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Hydrologic Relations Between Lakes and Aquifers in a Recharge Area Near Orlando, Florida

Geological Survey, Tallahassee, Fla Water Resources Div

Aug 76

HYDROLOGIC RELATIONS BETWEEN LAKES AND AQUIFERS IN A RECHARGE AREA NEAR ORLANDO, FLORIDA

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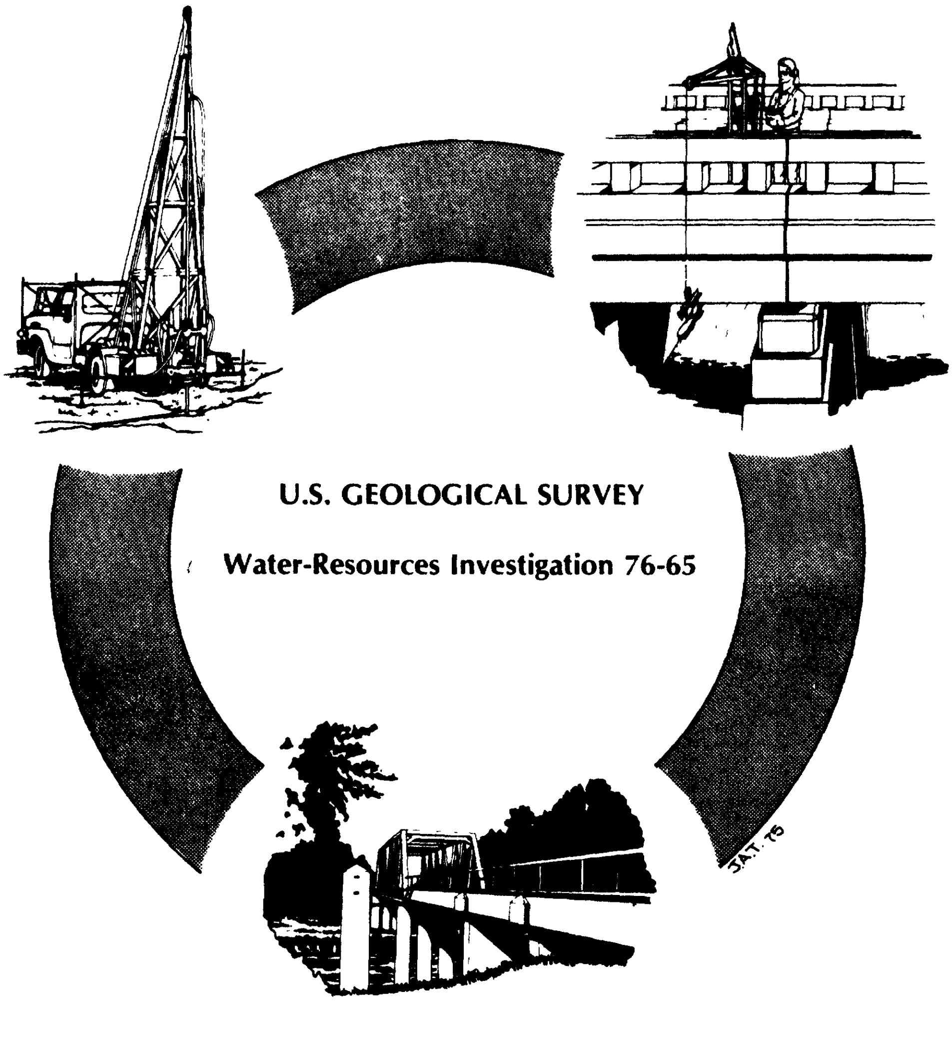

U.S. GEOLOGICAL SURVEY

Water-Resources Investigation 76-65

Prepared in cooperation with
BOARD OF COUNTY COMMISSIONERS OF ORANGE COUNTY, FLORIDA,
BUREAU OF GEOLOGY, FLORIDA DEPARTMENT OF NATURAL RESOURCES,
and
BUREAU OF WATER RESOURCES MANAGEMENT,
FLORIDA DEPARTMENT OF ENVIRONMENTAL REGULATION

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WRI 76-65 HYDROLOGIC RELATIONS BETWEEN LAKES AND AQUIFERS IN A RECHARGE AREA NEAR ORLANDO, FLORIDA

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16. Abstracts The three lakes investigated gain water from adjoining water-table aquifer and lose water to Floridan aquifer by downward leakage. Net seepage (net exchange of water between lake and aquifers) can be estimated by equation S = AX + BY, where S is net seepage, X represents hydraulic gradient between lake and water-table aquifer, A is lumped parameter representing effect of hydaulic conductivity and cross-sectional area of materials in flow section of water-table aquifer, Y is head difference between lake level and potentiometric surface of Floridan aquifer, and B is lumped parameter representing effect of hydraulic conductivity, area, and thickness of materials between lake bottom and Floridan aquifer. If values of S, X, and Y are available for two contrasting water-level conditions, coefficients A and B are determinable by solution of two simultaneous equations. If the relation between lake- and ground-water level is same on all sides of the lake--with regard to each aquifer--and if X and Y are truly representative of these relations, then X and Y terms of equation provide valid estimates of inflow to lake from water-table aquifer and outflow from lake to Floridan aquifer.

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August 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

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HYDROLOGIC RELATIONS BETWEEN LAKES AND AQUIFERS IN A RECHARGE AREA NEAR ORLANDO, FLORIDA

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ABSTRACT

The three lakes investigated--Lake Johio, the northern part of Lake Sherwood, and Lake Herrick--generally receive water from an adjoining water-table aquifer and lose water to the Floridan aquifer by downward leakage through the confining bed beneath the lakes. Lake and ground-water levels trended upward during wet spells and downward during dry spells. Lake levels rose abruptly from rainfall and overland flow; overland flow from the drainage basins generally was small because the surficial materials of the drainage basins are relatively sandy. Ground-water levels rose more gradually than the lake levels, but the range in water level was greater for the aquifers than for the lakes. Inflow to the lakes from the water-table aquifer tended to increase during wet spells and decrease during dry spells. Conversely, outflow from the lakes to the Floridan aquifer tended to decrease during wet spells and increase during dry spells. Much of the recharge to the Floridan aquifer that is derived from rainfall on the three lake basins apparently either moves downward through the lake bottoms or moves directly downward from the water-table aquifer near the lakes where the collapsed zone of the confining bed extends outward for some distance from the lakes.

Water-level conditions differed considerably from lake to lake. The water level of Lake Johio was 44 to 50 feet (13 to 15 metres) above the potentiometric surface of the Floridan aquifer. The water surface of the water-table aquifer always sloped toward the lake. The levels of Lakes Sherwood and Herrick usually were only slightly above the potentiometric surface of the Floridan aquifer; during wet spells the potentiometric surface was briefly above the level of Lake Herrick. During part of the investigation at Lake Sherwood and most of the investigation of Lake Herrick the surface of the water-table aquifer sloped away from the lakes for some distance.

Net seepage (the net exchange of water between a lake and adjacent and subjacent aquifers) can be estimated by use of the equation $S = AX + BY$, wherein S is net seepage, X represents the hydraulic gradient between the lake and the water-table aquifer, A is a lumped parameter representing the effect of the hydraulic conductivity

and cross-sectional area of materials in the flow section of the water-table aquifer, Y is the head difference between the lake level and the potentiometric surface of the Floridan aquifer, and B is a lumped parameter representing the effect of the hydraulic conductivity, cross-sectional area, and thickness of materials between the lake bottom and the top of the Floridan aquifer. If values of S, X, and Y are available for each of two contrasting water-level conditions, the coefficients A and B are determinable by the solution of two simultaneous equations. If the relation between the lake and ground-water levels is basically the same on all sides of the lake--with regard to each of the aquifers and if X and Y are truly representative of these relations, then the X and Y terms of the equation provide valid estimates of inflow to the lake from the water-table aquifer and outflow from the lake to the Floridan aquifer.

INTRODUCTION

Orange County is blessed with an abundance of natural freshwater lakes which provide or potentially can provide an ample supply of water for industrial processing, irrigation, and domestic and recreational uses. Residential sites with lake frontage are in great demand and, hence, highly valued. The benefits to be derived from lakes are many and diverse, but these benefits often are not without attendant problems. One important problem is the flood hazard associated with the development of areas adjacent to lakes, especially those that are landlocked. Unless suitable precautions are taken, lake levels may rise high enough to damage lake front property during wet spells.

The flood hazard can be limited or reduced either by regulating the types of buildings to be constructed in flood-prone areas around lakes or by controlling or regulating lake levels. High lake levels can be controlled or regulated by removal of water through pumping or drainage facilities; however, doing so may reduce ground-water recharge to the Floridan aquifer, and also may cause lake levels to be lower than they otherwise would be during dry spells.

