporation from a pan at Lake Lucerne (FWS_p) was a better predictor of actual lake evaporation (energy budget) than it was of its theoretical counterpart, the free water-surface evaporation computed for Lake Lucerne (FWS_1). FWS_p evaporation was 54.54 in/yr, and it underestimated lake evaporation calculated by the energy budget by 6 percent on an annual basis. On an annual basis, the pan coefficient calculated for the 1986 water year using the Lake Lucerne pan data, or the data from the Lake Alfred NOAA site, was 0.73. These results agreed well with the long-term annual average coefficient of 0.74. The pan coefficient derived from the corrected energy-budget evaporation (FWS_1) was higher, the average for the year being 0.75. Significantly larger differences appeared between pan coefficients calculated on a monthly basis.

Ground-water interactions with Lake Lucerne are controlled by the geologic setting of the lake, recharge to the surficial aquifer, and the head in the Upper Floridan aquifer. Modeling the steady-state ground-water flow patterns along a cross section through the Lake Lucerne basin provided a simple tool for testing the conceptual and physical model of ground-water interactions in a sinkhole-type seepage lake. Model results corroborated the presence of breaches in the confining unit beneath the lake that were inferred from a marine seismic-reflection survey. These breaches (where the confining unit is replaced by material 200 times more conductive) result in an increased hydraulic connection between the Upper Floridan aquifer and the surficial aquifer below the lake and also provide a preferential flow path for water in the surrounding basin to recharge the Upper Floridan aquifer.

A model anisotropy of 100 in the surficial aquifer best simulated the observed head distribution around the lake and the ground-water inflow and leakage rates calculated by flow-net analyses. With this anisotropy value, the ground-water basin was simulated for the seasonal extremes in observed ground-water level conditions (May and October). The potentiometric surface of the Upper Floridan aquifer, which is primarily controlled by local pumping for citrus irrigation, showed the largest differences between seasonal extremes.

Leakage was more than doubled under the low water-level condition compared with the high water-level condition, and the rate of ground-water inflow was reduced by approximately one-third. Low water-level conditions (May) were dominated by leakage outflow from 88 percent of the length of the lake cross section. Ground-water inflow from the surficial aquifer occurred only to a depth of 6 to 8 ft below the lake surface. At high water-level conditions (October), ground-water inflow occurred to a depth of about 16 ft below the lake surface, and leakage was predicted to occur from approximately 74 percent of the length of the lake cross section. Under both high and low water-level conditions, the majority of the ground-water inflow occurred near the shallow margin of the lakebed.

Low-permeability organic sediments could function like a confining unit and inhibit leakage rates through deeper, and thus more thickly covered, areas of the lake bottom. However, higher leakage rates could still occur through elevated regions of the lakebed where sediments are thin or absent.

The conclusions derived from the use of a two-dimensional model would be subject to refinements using a three-dimensional model. The use of a two-dimensional model could explain the inability of the model to reproduce the magnitude of upward head gradients observed in the surficial aquifer around Lake Lucerne. The two-dimensional model also might overpredict the length of the lakebed that is experiencing leakage and underpredict the depth and magnitude of ground-water inflow. Alternately, the use of a three-dimensional model could require the use of higher vertical hydraulic conductivity in the sublake region.

Monthly ground-water inflow to Lake Lucerne calculated by flow-net analysis was highest during and for several months after the summer rainy season in 1985. The highest monthly inflow of 2.0 in. occurred in October 1985, although the highest monthly rainfall occurred in July and August 1985. Ground-water inflows steadily decreased to a minimum value of 0.4 in. in March 1986. Transient recharge conditions resulted in a twofold increase in the ground-water inflow to the lake in June over May 1986, but was followed in July by lower ground-water inflow rates after the transient recharge mounds dissipated. The annual ground-water inflow was estimated to equal 10.5 in/yr. Rainfall was well below normal during the 1986 water year, particularly July through September 1986, and probably resulted in ground-water inflow rates that were significantly less than the long-term average. The error in the independent estimates of ground-water inflow was estimated to be 106 percent.

Monthly leakage outflow was directly proportional to the downward head gradients below the lake and ranged from a minimum of 0.7 in. in September 1986 to a maximum of 1.8 in. per month in May 1985. Annual leakage was estimated to be 12.6 in. The annual leakage induced by manmade drawdown of the Upper Floridan aquifer was estimated to be 2.3 in., or a 22-percent increase in the estimated annual leakage without pumping effects. Ninety-two percent of the induced leakage occurred in April, May, and June 1986. The area of the lake bottom that experienced leakage was assumed to be constant; however, modeling results indicated that this area varies considerably between the seasonal extremes of head conditions at Lake Lucerne.

