Methods, Instrumentation, and Preliminary Evaluation of Data for the Hydrologic Budget Assessment of Lake Lucerne, Polk County, Florida

By T.M. Lee, D.B. Adams, A.B. Tihansky, and Amy Swancar

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 90–4111

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Tallahassee, Florida
1991

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

Copies of this report can be
purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Building 810
Box 25425
Denver, Colorado 80225

CONTENTS

FIGURES

TABLES

Conversion Factors, Vertical Datum, Acronyms, and Additional Abbreviations

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
inch per year (in/yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
inch per day (in/d)	25.4	millimeter per day
mile per hour (mi/h)	1.609	kilometer per hour
square foot (ft^2)	0.09294	square meter
foot squared per day (ft^2/d)	0.09294	meter squared per day
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
gallon per hour (gal/h)	0.00000105	cubic meter per second

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9\ (°F - 32)$$

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.

Acronyms used in report:

Lake Alfred Agricultural Research and Education Center = AREC
Long Range Navigation = LORAN
National Oceanic and Atmospheric Administration = NOAA
polyvinyl chloride = PVC

Additional abbreviations used in report:

calories per square centimeter per day = $(cal/cm^2)/d$
centimeter = cm
centimeter per day = cm/d
langley = ly
langleys per day = ly/d
langley = calories per square centimeter = cal/cm^2
meter = m
millibar = mb
millimeter = mm

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 have been left in the compatible metric unit of degrees Celsius. The mixed units that are conventionally used to describe the components of the mass-transfer evaporation method (Harbeck, 1962; Sturrock, 1985) also are used in this report.

Methods, Instrumentation, and Preliminary Evaluation of Data for the Hydrologic Budget Assessment of Lake Lucerne, Polk County, Florida

By T.M. Lee, D.B. Adams, A.B. Tihansky, and Amy Swancar

ABSTRACT

The karst physiography of Florida's Central Highlands Ridge is characterized by numerous solution-type lakes that naturally recharge the underlying Upper Floridan aquifer. Declining lake levels along the Central Highlands Ridge during the last decade have been attributed to precipitation deficits and also to increased lake leakage caused by pumping from the underlying Upper Floridan aquifer. Defining the effect of ground-water pumping on lake levels has been significantly hampered by a lack of accurate hydrologic data describing evaporation processes and ground-water interactions with Florida's lakes. A hydrologic-budget investigation of Lake Lucerne was initiated to determine the relative importance of evaporative losses and ground-water fluxes in regulating the stage of a solution-type lake. A data-collection network, operated at Lake Lucerne between April 1984 and September 1986, measured precipitation and lake and ground-water levels. The climatic data that are required to compute evaporation by the energy-budget and mass-transfer methods were collected for the 1986 water year, from October 1985 through September 1986. This report describes the hydrogeologic setting of Lake Lucerne and gives a detailed description of the data-collection network, methods, and the climatic and hydrologic data that will be used to construct a hydrologic budget for Lake Lucerne.

Climatic data were collected at three locations—a land-climate station, a raft-climate station, and a stage and reflected-radiation station on the lake. The data include measurements of air temperature, wind speed, relative humidity, and incoming and reflected longwave and shortwave radiation. The hydrogeologic setting of the lake was defined as an important prerequisite to understanding and quantifying ground-water inflows and outflows to the lake. Geologic data described in this report include the lithology of drill cuttings, results of mineralogical analyses, and results from borehole and surface geophysical surveys. Vertical hydraulic head gradients within different aquifers were monitored in three groups of observation wells around the lake and in a well finished 8 feet below the center of the lakebed. Additional wells finished in the surficial aquifer were used to monitor changes in the water-table altitude.

The surficial aquifer surrounding Lake Lucerne is hydraulically separated from the Upper Floridan aquifer by approximately 15 feet of confining clays. Beneath the lake, however, a seismic-reflection survey of the sublake geology revealed a system of vertical solution features in the limestone that are filled in by the collapse of the overlying clays and sands. This geologic interpretation is supported by the results of a regression analysis of surficial versus Upper Floridan aquifer head values, which shows a better hydraulic connection between these two aquifers beneath the lake than in the surrounding basin. Maps of the cross-sectional and areal head distribution around Lake Lucerne indicate that the lake is the focal point for ground-water discharge from the adjacent surficial aquifer. Also, because of breaches in the underlying confining unit, Lake Lucerne is a focal point for recharge from the surficial aquifer to the Upper Floridan aquifer. Ground-water flow patterns around Lake Lucerne varied significantly between the wet and dry seasons and also were influenced by geologic conditions and by drawdown in the Upper Floridan aquifer. This highly seasonal drawdown was primarily the result of localized irrigation pumping.

INTRODUCTION

The Central Highlands Ridge physiographic region encompasses most of the nearly 7,800 lakes that exist in Florida. The thousands of warm-temperate and subtropical lakes distributed along this hilly backbone of peninsular Florida are a valuable natural resource, providing esthetic settings for homes and recreation for residents and tourists. The rapidly expanding population of Florida and the concurrent demand for more water for domestic, industrial, and agricultural uses, however, threaten lakes with abnormal water-level declines.

Lake levels along the Central Highlands of west-central Florida have declined over the past decade causing degradation of water quality in some areas and leaving homes and dock facilities far from the water's edge. These declines have been attributed to precipitation deficits and also to increased leakage from the surficial aquifer due to pumping from the underlying Upper Floridan aquifer (Geraghty and Miller, Inc., 1980; Palmer and Nguyen, 1986). Quantifying the effect of ground-water pumping on lake levels, however, has been hampered by a lack of accurate hydrologic data to describe evaporation processes and ground-water interactions in Florida lakes.

Most of the Central Highlands has a karst physiography characterized by internally drained basins and seepage lakes that lack surface-water inflows or outflows. Sinkholes, created by dissolution of the underlying limestone, are considered to be the origin of many of the lakes in the region, and consequently, these lakes are referred to as solution-type lakes. The most profound implication of the ground-water interactions with solution-type lakes is the potential for pumping to induce preferential recharge, or leakage, directly from lakes due to the sinkhole structure of the sublake geology. In general, the recharge induced from the surficial aquifer by pumping in the Upper Floridan aquifer depends upon the permeability of the clay confining unit separating these two aquifers. Defining the recharge induced directly from solution-type lakes is difficult, however, because insufficient data exist to describe the configuration of the confining unit below them and extrapolation of regional geologic information beneath such lakes is inappropriate.

Another factor that confounds the assessment of lake and ground-water interactions on lake levels is the lack of accurate information on lake evaporation in Florida. Most of the lakes are seepage lakes, and as such, losses of water by evaporation and leakage control lake-level declines. Although annual evaporation from lakes in west-central Florida approaches the magnitude of the average annual rainfall, evaporation remains a poorly understood component of the hydrologic budget. Accurate lake evaporation rates are fundamental to constructing realistic lake hydrologic budgets, yet data from theoretically approached evaporation studies are not available for Florida. Accurate measurements of evaporation and other hydrologic-budget components, including some indication of potential errors, are needed before informative relations between surface-water and ground-water resources can be developed.

In 1983, the U.S. Geological Survey, in cooperation with the Southwest Florida Water Management District, began a 5-year study of the hydrologic budget of Lake Lucerne in Polk County, Fla. The study focuses on the role of evaporation and ground water in the overall hydrologic budget and includes an evaluation of the errors in each budget component. The study also examines the influence of the lake's geologic setting and pumping from the Upper Floridan aquifer on ground-water interactions with the lake.

Purpose and Scope

The specific objectives of this report are to: (1) describe the geologic and hydrologic setting of Lake Lucerne, (2) describe the methods and instrumentation that were used to collect data for a hydrologic budget of Lake Lucerne, and (3) present a summary of the hydrologic data collected between April 1984 and September 1986.

The overall purpose of the hydrologic investigation of Lake Lucerne is to determine the role of evaporation and ground-water fluxes in regulating lake stage. The approach of the study is to define each component of the lake's hydrologic budget accurately and to include an estimate of the error associated with each budget component. Subsequent reports that will present the summary findings of the study, including an assessment of lake evaporation rates and ground-water fluxes between the lake, the surficial aquifer, and the Floridan aquifer system, are planned.

The study, which began in 1983, is the first in Florida to collect the data to assess the relations between lake water levels, evaporation, and ground-water fluxes. An extensive field effort was undertaken to collect the geologic, hydrologic, and climatic data that were needed to evaluate the components of the hydrologic budget for the lake. Hydrogeologic data were collected by drilling monitor wells, conducting borehole and surface geophysical surveys, analyzing drill cuttings with X-ray diffraction, and monitoring lake and ground-water levels.

Climatic and hydrologic data collected at a raft on the lake, at a platform mounted in the lake, and at a land site were used to quantify evaporation and precipitation fluxes. The data included lake stage, water temperature, wet- and dry-bulb temperature, wind speed, barometric pressure, rainfall, and incoming and reflected longwave and shortwave radiation. Surveys also were made periodically to define the heat stored in the lake water.

Acknowledgments

The authors are grateful to the residents of Lake Lucerne and to representatives of OrangeCo, Inc., for accommodating and assisting our project activities in and around the lake. We are particularly thankful to the landowners who granted us permission to construct wells on their property and to Andrew and Lois Kinsey who provided the site for the land-climate station. Lois Kinsey also assisted the project as the climate-station observer.

We are also grateful to the many researchers within and outside of the U.S. Geological Survey who contributed their advice and efforts to this study. We specifically wish to thank Albert Hine of the University of South Florida, Department of Marine Sciences, for interpreting the marine seismic-reflection data; and Blair Jones, U.S. Geological Survey, for interpreting the X-ray diffraction data provided by the Florida Institute of Phosphate Research.

DESCRIPTION OF THE STUDY AREA

The development of natural lakes in the landscape depends on the physiography, climate, and geology of the area. The presence of a lake, and its rise and fall through the years, affects the soil and vegetation in its vicinity. To gain an understanding of the hydrologic budget of the lake, it is pertinent to review these characteristics of the lake's drainage basin.

Physiography

Lake Lucerne is in the Central Highlands of Florida (fig. 1), which runs northwest to southeast through Polk County (White, 1970). The Central Highlands is characterized by ridges, some of the highest hills in the State, high swampy plains, and numerous lakes of varying size and depth along its entire length. Land-surface altitudes range from 40 to 325 ft above sea level. White (1970) identified several northwest-southeast trending ridges within Polk County. From west to east, they are the Lakeland, Winter Haven, and Lake Wales Ridges. Brooks (1981) includes the Winter Haven Ridge in a broad geomorphic unit called the "Winter Haven Karst," which is characterized by "sandhill" or "mantled" karst (Brooks, 1981; Sinclair and others, 1985). Circular lakes, such as Lake Lucerne (fig. 2), and hilltops between 150 and 190 ft above sea level are common features of the Winter Haven Karst region.

The Winter Haven Karst is characterized by the prevalence of cover-subsidence type sinkholes (Sinclair and others, 1985). In areas where the overlying sediment is relatively thick and unconsolidated, it fills the limestone voids before large cavities can develop. Subsidence migrates upward as overlying sediments fill the steep walled holes in a process known as "piping." These pipes may be up to 120 ft deep depending on the amount of infilling (Beck and others, 1984). If the infilling material is of sufficiently low permeability, the resultant topographic depression retains water. This is considered to be the origin of many small circular lakes in Florida, such as Lake Lucerne. Large irregularly shaped lakes are formed when several sinkholes develop in close enough proximity to merge (Beck and others, 1984). Periodically, lakes of this origin may drain when the infilling material is disturbed (Beck and others, 1984; Sinclair and others, 1985).

Lake Lucerne is 45 acres in area and has a volume of 530 acre-ft at a stage of 130 ft above sea level (fig. 3). The maximum depth measured during the study period was approximately 22 ft and the average depth was about 15 ft. The lake is in a closed basin and has no surface-water inflow or outflow. It is situated topographically higher than four larger surrounding lakes (fig. 2), which isolates the lake from surface-water and ground-water inflow into the drainage basin. The sandy hills of Lake Lucerne's 0.26-mi^2 drainage basin are covered largely by irrigated citrus groves and a ring of low-density residential homesites immediately adjacent to the lake. In addition to Lake Lucerne, the drainage basin includes a small wetland pond that is upgradient to and northwest of the lake (fig. 2). For the purpose of this report, this pond is referred to as "Terrie Pond."

Climate

Because Lake Lucerne is a seepage lake, much of its water enters as precipitation and leaves as evaporation. Therefore, changes in climate have a significant effect on lake levels. The climate in the study area is classified as subtropical humid and is characterized by high temperatures and frequent rainfall from localized afternoon and evening thunderstorms between June and September. Cooler temperatures and less rainfall from frontal storms that are areal in nature occur between October and May. Long-term climatic data (71 years) for the area are available from the Lake Alfred Agricultural Research and Education Center (AREC), which is a National Oceanic and Atmospheric Administration (NOAA) climate reporting station, 2 mi northwest of the study area. Long-term rainfall at Lake Alfred AREC averages 50.83 in/yr; monthly averages range from 1.95 in. in November to 7.25 in. in August (fig. 4). The average annual air temperature at Lake Alfred AREC is 71.6 °F, and daily average temperatures range from about 60 °F in January to about 82 °F in August.

Soils and Vegetation

Soils in the study area generally consist of washed silica sand that is overlain by a highly enriched organic layer near the lake. According to a regional soil survey by the U.S. Soil Conservation Service (written commun., 1986), the soils, except in the vicinity of the lake, are composed of an extremely well-drained, fine sand and are nearly level or only gently sloping. The area surrounding the lake is composed of a moderately well-drained, sandy upland soil. The soils in the vegetated area immediately adjacent to the lake are poorly drained and are typical of those commonly found in wetland areas of Polk County.

The soils surrounding "Terrie Pond" are much the same as those surrounding Lake Lucerne. The soil immediately surrounding the pond is a poorly drained, organic soil, and the pond bottom sediment is an organic muck that is periodically exposed during extremely dry conditions. The thickness of the muck averages about 36 in.

The entire drainage basin outside the immediate area surrounding Lake Lucerne is cultivated in citrus groves. During the study period, two hard freezes (December 25, 1983, and January 23, 1985) caused extensive damage to the citrus groves. As a result, some mature citrus trees in the

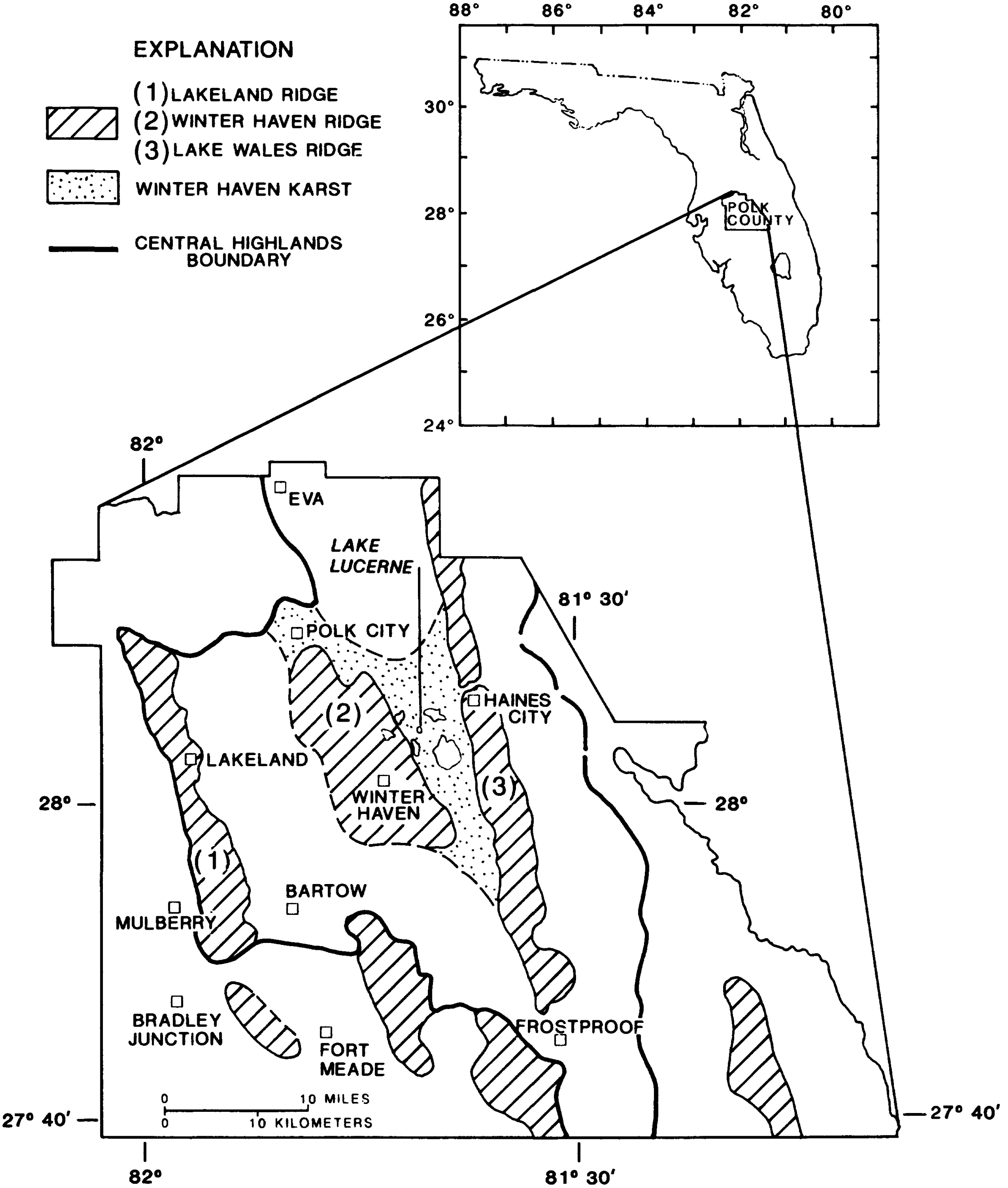


Figure 1. Location of the study area and physiographic divisions.

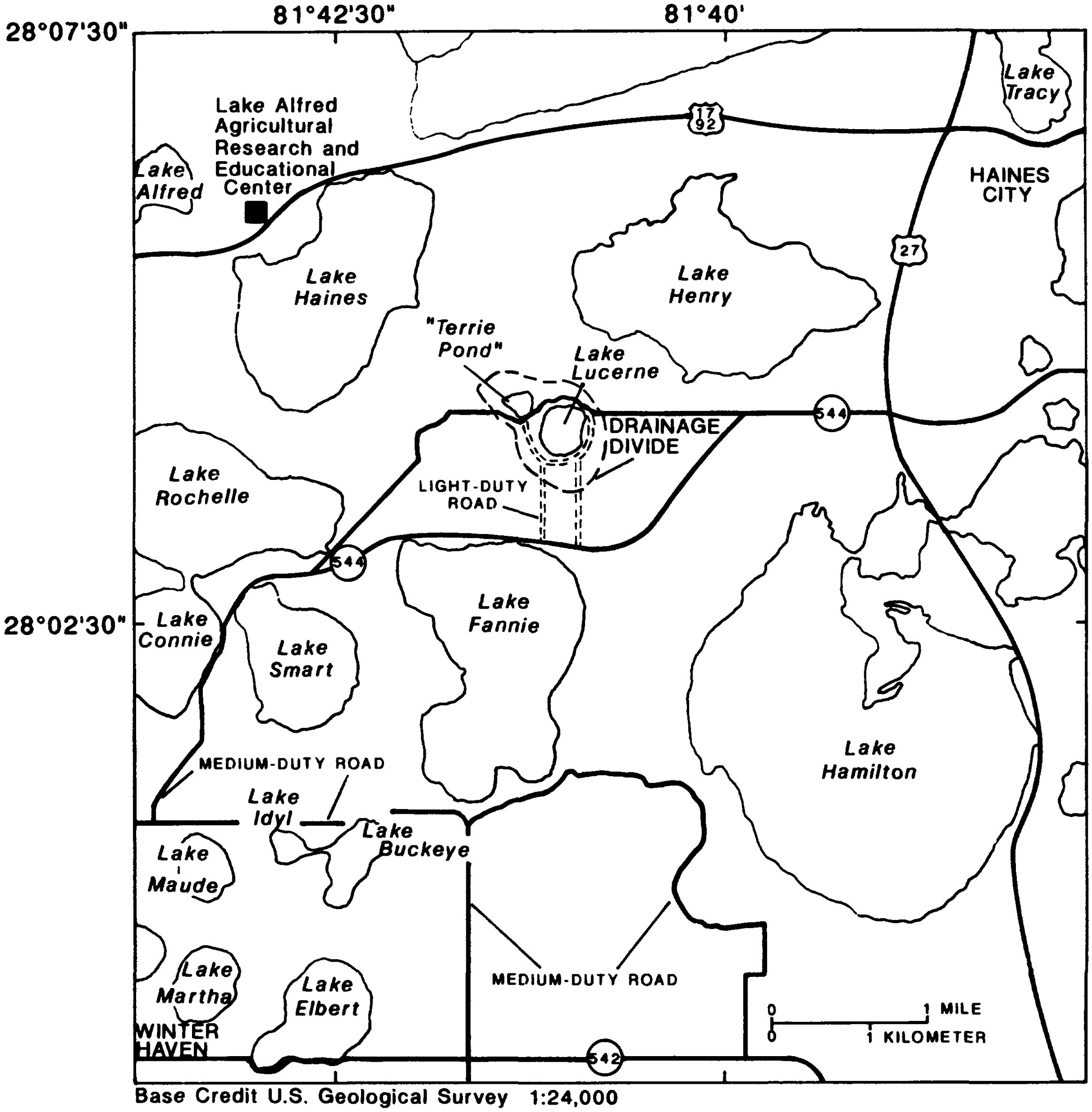


Figure 2. Lakes in vicinity of the study area.

basin were either replaced with saplings or abandoned. The residential area immediately surrounding the lake is landscaped with grasses, shrubs, and domestic gardens. Native trees such as live oak and longleaf pine grow in this area, as well as two stands of the imported punk tree (*Melaleuca quinquenervia*).

On November 26, 1985, a detailed survey of the aquatic vegetation of Lake Lucerne (fig. 5) was conducted by T.F. Rochow of the Southwest Florida Water Management District (written commun., 1986). He noted at that time that about 90 percent of the central lake area was devoid of floating macrophytes, and no plant life was observed in several feet of water to the limit of visibility. Shoreline vegetation included umbrella-grass (*Fuirena scirpoidea*), white waterlily (*Nymphaea odorata*), pickerelweed (*Pontederia cordata*), southern cattail (*Typha domingensis*), spikerush (*Eleocharis* sp.), and punk trees (*Melaleuca quinguenervia*).

HYDROGEOLOGIC SETTING

The local geologic setting largely determines the movement of ground water into and out of Lake Lucerne. A detailed description of the geologic framework within the Lake Lucerne basin, including the geology beneath the lake, and the hydraulic characteristics of the aquifers is presented in this section. This information is an important companion to the ground-water sections of this report. Prior to the discussion of the geology within the lake basin, however, it is important to review the general geology of the study area.

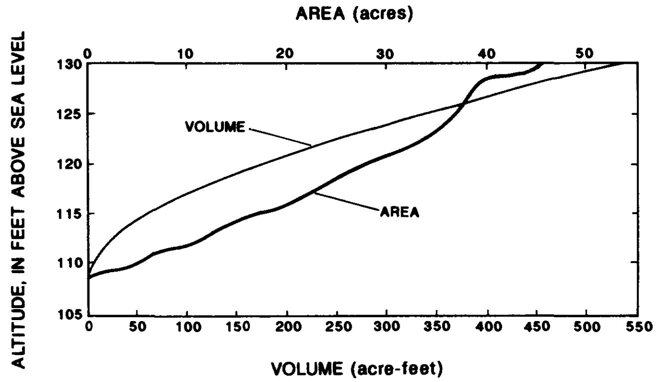


Figure 3. Stage-area and stage-volume curves for Lake Lucerne.