For use of those readers who may prefer to use metric units rather than English units, the conversion factors for terms used in this report are listed below:

Multiply English unit	By	To obtain metric unit
inch (in)	25.40	millimetre (mm)
foot (ft)	.3048	metre (m)
mile (mi)	1.609	kilometre (km)
mile per hour (mi/hr)	.4470	metre per second (m/s)
acre	.4047	hectare (ha)
acre-foot (acre-ft)	1.233×10^{-3}	cubic hectometre (hm^3)
gallon per minute (gal/min)	.06309	litre per second (l/s)

PURPOSE AND SCOPE

The hydrologic consequences of controlling high lake levels cannot be fully evaluated unless the relation between lakes and the remainder of the hydrologic system is completely understood. To provide a better basis for understanding the role that lakes play in the hydrology of an area, the U.S. Geological Survey in 1966-68 collected hydrologic data at three landlocked lakes--Lake Johio, Sherwood, and Herrick--in a recharge area for the Floridan aquifer in western Orange County. These lakes were selected to obtain some diversity in local hydrologic conditions. The choice was restricted to lakes that had reasonably convenient access for drilling shallow observation wells near the lakeshore, and also had deep wells which tapped the Floridan aquifer nearby. Consequently, the hydrologic conditions represented by these three lakes do not necessarily span the full range of conditions existing at other lakes in the recharge area. Thus, the inferences drawn from the data for these three lakes cannot be expected to apply in full to all other lakes in the area.

The investigation was made in cooperation with the Board of County Commissioners of Orange County, and also with the Bureau of Geology, Florida Department of Natural Resources, and Bureau of Water Resources Management, Florida Department of Environmental Regulation, as part of a program to evaluate the water resources of Florida.

The purpose of this report is to describe the response of the three lakes to their hydrologic environments with special emphasis given to the effect of the net exchange of water between the lakes and the adjacent and subjacent aquifers. The hydrologic data are graphically portrayed for Lakes Johio, Sherwood, and Herrick, and analyzed in some detail. The data were more intensively analyzed for Lake Johio than for the other two lakes because the data for Lake Johio were generally more complete and of better quality than the data for the other two lakes.

The basic approach of the study was to determine the net quantities of ground water moving into and out of each lake (herein called net seepage) as a residual by the water-budget method. The inflow and outflow components of net seepage were then determined by relating net seepage to indices of the hydraulic gradients between the lakes and the adjacent water-table aquifers, and between the lakes and the Floridan aquifer. The significance of errors resulting from various approximations and simplifying assumptions was examined. The hydrologic conditions under which the analysis provides valid estimates of the inflow and outflow components of net seepage are considered.

ENVIRONMENTAL SETTING

Geologic and Hydrologic Features

The general area of this investigation--in Orange County west of the City of Orlando, as shown in figure 1--has been described in detail by Lichtler and others (1968). The area is one of rolling hills wherein land-surface altitudes range from 100 to 200 ft (30 to 60 m). Locally, in numerous depressions created by the solution of limestone at depth and the subsequent slump or collapse of surficial materials into solution cavities, land-surface altitudes may be substantially less than 100 ft (30 m). Most of the depressions contain lakes, many of which are landlocked.

The geologic features of importance to this study are shown in figure 2 (adapted from Lichtler and others, 1968, fig. 6). The surficial materials in general consist of fine sand. They are underlain by the Hawthorn Formation of Miocene age which contains sand mixed in varying proportions with clay and interspersed with lenses of relatively pure clay. From place to place these lenses vary in vertical thickness and horizontal extent. In general the Hawthorn Formation is relatively impermeable and, hence, it forms a confining layer. The underlying Floridan aquifer consists of limestone and dolomite formations of upper and middle Eocene age--in this area the Ocala Group and Avon Park Limestone.

Dissolution of the limestone and dolomite of the Floridan has caused slump or collapse of the overlying formations into solution cavities. The collapse has ruptured the clay zones in the Hawthorn overlying and surrounding the solution cavities thus creating permeable zones conducive to the vertical movement of ground water.

The sandy surficial materials are of sufficient depth and permeability to absorb most of the rainfall. In many instances the small quantity of runoff that occurs terminates in closed depressions. Thus, in many parts of this general area, the rainfall either returns to the atmosphere by evapotranspiration or it moves underground.

Water moves underground first to a water-table aquifer in the surficial materials. In the water-table aquifer, water may move laterally toward lakes in the closed depressions of the land surface and--in some instances--toward streams. Significant quantities of water may move vertically downward to the Floridan aquifer. Inasmuch as the lakes in deep closed depressions do not overflow, the water entering these lakes from the water-table aquifer either moves downward through the lake bottom to the Floridan aquifer or moves to the atmosphere by evaporation.

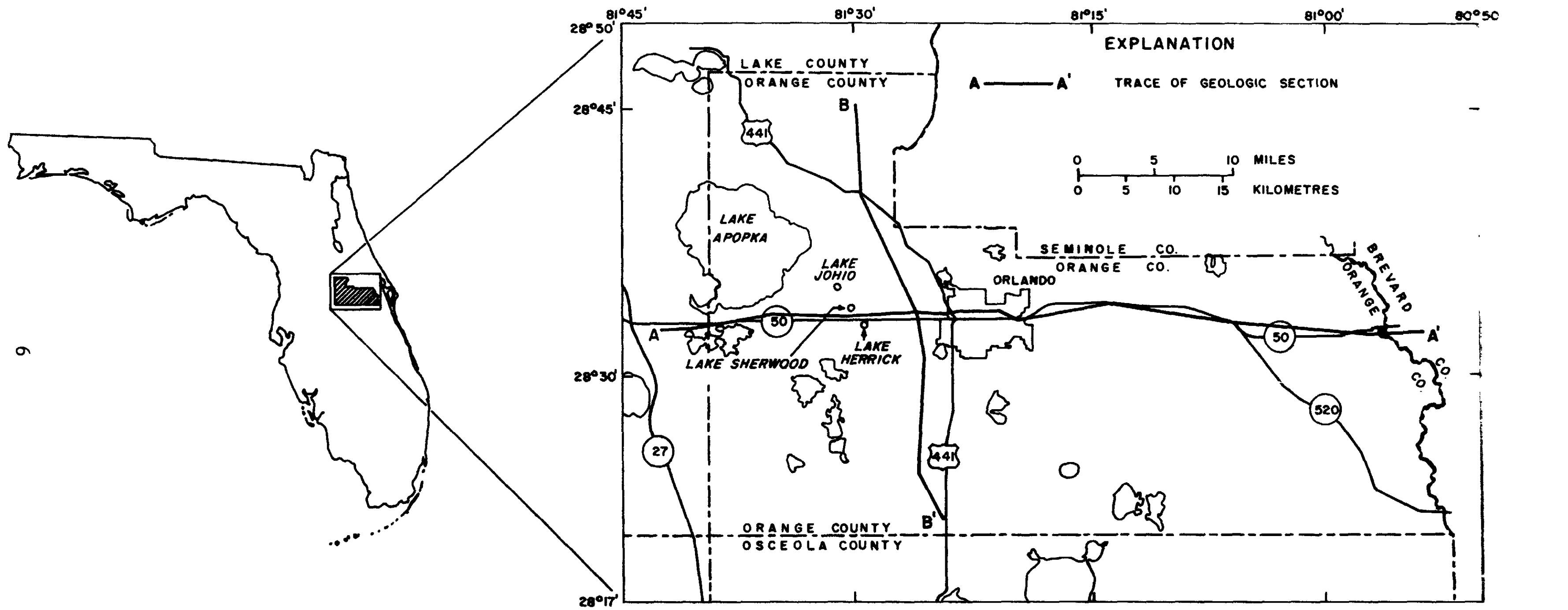


FIGURE 1.--LOCATION OF LAKES JOHIO, SHERWOOD, AND HERRICK IN ORANGE COUNTY.