Ground-water inflow is a significant part of the hydrologic budget of Lake Lucerne. The flow-net estimate of ground-water inflow made up approximately 20 percent of the total annual inflow to Lake Lucerne. Ground-water inflow would presumably make up an even greater part of the total inflow in wetter years, as the fraction of ground-water recharge lost to evapotranspiration would be smaller.

The flow-net estimate of leakage made up 18 percent of the annual outflow from the lake and ranged from 10 to 28 percent of the monthly outflow. Without pumping, leakage would have been reduced to 15 percent of the total outflow for the 1986 water year. The maximum leakage and evaporation rates occurred concurrently in May 1986, causing the largest monthly drop in stage, 8.5 in.

The error in the monthly hydrologic budget was not random but was correlated with monthly leakage and with net ground-water flow. Reinterpreting ground-water inflow and leakage from the residual net ground-water flow indicates that ground-water inflow to Lake Lucerne might be more than twice as high as the independent estimate derived from flow-net analysis, for a total of 23.6 in/yr. The difference, 120 percent, between these two estimates of ground-water inflow was slightly greater than the 100-percent error attributed to the horizontal hydraulic conductivity in the surficial aquifer.

Leakage revised from the analysis of the residual net ground-water flow term was 40 percent higher than the independent estimate, for an annual total of 17.5 in/yr. When using the revised estimates, ground-water inflow would increase to 37 percent of the total inflow to Lake Lucerne during the 1986 water year and would exceed monthly rainfall in October through December 1985. Leakage would increase only moderately to 23 percent of the total outflow and would never approach the monthly loss by evaporation.

The revised estimates of ground-water flow also had substantial uncertainty in them; however, they indicate that ground-water fluxes were greater than the independent estimates. The increases indicated by this analysis are comparable to the range of uncertainty associated with the estimates of hydraulic conductivity in the surficial aquifer and sublake region.

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APPENDIX A. Energy-Budget Components and Evaporation Calculations for Each Thermal Survey Period

Table A1. Summary of energy-budget components and evaporation calculations for each thermal survey period

[Q_s, incident shortwave radiation; Q_r, reflected shortwave radiation; Q_a, incident longwave radiation; Q_{ar}, reflected longwave radiation; Q_{bs}, emitted longwave radiation; Q_v, advected heat; Q_x, change in stored heat; T_0, water-surface temperature; E_{EB}, energy-budget evaporation; cal/g, calories per gram; °C, degrees Celsius; cm/d, centimeters per day; Q values given in calories per square centimeter per day]