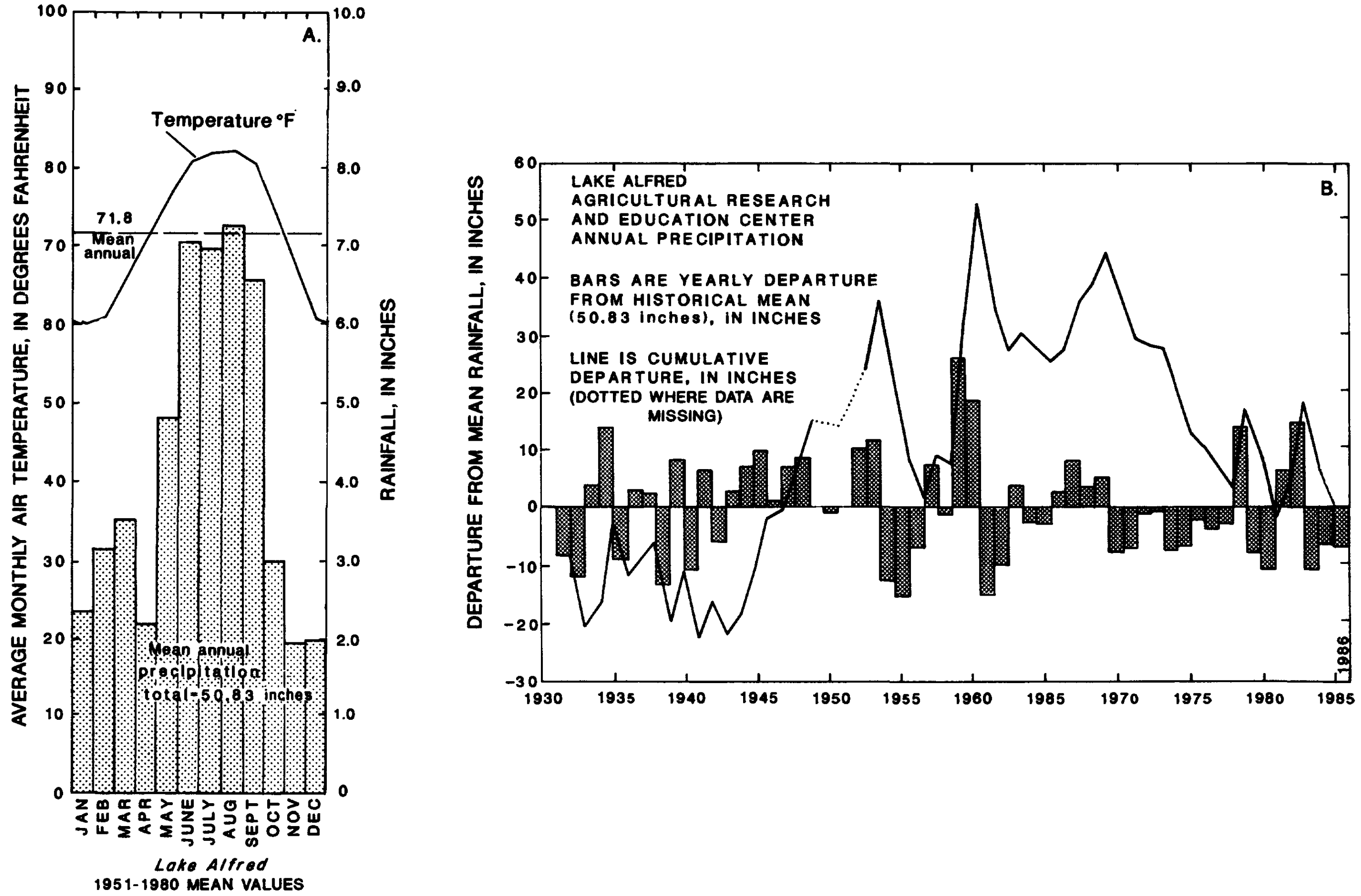


Figure 4. (A) long-term average monthly temperature and precipitation and (B) annual and cumulative departure of precipitation from the 1951-80 mean.

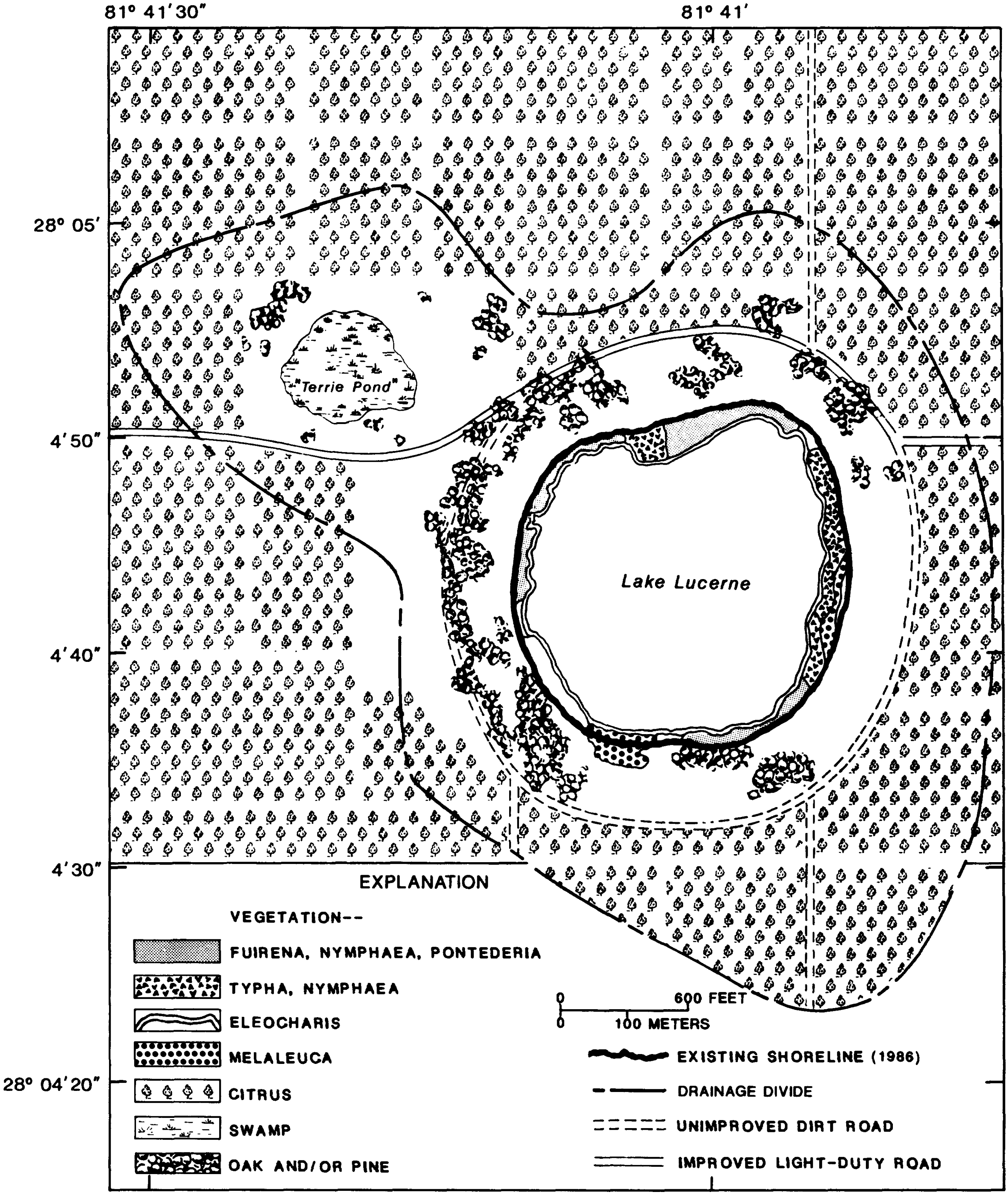


Figure 5. Distribution of vegetation in the study area.

General Geology

The stratigraphy of the study area generally is that of a regressive sequence. Limestones and dolomitized limestones are buried by phosphatic and dolomitic clays that are overlain by undifferentiated sands and clays with quartz sand content increasing toward the surface. The limestones that comprise the Floridan aquifer system are an extensive sequence that range from late Paleocene to early Miocene in age (Miller, 1986). This investigation is limited in scope to the upper part of the Floridan aquifer system and the overlying formations because they encompass the ground-water flow system relevant to Lake Lucerne. For a thorough discussion of the Floridan aquifer system and associated geologic formations, the reader is referred to Miller (1986). The geologic units that comprise the sequence of interest in the study area, from bottom to top, are: the Ocala Group of late Eocene age, the Hawthorn Group of Miocene and Pliocene age, and the unconsolidated sands and clays of Quaternary age. The Suwannee Limestone of Oligocene age was not observed in the study area, and the approximate updip limit of this formation is to the south and west of the study area (Miller, 1986). The stratigraphic nomenclature used in this report is that of the Florida Geological Survey and does not necessarily follow usage of the U.S. Geological Survey.

The lithologic sequence that exists in the study area can be divided into hydrogeologic units based on hydrologic characteristics of the formations. These units from top to bottom are: the surficial aquifer, the intermediate confining unit, and the Upper Floridan aquifer. Table 1 lists these hydrogeologic units based on hydrostratigraphic nomenclature of the Southeastern Geological Society (1986).

Table 1. Generalized stratigraphy, hydrogeology, and lithology of the study area.

SYSTEM	SERIES		FORMATION			HYDROGEOLOGIC UNIT	LITHOLOGY
QUATERNARY	HOLOCENE		SURFICIAL SAND			SURFICIAL AQUIFER	SAND AND CLAY QUARTZ KAOLINITE APATITE
	PLEISTOCENE		UNDIFFERENTIATED SAND AND CLAY				
TERTIARY	PLIOCENE		BONE VALLEY MEMBER (IN LIMITED AREA)	PEACE RIVER FORMATION	HAWTHORN GROUP	INTERMEDIATE CONFINING UNIT	DOLOSILT AND CLAY DOLOMITE QUARTZ KAOLINITE APATITE CALCITE SMECTITE ILLITE
	MIOCENE	UPPER					
		MIDDLE					
		LOWER	ARCADIA FORMATION			UPPER FLORIDAN AQUIFER	
	OLIGOCENE		SUWANNEE LIMESTONE				LIMESTONE CALCITE
	EOCENE	UPPER	OCALA GROUP				

The Eocene is perhaps the last stable epoch of the depositional sequence that underlies Lake Lucerne. The pure limestones of the Ocala Group are the result of deposition in a shallow, open marine environment (Cooke, 1945). These deposits were modified by subaerial erosion and fracturing as the Ocala uplift developed. The resulting paleokarst surface contains sinkholes and coast-parallel valleys (Pirkle and others, 1965).

As the sea regressed, deposits overlying the Ocala Group became more clastic. These formations consist of interfingered dolomites, dolosilts, and clays; phosphate is associated with most of these formations. Deposits containing this varying lithology make up the formations of the Hawthorn Group in the study area (Scott, 1986). The overlying blanket of sediments is smoothly graded on the surface, but varies in thickness where it fills in sinkholes and valleys (White, 1970). During the Pliocene, the upper part of these phosphatic, dolomitic, sandy clays were weathered as uplift and a lowering of sea level occurred (Altschuler and Young, 1960). The uplift within the area increased the potential for water to move downward.

The undifferentiated sands and clays of the Quaternary Period consist of alternating lenses of fine to coarse sand, clay, and clayey sand. These deposits are marked by an irregular, upward gradational increase of kaolinite and quartz sand as the phosphate and dolomite of the Hawthorn Group decrease.

Because these mineralogic changes are representative of intense weathering, Altschuler and Young (1960) concluded that these clayey sands are the insoluble residue of lateritic alteration of the Hawthorn deposits. Ketner and McGreevy (1959) also favored the residual origin. This theory proposes that the clays (illite and mica of the upper Hawthorn Group) were altered to residual kaolinite as magnesium oxide was released. The release of magnesium oxide probably contributed to the dolomitization of the underlying lower part of the Hawthorn Group (Arcadia Formation) (Cathcart, 1966). The weathering of primary phosphate (apatite) to secondary phosphate caused uranium enrichment of the underlying material. A characteristic peak in the gamma-ray logs at the top of the Hawthorn Group is indicative of this enrichment (Ketner and McGreevy, 1959; Cathcart, 1966). Nonresidual deposits of undifferentiated sands and clays consist of a few channel and dune deposits of Pleistocene to Holocene age, as well as a thin veneer of material reworked by the wind (Altschuler and Young, 1960).

White (1970) proposed a "topographic inversion" for the formation of the present ridges and karst features. Differential dissolution of the landscape eroded the highlands where soluble limestones were covered by a thin veneer of clays of the Hawthorn Group. The lowlands were protected by thick beds of insoluble clays and became the present residual ridges. The continued downward movement of water during the Pliocene Epoch created a cavernous drainage network in the underlying limestone. Subaerial erosion and dissolution continued through the Pleistocene Epoch as sea-level fluctuations affected the area. Weathering of the surface material created the surficial sand and undifferentiated deposits of the Quaternary Period (Altschuler and Young, 1960). Over time, these overlying deposits subsided into sinkholes of the underlying karst. The result is the "mantled karst" seen in the present-day landscape of the study area.

Geotechnical Methods

The geologic framework of the area around the lake was determined through analyses of drill cuttings, soil X-ray diffraction, well-completion reports, borehole geophysical logs, and a marine seismic-reflection survey. Primary geologic information was obtained from nests, or groups, of wells that were drilled at three sites around the lake: 1PN, 2PN, and 3PN (fig. 6). Additional lithologic descriptions were obtained from well-completion reports for existing wells within the study area: OC1, OC2, OC6, OC7, and PW5 (fig. 6).

Natural gamma, gamma gamma, and neutron geophysical logs were run in the deepest well at each nest of wells: 1PN-155, 2PN-130, and 3PN-65 (table 2). In addition, fluid conductivity and temperature logs were run in 1PN-155. At site 1PN, split-spoon samples were collected at 5-ft intervals to a depth of 85 ft and were analyzed for grain-size distribution. These samples were used to establish mineralogic continuity of lithologic units and to supplement and check geophysical log observations. Mineralogic identification was based on X-ray diffraction analyses.

A high resolution seismic-reflection survey of the lake aided in the determination of sublake geology. The system consisted of hydrophones towed behind a boat equipped with a high resolution boomer LORAN (Long Range Navigation) equipment. Reflection data from multiple transects were used to trace a basal reflector horizon that corresponds to a lithologic contact observed in nearby wells.

The horizontal hydraulic conductivity in the surficial aquifer was determined by slug tests performed at a total of 11 water-table and nested observation wells (Bouwer and Rice, 1976). Other hydraulic characteristics for hydrogeologic units in the ground-water basin were based on literature values.

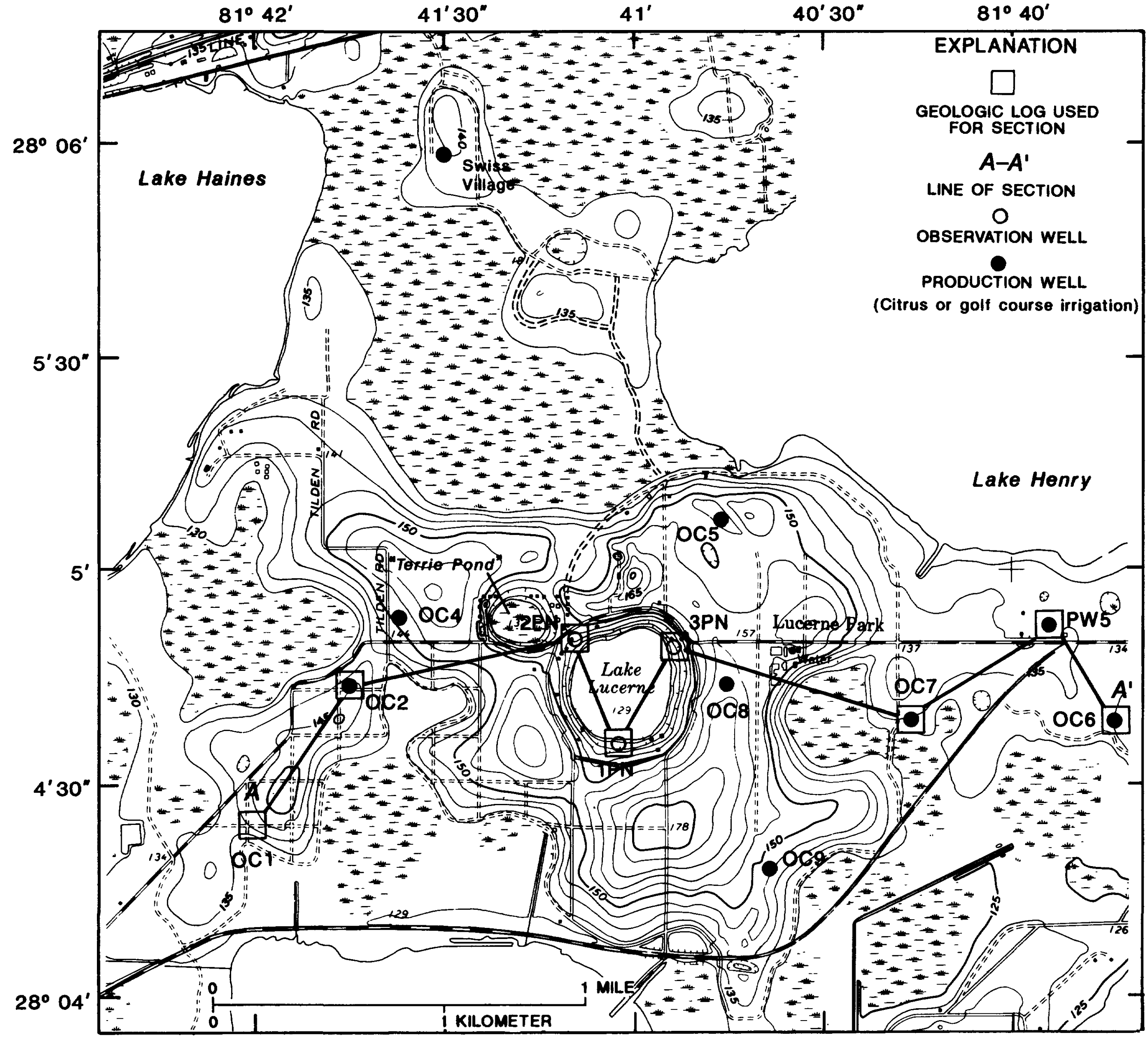


Figure 6. Locations of wells whose logs were used to construct geologic cross section.

Table 2. Observation-well construction information

Latitude-longitude	Well	Depth below land surface (feet)	Casing		Altitude of top of casing (feet above sea level)
			Diameter[1] (inches)	Depth (feet)	
Water-Table Observation Wells[2]					
280459081405401	WT-1	35	2	33	159.87
280450081404601	WT-2	34	2	32	160.42
280443081404401	WT-3	36	2	34	163.38
280438081404701	WT-4	34	2	32	166.18
280434081405301	WT-5	25	2	23	154.04
280426081410001	WT-6	42	2	40	170.52
280429081410801	WT-7	35	2	33	154.34
280435081411001	WT-8	31	2	29	158.57
280443081411501	WT-9	30	2	28	159.00
280448081412201	WT-10	26	2	24	153.24
280450081412601	WT-11	36	2	34	160.00
280453081412801	WT-12	31	2	29	164.72
280502081411201	WT-13	25	2	23	149.10
280457081410801	WT-14	34	2	32	156.06
280451081411201	WT-15	16	2	14	141.11
280431081410301	WT-17	26	2	24	—
280455081410601	WT-18	41	2	39	162.90
Nested Observation Wells					
280437081410201	1PN-7	[3]7	2	5	132.45
280437081410202	1PN-20	[3]20	2	18	132.68
280437081410203	1PN-35	[3]35	2	33	132.70
280437081410204	1PN-50	[3]50	2	48	132.79
280437081410205	1PN-65	[4]65	2	63	132.94
280437081410206	1PN-72	[4]72	2	70	133.08
280437081410207	1PN-155	[5]155	6	0-85	134.58
			4	65-120	
		Open hole	2-3/8	120-155	
280448081410701	2PN-9	[3]9	2	7	134.58
280448081410702	2PN-20	[3]20	2	18	134.66
280448081410703	2PN-35	[3]35	2	33	134.74
280448081410704	2PN-50	[3]50	2	48	134.81
280448081410705	2PN-130	[5]130	2	128	134.80
280450081405302	3PN-7	[3]8	2	6	133.53
280450081405303	3PN-20	[3]20	2	18	134.13
280450081405304	3PN-35	[3]35	2	33	134.34
280450081405305	3PN-50	[3]50	2	48	134.65
280450081405306	3PN-65	[4]65	2	63	134.83

---

[1] The screened interval for all 2-inch wells is 2 feet of 0.010 slot PVC, 2 inches in diameter, and all casings used were schedule 40 PVC.

[2] All water-table observation wells tap the surficial aquifer.

[3] Well taps surficial aquifer.

[4] Well taps Upper Floridan aquifer (clays).

[5] Well taps Upper Floridan aquifer (limestone).

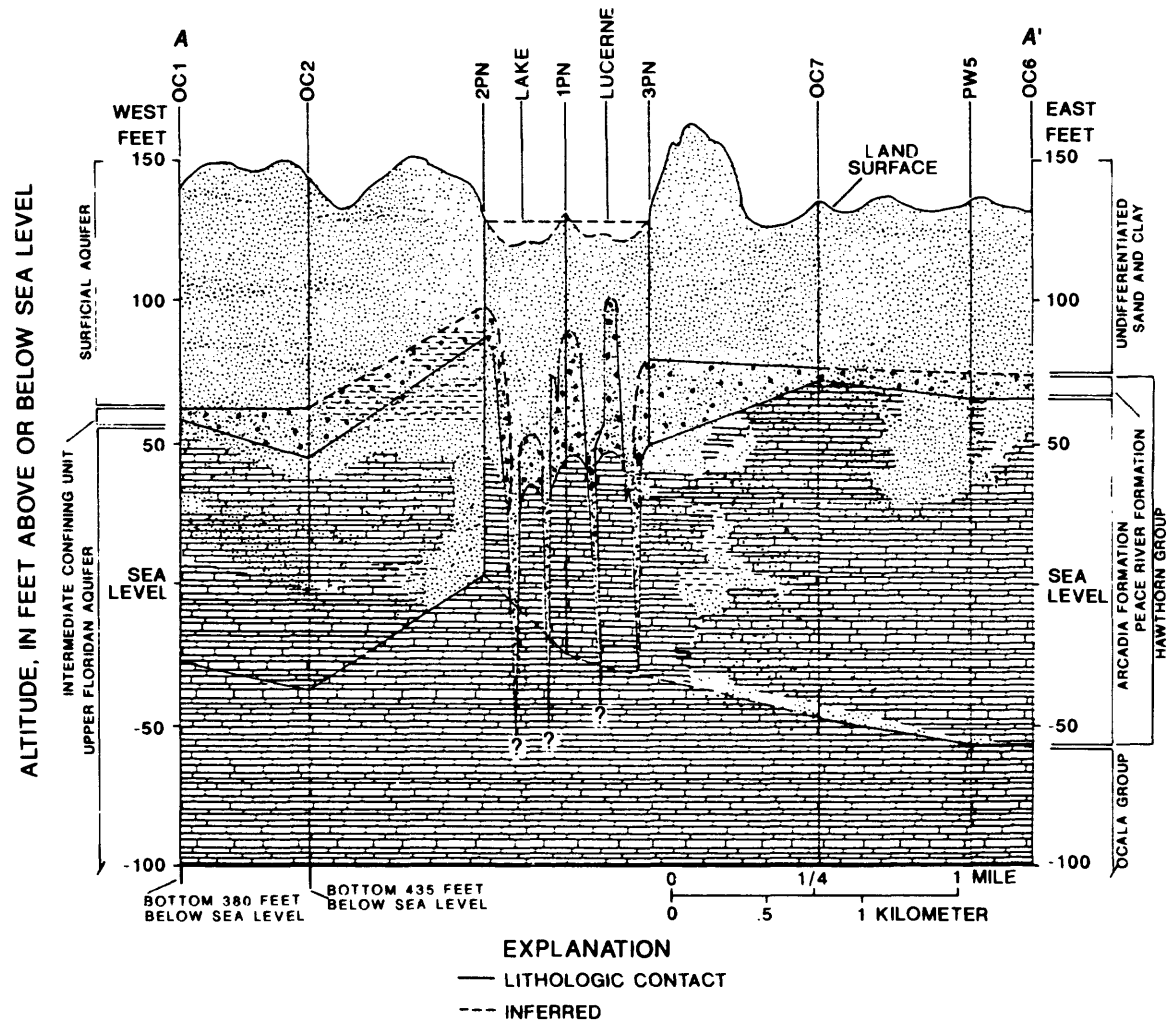


Figure 7. Hydrogeologic section of the study area.