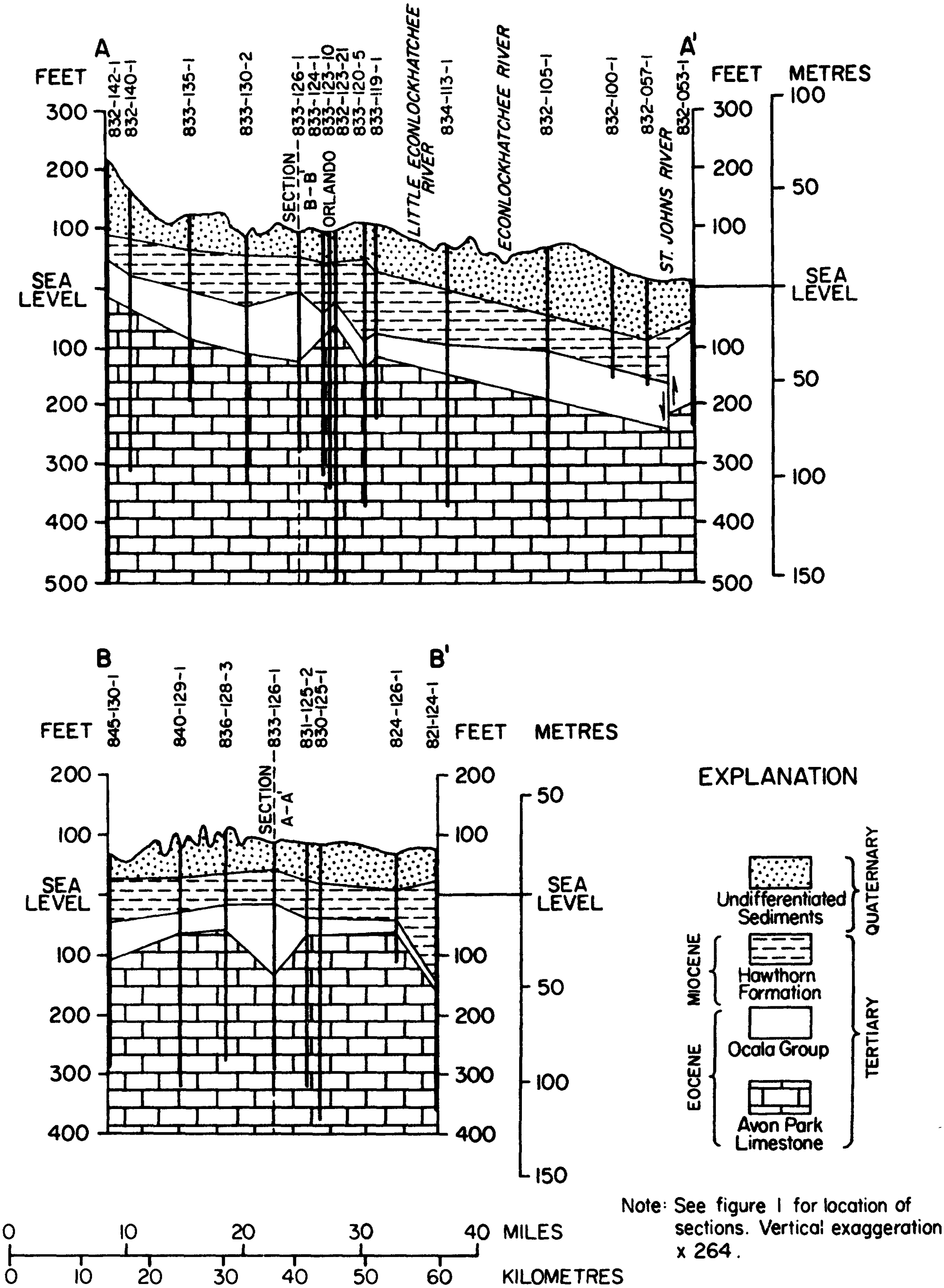


FIGURE 2.--GEOLOGIC SECTIONS IN ORANGE COUNTY (ADAPTED FROM LICHTLER AND OTHERS, 1968, FIG. 6).

With respect to the total recharge to the Floridan aquifer from a given lake basin, whether the majority of recharge occurs through the lake bottom or directly from the water-table aquifer depends primarily on the areal distribution of the thickness and permeability of the confining layer. Thus, depending on where it fits into the areal pattern, a lake may or may not be an important point of recharge to the Floridan aquifer.

Climate

The climate of the area is subtropical; summer and winter are the only pronounced seasons. Daily maximum air temperatures normally range from 88 to 92°F (31 to 33.5°C) in summer and 71 to 73°F (21.5 to 23°C) in winter; daily minimum normally range from 71 to 74°F (21.5 to 23.5°C) in summer and 49 to 52°F (9.5 to 11°C) in winter. Wind speeds usually are highest in February through April, averaging about 10 miles per hour (4.5 m/s), and lowest in July and August, averaging about 7.5 miles per hour (3.4 m/s). Annual rainfall averages 51.37 inches (1,305 mm) at the National Weather Service Office in Orlando; more than half the rain falls in June through September. During winter the monthly rainfall averages about 2 inches (51 mm).

Evaporation maps (Kohler and others, 1959, pls. 2,3) indicate that annual lake evaporation in the Orlando area averages about 47 inches (1,200 mm) and that the annual coefficient for a Class A pan is about 0.78.

Water-budget studies of large river basins in central Florida indicate that annual evapotranspiration ranges from 37.5 to 42.6 inches (952 to 1,082 mm) (Cherry and others, 1970, p. 77-79; Langbein, 1955, p. 512). The involved river basins include many different types of areas ranging from sandy uplands to lakes and swamps. Annual evapotranspiration from swamps and marshland probably is about as great as annual lake evaporation; hence, evapotranspiration from sandy upland areas presumably is substantially less than indicated above for a large river basin. On basis of a flow-net analysis which relates the known discharge of the Floridan aquifer at a large spring north of Orlando to the recharge area that supplies the spring, Charles H. Tibbals, U.S. Geological Survey, concluded (oral commun., August 1973) that annual evapotranspiration from the recharge area was about 30 inches (760 mm).

LAKE JOHIO

Description of Study Site

Lake Johio is in a closed depression about 7 miles (11 km) west of Orlando. The general shape of the land surface within the lake basin is indicated in figure 3. The altitude of the rim of the surface-water drainage basin ranges from about 130 to 150 feet (40 to 46 m). The drainage basin encloses an area of 240 acres (97 ha) including the lake area; at a stage of 112 feet (34 m) above sea level the lake covers about 28 acres (11 ha). About 80 percent of the basin area is planted in citrus groves; a small airplane landing strip and numerous homesites take up some of the area. The surficial material is sandy.

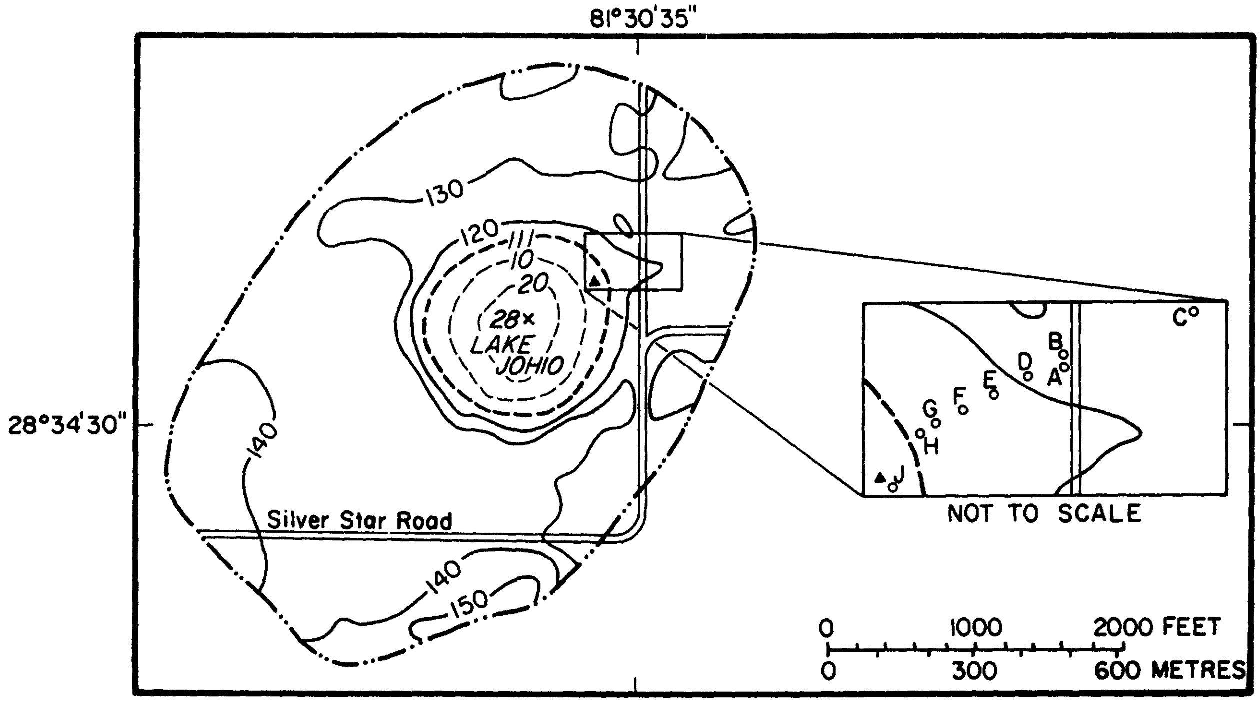
The level of Lake Johio fluctuates considerably between extreme wet and dry spells. The maximum known lake stage was 122.1 feet (37.2 m) above sea level in 1960; the minimum, 107.9 feet (32.9 m) in 1962. From April 13, 1967 to October 2, 1968, when data were collected for the study of this particular lake, the lake stage fluctuated between 109.0 and 112.9 feet (33.2 to 34.4 m) above sea level.