Thermal survey period	Dates	Q_s	Q_r	Q_a	Q_{ar} + Q_{bs}	Q_v	Q_x	Latent heat (cal/g)	Bowen ratio	T_0 (°C)	E_{EB} (cm/d)
	1985										
1	Oct. 1-7	400.76	17.56	866.33	955.00	20.35	-21.21	580.34	0.26	28.47	0.44
2	Oct. 8-15	347.03	15.04	872.29	953.37	.53	52.23	580.62	.18	27.96	.28
3	Oct. 16-21	376.72	16.43	879.36	953.17	4.64	-31.32	580.60	.19	28.00	.45
4	Oct. 22-28	314.97	13.53	869.35	936.50	.85	-21.31	581.09	.16	27.11	.37
5	Oct. 29-Nov. 4	311.08	11.76	837.62	929.75	3.63	-139.26	581.49	.29	26.37	.45
6	Nov. 5-11	329.76	14.07	757.89	888.15	.20	-22.99	583.23	.65	23.21	.21
7	Nov. 12-18	328.89	14.69	825.71	901.91	.47	23.02	582.70	.09	24.18	.33
8	Nov. 19-25	221.76	8.09	860.21	905.83	2.43	12.45	582.57	.09	24.42	.24
9	Nov. 26-Dec. 2	264.12	11.09	838.26	908.16	1.65	-42.03	582.43	.15	24.67	.33
10	Dec. 3-9	239.96	10.79	716.53	868.37	7.49	-129.60	584.07	.68	21.69	.21
11	Dec. 10-16	251.95	11.26	726.73	853.96	2.15	-106.76	584.73	.50	20.49	.25
12	Dec. 17-23	257.14	11.80	640.14	800.77	0	-115.59	586.55	.65	17.19	.20
13	Dec. 24-30	301.69	13.79	621.82	777.42	2.33	-50.58	587.76	.64	14.98	.19
14	Dec. 31-Jan. 6	250.06	10.54	729.26	818.15	7.00	95.26	586.59	.03	17.12	.10
	1986										
15	Jan. 7-12	193.19	7.17	752.57	816.71	16.73	21.64	586.77	.04	16.78	.19
16	Jan. 13-20	283.27	12.68	666.90	807.50	.11	.27	586.85	.22	16.63	.18
17	Jan. 21-27	298.88	11.67	675.56	812.29	1.06	-101.66	586.36	.35	17.52	.31
18	Jan. 28-Feb. 3	358.09	14.60	656.39	791.29	0	106.39	587.08	.38	16.23	.12
19	Feb. 4-12	260.61	11.96	771.76	863.23	10.69	43.06	584.91	.02	20.17	.20
20	Feb. 13-17	423.68	19.06	651.82	822.80	0	47.09	586.01	.33	18.17	.23
21	Feb. 18-24	339.92	15.11	779.29	879.43	2.03	60.21	584.32	.07	21.24	.26
22	Feb. 25-Mar. 3	420.94	22.61	638.33	822.57	.70	-133.19	585.52	.75	19.05	.33
23	Mar. 4-10	418.59	19.60	707.44	834.00	1.38	103.70	585.91	.16	18.35	.24
24	Mar. 11-17	350.87	13.89	820.29	892.57	14.45	119.31	584.04	- .05	21.75	.28
25	Mar. 18-24	505.64	22.73	729.03	870.71	.85	-115.11	583.95	.40	21.92	.55
26	Mar. 25-31	463.40	21.36	770.63	865.11	1.71	111.44	584.40	.10	21.09	.36
27	Apr. 1-7	561.76	23.67	810.84	895.51	0	62.02	582.90	.15	23.81	.56
28	Apr. 8-14	541.73	24.06	781.07	895.17	3.81	-29.60	582.89	.28	23.84	.57
29	Apr. 15-21	601.92	25.61	785.53	897.39	0	-21.64	582.79	.26	24.02	.64
30	Apr. 22-28	660.43	27.37	761.80	899.93	0	36.82	582.66	.19	24.25	.64
31	Apr. 29-May 5	590.07	24.30	837.42	930.01	0	26.00	581.46	.10	26.44	.67
32	May 6-12	502.55	22.33	815.14	924.93	4.12	-25.43	581.67	.17	26.06	.57
33	May 13-19	540.71	22.95	817.97	930.86	.22	20.44	581.42	.19	26.51	.53
34	May 20-26	542.04	24.11	844.01	948.30	2.78	49.20	580.70	.15	27.82	.53
35	May 27-June 2	627.53	25.45	866.79	965.95	3.64	44.53	579.97	.15	29.14	.67
36	June 3-9	492.95	23.36	913.60	967.73	2.17	11.75	579.94	.16	29.19	.58
37	June 10-16	415.81	18.57	900.57	977.29	37.58	-1.85	579.78	.44	29.50	.42
38	June 17-23	431.43	19.99	895.71	969.29	18.94	11.40	579.80	.51	29.46	.38
39	June 24-30	549.90	24.27	888.29	980.43	4.96	52.24	579.28	.34	30.40	.48
40	July 1-7	479.43	22.72	904.43	981.00	11.42	-21.02	579.25	.43	30.46	.48
41	July 8-14	525.47	23.05	911.58	990.86	2.73	32.10	578.75	.31	31.36	.50
42	July 15-21	508.48	22.61	965.60	1,003.57	10.05	2.30	578.30	.30	32.18	.58
43	July 22-28	431.41	18.65	914.28	983.86	5.84	-54.15	578.97	.48	30.97	.45
44	July 29-Aug. 4	433.56	21.33	931.71	984.72	37.09	63.73	579.05	.30	30.82	.42
45	Aug. 5-11	555.86	24.61	914.71	991.52	4.14	-16.90	578.68	.33	31.50	.60
46	Aug. 12-18	467.17	22.44	920.38	986.29	14.75	23.46	579.18	.46	30.58	.42
47	Aug. 19-26	480.26	21.29	910.52	987.94	12.67	13.93	579.10	.30	30.72	.48
48	Aug. 27-Sept. 1	511.09	23.05	923.48	995.12	24.29	-9.58	578.82	.37	31.23	.55
49	Sept. 2-8	475.94	21.35	919.99	988.53	13.92	-16.95	587.98	.35	30.95	.51
50	Sept. 9-15	415.61	19.04	920.03	1,022.41	9.57	1.98	579.34	.30	30.28	.41
51	Sept. 16-22	435.83	22.08	897.43	973.29	.67	-61.20	579.95	.24	29.19	.54
52	Sept. 23-30	483.73	22.14	908.29	976.43	.25	28.90	579.54	.19	29.93	.51