Local Hydrogeology

Hydrostratigraphy

The locations of the wells whose logs were used to construct a hydrogeologic section of the study area are shown in figure 6, and the section is shown in figure 7. The top of vertically persistent limestone generally marks the contact between the Ocala Group and the overlying formations. One mile east of Lake Lucerne, the vertically persistent limestone was identified as the Ocala Group at 55 ft below sea level (Southwest Florida Water Management District, written commun., 1986). Wells 1PN-155 and 2PN-130, drilled on the perimeter of Lake Lucerne, encountered limestone at 20 ft below sea level and 5 ft above sea level, respectively (fig. 7). The variability of the depth to the Ocala Group in these wells is attributed to the karst features of the eroded limestone surface. This variability may exceed 30 to 40 ft over short lateral distances (K.M. Campbell, Florida Bureau of Geology, written commun., 1986).

Overlying the Ocala Group is the Hawthorn Group, which consists of interbedded deposits of sand, silt, clay, and phosphate. In Polk County, the Hawthorn Group is comprised of two formations. The upper clastic part constitutes the Peace River Formation and the lower carbonate part is the Arcadia Formation. The contact is gradational and the two formations are distinguished locally by whether the dominant lithologic characteristic is carbonate or clastic (Campbell, 1986). The Arcadia Formation is made up of areally extensive carbonates that vary in thickness and are not individually distinguishable. The lowest of these, however, is generally hard crystalline dolomite (Stewart, 1966). The Peace River Formation is a sandy clay that ranges from red and orange-brown to gray and blue-green. It lacks the carbonate fraction found in the Arcadia Formation. The Bone Valley member is the uppermost member of the Peace River Formation, and where it is present in Polk County, it generally constitutes the entire Peace River Formation (Scott, 1986) (table 1).

In the study area, the Arcadia and the Peace River Formations generally constitute two separate hydrogeologic units. The lower part of the Arcadia Formation marks the top of the "vertically persistent permeable carbonate section" and thus defines the top of the Upper Floridan aquifer (Southeastern Geological Society, 1986). The fine clastics of the Peace River Formation, and, to a lesser extent, clayey, low permeability carbonate beds in the upper part of the Arcadia Formation comprise the intermediate confining unit within the Hawthorn Group. This intermediate confining unit hydraulically separates the Upper Floridan aquifer from the overlying surficial aquifer.

In the study area, the transition from the pure white limestone of the Ocala Group into the overlying Arcadia Formation is easily recognized. The lower contact occurs at about 20 ft below sea level at well 1PN-155 between a resistant microcrystalline brown to blue-gray dolomite and the soft biogenic limestone of the Ocala Group. At well 2PN-130, the contact occurs at 5 ft above sea level between dark-green phosphatic dolosilt and the underlying Ocala Group (table 1).

At wells 1PN-155 and 3PN-82, the contact between the Arcadia Formation and the overlying Peace River Formation was at approximately 50 ft above sea level between a moderate to poorly indurated white sandy clay overlying a moderate- to well-indurated sandy, clayey, light-green to cream-colored limestone. At site 2PN, the Peace River Formation was not as distinguishable as at sites 1PN and 3PN. Instead, dolomite of the Arcadia Formation was found from 5 to 87 ft above sea level. The dolomite was dark gray to green, ranged from moderate to well indurated, and contained varying amounts of sand and phosphate nodules. The phosphate nodules were black, but dark-brown nodules were observed at 85 ft above sea level.

The presence of phosphate characterizes the Hawthorn Group and it occurs throughout in various forms and concentrations. It is generally black, but brown was observed in weathered sections at the top of the formation at Lake Lucerne. It is found at all three well nest sites as allochemical grains, pebbles, and phosphatized skeletal debris. Sand-sized phosphate flecks within indurated dolomite were observed at well 2PN-130 from 67 to 87 ft above sea level.

The undifferentiated sands and clays that contain the surficial aquifer consist of alternating lenses of fine to coarse sand, clay, and clayey sand. Mineralogic analyses of this formation reveal that the dominant minerals are kaolinite and quartz. The contact between the undifferentiated sand and clay unit and the Hawthorn Group occurs at 85 ft above sea level at well 1PN-155 and at 80 ft above sea level at well 3PN-82. This contact is marked by an irregular, upward gradational increase of kaolinite and quartz sand as the phosphate and dolomite of the Hawthorn Group diminish. The weathering of primary phosphate (apatite) to secondary phosphate may cause uranium enrichment of the underlying material (Ketner and McGreevy, 1959; Cathcart, 1966). A peak in gamma-ray logs (fig. 8) at the top of the Hawthorn Group is indicative of this enrichment.

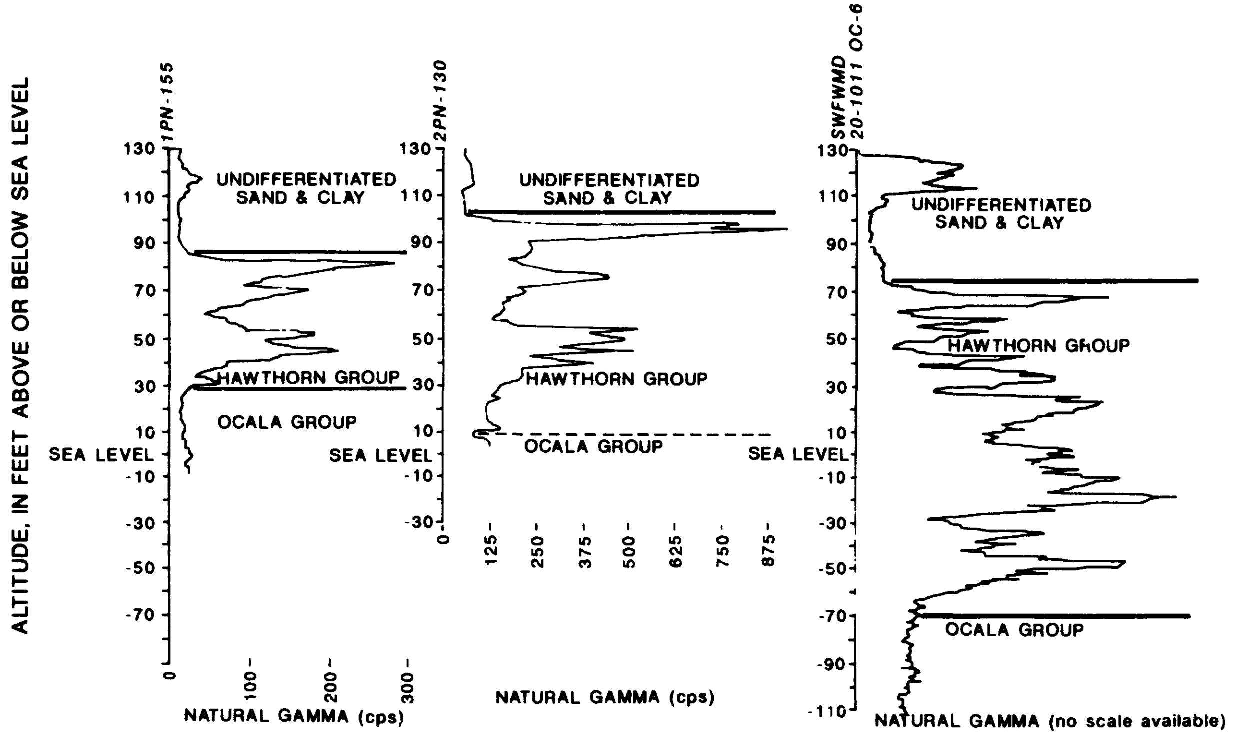


Figure 8. Natural gamma-ray logs for selected wells.

Sublake Geology

Although the regional physiography suggests that Lake Lucerne was formed as a result of subsidence-type sinkhole activity, structural information to indicate this origin cannot be inferred from the test-drilling data. The localized orientation of sinkhole structures makes them difficult to define without extremely closely spaced drill holes (fig. 7). The results of the marine seismic-reflection survey, however, show distinct evidence of sinkhole structures below the lake. The primary reflector surface, as seen in the seismic-reflection record, was correlated to the boundary between the undifferentiated surficial deposits and the Hawthorn Group. The clay-rich Hawthorn Group was observed at all three well-nest sites that surround the lake. However, variations in the altitude of this reflector surface beneath the lake indicate subsidence and discontinuity of the clay layer as a result of sinkhole development.

Features suggested by the configuration of the reflector surface beneath the lake include voids, vertical pipes, and pinnacles (fig. 9). The steep sided walls of the pipe structures are probably boundaries between the underlying limestone and the subsided overburden. It is likely that, as the overburden subsided into the developing sinkhole complex, the clay of the intermediate confining unit was disrupted and rendered discontinuous. The pinnacles and areas between the pipe features are probably residual limestone features and may retain overlying caps of the clay layer.

Although the relief is of different scales, figure 9 shows a general correspondence between the bathymetry and seismic-reflection surface. The results of the seismic-reflection survey are incorporated into the geologic cross section of Lake Lucerne (fig. 7).

Aquifer Hydraulic Characteristics

The hydraulic characteristics of the surficial aquifer were determined at Lake Lucerne during the study and at nearby sites by other investigators. Horizontal hydraulic conductivities were calculated from slug tests of observation wells using the Bouwer and Rice (1976) method and ranged from less than 1 to 8 ft/d. The higher values were measured in water-table wells finished in the uppermost part of the surficial aquifer along the ridges in the basin. Values of 1 ft/d or less were measured in several nested observation wells finished in the middle and lower parts of the surficial aquifer and were probably lower than the upper surficial aquifer because of the increasing clay content with depth. Pride and others (1966) reported horizontal hydraulic conductivity values of 5.3 and 6.6 ft/d at wells in the vicinity of Lake Lucerne.

The hydraulic properties of the overburden that infilled the solution features in the Upper Floridan aquifer beneath Lake Lucerne are unknown. However, the hydraulic properties most likely would reflect the source of this material and be similar to that of the surrounding surficial deposits. The less permeable clays that are contributed by the collapsed confining unit may reduce the resulting hydraulic conductance of this material. Ultimately, the degree to which breaches in the confining unit act as conduits of flow from the surficial aquifer to the Upper Floridan aquifer depends largely on the hydraulic characteristics of this infilled material.

The hydraulic characteristics of the intermediate confining unit were not determined at Lake Lucerne; however, Grubb (1978) generalized three regions of the nearby Green Swamp that have poor, moderate, and good potential for downward leakage to the Floridan aquifer system. Lake Lucerne is approximately 3 mi south of a region in the Green Swamp that is characterized as having moderate recharge potential and confining unit vertical hydraulic conductivities that range from 0.001 to 0.09 ft/d. A region of poor recharge about 7 mi northwest of Lake Lucerne has vertical hydraulic conductivity values of less than 0.001 ft/d (Grubb, 1978). Pride and others (1966) determined the leakance coefficient of 0.0056 d^{-1} from an aquifer test on a well completed in the Upper Floridan aquifer about 10 mi north of Lake Lucerne.

In general, vertical hydraulic conductivity values for the clays of the Hawthorn Group range from $1.5x10^{-2}$ to $7.8x10^{-7}$ ft/d (Miller, 1986). In areas where the confining unit is relatively thin (much less than 100 ft), it may be breached by sinkholes and erosional activity (Miller, 1986).

The hydraulic transmissivity of the Upper Floridan aquifer at Lake Lucerne was estimated from aquifer tests conducted nearby and reported in the literature. Pride and others (1966) reported a transmissivity value of 14,700 ft^2/d for a site about 5 mi north of Lake Lucerne. A transmissivity of 26,700 ft^2/d was reported by Geraghty and Miller, Inc. (1980), for a site approximately 5 mi to the southwest. In general, transmissivities assigned to the Ocala Group of the aquifer are greater than 25,000 ft^2/d, and yields can be as high as 5,000 gal/min (Hutchinson, 1978). Geologic and hydrologic data indicate that the transmissivities and yields of the permeable zones of the Arcadia Formation are at least an order of magnitude less than those specified for the limestone part of the Upper Floridan aquifer (Miller, 1986).

METHODS AND INSTRUMENTATION

The hydrologic budget of Lake Lucerne is an expression of the conservation of water mass for the lake. Simply stated, this means that the difference between the water moving into and out of the lake during a given time period must equal the change in lake volume during the same period. The components of the hydrologic budget, as applied in this study, are shown in figure 10 and equation 1. The unit of volume for each term is expressed as an equivalent depth over the surface area of the lake.

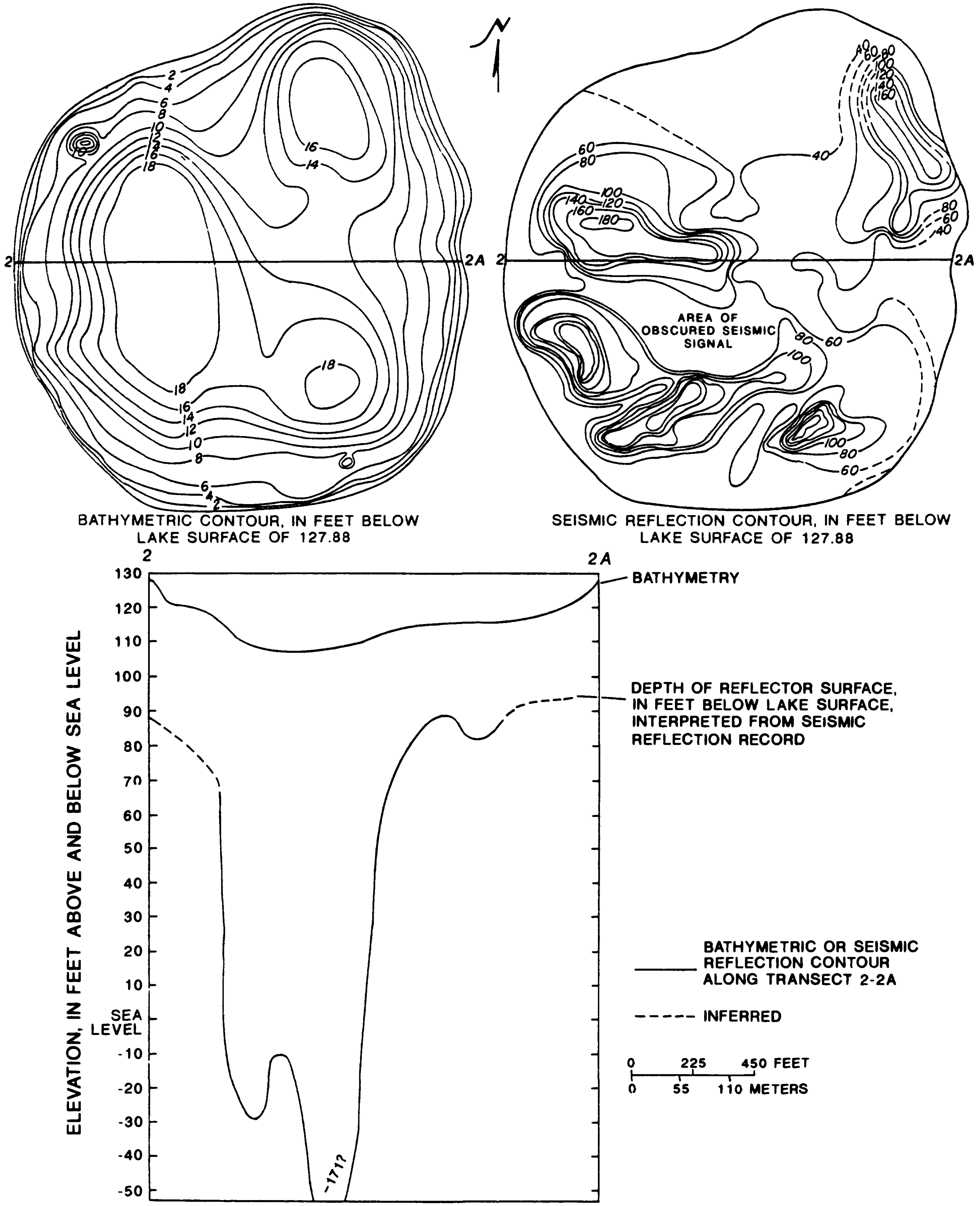


Figure 9. Bathymetric and seismic-reflection contours and cross section of Lake Lucerne.

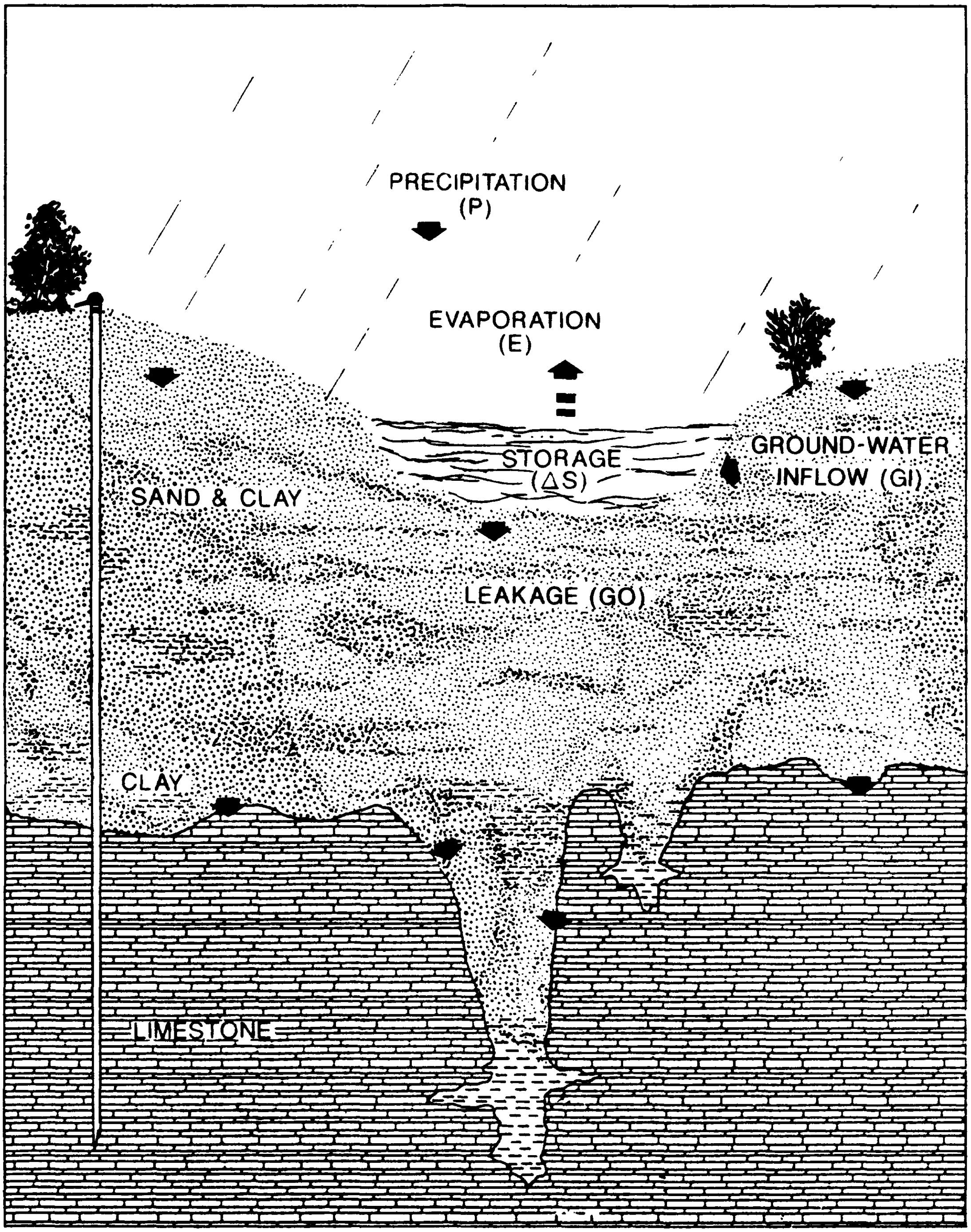


Figure 10. Hydrologic cycle and Lake Lucerne hydrologic-budget components.

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

where

ΔS = change in lake storage, in inches;
P = precipitation, in inches;
E = evaporation, in inches;
GO = ground-water flowing out of the lake, in inches;
GI = ground-water flowing into the lake, in inches; and
e = error in each measurement, in inches.

In general, hydrologic-budget components can be classified into three categories: atmospheric water, surface water, and ground water. Atmospheric water includes precipitation and evaporation; surface water includes the water in the lake, overland flow, and surface-water inflows and outflows; and ground water includes all ground water that flows into or out of the lake, both vertically and horizontally. Lake Lucerne is a seepage lake and thus lacks surface-water inflows and outflows. Overland flow is presumed to be zero because of rapid infiltration of rainwater into the highly permeable surface sands of the study area. Therefore, these terms have been eliminated from the hydrologic budget equation for the lake.

Some of the hydrologic-budget components, such as precipitation (P) and lake stage, an index of change in lake storage (ΔS), can be measured directly, whereas others, evaporation (E) and ground-water (GO and GI), must be computed from measured parameters. This study concentrates on the accurate estimation of the computed terms because these terms have not previously been well described for lakes in Florida, and because ground-water interactions with the lake, particularly ground-water outflow, is a major focus of the hydrologic budget. Estimates of evaporation rates for the lake, besides being a large part of the hydrologic budget, provide an important check on the validity of the ground-water outflow term. The lack of information on these two components for lakes in Florida is due to the complexity of data collection required to compute these components.

The following sections describe the methods and instrumentation that were used to determine each component of the hydrologic budget. Particular attention is focused on the evaporation and ground-water components because of the intricacy of the indirect measurement methods.

Climatic Stations

The climatic and hydrologic data used to compute precipitation and evaporation fluxes and changes in lake storage were measured at three sites within the drainage basin: the land-climate station, the stage and reflected-radiation station, and the raft-climate station (figs. 11-14). Because the methods are data intensive, most of the sensors at these three sites measured climatic variables used to compute evaporation by the energy-budget and mass-transfer methods. Precipitation also was measured at the land-climate station and lake stage was measured at the stage and reflected-radiation station. The instrumentation used to measure climatic and hydrologic variables at each of the three sites is listed in table 3.

At each site, a data logger continuously recorded analog signals from as few as 3 (stage and reflected-radiation station) to as many as 45 separate sensors (raft-climate station). In addition to the continuous recorder at the land-climate station, backup instrumentation, identical to that used at the National Weather Service daily weather observation stations, was installed at the site. Daily weather observations, which include rainfall, pan evaporation, minimum and maximum air temperatures, relative humidity, and barometric pressure, were made by an observer according to the protocol of the National Weather Service (1972).