The water table is about 15 to 25 feet (5 to 8 m) below land surface throughout most of the drainage basin and is close to land surface only in the immediate vicinity of the lake. The loss of water by evapotranspiration from the water-table aquifer is thus considered to be small except near the lake.

The level of Lake Johio is always well above the level of the potentiometric surface of the Floridan aquifer. (The potentiometric surface of a confined aquifer is the surface defined by the level to which water will rise in tightly cased wells penetrating the aquifer.) During the study, the lake level was 44 to 50 feet (13 to 15 m) above the potentiometric surface.

Instrumentation

Water-level recording gages were installed in Lake Johio and in two wells about 300 feet (91 m) from the lake. One of the wells (well B) was developed in the water-table aquifer; the other (well A) in the Floridan aquifer. In addition, seven 1¼-inch (32 mm) diameter sandpoint wells were installed, six (wells C-H) in a line extending radially from the northeast side of the lake, and one (well J) driven several feet into the lake bottom near the lake-level recording gage. The screened sections of the sandpoint wells for the most part were placed a few feet below the water table. The general layout of the observations wells is shown in figures 3 and 4.



EXPLANATION

○A	Observation well.	28×	Point of maximum depth; number is depth in feet, referenced to stage 111 feet above mean sea level.
▲	Lake-level recorder.	--111--	Outline of lake surface at stage 111 feet above sea level.
—··—··—	Basin boundary.	--10--	Line of equal depth to lake bottom. Interval 10 feet. Datum is lake surface at 111 feet above sea level.
—140—	Land-surface contour--Shows altitude of land surface. Contour interval is 10 feet. Datum is mean sea level.		

FIGURE 3.--LOCATION OF LAKE GAGE AND GROUND-WATER OBSERVATION WELLS IN LAKE JOHIO DRAINAGE BASIN.

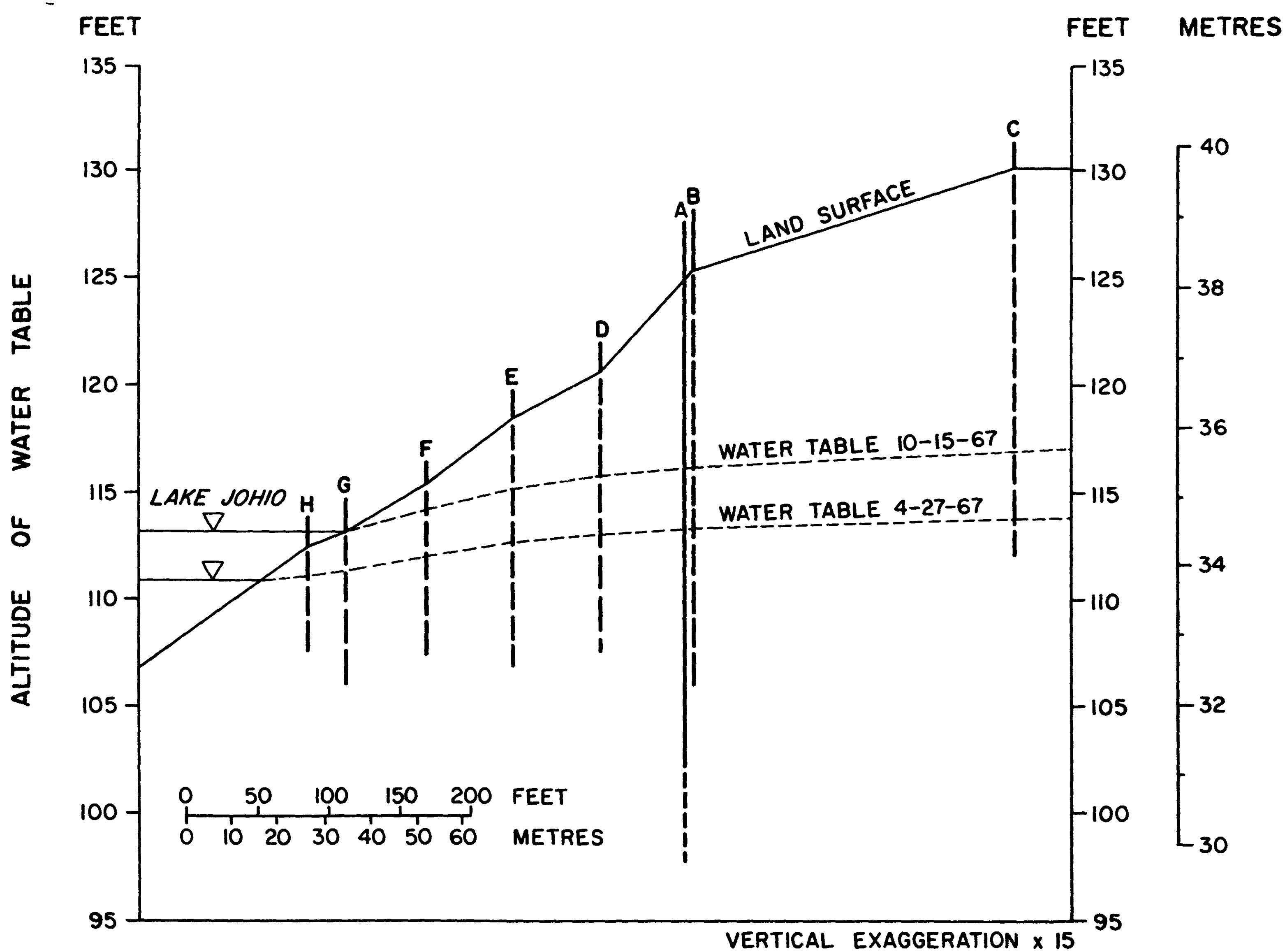


FIGURE 4.--GENERAL SLOPE OF LAND SURFACE AND WATER TABLE ALONG A LINE OF OBSERVATION WELLS NEAR LAKE JOHIO; WELL A TAPS THE FLORIDAN AQUIFER, ALL OTHERS TAP THE WATER-TABLE AQUIFER.

Except in well F, water levels in the sandpoint wells were measured only periodically by taping down to the water surface from the tops of the wells. In well F, which was only a short distance from the edge of the lake, the level of water was recorded during one relatively brief period.

Before June 30, 1967, rainfall was recorded only at Lakes Sherwood and Herrick. Beginning June 30, 1967, rainfall was recorded by a weighing-type gage on the shore of Lake Johio, as well as at the other two lakes. Lake evaporation was estimated from National Weather Service records of daily pan evaporation at Lisbon, Fla., which is in Lake County about 25 miles northwest of Lake Johio.

Data Analysis

The water levels of Lake Johio and nearby observation wells follow the same general trend, as shown in figure 5. Both the lake and ground-water levels rise when it rains. The promptness with which the water levels respond to rainfall is shown in figures 6-11. The lake level rises rapidly at the time of the rainfall and the rise in level closely reflects the cumulative rainfall of the storm. Figure 12 shows that for most of the storms the rapid rise in lake level tends to be slightly greater than the depth of the cumulative rainfall especially for the larger storms. This is consistent with the fact that the rapid rise in level includes the effect of any overland flow that enters the lake during and immediately after the storm. Appreciable quantities of runoff likely would be produced only by the more intensive storms. The data of figure 12 are presented as a double-mass relation in figure 13. This relation indicates that during the study the overland flow into Lake Johio accounted for 0.5 foot (0.15 m) or about 8 percent of the rapid rise in lake level.