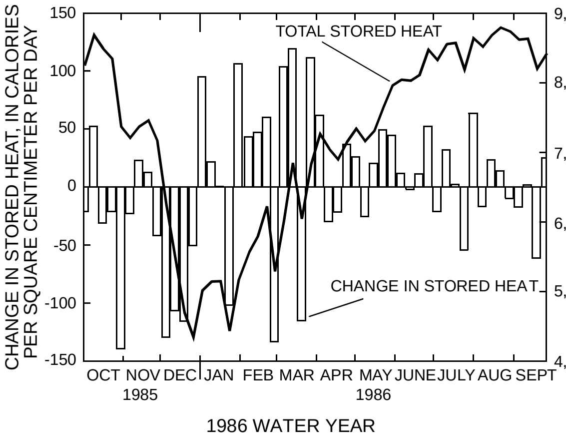

Figure A1. Total stored heat and daily average change in stored heat in Lake Lucerne by thermal survey period for the 1986 water year.

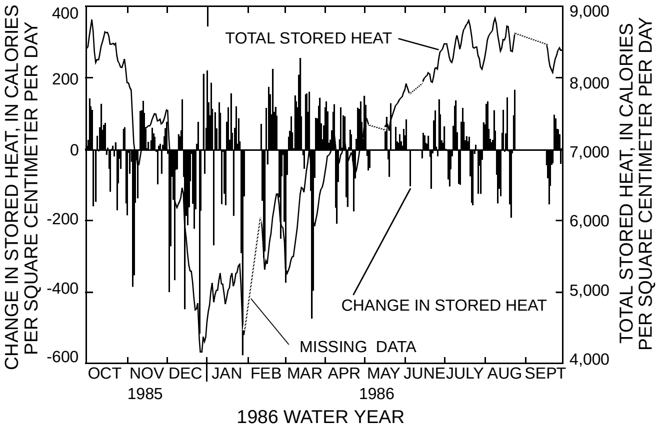

Figure A2. Total stored heat and daily change in stored heat in Lake Lucerne for the 1986 water year.

Table A2. Annual average values, weighted average errors, and relative errors for energy-budget components and evaporation, October 1985 to September 1986

[Values are in calories per square centimeter per day unless otherwise noted. Q_s, incident shortwave radiation; Q_r, reflected shortwave radiation; Q_a, incident longwave radiation; Q_{ar}, reflected longwave radiation; Q_{bs}, emitted longwave radiation; Q_v, advected heat; $|Q_x|$, absolute value of the change in stored heat; T_0, water-surface temperature; E_{EB}, energy-budget evaporation; cal/g, calories per gram; °C, degrees Celsius; cm/d, centimeters per day]

Term	Average value	Weighted average error	Relative error (percent)
Q_s	419.4	19.9	4.8
Q_r	18.5	.33	1.8
Q_a	819.2	23.0	2.8
$Q_{ar} + Q_{b\,s}$	915.4	21.5	2.3
Q_v	6.3	.68	10.8
$\|Q_x\|$	48.6	29.5	60.7
Latent heat (cal/g)	582	6.4	1.1
T_0 (°C)	25.2	.29	1.1
Bowen ratio (unitless)	.327	.080	24.4
E_{EB} (cm/d)	.390	.064	16.4

APPENDIX B. Conversion Tables for Calculation of Free Water-Surface Evaporation Rates

Table B1. Conversion table for calculating monthly total free water-surface evaporation from monthly total pan evaporation at Lake Lucerne

[in/d, inches per day; °F, degrees Fahrenheit; mi/d, miles per day; in/month, inches per month; α_p, ratio of advected energy used in evaporation to total energy advected from the pan; FWS_p, free water-surface evaporation from the pan]