Electrical signals from the sensors were recorded on microprocessor-controlled data loggers (table 3). The data loggers have the ability to accept analog and pulse inputs from sensors, to apply a linear correction, and to tabulate the input data, as well as a variety of data statistics. For this study, sensors generally were scanned every 10 seconds and the data were totaled, averaged, and tabulated for output on hourly and daily schedules. Generally, these data loggers are limited to nine sensor input channels. Because of the requirements for more sensor input channels on the raft-climate station, a multiplexer was installed on one of the input channels to the data logger to allow up to 32 additional sensor inputs (fig. 15).

Precipitation

Daily precipitation was measured during the study using two rain gages at the land-climate station (figs. 11 and 12). A standard 8-in. nonrecording gage was serviced daily by an observer, and a tipping-bucket rain gage was operated continuously, with data recorded on an electronic data logger. Incremental units of rainfall from the tipping bucket rain gage (10 mm) were time-tagged and recorded on the data logger, thus providing a measure of rainfall intensity as well as total volume.

Lake Stage

Measurements of lake stage were used to compute the change in storage components to the hydrologic budget for the lake (eq. 1). Lake stage (elevation) was measured hourly at the stage and reflected-radiation station using a digital recorder (figs. 11 and 13). A daily average value of lake stage was computed from the hourly values. The relation between lake stage and lake area and volume (fig. 2) was determined from a bathymetric map that was constructed during the

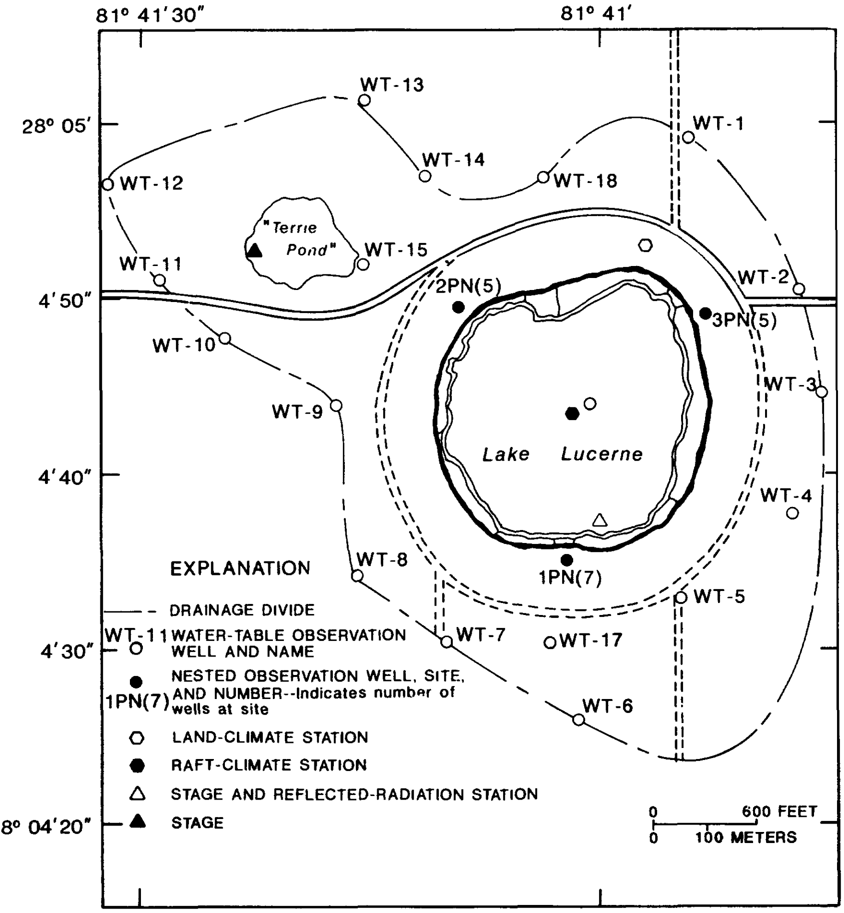


Figure 11. Data-collection sites.

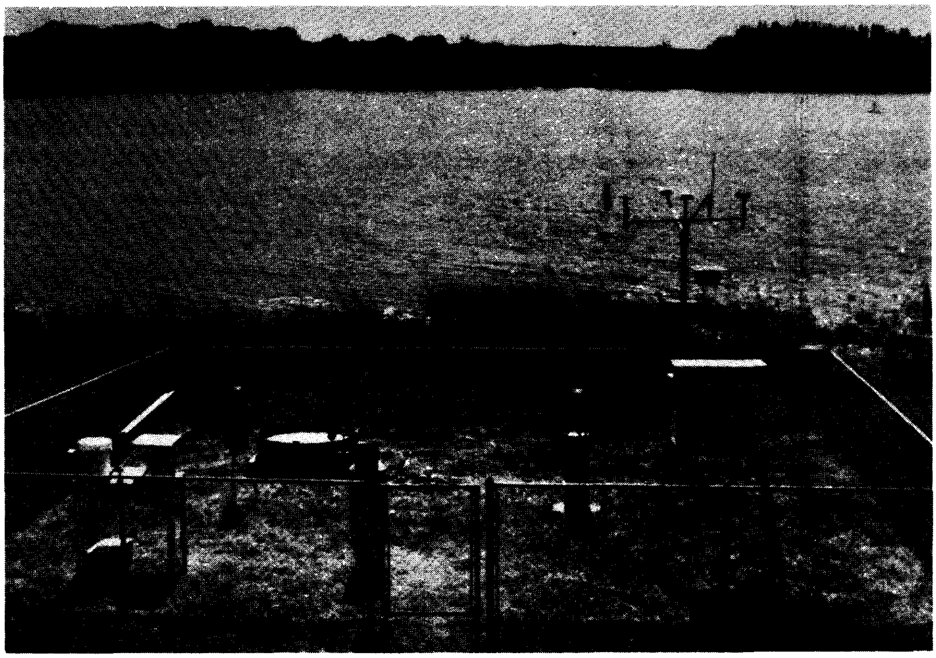


Figure 12. Land-climate station.

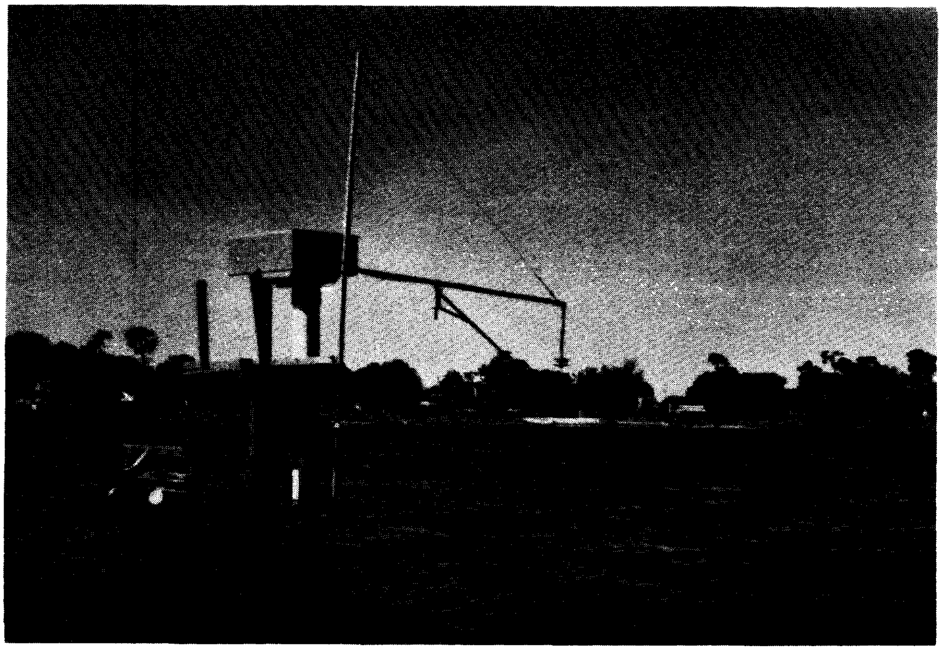


Figure 13. Stage and reflected-radiation station.

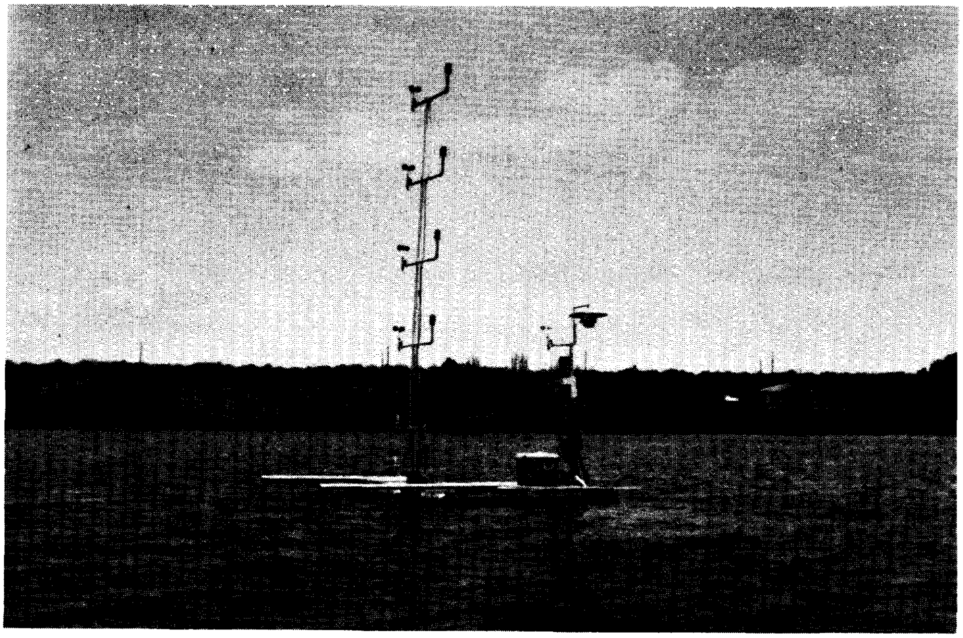


Figure 14. Raft-climate station.

Table 3. List of instrumentation used in the study

Instrument type	Manufacturer[1] (Supplier model)	Function
	Land-Climate Station[2]	
Data logger	Campbell Scientific (CR21)	Record and process data
Cassette recorder	Panasonic (RQ335A or RQ8300)	Long-term data storage
Radiation shield	Campbell Scientific (021)	Enclosure for data logger
Radiometer	Eppley Laboratory (PSP)	Incoming shortwave radiation
Radiometer	Eppley Laboratory (PIR)	Incoming longwave radiation
Temperature/humidity probe	Campbell Scientific (201)	Air temperature/relative humidity
Anemometer	Met One (024A)	Wind speed
Wind vane	Met One (014A)	Wind direction
Tipping-bucket rain gage	Sierra (RG2501)	Rainfall volume/intensity
Evaporation pan[3]	Belfort Inst. (Std. class A)	Pan evaporation
Storage rain gage[3]	Belfort Inst. (5-400)	Rainfall
Thermometer[3]	Belfort Inst. (6067)	Maximum/minimum pan water temperature
Totalizing anemometer[3]	Belfort Inst. (5-349C)	Pan station total wind run
Stilling well[3]	Belfort Inst. (5-745)	Pan station
Hook gage[3]	Belfort Inst. (5-744)	Pan station
Shelter	NOAA (NWS spec)	Class A weather station
Thermometers[3]	Science Assoc. (NWS spec)	Maximum/minimum air temperature
Sling psychrometer[3]	Science Assoc. (NWS spec)	Wet/dry bulb temperature
Hygrothermograph[3]	Belfort Inst. (5-594)	Temperature/relative humidity
Microbarograph[3]	Belfort Inst. (5-800A)	Barometric pressure
Weighing-bucket rain gage[3]	Belfort Inst. (5-780)	Rainfall
Event recorder[3]	Aerochemetrics (EMB-1)	Record rainfall events
Wet/dry precipitation collector	Aerochemetrics	Rainfall quality sampling
Solar cell	Solenergy Corp. (S6-1263-8LAD) batteries	Recharge data logger
	Raft-Climate Station[4]	
Data logger	Campbell Scientific (CR21X)	Record and process data
Cassette recorder	Panasonic (RQ335A or RQ8300)	Long-term data storage
Multiplexer	Campbell Scientific (AM32)	Expand data logger input channels
Thermocouples	Campbell Scientific (105T)	Water temperature profile
Anemometers	RM Young (12102)	Wind profile (analog signal)
	(12102D)	Wind speed at 2 meters (pulse signal)
Psychrometers	Campbell Delta-T (WVU-7)	Vapor pressure profile
	Nonventilated thermocouple psychrometer[5]	Wet/dry bulb temperatures at 2 meters
Thermistor	Campbell Scientific (107)	Air and water temperatures
Pressure transducer	Yellow Springs Inst. (2014)	Barometric pressure
Solar cell	Solenergy (1263-286)	Recharge batteries
Pump	Shurflo (120-019)	Water supply for psychrometer
Relay	Campbell Scientific (A21REL-12)	Data logger/pump control
Junction box	Campbell Scientific (036)	Sensor to cable connection
Radiation shield	Campbell Scientific (021)	Enclosure for data logger
	Stage and Reflected-Radiation Station[6]	
Recorder/float	Stevens (ADR-paper tape)	Lake stage
Rain gage	U.S. Geological Survey (8-inch float)	Rainfall
Data logger	Campbell Scientific (CR21)	Record and process data
Cassette recorder	Panasonic (RQ335A or RQ8300)	Long-term data storage
Solar cell	Solenergy Corp. (SG-1263-8LAD)	Recharge data logger
Radiometer	Eppley Laboratory (PSP)	Reflected shortwave radiation
Radiometer	Eppley Laboratory (PIR)	Reflected longwave radiation
	1PN Well Nest	
Data logger	Campbell Scientific (CR21)	Record and process data
Float-potentiometer	(10-turn)	Continuous water-level measurements

[1] Use of brand names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

[2] See figure 8.

[3] Observer operated instruments.

[4] See figure 11.

[5] From Bellaire and Anderson (1951).

[6] See figure 9.

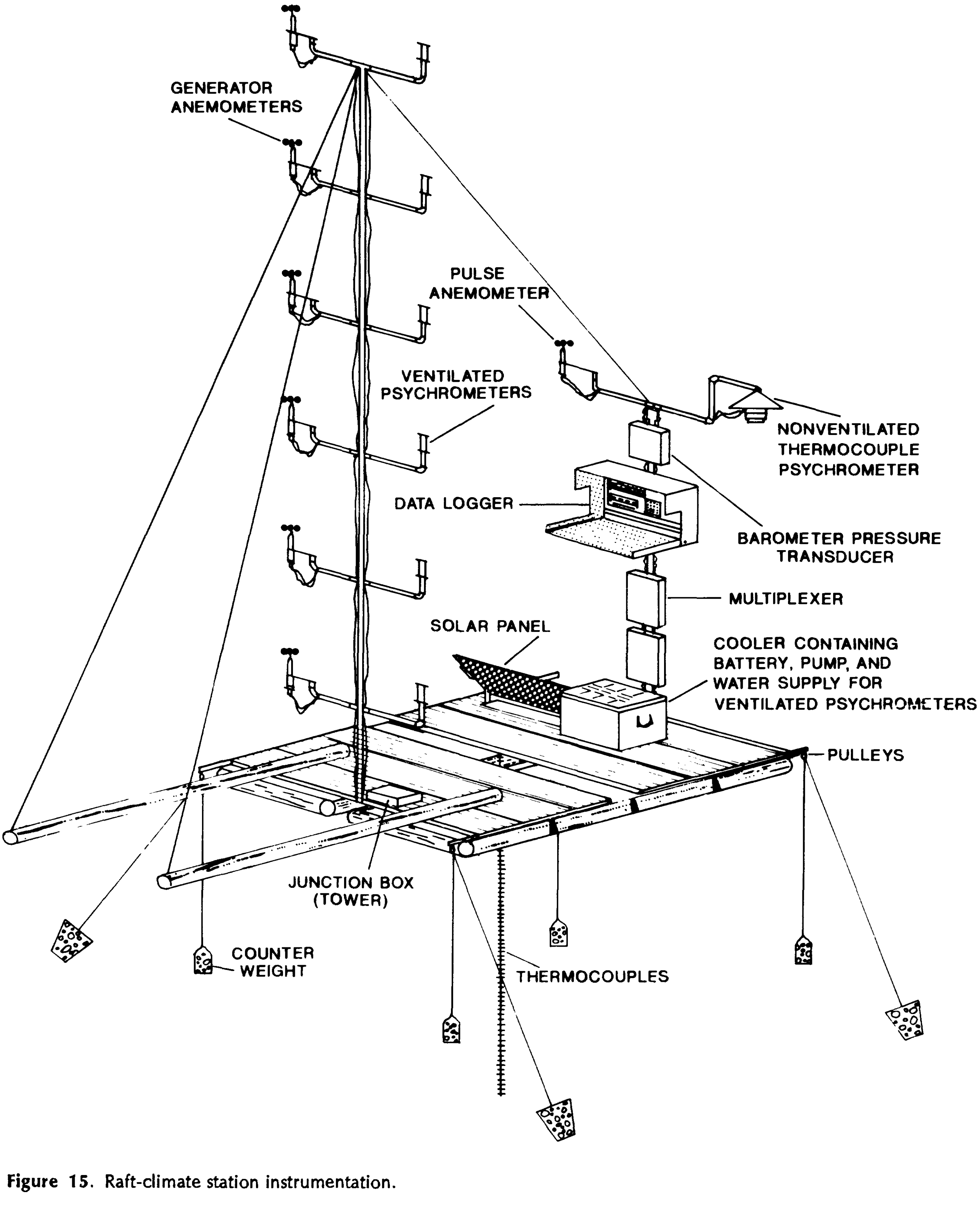


Figure 15. Raft-climate station instrumentation.

study from fathometric profiles of lake depth. From a dense grid of fathometric profiles, the elevation of the lake bottom was mapped to the closest 1-ft contour interval. The surface area of the lake at every 1-ft change in stage was determined using a computer-controlled graphical digitizer, and lake volume was determined by numerical integration of the relation between lake stage and area.

Evaporation

Several techniques have been developed and used to compute evaporation. A detailed discussion of these techniques and the relative accuracy of each is given by the World Meteorological Organization (1966) and Ficke (1972). Three methods of significantly different complexity, accuracy, and cost were selected for this study. These methods are the energy-budget, mass-transfer, and pan evaporation methods.

Energy Budget

The energy-budget method generally is considered to be the most accurate of the theoretically based methods for computing evaporation, but because of its complexity, it is not frequently used by investigators. This method was used in the early pioneering work at Lake Hefner (Anderson, 1954) and later by investigators on Lake Mead (Koberg, 1958) and on reservoirs in central Colorado (Ficke and others, 1977).

An energy budget, as the term implies, is an accounting of the gains and losses of energy in a system. Water lost from the lake by evaporation is computed by determining the difference between the change in the stored energy of the lake over a set time period and the sum of energy gains and losses by the lake for the same time period. This difference is attributed to the energy required as latent heat of vaporization to evaporate a volume of water from the lake. The energy-budget equation generally is written as follows:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_x, \quad (2)$$

where

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

The units of energy that are used in this analysis are calories per square centimeter per day, also equivalent to langleys per day. The first five variables in equation 2 are measured directly, and the remaining five terms (Q_v, Q_e, Q_h, Q_w, and Q_x) are computed using other measured parameters.

Net energy advected, Q_v, is computed from the air temperature and volume of precipitation, whereas change in stored energy, Q_x, is computed from the change in temperature and volume of the lake. The remaining three terms, Q_e, Q_h, and Q_w, are calculated through relations described in detail by Anderson (1952). Briefly, the calculation of the energy used for evaporation, Q_e, uses the latent heat of vaporization of water and the density and volume of water evaporated; the energy conducted from the water as sensible heat, Q_h, is determined from Q_e and an empirical term known as the Bowen ratio (Bowen, 1926), which is a function of temperature and vapor pressure gradients; and energy advected by the volume of evaporated water, Q_w, is calculated from the specific heat of water and the density, volume, and temperature of the evaporated water. The calculation of these variables requires the direct measurement of precipitation, lake volume (stage), air and water temperature, and barometric and vapor pressures.

Mass Transfer

The mass-transfer method relates the evaporative losses from a lake to the movement of water vapor above the lake. Evaporation is calculated as the product of the vertical water-vapor pressure gradient above the lake surface, the wind speed across the lake surface, and an empirical coefficient. The technique is derived from boundary layer theory and is described in detail by Marciano and Harbeck (1952). Of the several mass-transfer equations available, the equation presented by Harbeck (1962) in his discussion of field techniques was used in this study:

$$E_{MT} = Nu_2 \, (e_o - e_a), \quad (3)$$

where

E_{MT} = mass-transfer evaporation, in centimeters per day;
N = an empirical coefficient, in centimeters per day per miles per hour-millibar;
u_2 = average wind speed at 2 m above the water surface, in miles per hour;
e_o = saturation vapor pressure of the air at the temperature of the water surface, in millibars; and
e_a = vapor pressure of the air at 2 m above the water surface, in millibars.

This method is considerably simpler than the energy-budget method because data collection is reduced to four relatively simple parameters: wind speed, wet- and dry-bulb temperatures at 2 m above the water surface, and water-surface temperature. Values of the empirical coefficient, N, are assumed to be constant for each lake and must be determined from an independent measure of evaporation, usually an energy-budget analysis.

Climatic measurements needed for the mass-transfer method are also common to the energy-budget method with one exception: wind speed measured at 2 m above the lake surface is unique to the mass-transfer method. Therefore, the methods and instrumentation for both the energy-budget and mass-transfer method are discussed together.

Water-surface temperature was measured near the center of the lake using a thermistor and a thermocouple mounted on the raft. The temperature of the water column at 1-ft depth intervals and the bottom sediment temperature were monitored continuously by a vertical string of copper-constantan thermocouples anchored under the raft-climate station (fig. 15). Sensor calibration was checked in the office with a mercury-in-glass laboratory thermometer.

Thermal surveys were conducted at intervals of about 1 week and provided the basis for computing mean temperatures of the lake. During each survey, water temperature was measured from surface to bottom at each of six measuring sites on the lake. The measuring sites were uniformly distributed over the surface of the lake in both shallow and deep waters. Temperatures were measured with a thermistor-type thermometer that was checked over its range with a precision mercury-in-glass thermometer.

Incoming longwave and shortwave radiation was measured at the land-climate station (fig. 12) using upward-facing radiometers. Reflected shortwave radiation and the sum of reflected and emitted longwave radiation from the lake surface were measured at the stage and reflected-radiation station (fig. 13) using two downward-facing radiometers.

Wind velocity at the lake was measured by a three-cup, pulse anemometer that was mounted 2 m above the water surface on the raft-climate station (fig. 15). To further monitor wind profiles over the lake surface, a 5-m mast also was installed on the raft-climate station. This mast supported five analog-signal, three-cup anemometers at elevations of 0.5, 1, 2, 3, and 5 m above the water surface.

Barometric pressure at the lake was monitored by a microbarograph at the land-climate station. Wet- and dry-bulb temperatures were measured by a nonventilated thermocouple psychrometer mounted on the raft-climate station at 2 m above the water surface. This psychrometer design (Bellaire and Anderson, 1951) was used in earlier work by Harbeck (1962) and is further described by Sturrock (1985). To study vapor pressure profiles above the lake surface, motorized-fan psychrometers also were installed on the raft-climate station at the same elevations as the five analog anemometers.

Pan Evaporation

The pan method for estimating evaporation is the most commonly used technique. In this method, lake evaporation is estimated by multiplying the measured pan evaporation by a pan coefficient. If the pan and lake responded identically to meteorological factors, such as wind, radiation, and temperature, evaporation rates would be the same for both and the pan coefficient would be 1.0. However, solar radiation and heat transfer acting upon the sides and bottom of a pan produce evaporation rates from a pan that, on the average, exceed those from a nearby lake. Also, wind turbulence over the pan is greater than over a lake, thus increasing evaporation. On average, the ratio of evaporation from a shallow lake to that from a pan (the pan coefficient) for the May to October open-water period has been reported in the range of 0.64 to 0.88 (Farnsworth and others, 1982). A more detailed description of the factors that affect pan coefficients is presented in reports by Kohler and others (1955; 1959). Ficke (1972), Ficke and others (1977), and Spahr and Ruddy (1983) have reported short-term (less than annual) pan coefficients in the range of 0.15 to 4.5, but estimates of lake evaporation from pan evaporation for time periods less than annual generally are regarded as inaccurate.