The water table near Lake Johio and the potentiometric surface of the Floridan aquifer also start to rise at the time of the rainfall. Sometimes the responses of the two are somewhat similar; sometimes they are not. For example, in figures 7-9 the response of the water table and the potentiometric surface are somewhat consistent with each other and also with the rise of the lake level. In figure 6, however, on July 5-8, 1967, the response of the level of the potentiometric surface is not apparent whereas the response of the water table is clearly evident. The situation is the same on June 29, 30, 1968, in figure 10. On the other hand, in figure 11, during a period of rather light rainfall at the lake, the potentiometric surface shows a marked rise in level whereas the water table shows virtually none. The apparent discrepancies probably are the result of uneven distribution of rainfall. The level of the water table near the lake is affected primarily by rainfall in the drainage basin of the lake. The level of potentiometric

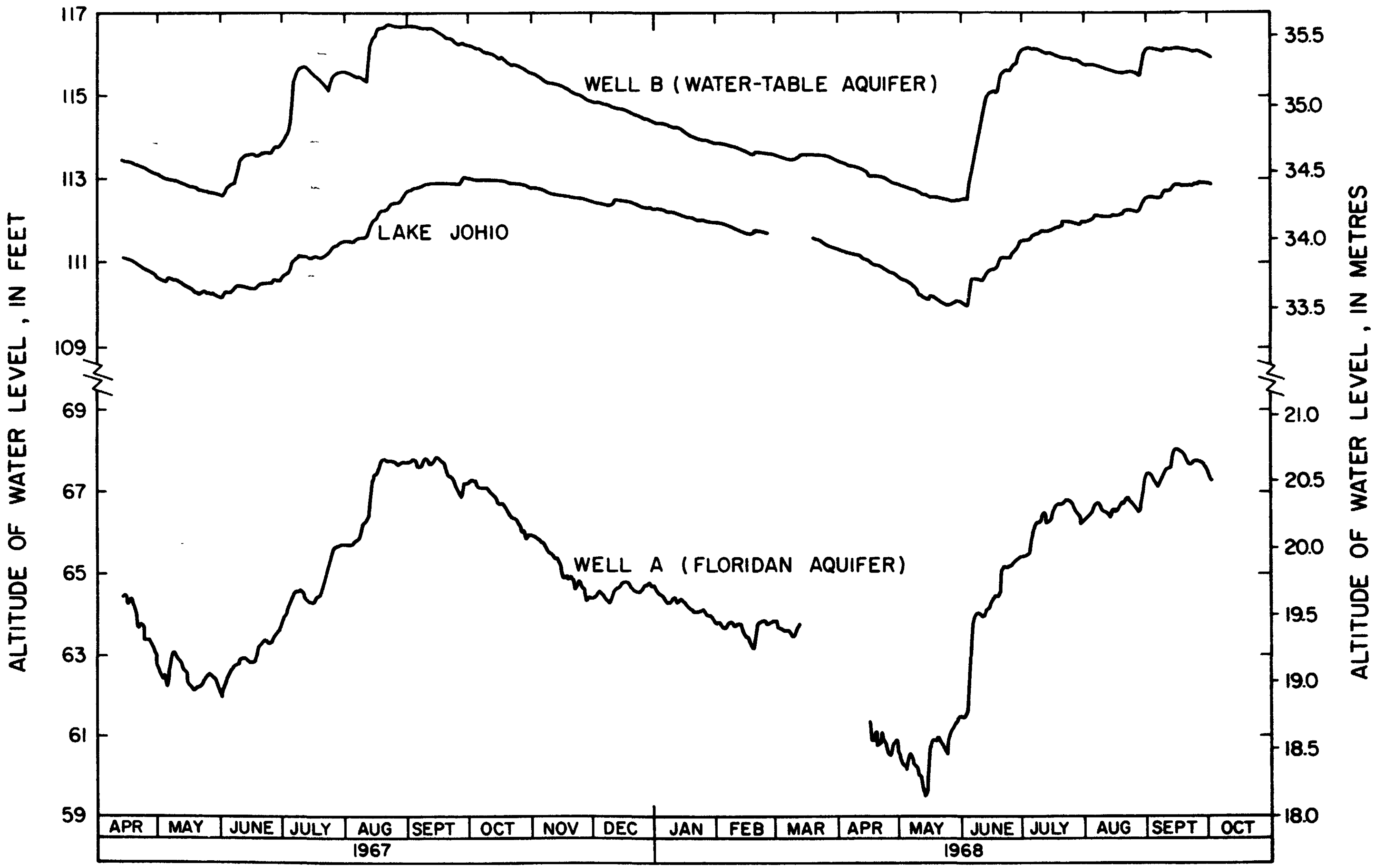


FIGURE 5.--WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, APRIL 13, 1967 TO OCTOBER 2, 1968.

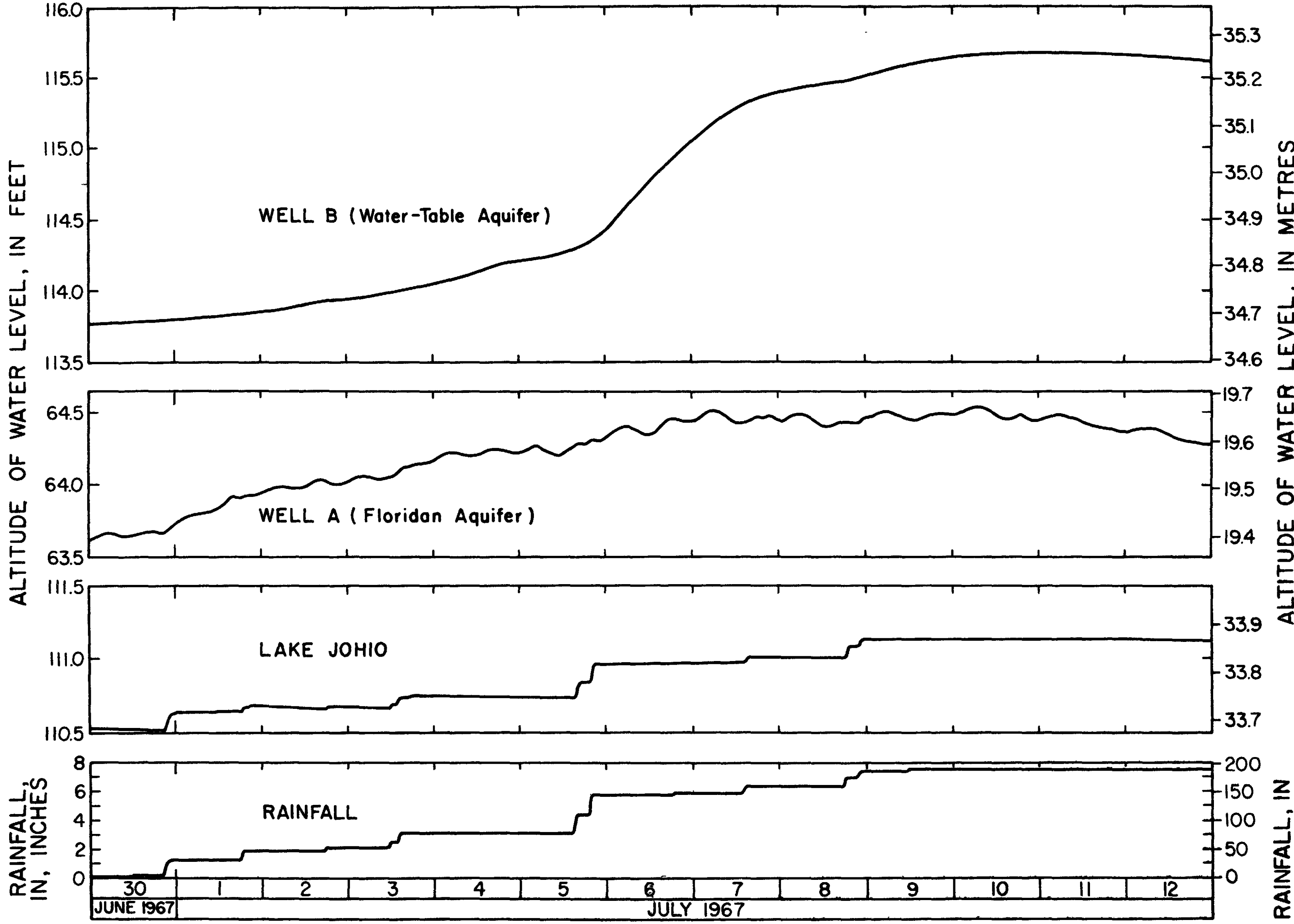


FIGURE 6.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, JUNE 30 TO JULY 12, 1967.