Year and month	Pan evaporation (in/d)	Mean pan temperature (°F)	Mean air temperature (°F)	Mean wind speed (mi/d)	α_p	FWS_p (in/d)	FWS_p (in/month)
1985							
October	0.19	79.6	77.6	36.61	0.66	0.141	4.38
November	.15	73.0	72.2	39.99	.64	.108	3.23
December	.11	58.5	58.7	42.42	.56	.078	2.41
1986							
January	.11	59.5	59.6	47.50	.57	.080	2.47
February	.16	66.6	63.4	60.94	.62	.124	3.46
March	.20	65.8	65.1	62.31	.62	.140	4.35
April	.26	72.5	69.5	46.36	.64	.192	5.75
May	.29	78.8	77.3	41.99	.67	.208	6.44
June	.25	83.6	78.4	34.82	.68	.188	5.65
July	.24	84.1	80.9	49.72	.70	.181	5.60
August	.26	85.0	80.2	34.91	.69	.197	6.10
September	.21	83.1	79.9	27.09	.68	.157	4.70
Total							54.54

Table B2. Conversion table for calculating monthly total free water-surface evaporation from monthly total pan evaporation at Lake Alfred National Oceanic and Atmospheric Administration site

[in/d, inches per day; °F, degrees Fahrenheit; mi/d, miles per day; in/month, inches per month; α_p, ratio of advected energy used in evaporation to total energy advected from the pan; FWS_p, free water-surface evaporation from the pan]

Year and month	Pan evaporation (in/d)	Daily mean pan temperature, T_0 (°F)	Daily mean air temperature, T_a (°F)	Mean daily wind run (mi/d)	α_p	FWS_p (in/d)	FWS_p (in/month)
1985							
October	0.21	80.55	78.9	43.81	0.68	0.151	4.69
November	.16	72.55	72.0	53.07	.65	.113	3.38
December	.14	58.70	58.0	49.29	.56	.098	3.04
1986							
January	.13	58.65	58.3	55.23	.55	.094	2.91
February	.18	66.05	64.2	52.64	.61	.131	3.68
March	.22	66.35	64.2	63.10	.61	.163	5.07
April	.31	71.45	67.8	58.50	.65	.229	6.87
May	.34	78.65	76.1	57.71	.68	.247	7.64
June	.26	84.10	81.0	37.57	.69	.194	5.82
July	.26	85.15	81.7	36.61	.69	.192	5.96
August	.27	85.95	82.2	36.26	.70	.204	6.32
September	.24	84.25	80.7	35.97	.69	.175	5.26
Total							60.64

Table B3. Conversion table for calculating monthly free water-surface evaporation from monthly energy-budget evaporation

[α_l, ratio of advected energy used in evaporation to total advected energy from lake; Q_x, change in stored heat in the lake; Q_v, heat advected to the lake; Q_w, energy advected by evaporating water; L, latent heat of evaporation; E_{EB}, energy-budget evaporation; ΔE, energy-budget correction factor; FWS_l, free water-surface evaporation from corrected lake evaporation; (cal/cm^2)/d, calories per square centimeter per day; cal/g, calories per gram; cm/d, centimeters per day; in/d, inches per day; in/month, inches per month]

Year and month	α_l	Q_x [(cal/cm^2)/d]	Q_v [(cal/cm^2)/d]	Q_w [(cal/cm^2)/d]	L (cal/g)	E_{EB} (cm/d)	ΔE (cm/d)	FWS_l (cm/d)	FWS_l (in/d)	FWS_l (in/month)
1985										
October	0.60	–15.66	6.17	10.68	580.74	0.38	–0.01	0.37	0.147	4.56
November	.58	-22.66	1.48	7.28	582.59	.30	– .02	.28	.110	3.30
December	.51	-90.53	3.04	4.19	585.59	.22	– .08	.14	.055	1.70
1986										
January	.49	13.47	4.86	3.20	586.70	.19	.01	.20	.078	2.42
February	.53	29.67	4.04	4.56	585.28	.23	.03	.26	.102	2.86
March	.56	36.64	4.22	7.40	584.66	.35	.04	.39	.154	4.79
April	.57	12.84	.89	14.65	582.72	.61	.03	.63	.249	7.46
May	.61	21.36	2.19	15.84	581.09	.58	.04	.62	.244	7.57
June	.61	20.13	15.09	14.10	579.72	.48	.02	.50	.196	5.87
July	.62	– 3.04	10.37	15.48	578.84	.50	.00	.50	.196	6.07
August	.63	11.75	16.24	15.43	578.97	.50	.01	.51	.201	6.22
September	.61	–11.74	6.73	14.86	579.43	.49	.00	.49	.193	5.79
Total										58.61

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