A standard U.S. class-A evaporation pan was operated at the land-climate station (fig. 12) for the entire period of study in accordance with National Weather Service (1972) guidelines. The class-A pan is a steel tank 4 ft in diameter, 10 in. deep, and mounted on a wooden platform on the ground. The water level in the pan was measured daily using a hook gage and stilling well. Water was added or removed from the pan as necessary to maintain the water level at approximately 2 in. below the top of the pan. The pan used in the study was equipped with a totalizing anemometer mounted 6 in. above the rim of the pan and a thermometer to record daily maximum and minimum water temperatures. The anemometer dial and maximum and minimum temperatures were read and recorded daily by an observer.

Ground Water

Ground-water flow into and out of lakes is probably the most difficult of all hydrologic-budget components to determine. Generally, investigators compute this component as the residual in the hydrologic-balance equation and, in so doing, include the residual error of all other components in the ground-water term. This can result in serious errors in the flow analysis, including some unlikely and unreasonable representations of the flow system, such as apparent reversals of ground-water flow direction. An extensive discussion of this phenomenon is given by Winter (1981).

A detailed description of the hydrogeologic setting of the lake is a prerequisite to calculating ground-water fluxes using flow-net analyses or ground-water flow models, as is being done to compute the hydrologic budget of Lake Lucerne. The hydrogeologic information required includes: (1) the geologic framework of the lake and the geologic and hydrologic conditions that define the boundaries of the surrounding ground-water flow system; (2) the hydraulic properties of the materials within the ground-water basin (for example, horizontal hydraulic conductivity, vertical anisotropy or the ratio of horizontal to vertical hydraulic conductivity, and storativity); (3) the temporal and spatial distribution of hydraulic head within the ground-water basin; and (4) the external "stresses" on the ground-water system, such as pumping and recharge.

The distribution of hydraulic head within the basin defines the pattern of ground-water flow around the lake and the flow lines that are intercepted by the lakebed. Therefore, the areal and vertical head distribution around the lake is necessary to compute ground-water flow into and out of the lake and to calibrate simulated head distributions.

Two types of observation wells were constructed in the Lake Lucerne basin for monitoring ground-water levels during the study: water-table wells and nested wells. Water-table observation wells were augered in the surficial aquifer along the basin drainage divide and at points between the lake and drainage divide to map the altitude of the water table and to define boundary conditions in the surficial aquifer. These wells, which are shown in figure 11 and numbered from WT-1 to WT-18 (excluding abandoned well WT-16), were constructed of 2-in. polyvinyl chloride (PVC) casing with 2 ft of 0.010-in. slotted well screen. The depth of each well was set such that the well screen was near the normal altitude of the water table so that measured heads would reflect the head at the water table rather than the head below. Because of this and the below normal precipitation during the study, a few wells went dry during the extremely low water-table conditions in the late spring. Information on the construction of the surficial aquifer wells is presented in table 2.

To measure the vertical distribution of hydraulic head near the margin of Lake Lucerne, 18 observation wells that ranged in depth from 7 to 155 ft were drilled at three locations (1PN, 2PN, and 3PN) around the lake as indicated in figure 11. For example, at location 1PN, wells were drilled to depths of 7, 20, 35, 50, 65, 72, and 155 ft below land surface. These nested observation wells were constructed by drilling holes using the mud-rotary method with an organic drilling fluid, which biodegrades to the viscosity of water and prevents the plugging of formation pores. Except for 1PN-155, all of the nested observation wells were constructed of 2-in. PVC casing and 2 ft of 0.010-in. slotted PVC well screen. The screened length was limited to provide a measurement of the hydraulic head at a relatively discrete point in the vertical dimension of the aquifer. To prevent vertical flow from occurring in the borehole, a petal-cement basket (Halliburton, 2-3/8 in., #800.8873) was fixed to the casing above the well screen, and cement was pumped into the borehole above the basket through a plastic grout line attached to the casing. As the petal-cement basket fills with cement, it expands to the diameter of the borehole, and cement backfills the hole above the well screen (fig. 16). In this report, wells that were constructed in this manner are distinguished by the prefix PN in the well name.

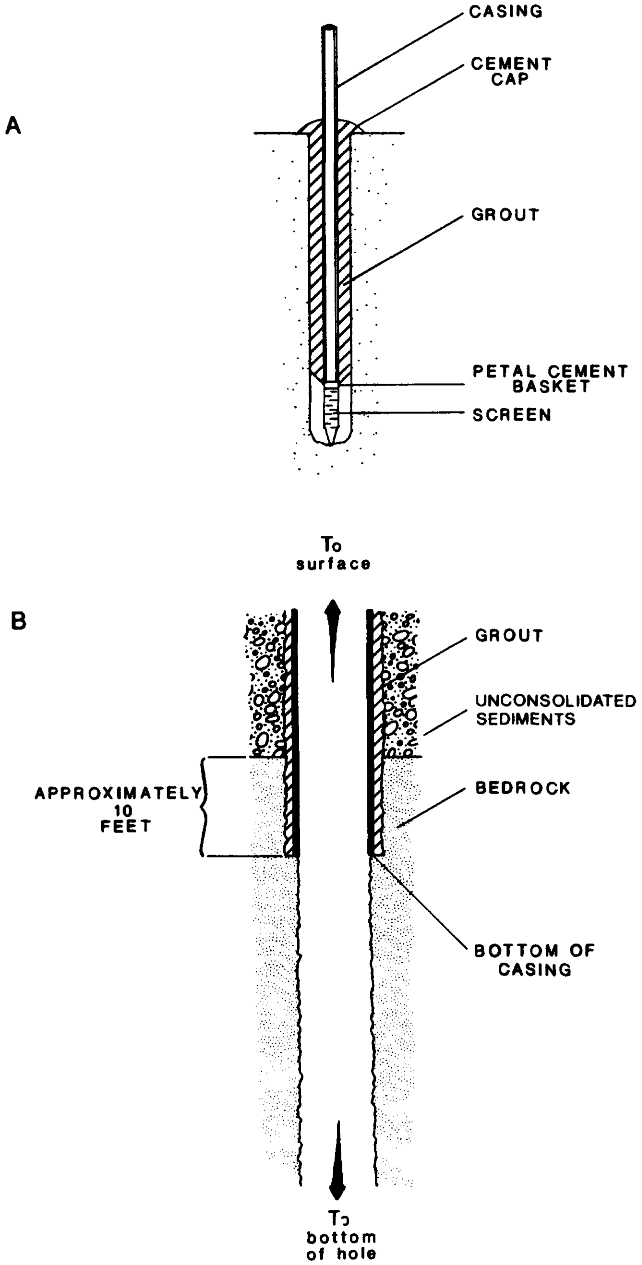


Figure 16. Construction technique for nested observation wells: (A) wells finished in unconsolidated sediments, (B) wells finished in bedrock.

The deepest observation well, 1PN-155, was constructed of 6-in. diameter PVC casing to a depth of 85 ft; 4-in. diameter PVC casing to a depth of 120 ft; and open hole to 155 ft. The 6-in. and 4-in. casings were grouted by pumping cement under pressure into the annular space between the casing and hole wall. After the cement dried, drilling continued within the set casing to the desired depth.

During most of the study, water levels in the water-table wells were measured once each month. Weekly and biweekly water-level measurements were made during the summer of 1985 in both the water-table wells and the nested wells to compare shorter duration changes in the head of the surficial aquifer against those in the underlying Upper Floridan aquifer. Water levels in wells finished approximately 82 ft below sea level showed a rapid response to pumping from nearby irrigation wells; therefore, a data logger was installed at site 1PN to make continuous hourly measurements of head in the seven nested wells. In each well, 10-turn potentiometers were connected to a float wheel driven by a float and counterweight assembly and calibrated to measure water-level changes of up to 10 ft.

An observation well was installed near the middle of Lake Lucerne by jetting a 1.25-in. PVC casing with 2 ft of 0.010-in. slotted well screen through the lake bottom. The well was finished at a depth of 8 ft below the lake bottom in the surficial aquifer, and the screened length was set in an uncharacterized clayey sand. The lake bottom at the location of the midlake well had only a thin layer of organic sediment (<2 in.) overlying the clayey sand sediments. The organic-sediment consisted of flocculent organic muck overlying a thin layer of fibrous peat, possibly from macrophytes growing in or around the lake during a historical period of extremely low stage. Residents who have lived around Lake Lucerne since 1939 have observed no floating or emergent macrophytes in the open water of the lake.

The casing of the midlake well was held in a vertical position in the water column by a floating styrofoam and plywood platform around the casing. The platform was anchored to allow it to rise and fall with the lake stage. To compare the hydraulic head at a point 8 ft below the lake bottom to the head in the lake, the depth to water inside the casing was compared to the length of casing above the water surface. The difference between the two measurements indicated the direction and magnitude of the head gradient across the lake bottom at this location.

The primary influence on head in the Upper Floridan aquifer underlying Lake Lucerne is from irrigation pumping from wells within and immediately around the drainage basin. Eight citrus grove irrigation wells and one golf course irrigation well within 7,500 ft of the lake margin were monitored to determine the number of hours they were operated each month. For some months, a summary of pumpage, by day, for each of the citrus grove wells was provided by grove operators. Discharge rates for most of the citrus grove wells were measured using a polysonic flowmeter. The golf course irrigation well had an in-line flowmeter. Information on the construction and operation of these wells is summarized in table 4.

Table 4. Summary of construction and pumpage information on production wells in and surrounding the Lake Lucerne study area

[Mgal/d, million gallons per day]

Latitude-longitude	Well name	Year drilled	Well depth (feet)	Casing depth (feet)	Diameter (inches)	Distance to margin of Lake Lucerne (feet)	Rated pump discharge[1] (gallons) per hour)	Average monthly hours of operation[2] December 1985-November 1986	Estimated average monthly discharge[3] December 1985-November 1986 (Mgal/d)
2804430814145	OC2 (Block 4)[4]	1983	580	126	10	3,400	60,240	[3]34	2.02
2804520814138	OC4 (Block 4)	1966	247	78	12	2,700	[5]135,120	18	2.40
2805020814048	OC5 (Block 10)	1966	959	138	12	1,900	72,900	85	6.20
2804420813951	OC6 (Block 7 canal)	1982	497	105	10	5,800	38,520	[3]37	1.43
2804390814019	OC7 (Block 7)	1982	260	87	10	4,900	57,360	29	1.66
2804380814050	OC8 (Block 8 queen)	1968	578	169	12	700	84,660	87	7.36
2804100814038	OC9 (Block 8 south)	1969	440	101	12	2,100	37,620	[3]39	1.45
2805390814132	Swiss Village Golf and Country Club irrigation well				12	7,500	—	—	[6]8.57

[1] Rated by polysonic flowmeter August 20, 1985. Values assumed to be representative of average operating conditions.

[2] Determined by logs of diesel engine running time.

[3] Pumps for wells OC2, OC6, and OC9 were removed in August 1986. Values presented for comparison are for period August 1984 through November 1986.

[4] Well name in parentheses is that of OrangeCo, Inc.

[5] Unconfirmed value provided by OrangeCo, Inc.

[6] Readings obtained from inline flowmeter.

PRELIMINARY EVALUATION OF HYDROLOGIC BUDGET DATA

Most climatic and hydrologic data were available from April 1984 through September 1986; however, data from the raft-climate station were available only for September 24, 1985, to September 30, 1986. Accordingly, most comparisons of the data made herein include only the 1986 water year. Hourly and daily values for all climatic conditions are available in the computer files of the U.S. Geological Survey.

As in most studies that involve intensive data collection, there are some instances of recorder or sensor malfunction due to a variety of causes. Because of the potential for this kind of malfunction, a variety of backup or supplemental instrumentation was installed and operated during the study. In instances of missing or inaccurate data, these voids were filled in or estimated by using data from the backup instrumentation, predicted from regression analysis of primary data with backup data, or predicted from regressions by using related climatic parameters as the independent variable. Relations are based on all available data, some of which was outside of the 1986 water year. The estimated or revised data are summarized in table 5, and the methods used for estimating missing or inaccurate data are presented in the discussion of each parameter.

Precipitation

Daily total rainfall at the observer-read storage rain gage provided the most continuous record and was used as the primary data set (fig. 17). A significant amount of the tipping-bucket rainfall data was missing; however, when the two records coincided, differences between weekly total rainfall amounts were slight.

Rainfall totaled 40.88 in. at Lake Lucerne for the 1986 water year (October 1985 through September 1986), considerably less than the long-term average of 50.83 in. computed from the NOAA climate reporting station at Lake Alfred AREC and somewhat less than that measured at the Lake Alfred AREC site for the same period (42.99 in.). The monthly distribution of rainfall at Lake Lucerne during the 1986 water year followed the typical seasonal pattern and ranged from 0.61 in. in April to 9.89 in. in August (fig. 17).

Lake Stage

The stage of Lake Lucerne averaged 125.48 ft above sea level during the 1986 water year and ranged from 124.40 ft in June to 126.14 ft in February (fig. 18). Over this 1.74-ft range in lake stage, lake volume varied by 19 percent (13,956,000 ft^3 to 16,630,400 ft^3) and lake surface area varied by less than 4 percent (1,573,200 ft^2 to 1,635,000 ft^2). During the same period, the stage of "Terrie Pond" ranged from 128.08 ft in June to 130.62 ft in October. These levels reflect the below normal precipitation that occurred in 1986. Over the entire period of record, the stage of "Terrie Pond" peaked at 131.92 ft in August 1984, and Lake Lucerne peaked at 129.16 ft in February 1984. Long-term data are not available for these sites; however, long-term stage data for nearby Lake Hamilton (fig. 2) for the period 1950 to 1986 has a significant downward trend (Henderson and Lopez, 1989).

Evidence of the historical variation in the stage of Lake Lucerne can be seen around the lake and is supported by descriptions given by long-term residents. An old lake shoreline and pilings for a dock indicate that lake stage had been much higher than was observed during this study. The submerged dock on which the stage and reflected-radiation station is mounted indicates that the lake also had been lower (fig. 13). In a report on regional flood relations for unregulated lakes, Lopez and Hayes (1984) estimated flood altitudes for specified recurrence intervals for Lake Lucerne as follows:

Recurrence interval, in years	Maximum lake stage, in feet above sea level
2	128.8
5	130.2
10	131.2
25	132.5
50	133.4
100	134.3
500	136.4

Evaporation

Daily mean water temperatures at the surface and at 1-ft intervals beneath the raft-climate station at the center of the lake were available for 316 days during the 1986 water year. Periods of missing record for water-surface temperature were estimated by linear interpolation for periods of a few days or by multiple regression using the weather station air temperature and the previous day's air temperature (table 5). Daily average water-surface temperatures averaged 25.2 °C (77.4 °F) and ranged from 14.2 °C (57.6 °F) in December to 32.4 °C (90.3 °F) in July (fig. 19). The lake generally was not thermally stratified as indicated by the results of periodic thermal surveys (fig. 20). Between May 1985 and May 1986, the maximum difference between surface and bottom temperatures was less than 5 °C (9 °F), and most of the time, this difference was less than 2 °C (4 °F). As expected, the maximum vertical variation in water temperature occurred in May, June, and July.

The mean air temperature for the 1986 water year was 22.2 °C (72.0 °F) at Lake Lucerne and 22.3 °C (72.1 °F) at the Lake Alfred climate station. This may be compared to the long-term average of 22.0 °C (71.6 °F) at Lake Alfred. Daily mean air temperatures ranged from a minimum of 2.9 °C (37.2 °F) on December 26, 1985, to a maximum of 29.6 °C (85.1 °F) on July 8, 1986 (fig. 21).

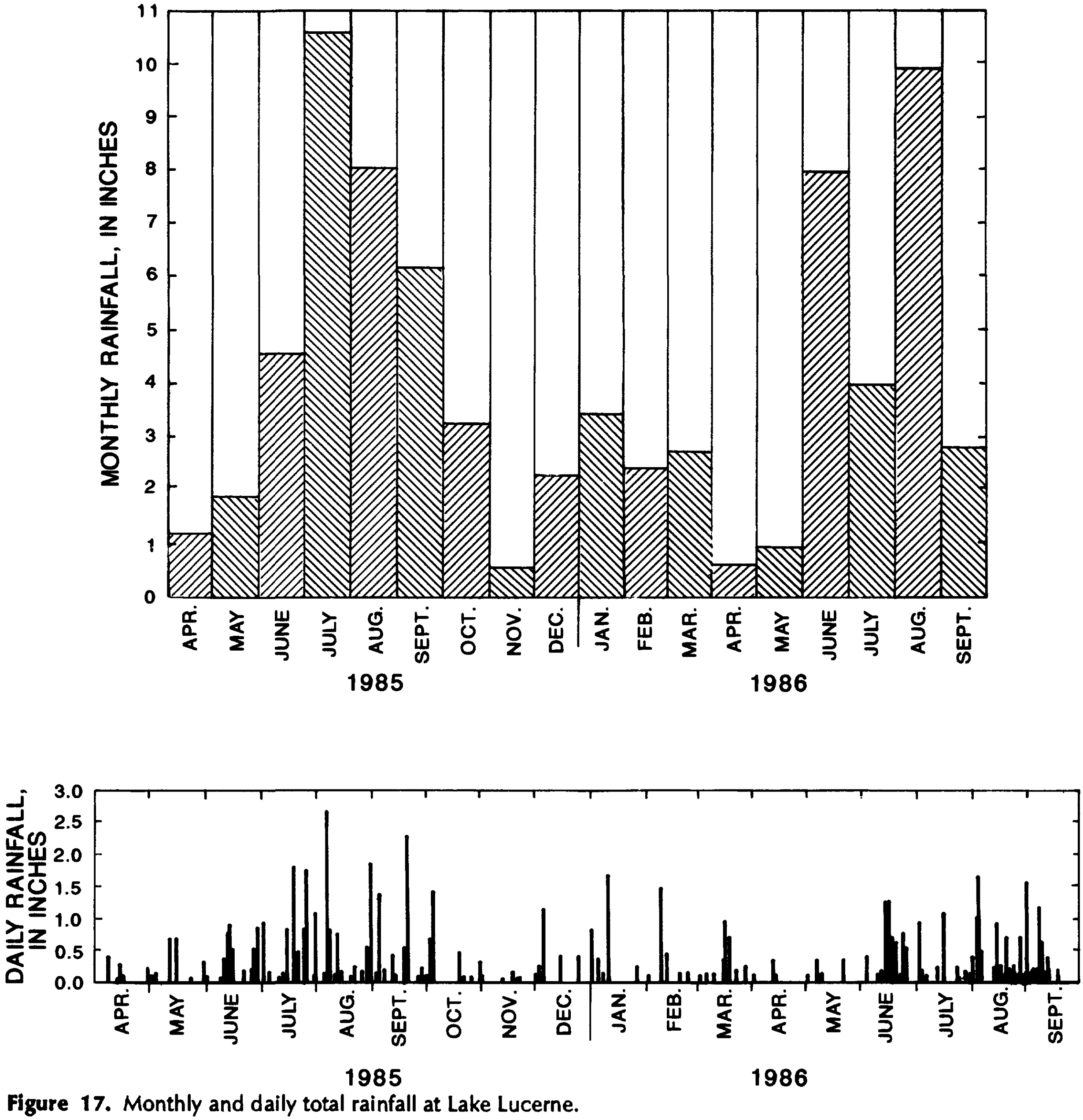


Figure 17. Monthly and daily total rainfall at Lake Lucerne.

Wind speeds were recorded at the pulse anemometer on the raft-climate station and were available for 296 days during the water year. Daily average wind speed for the periods of missing record were estimated from three separate regression equations that were based on the relation between the pulse anemometer at the raft-climate station and each of three other wind speed sensors at the raft-climate or the land-climate stations (table 5). Daily wind speed averaged 5.21 mi/h, and daily averages ranged from 1.26 to 11.02 mi/h in October and November 1985, respectively (fig. 22). The greatest variation in daily average wind speed occurred in late fall and early winter, and the least day-to-day variation occurred in June and July.

Barometric pressure was available for the entire 1986 water year. Pressure averaged 1,021 mb during the year and about 1,025 mb from late fall to early spring and 1,019 mb in the spring and summer (fig. 23). The extremes of 1,008 and 1,033 mb occurred in October and March, respectively.

Daily average vapor pressure at 2 m above the water surface and the saturation vapor pressure at the water surface were calculated from wet- and dry-bulb temperatures and water-surface temperature, respectively. The nonventilated thermocouple psychrometer record was complete for 142 days during the 1986 water year; the relation of vapor pressure to hygrothermograph data at the land-climate station or to dewpoint measurements at Tampa International Airport

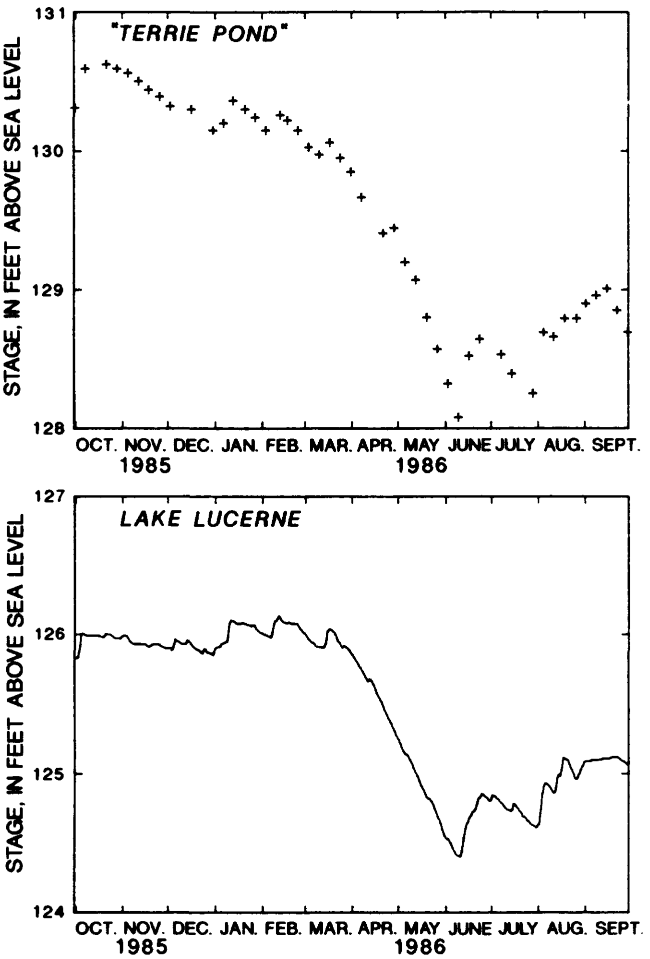


Figure 18. Daily mean stage of Lake Lucerne and weekly stage at "Terrie Pond" for the 1986 water year.

(National Oceanic and Atmospheric Administration, 1986) was used to estimate missing record (table 5). Vapor pressure and saturation vapor pressure averaged 21.0 and 27.8 mb, respectively, during the year. Vapor pressure ranged from 4.71 mb in December to 35.9 mb in July (fig. 24), and saturation vapor pressure ranged from 7.54 mb in December to 41.15 mb in July (fig. 24).

Incident and reflected shortwave radiation data were available for 285 and 354 days, respectively, during the 1986 water year. Linear relations between these two variables were used to predict one or the other variable for periods of missing record (table 5). Daily total incident shortwave radiation averaged 418 ly and ranged from 35 to 693 ly in December and May, respectively (fig. 25). Generally, incident shortwave radiation did not exceed 400 ly in November, December, and January and commonly exceeded 600 ly in April, May, and June. Reflected shortwave radiation generally was less than 5 percent of incident radiation (fig. 26).