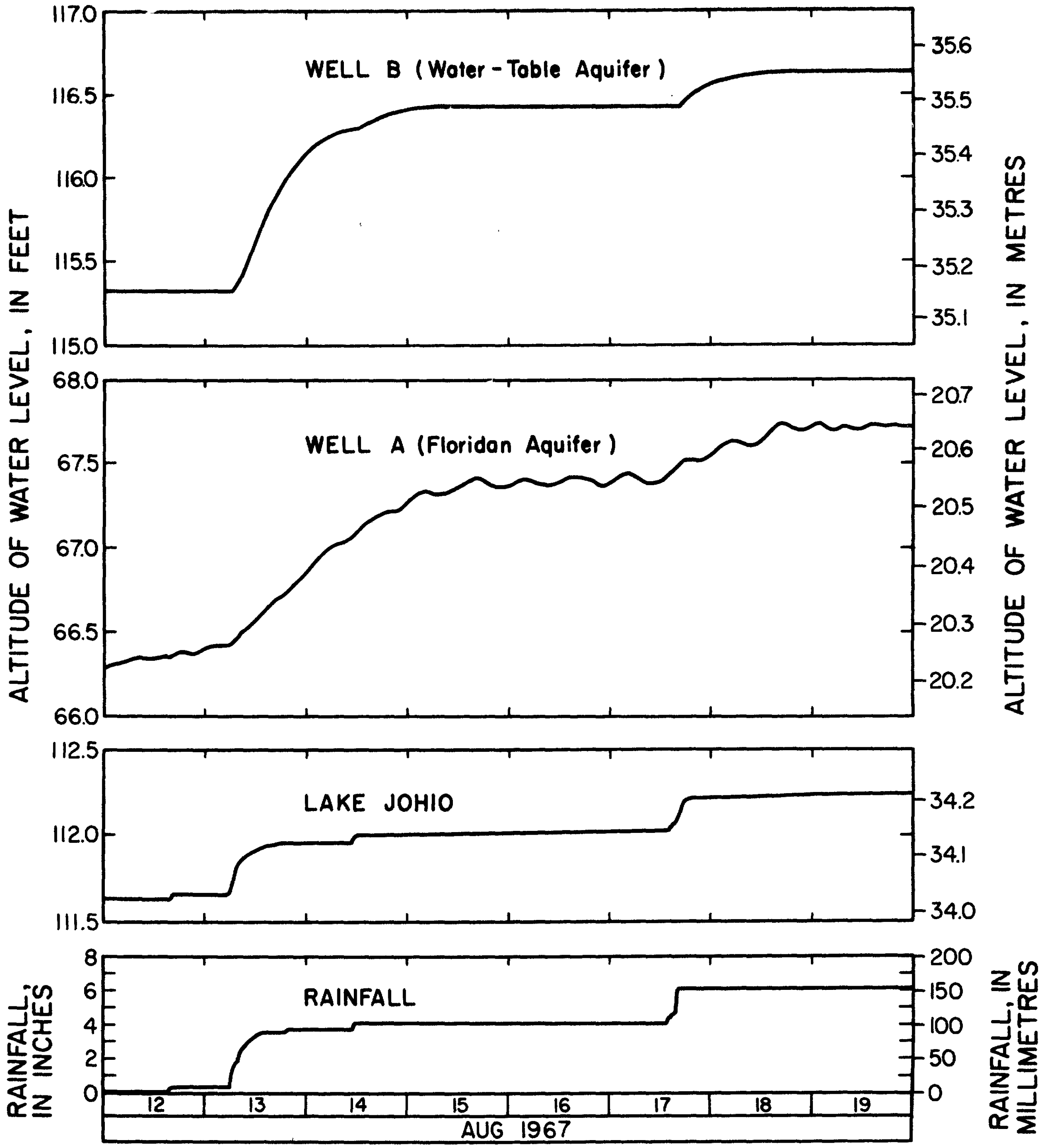


FIGURE 7.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, AUGUST 12-19, 1967.

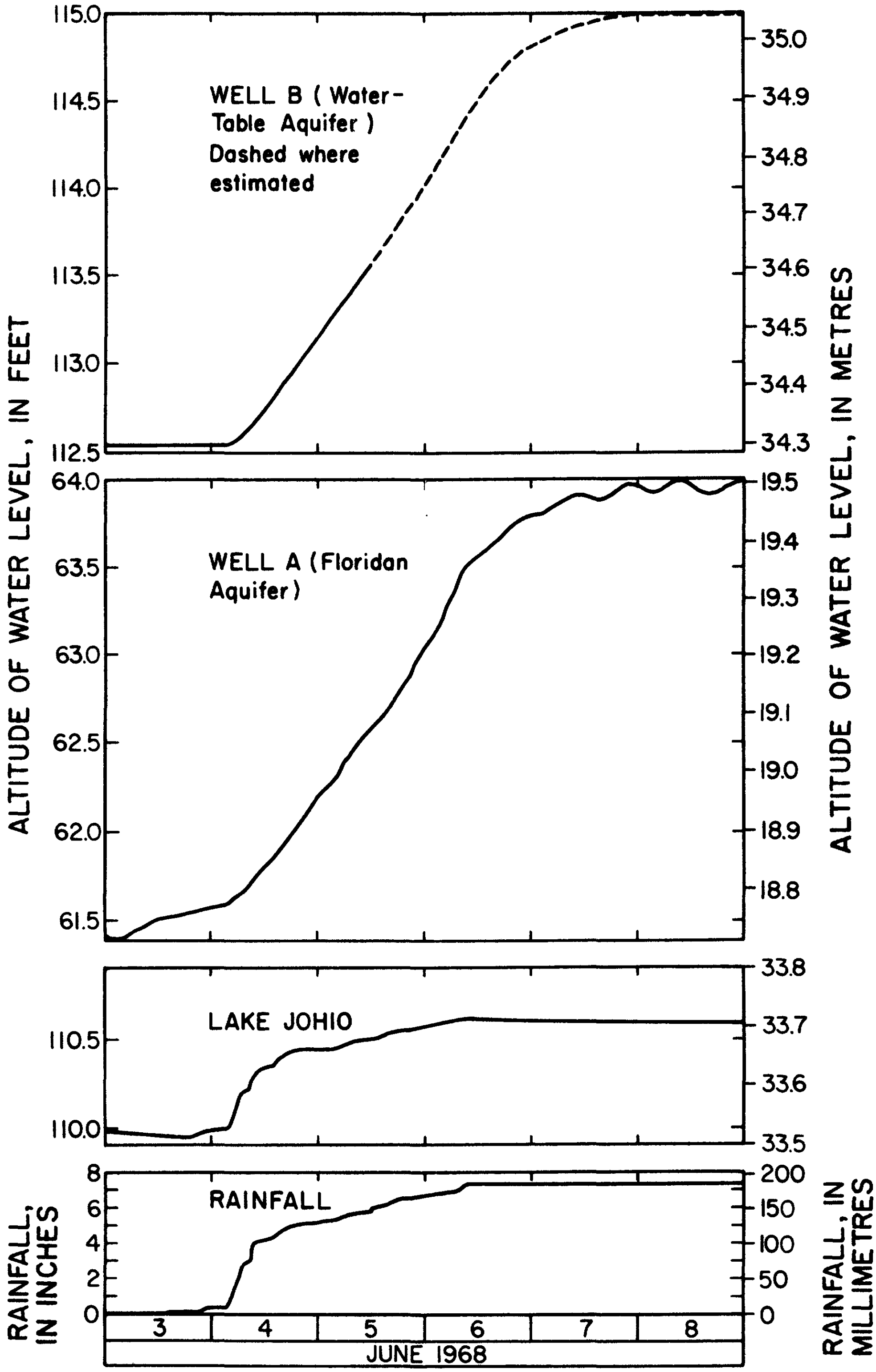


FIGURE 8.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, JUNE 3-8, 1968.