Incident longwave radiation and the sum of reflected and emitted longwave radiation data were complete for 183 and 142 days, respectively, during the 1986 water year. The longwave radiometer that faced downward over the lake measured the sum of both reflected and emitted longwave radiation. Therefore, for periods of missing record, the reflected and emitted parts of the total reflected term were estimated separately and then summed. Emitted radiation was calculated from the Stefan-Boltzmann law using water-surface temperature with an emissivity of 0.97. The reflected longwave was estimated as 3 percent of incident longwave radiation (Ficke, 1972) (table 5). Missing incident longwave radiation data were estimated as a function of vapor pressure and air temperature using the equation developed by Idso (1981). Incident longwave radiation averaged 818 ly, and reflected plus emitted longwave radiation averaged 915 ly (figs. 27 and 28). The variation in the reflected plus emitted radiation follows the same pattern observed in water-surface temperature (fig. 19) because the larger emitted longwave radiation term is a function of water-surface temperature.

Daily pan evaporation data were complete for 353 days during the 1986 water year (fig. 29). Missing values were scattered throughout the record and were estimated from the mean of the preceding and following day's value. Total pan evaporation at Lake Lucerne for the 1986 water year was 71.62 in. compared to 77.96 in. at the Lake Alfred climate station. The long-term average pan evaporation at Lake Alfred is 72.03 in.

Ground Water

Although ground-water interactions occur directly between Lake Lucerne and the adjacent surficial aquifer, these fluxes are a part of the larger scale interaction between the surficial and Upper Floridan aquifers. In this section, the vertical recharge between these two aquifers is defined for the area around the lake and for the sublake region on the basis of observed vertical head distributions. Ground-water interactions with Lake Lucerne, and the larger scale flow patterns surrounding the lake are interpreted from areal and vertical head distributions in the basin.

Vertical Head Distribution

At each of the three nested well sites, a distinct separation in heads existed between wells that were finished in the surficial aquifer and wells that were finished in the confined Upper Floridan aquifer (figs. 30-32). From hydrographs for site 1PN (fig. 30), the vertical interval of the confining unit that separates the two flow systems is easily inferred. Wells 1PN-50 and 1PN-65 are 15 ft apart in vertical spacing but tap the surficial aquifer and the Upper Floridan aquifer, respectively. The altitude of the land surface at site 1PN is 131 ft above sea level; therefore, the depths of wells

Table 5. Summary of substitutions for climatic variables monitored at Lake Lucerne

Sensor	Percent of record good	Back-up sensor	Percent of record substituted	Regression			
				R^2	Standard error	Slope	Y-intercept
Pulse anemometer at raft station.	81	Generating anemometer at raft station.	8	0.96	0.31	0.73	0.01
		Generating anemometer at land station.	7	.52	1.13	.70	2.22
		Totalizing anemometer at land station.	4	.20	1.43	.65	4.10
Water-surface thermistor at raft station.	87	Linear interpolation.	8	—	—	—	—
		Air temperature at land station plus 1-day lag.	5	.65	.55	.48	9.77
Dry-bulb temperature at raft station.	59	Air temperature at land station.	41	.99	.61	.98	.86
Vapor pressure from psychrometer at raft station.	40	Hygrothermograph at land station.	57	.96	1.29	.82	2.91
		Dewpoint at Tampa International Airport.	3	.96	1.12	.85	2.45
Incident shortwave radiation at land station.	78	Reflected shortwave radiation at stage-reflected radiation station.	22	.81	55.4	21.3	26.6
Reflected shortwave radiation at stage-reflected radiation station.	97	Incident shortwave radiation at land station.	3	.81	2.63	.04	2.45
Incident longwave radiation at land station.	50	Vapor pressure from raft psychrometer and air temperature at raft station using equation from Idso (1981).	50	.94	29.25	1.11	-81.9
Sum of reflected and emitted long-wave radiation at stage-reflected radiation station.	39	Three percent of incident longwave radiation (Ficke, 1972) plus emitted longwave calculated from Stefan-Boltzmann law using water-surface temperature with emissivity = 0.97.	61	.97	13.77	1.02	-29.0

1PN-50 and 1PN-65 correspond to altitudes of 66 and 81 ft above sea level, respectively. The vertical interval between 66 and 81 ft above sea level corresponds to the Peace River Formation of the Hawthorn Group (fig. 7).

The Hawthorn Group extends from approximately -20 to 85 ft above sea level at site 1PN; however, the interval between 66 and 81 ft above sea level within the predominantly clastic Peace River Formation acts as a confining unit. The remainder of the Hawthorn Group, the Peace River Formation below 66 ft above sea level and the Arcadia Formation, acts hydraulically as part of the Upper Floridan aquifer. Head in this lower part of the Hawthorn Group (for example, wells 1PN-65 and 1PN-72) behaves similarly to the head in well 1PN-155, which is finished in the limestone of the Ocala Group. Heads measured in wells 1PN-65, 1PN-72, and 1PN-155 showed a small downward gradient that was never greater than 0.3 ft over the 90 ft of vertical distance (fig. 30).

The vertical head distribution at site 3PN also confirms the presence of the confining unit in the 15-ft interval that separates well 3PN-50 in the surficial aquifer from well 3PN-65 in the Upper Floridan aquifer. However, unlike well 1PN-65, the head of well 3PN-65 tracked above the head in the Ocala Group (1PN-155) by 1.6 to 7.0 ft (fig. 32). The difference in the vertical head distribution at sites 1PN and 3PN can be explained by the heterogeneous geology of the Hawthorn Group. The head in the Ocala Group at site 3PN was not measured; however, it is assumed to be similar to the head at sites 1PN and 2PN due to the high transmissivity of this formation.

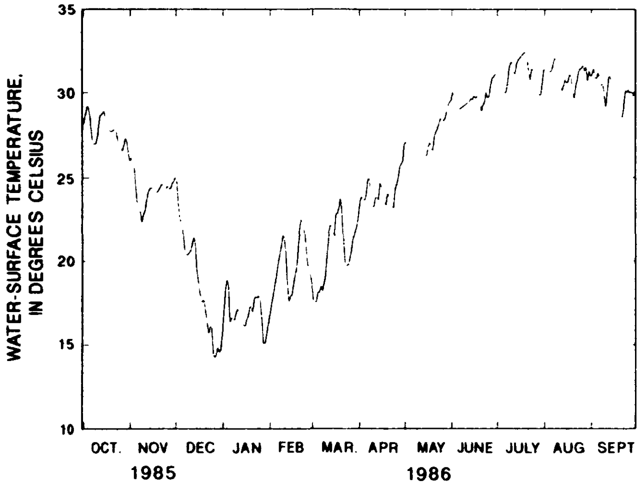


Figure 19. Daily average water-surface temperature at Lake Lucerne for the 1986 water year.

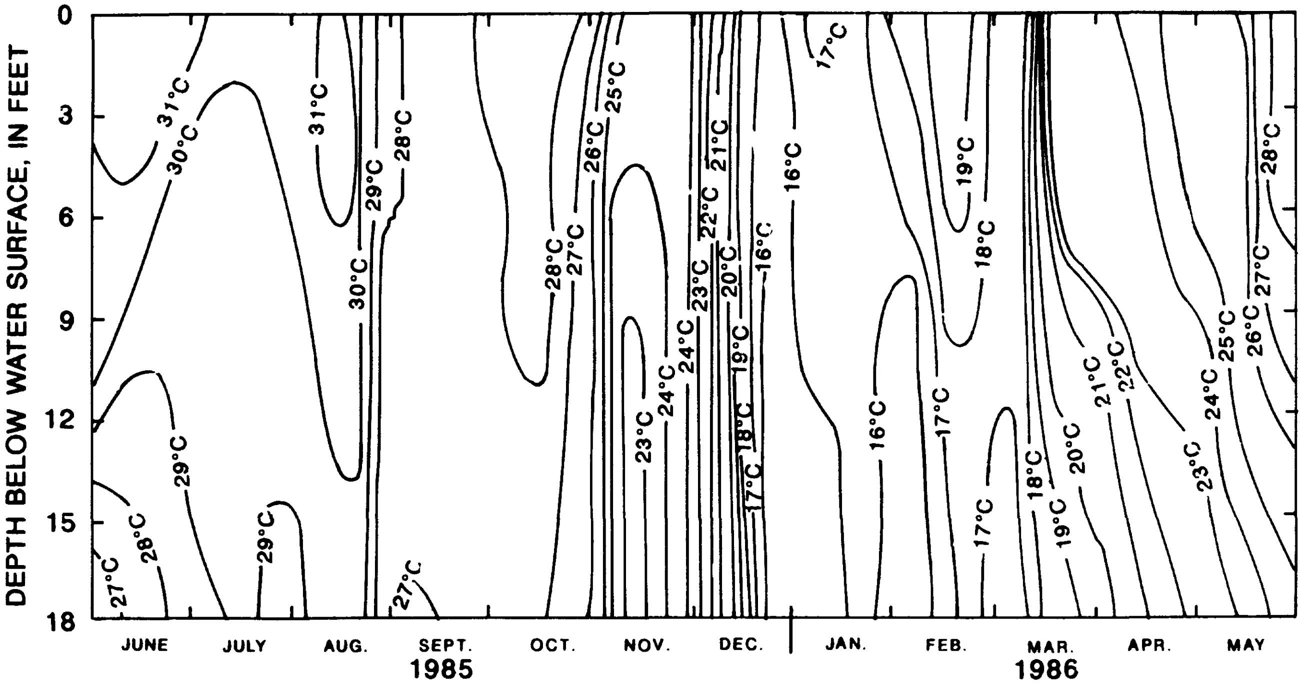


Figure 20. Annual isothermal variations in Lake Lucerne, June 1985-May 1986.

At site 2PN, no wells were finished within the Hawthorn Group; however, the overall vertical head distribution is similar to the other two sites (fig. 31). The head in the Upper Floridan aquifer well 2PN-130 was nearly identical to those measured at site 1PN (fig. 30 and 31). The downward head differences within the surficial aquifer at site 2PN were larger, however, than at the other two sites. This larger downward head difference was primarily due to low heads in well 2PN-50, particularly during the late spring (figs. 30-32).

During the study, heads in the midlake well were always below the lake level and indicated a constant downward head gradient across the deep bottom of the lake. The average head difference between Lake Lucerne and the midlake well for 36 observations between July 1985 and September 1986 was 0.52 ft and ranged from 0.14 ft in October 1985 to 1.01 ft in May 1986. The water level in the lake averaged 7.63 ft above the potentiometric surface of the Upper Floridan aquifer during the same time period.

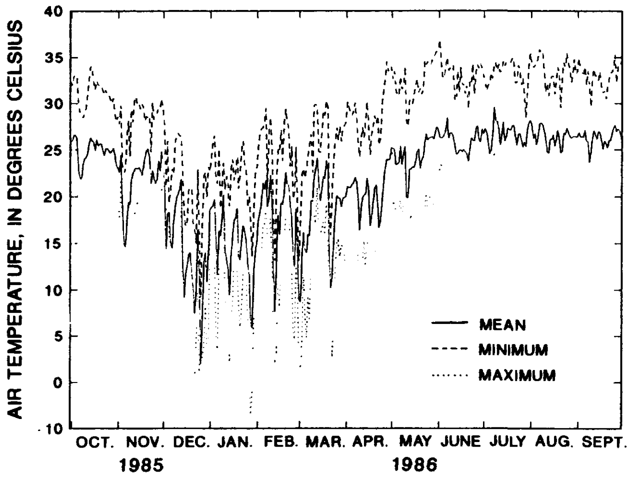


Figure 21. Daily maximum, mean, and minimum air temperature at Lake Lucerne for the 1986 water year.

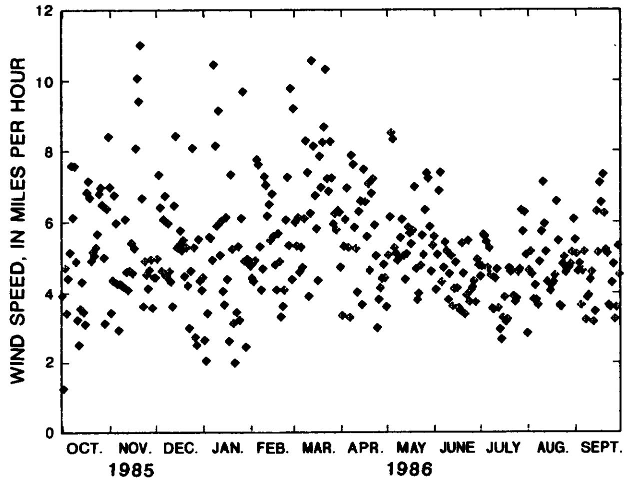


Figure 22. Daily average wind speed at the Lake Lucerne raft-climate station for the 1986 water year.

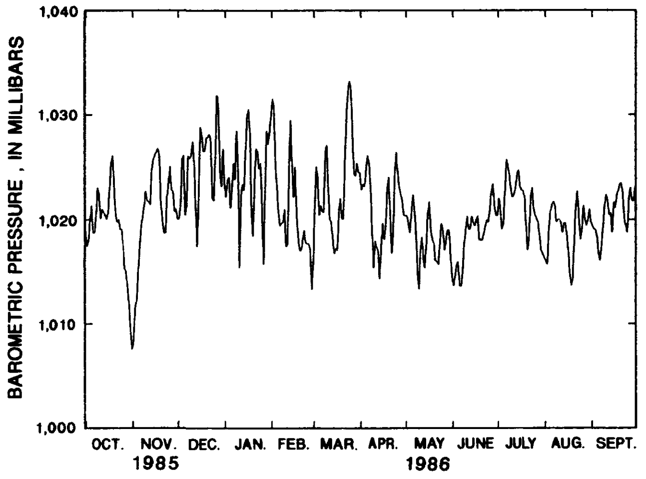
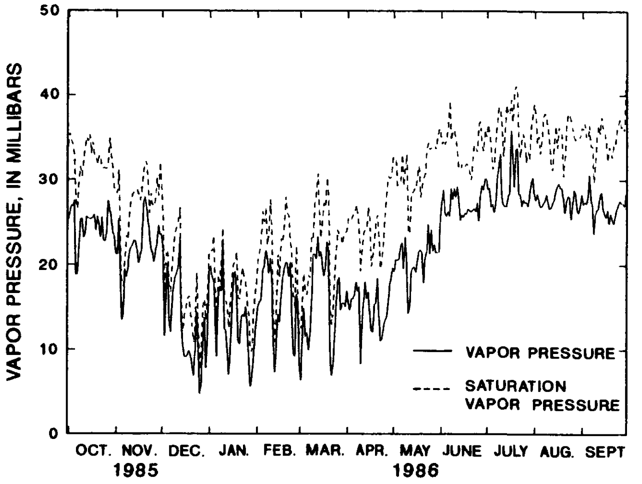


Figure 23. Daily average barometric pressure at Lake Lucerne for the 1986 water year.



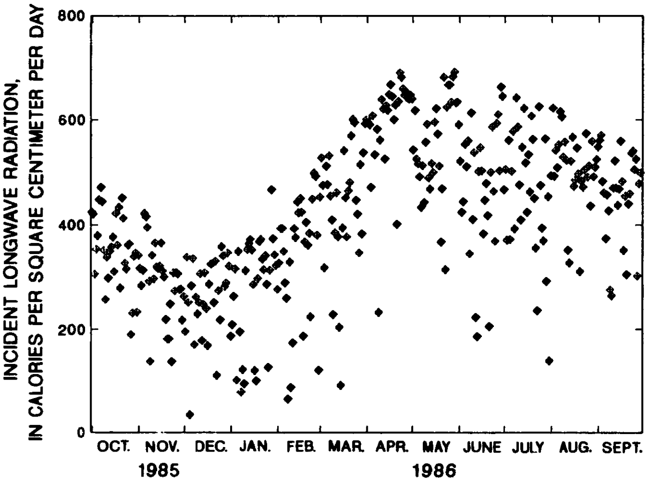


Figure 24. Daily average saturation vapor pressure and vapor pressure at 2 meters over Lake Lucerne for the 1986 water year.

Figure 25. Daily total incident shortwave radiation at Lake Lucerne for the 1986 water year.

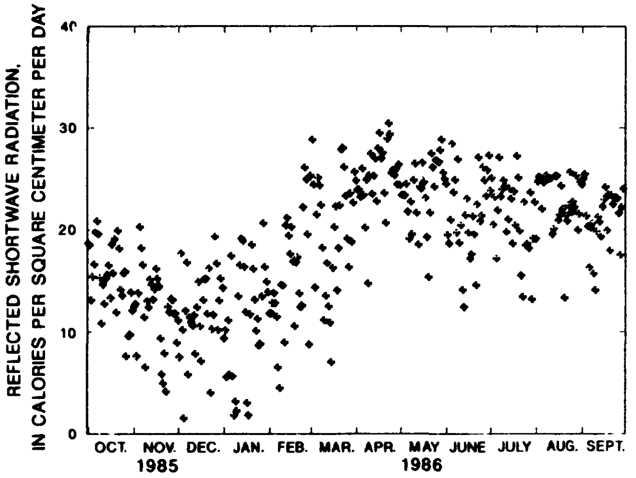


Figure 26. Daily total reflected shortwave radiation at Lake Lucerne for the 1986 water year.

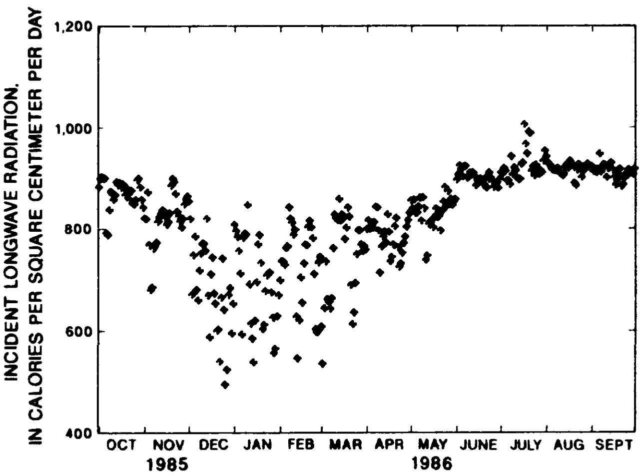


Figure 27. Daily total incident longwave radiation at Lake Lucerne for the 1986 water year.

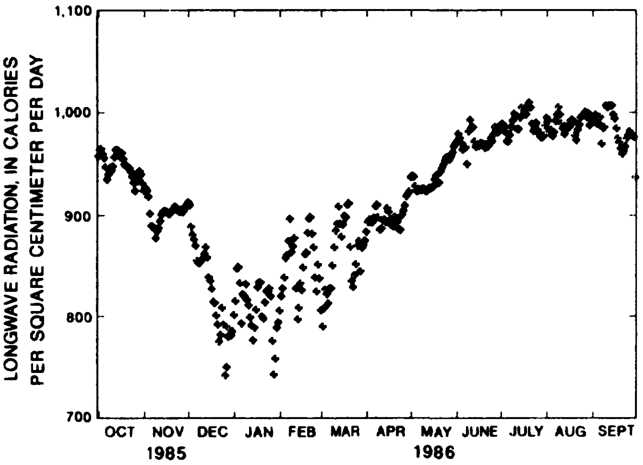


Figure 28. Daily total reflected plus emitted longwave radiation at Lake Lucerne for the 1986 water year.

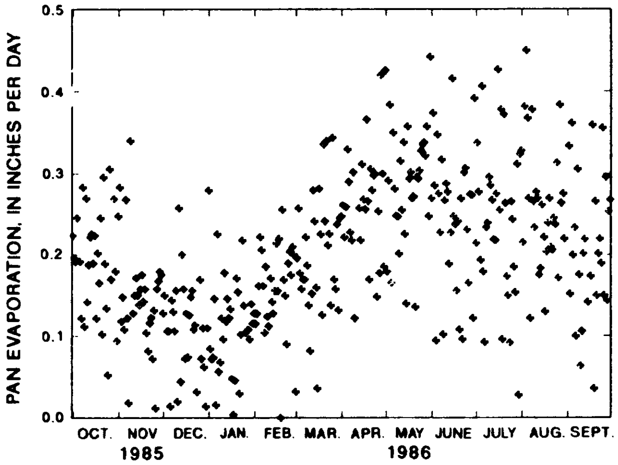


Figure 29. Daily total pan evaporation at Lake Lucerne for the 1986 water year.

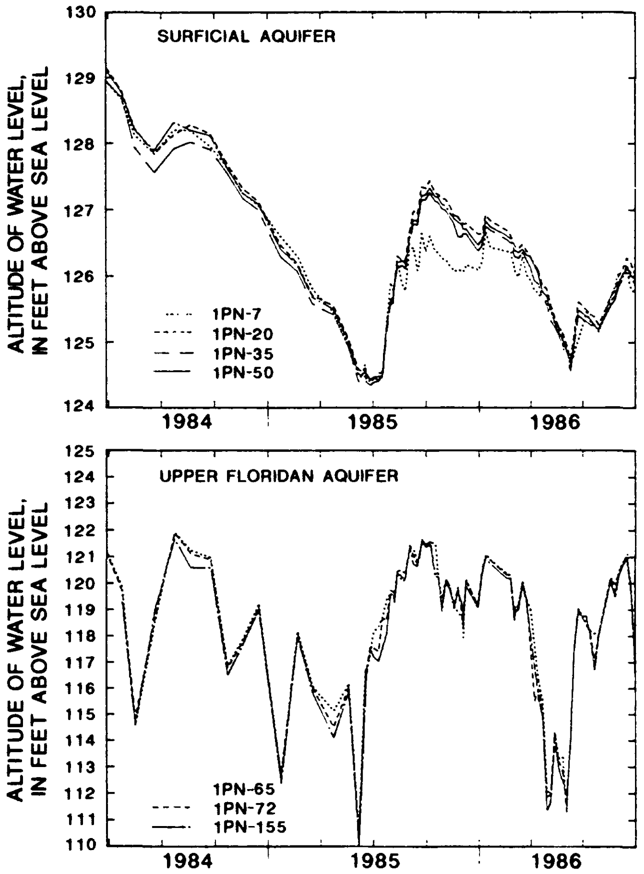


Figure 30. Water levels in wells at site 1PN for the period of record, April 25, 1984, through September 30, 1986.

Without pumping, the head in the Upper Floridan aquifer follows a seasonal trend similar to the surficial aquifer. Irrigation pumping superimposes onto this seasonal trend the erratic and steep drops in head that are seen in the hydrographs of wells finished in the Upper Floridan aquifer. This relation between local irrigation pumpage and drawdown in the Upper Floridan aquifer was identified using continuous water-level measurements recorded in the observation wells at site 1PN. Figure 33 shows the approximate time on and time off of several of the irrigation wells around Lake Lucerne over a 10-day period. These irrigation wells are described in table 4 and their locations are shown in figure 6. Continuous water-level measurements in wells 1PN-65, 1PN-72, and 1PN-155 are shown for the same 10-day period (fig. 33).

The three pumping periods shown coincided with the three drops in water levels in the Upper Floridan aquifer observation wells. During the same periods, wells above the confining unit at site 1PN (1PN-7, 1PN-20, 1PN-35, and 1PN-50) showed no discernible response to pumping. The drawdown in wells in the Upper Floridan aquifer was followed by a rapid recovery of the water levels after pumping stopped. Well OC1 was pumped between the three periods shown in figure 33. The operation of well OC1 alone, however, did not cause a significant drawdown in the observation wells at site 1PN.

Localized pumping resulted in large downward head differences between the surficial and Upper Floridan aquifers. During the period of study, heads in the Upper Floridan aquifer at well 1PN-155 ranged from 109.96 to 121.67 ft above sea level in June 1985 and July 1985, respectively (fig. 31). These large fluctuations resulted in head differences between the surficial aquifer at well 1PN-50 and the Upper Floridan aquifer at well 1PN-155 that ranged from 5.14 (September 16, 1986) to 14.44 ft (June 6, 1985). The average head difference between these two wells, as calculated from 86 observations over the period from March 29, 1984, to September 30, 1986, was 8.06 ft, and the hydraulic gradient was always downward.

Most of the head drop between the two aquifers occurred across the 15-ft thick confining unit, which demonstrates the effectiveness of this low permeability unit to retard flow. However, variability in the effectiveness of the confining unit to retard flow between the surficial and Upper Floridan aquifers was apparent in the behavior of the three deepest wells in the surficial aquifer: 1PN-50, 2PN-50, and 3PN-50 (figs. 30-32), as well as the midlake well.

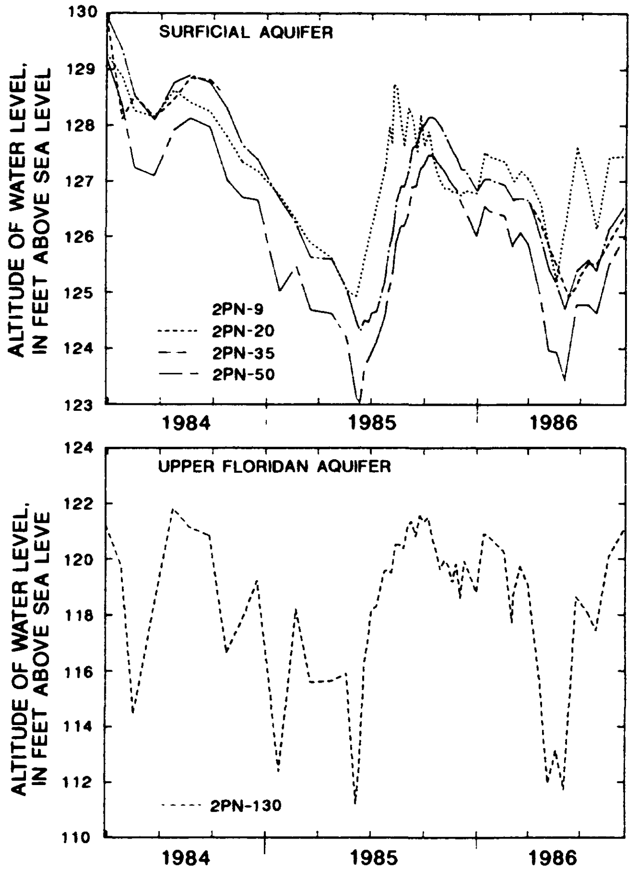


Figure 31. Water levels in wells at site 2PN for the period of record, April 25, 1984, through September 30, 1986.

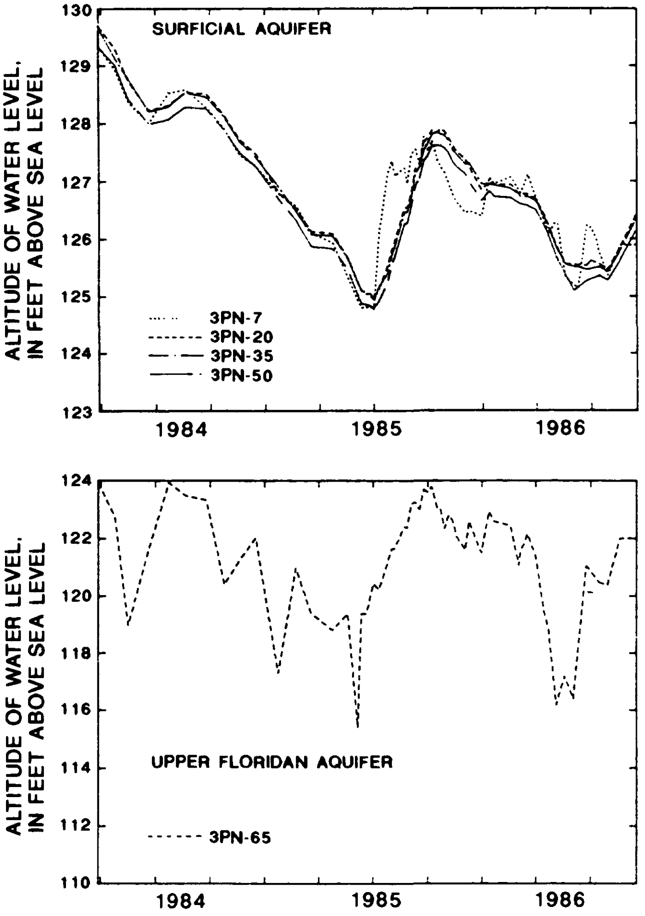


Figure 32. Water levels in wells at site 3PN for the period of record, April 25, 1984, through September 30, 1986.

At extremely low heads in the Upper Floridan aquifer, the hydrograph for well 2PN-50 loses its resemblance to the hydrographs for other wells completed in the surficial aquifer and begins a pattern of steeper declines that coincides with head declines in the Upper Floridan aquifer. For the same periods, wells 1PN-50 and 3PN-50 showed less or no apparent departure from the other wells completed in the surficial aquifer.

A correlation analysis was performed to test the influence of head in the Upper Floridan aquifer on heads above the confining unit in the surficial aquifer. To eliminate the effect of the seasonal correlation between heads in the surficial and Upper Floridan aquifers, a residual term was defined as the downward head difference between the two deepest wells in the surficial aquifer, the 35- and 50-ft deep wells at sites 1PN, 2PN, and 3PN.

The downward head difference between the two deepest wells in the surficial aquifer was checked for correlation with the head in the Upper Floridan aquifer on the same day. At a probability level of 0.05, no correlation was found between these parameters at sites 1PN or 3PN (fig. 34). At site 2PN, however, downward head differences in the lower part of the surficial aquifer were significantly correlated with head in the Upper Floridan aquifer on the same day (probability level 0.0, R = -0.82, fig. 35). Because the horizontal hydraulic conductivity in the 35- and 50-ft wells was shown to be comparable in the slug test analyses, the difference in the response between sites was attributed to the effectiveness of the confining unit. At site 2PN, the Peace River Formation, identified as the confining unit at sites 1PN and 3PN, was not evident. Less effective confinement between the surficial and Upper Floridan aquifers at site 2PN probably results from clays at the contact of the lower surficial deposits with the top of the Arcadia Formation.

To test the effectiveness of the confining unit below the lake, a similar correlation analysis was performed for the midlake well. The midlake well was finished 8 ft below the lake bottom in the surficial aquifer. The downward head difference between the lake and the midlake well was highly correlated with the head in the Upper Floridan aquifer on the same day (probability level 0.00, R = -0.87, fig. 35). This strong correlation suggests a significant hydraulic connection between the surficial and Upper Floridan aquifers beneath the lake. This connection can be explained by the breaches in the confining unit interpreted from the seismic-reflection survey. According to this survey, the midlake well is in an area where the confining unit is intact (fig. 9). Therefore, it is possible that a stronger correlation would occur in a midlake well located directly above a breach in the confining unit.

The correlations for the midlake well and site 2PN were repeated using only those observations in which the head in the Upper Floridan aquifer was greater than 119 ft above sea level. A head value of 119 ft above sea level was chosen to represent a likely minimum value that the potentiometric surface might experience without pumpage. This value is conservative and is below the estimated predevelopment potentiometric surface (Johnston and others, 1980), or the May 1964 potentiometric surface level (Yobbi, 1983) for the Lake Lucerne area.

When the same analysis was performed using only observations in which the head in well 1PN-155 or 2PN-130 was greater than 119 ft above sea level, no correlation was found between the head difference in the lower surficial aquifer and the head in the Upper Floridan aquifer at site 2PN (probability level 0.05). A weak but significant correlation, however, still existed for the midlake well site (probability level 0.01, R = -0.56).

These results support the interpretation of the seismic-reflection survey and indicate that, in areas where the confining unit is breached or absent, the surficial aquifer responds to head fluctuations in the Upper Floridan aquifer, particularly over the highly variable range of lowered heads due to pumping. Of the four locations that were compared, 1PN, 2PN, 3PN, and midlake, the midlake well location showed the best correlation with the head in the Upper Floridan aquifer. It also was well correlated over the widest range of head conditions in the Upper Floridan aquifer.

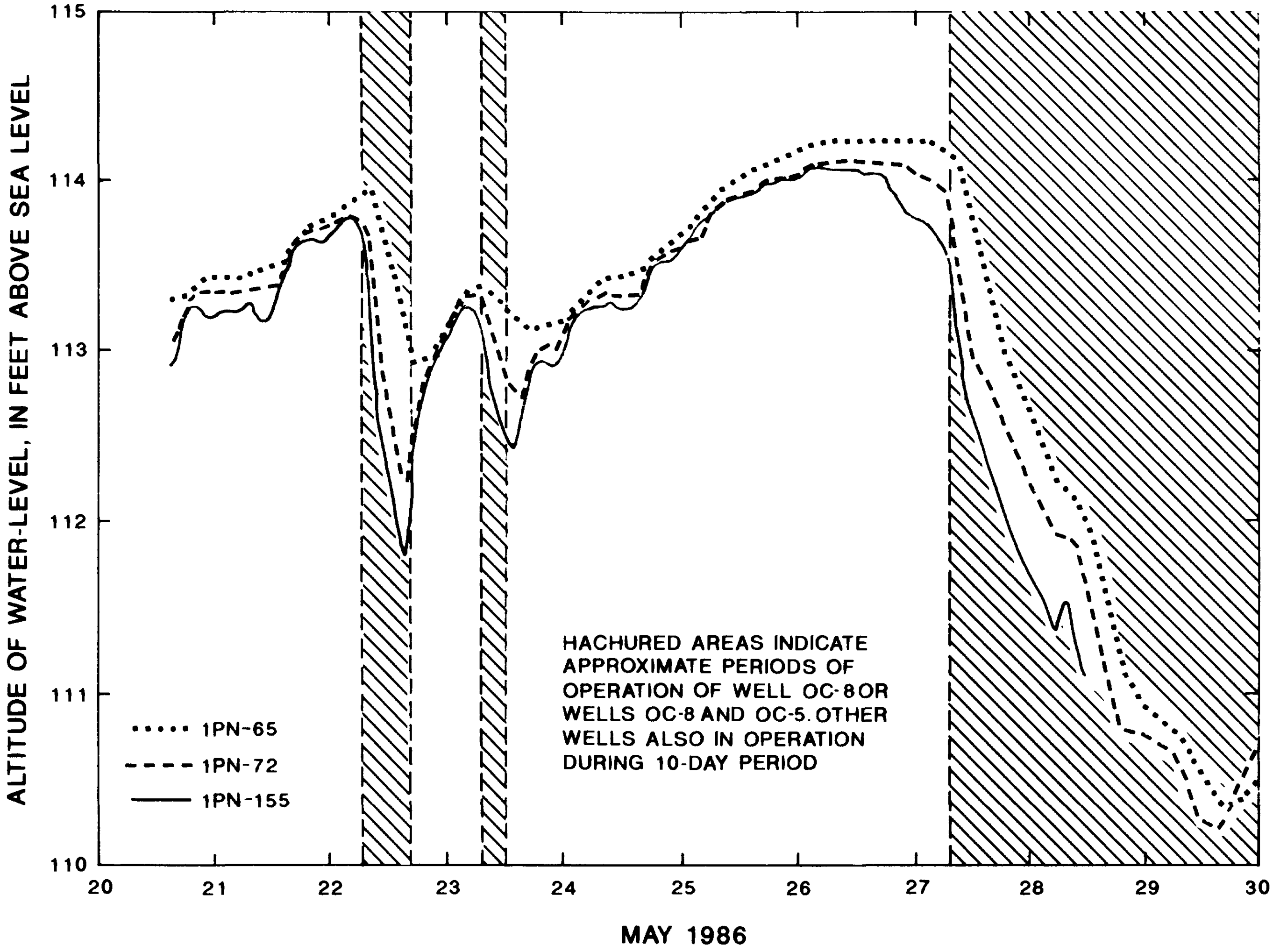


Figure 33. Continuous water levels in wells 1PN-65, 1PN-72, and 1PN-155 for May 20-30, 1986.

Areal Head Distribution

The areal head distribution around Lake Lucerne is controlled by fluctuations in the level of the water table. The water table in the surficial aquifer around Lake Lucerne characteristically rises in summer through early fall in response to the rainy season, and with the exception of a smaller rise during a short winter wet season, steadily declines until the following summer. The amplitude of this seasonal fluctuation in the 17 water-table wells ranged from 3 to 6 ft, depending upon the topographic position of the well. This seasonal variation in the altitude of the water table is shown for three representative wells in figure 36. Figure 37 shows the seasonal extremes in the areal head distribution around Lake Lucerne for the 1986 water year. The maximum water-table altitude that was measured in the basin during the study on September 17, 1985, was 8.5 ft above the lake level. At minimum water-table conditions on June 27, 1985, the maximum altitude was estimated to be 5 ft above the lake level. The maximum water-table gradient, which occurred between the lake and well WT-15, was less than 1 percent.

Ground-Water Flow Patterns

The vertical head distribution along transect A-A′ (fig. 37) illustrates two flow conditions that occur in the surficial aquifer at Lake Lucerne (figs. 38-40). Under most conditions, an upward head gradient exists above wells that are either 20 or 35 ft deep, and a downward gradient exists below the 20- or 35-ft deep wells (figs. 38 and 39). The vertical location of this split between upward and downward head gradients corresponds to a ground-water flow divide. This flow divide, at each of the three well nests, indicates a separation of flow within the surficial aquifer into an upper zone that contributes flow to the lake and a lower zone that does not. This pattern existed for both the minimum and maximum water-level conditions observed during the 1986 water year (figs. 38 and 39).

In the second and less common case, a downward head gradient existed between all wells at all depths (fig. 40). This pattern occurred at all three well nest sites during the study and was associated primarily with recharge to the surficial aquifer during the wet summer season. However, downward

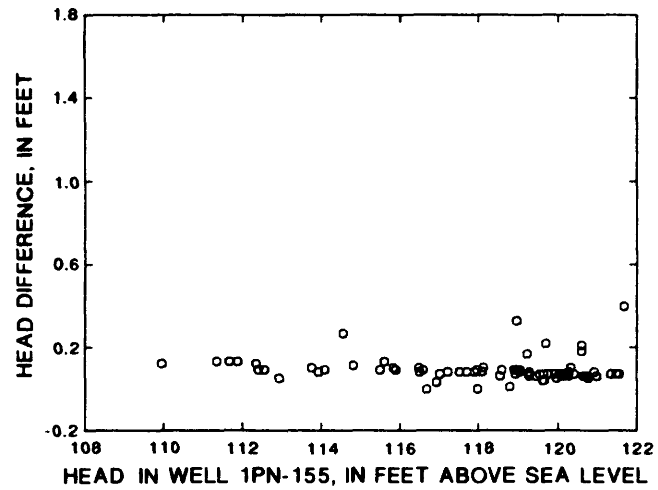


Figure 34. Relation between difference in head as measured by surficial aquifer wells 1PN-35 and 1PN-50 and the head in Upper Floridan aquifer well 1PN-155.

gradients between all wells at sites 1PN and 3PN also occurred during January through March 1985 when water levels in wells tapping both the surficial and Upper Floridan aquifers were rapidly decreasing and rainfall was well below normal.

Although the regional ground-water system is characterized by vertical flow from the surficial aquifer to the Upper Floridan aquifer, locally, Lake Lucerne receives lateral ground-water inflow from the surrounding surficial aquifer. Lake Lucerne is in a closed ground-water basin with respect to the surficial aquifer that coincides with the topographic drainage basin for most of the year. The areal head distribution indicates that ground water in the surficial aquifer generally flows in a centripetal pattern from the drainage divide toward the lake. This flow pattern indicates that Lake Lucerne is the focal point for discharge from the surrounding surficial aquifer. Occasionally, during extremely low water-table conditions, zero or slightly negative slopes in the water table indicated flow away from Lake Lucerne. The condition occurred in areas where topographic relief was minimal, and, thus, water-table altitudes were generally low (wells WT-18 and WT-1 along the northern drainage divide and well WT-7 on the southwestern part of the divide). Additional water-level measurements at points between the lake and these three wells, however, were not available to confirm the extent of these reversed head gradients. Head gradients also were reversed between the lake and wells 1PN-7 and 2PN-9 near the lake margin for brief periods during the spring of 1984 and 1985. This depression of the water table where it is closest to land surface near the lake may have been caused by localized evapotranspiration.

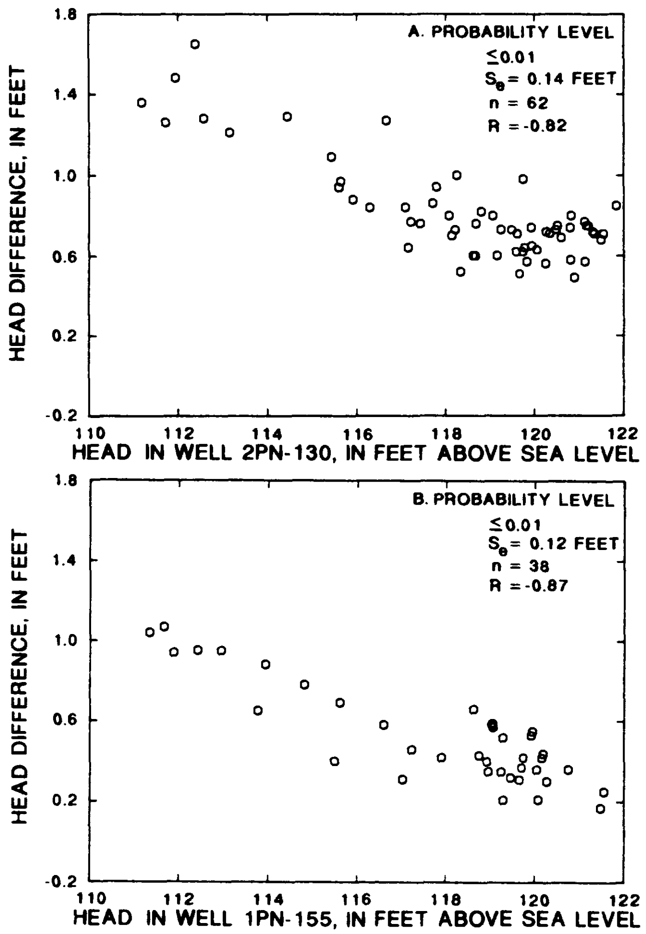


Figure 35. Relation between (A) difference in head as measured by surficial aquifer wells 2PN-35 and 2PN-50 and the head in Upper Floridan aquifer well 2PN-130 and (B) difference in head as measured by lake stage and the midlake surficial aquifer well and the head in Upper Floridan aquifer well 1PN-155.

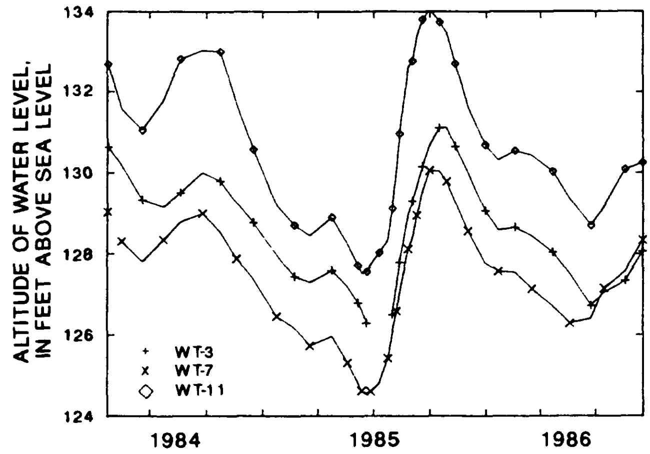


Figure 36. Water levels in representative surficial-aquifer wells in the study area.

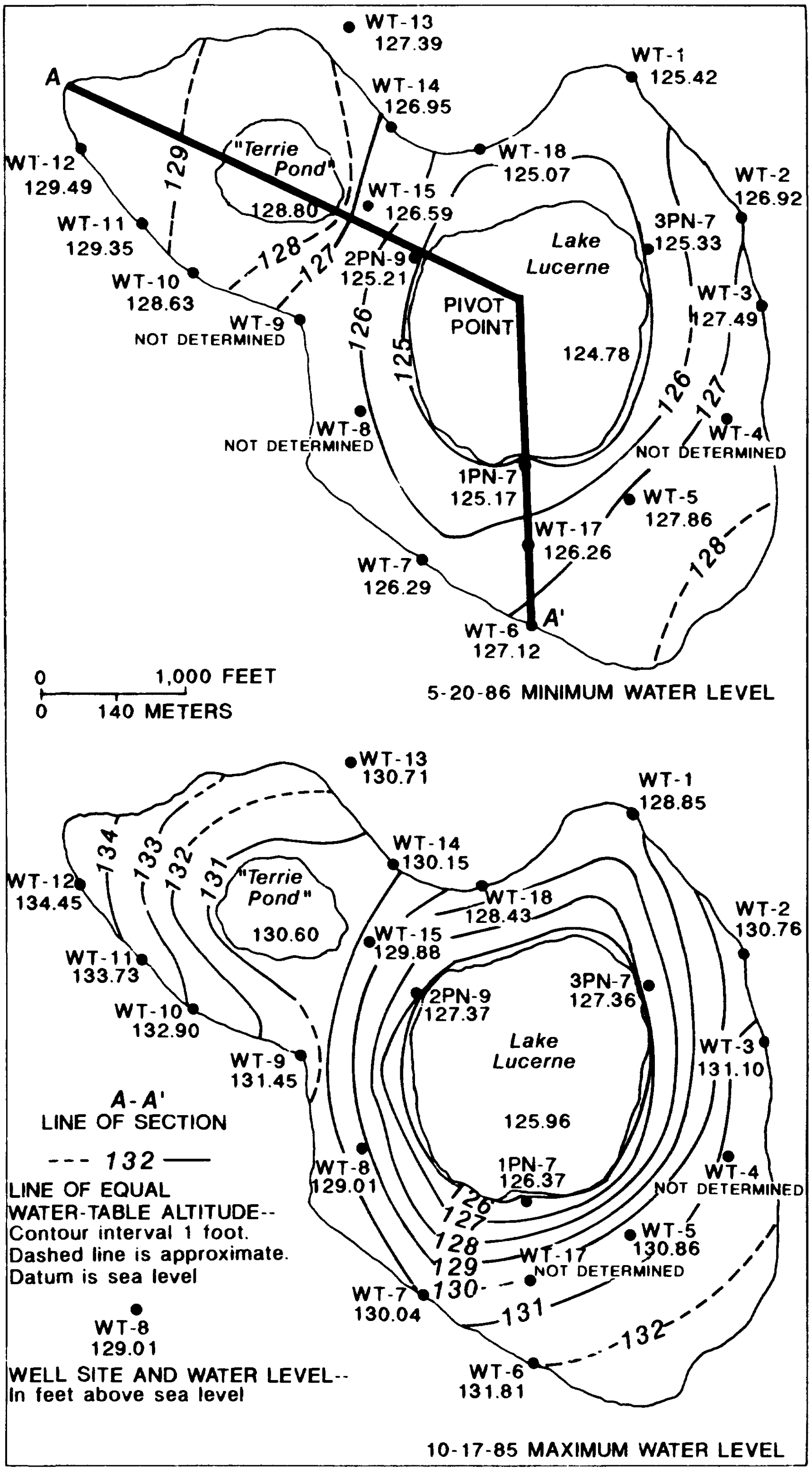


Figure 37. Configuration of the water table based on the maximum and minimum recorded water levels during the 1986 water year.