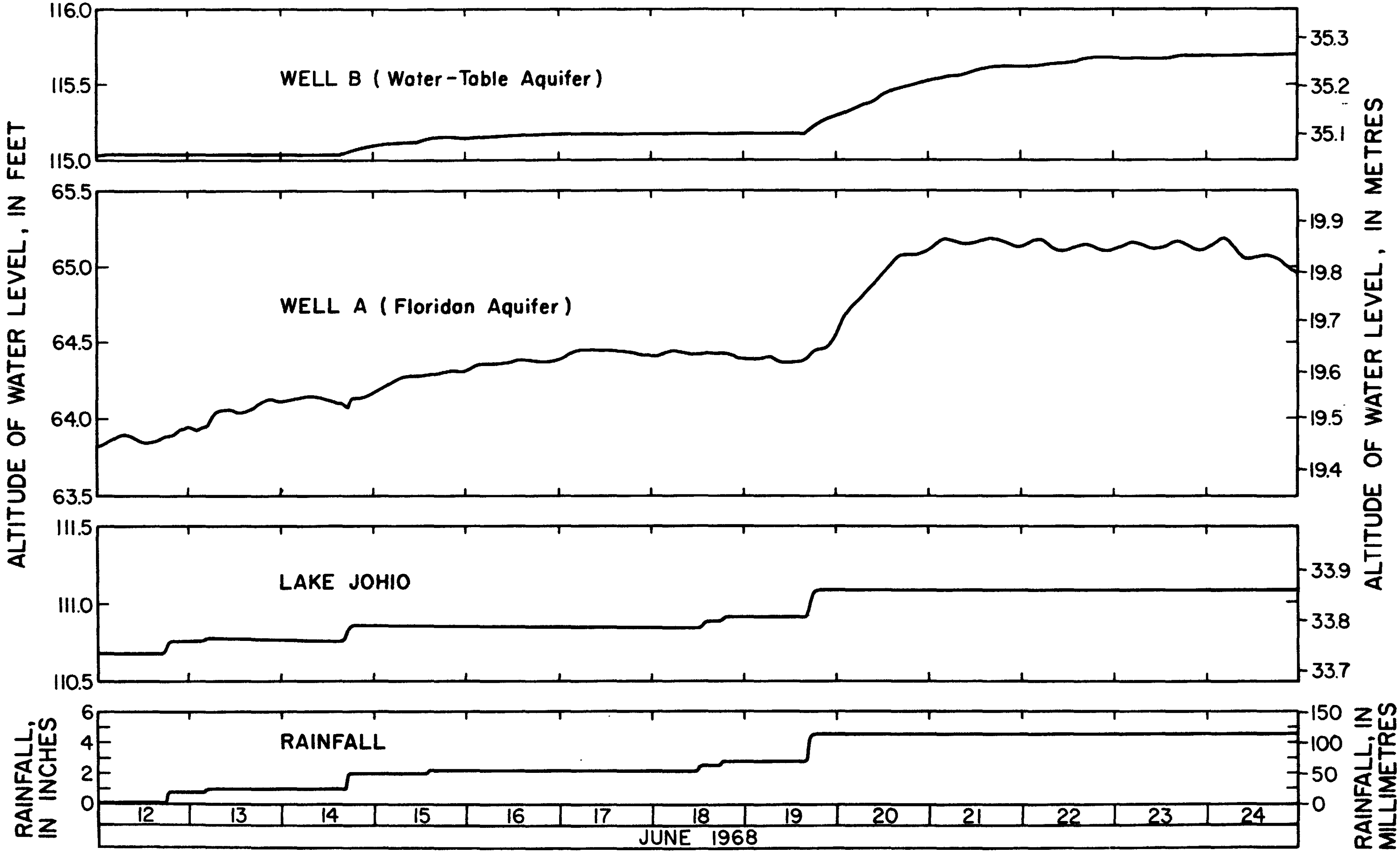


FIGURE 9.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, JUNE 12-24, 1968.

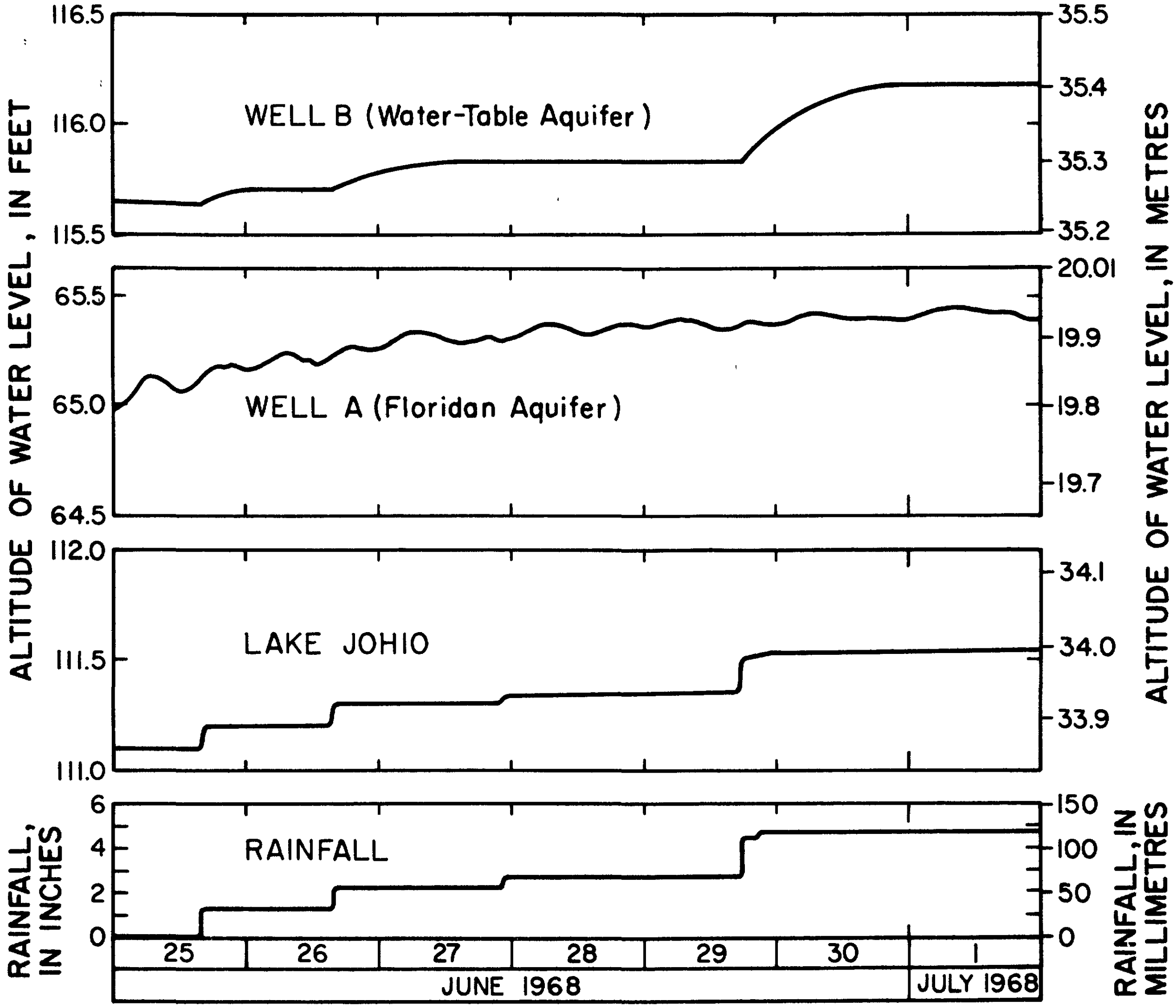


FIGURE 10.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, JUNE 25-30, 1968.

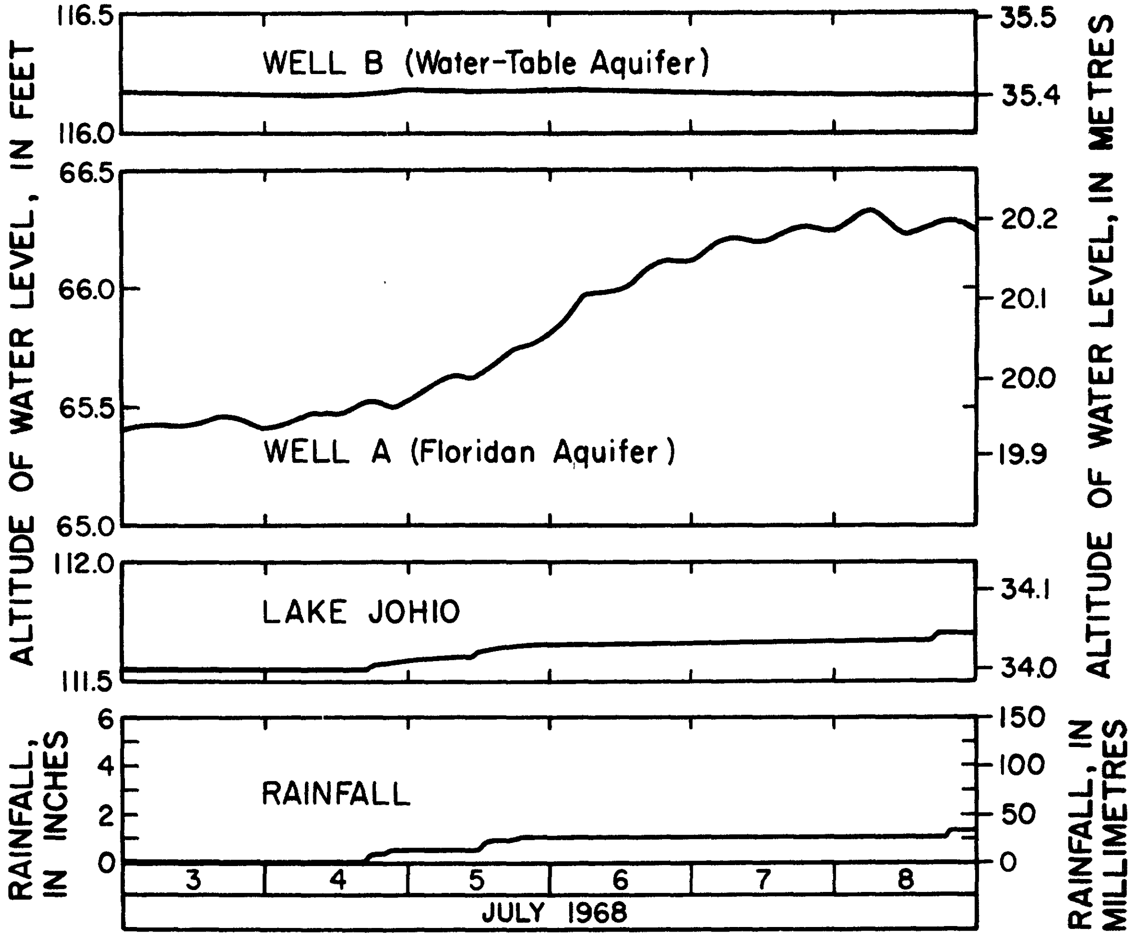


FIGURE 11.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, JULY 3-8, 1968.