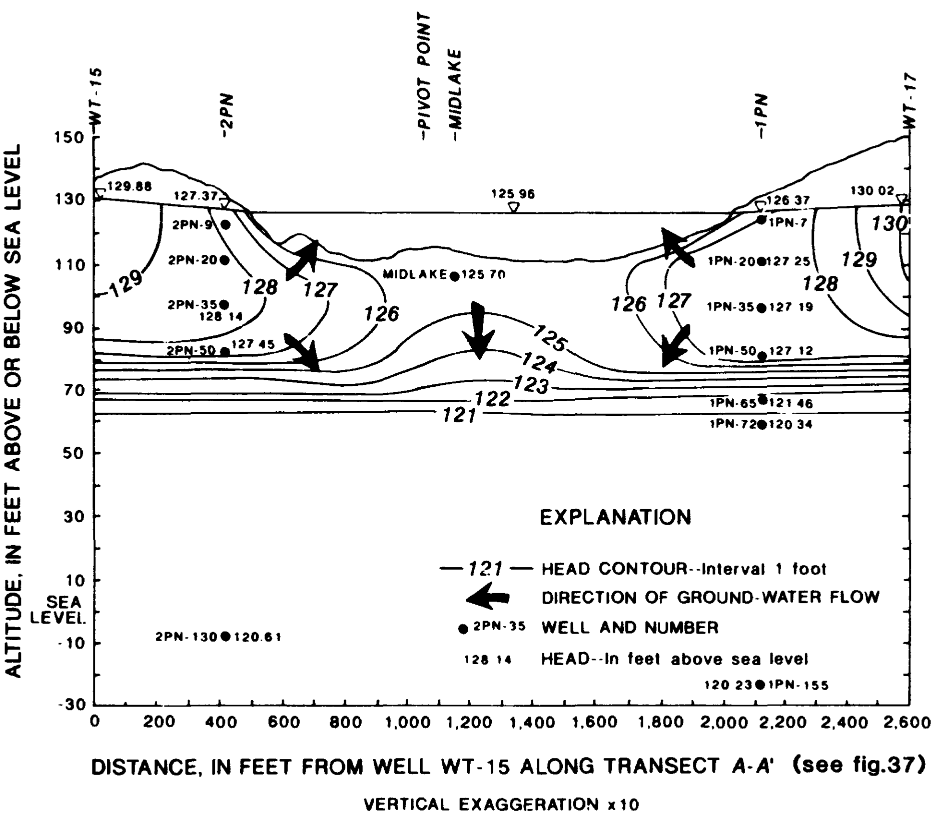


Figure 38. Vertical distribution of head during high water-level conditions, October 17, 1985.

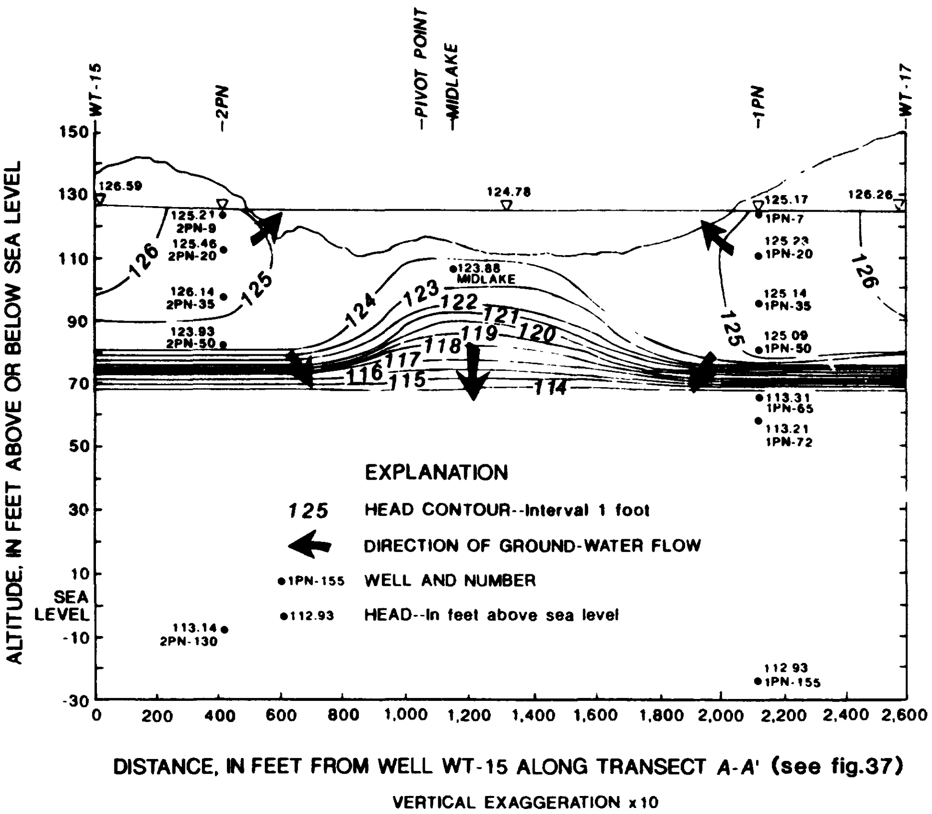


Figure 39. Vertical distribution of head during low water-level conditions, May 20, 1986.

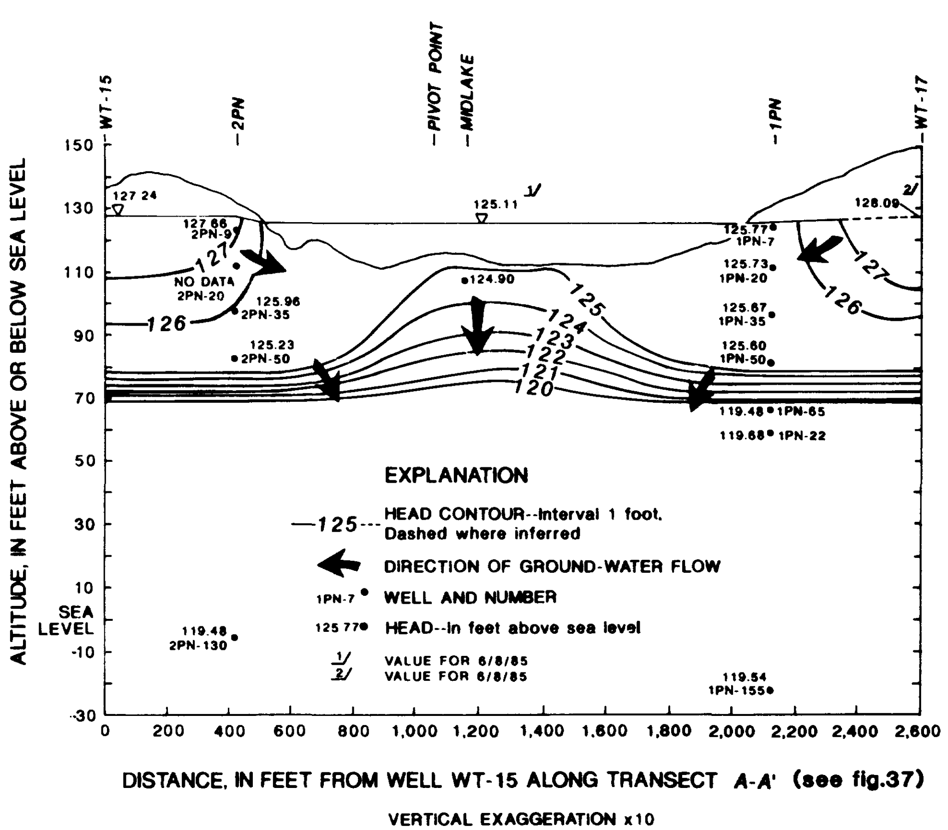


Figure 40. Vertical distribution of head showing downward head gradient conditions, August 6, 1985.

Localized, transient water-table mounds also were observed during early summer in 1985 and 1986. The water table surrounding Lake Lucerne uniformly declines during the dry months of spring and early summer until it reaches an annual minimum level. With the abrupt start of heavy summer rains (1-2 in/d), rapid infiltration of rainfall to the water table in the area concentric to the lake causes water-table mounds at 2PN-9 and 3PN-7. Although the water table close to the lake is measured only at three wells (1PN-7, 2PN-9, and 3PN-7), these mounds are believed to have a crescent shape (fig. 41). The formation of transient ground-water mounds has been shown to occur in porous surficial deposits where the water table is closest to land surface and, therefore, rapidly recharged (Winter, 1983; 1986). At Lake Lucerne, these mounds temporarily alter the drainage in the basin by creating an intermediate ground-water flow divide. On the outside of this ground-water mound, water flows away from the lake. On the inside of the mound, steep head gradients move ground water toward the lake. Over the following 5 weeks or so, as the water table rises throughout the remainder of the basin and declines near the lake, the flow patterns created by these transient mounds disappear. Regardless of subsequent rainfall during the summer, the water table near the lake never reaches equally high levels, and the transient ground-water flow pattern is not reproduced until the following summer.

SUMMARY

Lake Lucerne is one of numerous small solution-type lakes along the Central Highlands Ridge area of Florida for which the importance of evaporation and ground-water fluxes on lake stage is unknown. The mantled karst landscape is characterized by sandy ridges, numerous sinkholes and internally drained lakes, and the prevalence of subterranean flow systems over surface-water drainage. Lake Lucerne has an area of approximately 45 acres at a stage of 130 ft and a drainage basin area of 0.26 mi^2. The lake has a maximum depth of about 22 ft and a mean depth of about 15 ft. The highest point in the basin is approximately 180 ft above sea level.

An extensive hydrologic data-collection network was established in order to accurately determine all components of the hydrologic budget of Lake Lucerne and, ultimately, to predict the effect of evaporation and ground-water fluxes on lake stage. Lake-stage and ground-water level data are presented for Lake Lucerne for the period April 1984 through September 1986; however, climatic data for use in evaporation calculations are presented only for the 1986 water year. Daily values of the climatic data needed for computation of evaporation by the energy-budget and mass-transfer methods are available for this entire period. Missing values within the primary climatic record were substituted with measurements by backup sensors or estimated from other measured

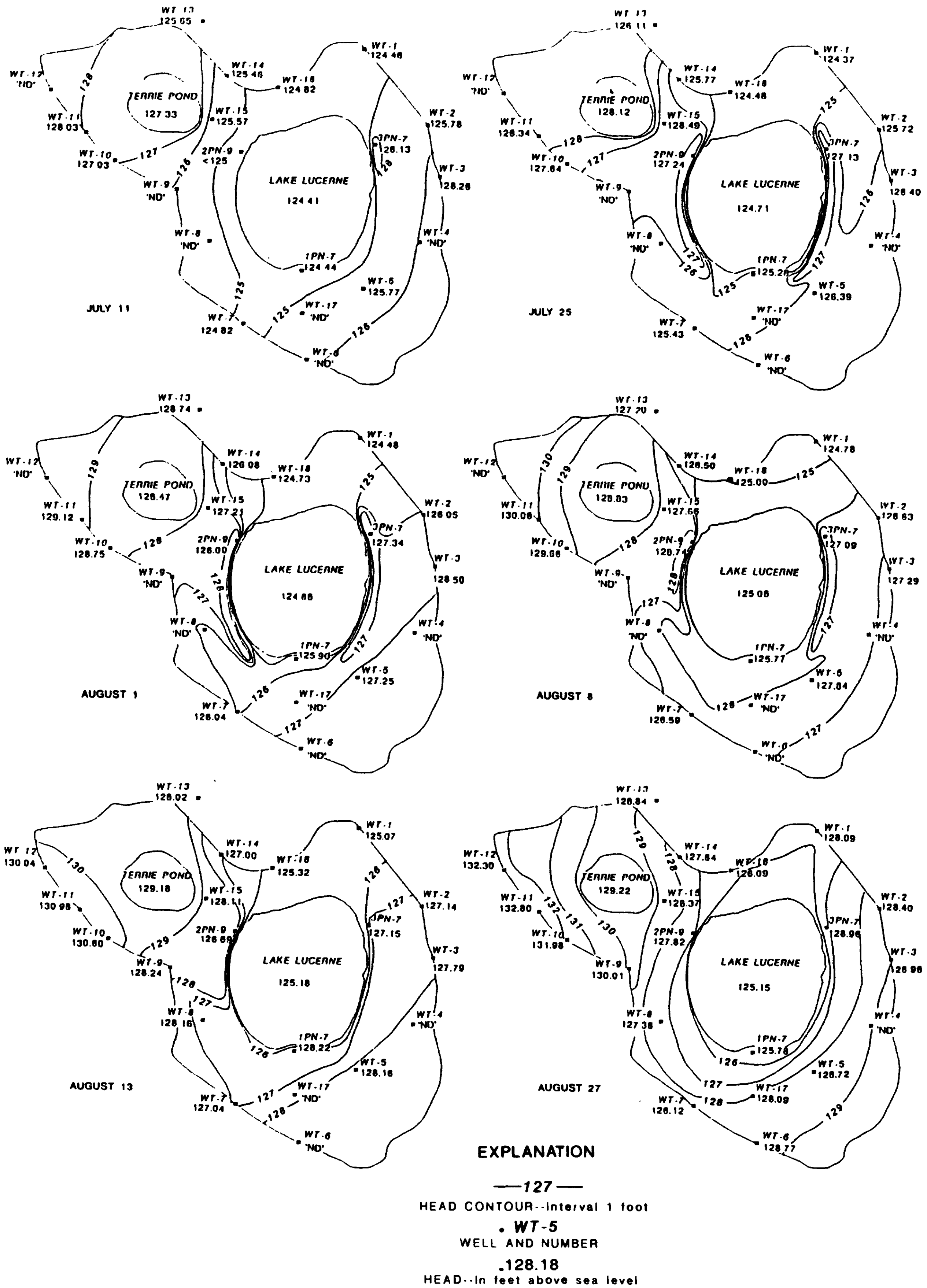


Figure 41. Assumed locations of transient water-table mounds in July and August 1985.

variables using relations derived by regression analysis. This regression information is summarized for each type of substitution made.

Climatic conditions during the 1986 water year were characterized by below normal rainfall. Total rainfall at Lake Lucerne was 40.88 in. compared with the long-term average rainfall of 50.83 in. measured at the Lake Alfred NOAA climate station. Below normal rainfall during the study was reflected in the declining lake-stage and water-table altitudes at Lake Lucerne and by higher than average pan evaporation values at the Lake Alfred climate station (77.96 in. compared with the long-term average of 72.03 in.).

The hydrogeologic setting of Lake Lucerne was defined in order to understand and eventually to quantify ground-water inflows and outflows to the lake. The local geology includes the transmissive limestones of the Upper Floridan aquifer overlain by approximately 60 ft of the Hawthorn Group and 50 to 100 ft of undifferentiated sands and clays that contain the surficial aquifer. Within the drainage basin, a 15-ft thick confining unit within the Hawthorn Group separates the Upper Floridan aquifer from the surficial aquifer, which encompasses the lake. Beneath the lake, however, a seismic-reflection survey revealed steep-sided solution features in the limestone that breach the confining unit and that are filled by the collapsed overburden. The survey also revealed apparently undisturbed areas where the confining unit remains intact.

Although the hydraulic characteristics of the material infilling the solution features beneath the lake are unknown, a regression analysis of vertical head gradients at the nested observation wells and at the midlake well site showed that heads in the midlake well had the highest correlation with heads in the Upper Floridan aquifer. This relation suggests that the overburden filling the solution features beneath the lake is significantly more conductive than the confining unit present in the surrounding basin and that the hydraulic interconnection between the surficial and Upper Floridan aquifers is highest beneath the lake.

Except during short periods of extremely low water levels, the boundaries of the ground-water basin in which Lake Lucerne occurs are coincident with those of the surface drainage areas to the lake. Contour maps of the vertical and areal head distribution around Lake Lucerne indicate that, above a vertical ground-water flow divide in the surficial aquifer, ground water flows laterally and upward into shallow regions of the lake bottom. Below the flow divide, leakage through the lake bottom and ground water in the lower surficial aquifer flow vertically downward toward the Upper Floridan aquifer through breaches in the confining unit. This pattern of head distribution indicates that, within the associated ground-water basin, Lake Lucerne is a focal point for ground-water discharge from the surrounding surficial aquifer. Because of breaches in the underlying confining unit, Lake Lucerne also lies in the preferential flow path for recharge from the surficial aquifer to the Upper Floridan aquifer.

The lowest seasonal water-table altitude occurred during the late spring and was accompanied in 1984 and 1985 by gradients away from the lake in certain areas. With the onset of the summer wet season, the lowest water-table condition was followed in the summers of 1985 and 1986 by the occurrence of transient, crescent-shaped recharge mounds in the water table adjacent to the lake. These localized mounds in the water table resulted in a temporary, partial reversal of the established ground-water flow paths.

REFERENCES

Altschuler, Z.S., and Young, E.J., 1960, Residual origin of the "Pleistocene" sand mantle in central Florida and its bearing on marine terraces and Cenozoic uplift: U.S. Geological Survey Professional Paper 400-B, p. B202-B207.

Anderson, E.R., 1954, Energy-budget studies, *in* Water-loss investigations, Lake Hefner studies, technical report (revised): U.S. Geological Survey Professional Paper 269, p. 71-119.

Beck, B.F., Ceryak, R., Jenkins, D.T., Scott, T.M., and Spangler, D.P., 1984, Field guide to some illustrative examples of karst hydrogeology, central and northern Florida: University of Central Florida Sinkhole Conference Field Guide Book, 43 p.

Bellaire, F.R., and Anderson, L.J., 1951, A thermocouple psychrometer for field measurements: American Meteorological Society Bulletin, v. 32, no. 6, p. 217-220.

Bouwer, H., and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Bowen, I.S., 1926, The ratio of heat losses by conduction and by evaporation from any water surface: Physical Review, v. 27, p. 779-787.

Brooks, H.K., 1981, Guide to the physiographic provinces of Florida: Gainesville, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 11 p.

Campbell, K.M., 1986, Geology of Polk County, Florida: Florida Bureau of Geology Open-File Report 13, 14 p.

Cathcart, J.B., 1966, Economic geology of the Fort Meade quadrangle, Polk and Hardee Counties, Florida: U.S. Geological Survey Bulletin 1207, 97 p.

Cooke, C.W., 1945, Geology of Florida: Florida Geological Survey Bulletin 29, 342 p.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States, National Oceanic and Atmospheric Administration Technical Report NWS 33, 26 p. and 4 sheets.

Ficke, J.F., 1972, Comparison of evaporation computation methods, Pretty Lake, Lagrange County, northeastern Indiana: U.S. Geological Survey Professional Paper 686-A, 49 p.

Ficke, J.F., Adams, D.B., and Danielson, T.W., 1977, Evaporation from seven reservoirs in the Denver water-supply system, central Colorado: U.S. Geological Survey Water-Resources Investigations 76-114, 170 p.

Geraghty and Miller, Inc., 1980, Highlands Ridge hydrologic investigation: Consultant's report in the files of the Southwest Florida Water Management District.

Grubb, H.F., 1978, Potential for downward leakage to the Floridan aquifer, Green Swamp area, central Florida: U.S. Geological Survey Water-Resources Investigations 77-71, 1 sheet.

Harbeck, G.E., Jr., 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory: U.S. Geological Survey Professional Paper 272-E, p. 101-105.

Henderson, S.E., and Lopez, M.A., 1989, Trend analysis of Lake Parker stage and relation to various hydrologic factors, 1950-1986, Lakeland, Florida: U.S. Geological Survey Water-Resources Investigations 89-4037, 19 p.

Hutchinson, C.B., 1978, Appraisal of shallow ground-water resources and management alternatives in the upper Peace and eastern Alafia River basins, Florida: U.S. Geological Survey Water-Resources Investigations 77-124, 57 p.

Idso, S.B., 1981, A set of equations for full spectrum and 8-14 μm and 10.5-12.5 μm thermal radiation from cloudless skies: Water Resources Research, v. 17, p. 295-304.

Johnston, R.H., Krause, R.E., Meyer, F.W., Ryder, P.D., Tibbals, C.H., and Hunn, J.D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development: U.S. Geological Survey Open-File Report 80-406, 1 sheet.

Ketner, K.B., and McGreevy, L.J., 1959, Stratigraphy of the area between Hernando and Hardee Counties, Florida: U.S. Geological Survey Bulletin 1074-C, 124 p.

Koberg, G.E., 1958, Energy-budget studies, *in* Water-loss investigations—Lake Mead studies: U.S. Geological Survey Professional Paper 298, p. 20-29.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959, Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37, 13 p.

Kohler, M.A., Nordenson, T.J., and Fox, W.E., 1955, Evaporation from pans and lakes: U.S. Weather Bureau Technical Paper 38, 21 p.

Lopez, M.A., and Hayes, R.D., 1984, Regional flood relations for unregulated lakes in west-central Florida: U.S. Geological Survey Water-Resources Investigations Report 84-4015, 60 p.

Marciano, J.J., and Harbeck, G.E., Jr., 1952, Mass-transfer studies in water loss investigations—Lake Hefner studies: U.S. Geological Survey Professional Paper 269, p. 46-70.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p., 28 pl.

National Oceanic and Atmospheric Administration, 1986, Local climatological data monthly summary for Tampa, Fla.

National Weather Service, 1972, National Weather Service observation handbook no. 2: Washington, D.C., U.S. Government Printing Office, 77 p.

Palmer, C.E., and Nguyen, H., 1986, Long term rainfall deficits in central Florida: Implications for water management: Polk County, Florida Board of County Commissioners, Water Resources Department, Bartow, Florida, 63 p.

Pirkle, E.C., Yoho, W.H., and Allen, A.T., 1965, Hawthorn, Bone Valley and Citronelle sediments of Florida: Florida Academy of Science, v. 28, p. 7-58.

Pride, R.W., Meyer, F.W., and Cherry, R.N., 1966, Hydrology of the Green Swamp area in Central Florida: Florida Bureau of Geology Report of Investigations 42, 137 p.

Scott, T.M., 1986, A revision of the Miocene lithostratigraphic nomenclature, southwest Florida: Gulf Coast Association of Geology Societies Transactions, v. 36, p 553-560.

——— 1988, The lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Florida Geological Survey Bulletin 59, 148 p.

Sinclair, W.C., Stewart, J.W., Knutilla, R.L., Gilboy, A.E., and Miller, R.L., 1985, Types, features, and occurrence of sinkholes in the karst of west-central Florida: U.S. Geological Survey Water-Resources Investigations Report 85-4126, 81 p.

Southeastern Geological Society, 1986, Hydrogeological units of Florida: Florida Bureau of Geology Special Publication 28, 8 p.

Spahr, N.E., and Ruddy, B.C., 1983, Reservoir evaporation in central Colorado: U.S. Geological Survey Water-Resources Investigations Report 83-4103, 232 p.

Stewart, H.G., Jr., 1966, Ground-water study of Polk County, Florida: Florida Geological Survey Report of Investigations 44, 170 p.

Sturrock, A.N., Jr., 1985, Instrumentation for measuring lake and reservoir evaporation by the energy-budget and mass-transfer methods: U.S. Geological Survey Open-File Report 84-863, 21 p.

White, W.A., 1970, Geomorphology of the Florida Peninsula: Florida Geological Survey Bulletin 51, 164 p.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, no. 1, p. 82-115.

——— 1983, The interaction of lakes with variably saturated porous media: Water Resources Research, v. 19, no. 5, p. 1203-1218.

——— 1984, Geohydrologic setting of Mirror Lake, West Thornton, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 84-4266, 61 p.

——— 1986, Effect of ground-water recharge on configuration of the water table beneath sand dunes and on seepage lakes in the sandhills of Nebraska: Journal of Hydrology, v. 86, p. 221-237.

World Meteorological Organization, 1966, Measurement and estimation of evaporation and evapotranspiration: World Meteorological Organization Technical Note 83, 121 p.

Yobbi, D.K., 1983, Trends and fluctuations in the potentiometric surface of the Floridan aquifer, west-central Florida, 1961-80: U.S. Geological Survey Water-Resources Investigations 82-4086, 1 sheet.