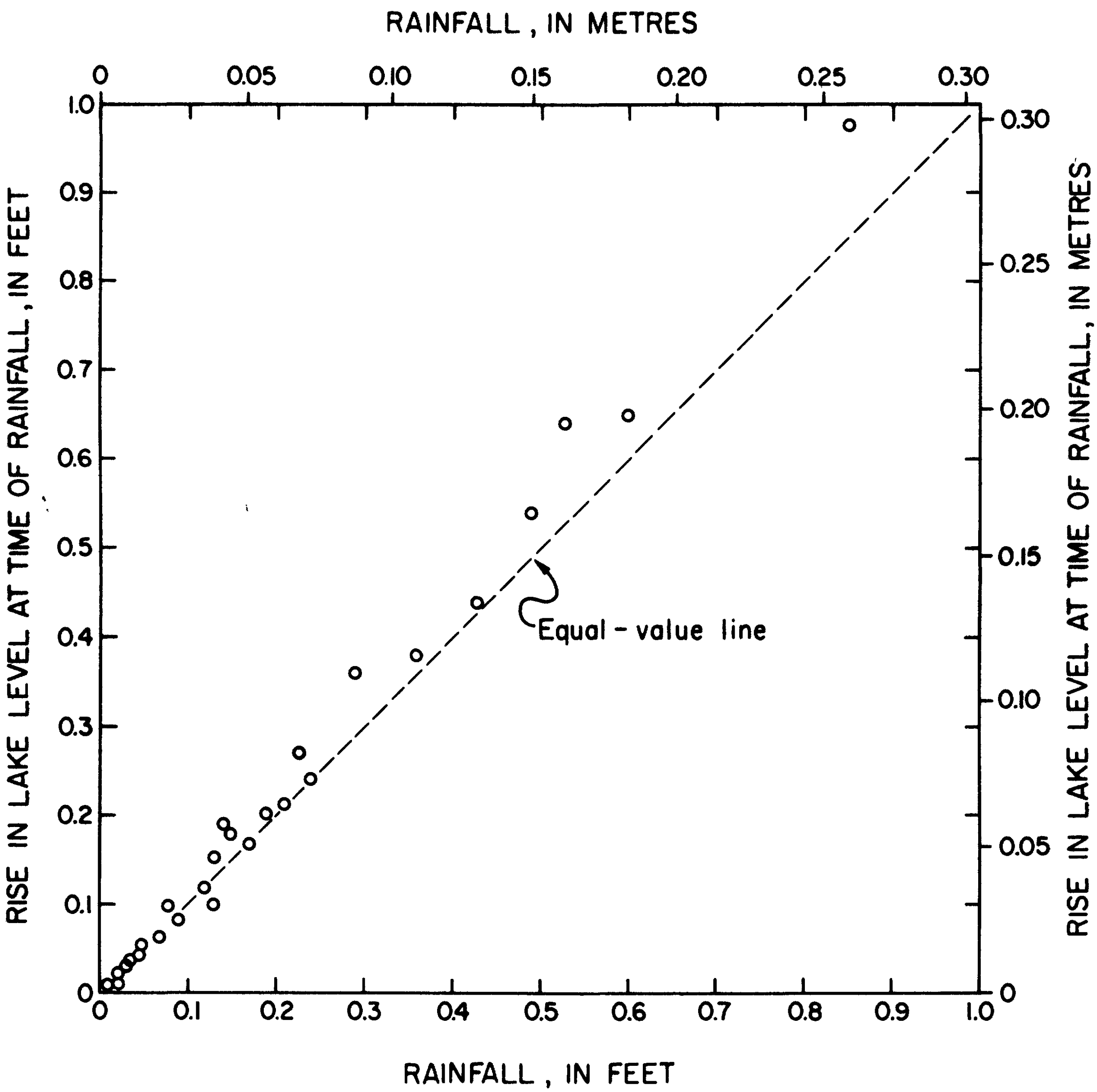


FIGURE 12.--RELATION BETWEEN RAINFALL MEASURED AT LAKE JOHIO AND RAPID RISE IN LAKE LEVEL; INDIVIDUAL RAINFALLS AND CORRESPONDING RISES IN LEVEL SUMMED FOR PERIOD OF 7 TO 14 DAYS.

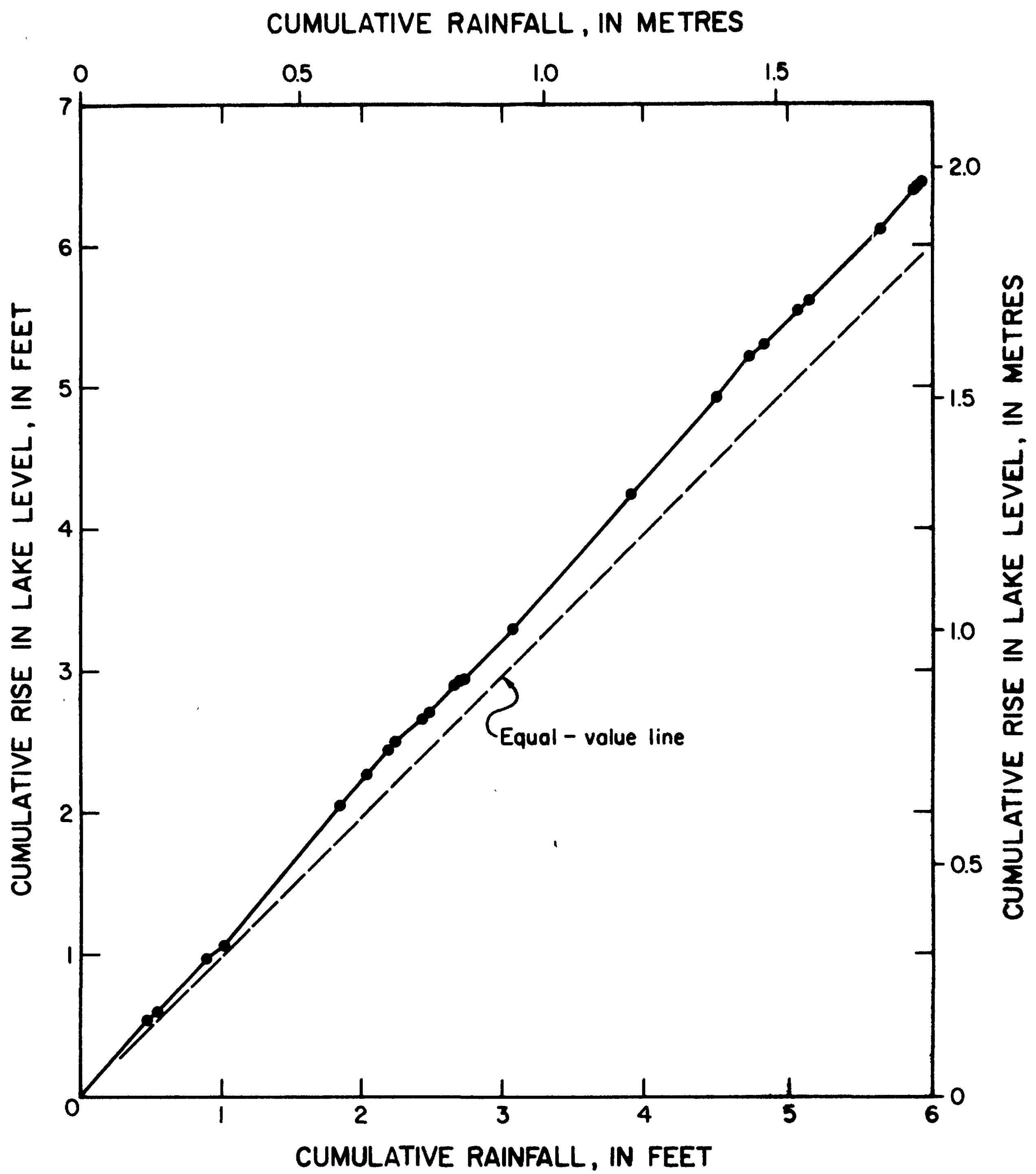


FIGURE 13.--DOUBLE-MASS RELATION BETWEEN RAINFALL MEASURED AT LAKE JOHIO AND RAPID RISE IN LAKE LEVEL AS ACCUMULATED FOR INDIVIDUAL STORM PERIODS FROM JULY 9, 1967 to OCTOBER 2, 1968.

surface of the Floridan aquifer is affected by rainfall over a much larger area. When rainfall is not uniform over a fairly large area including the drainage basin of the lake, the levels of the water table and the potentiometric surface of the Floridan aquifer can be expected to react differently.

For any given storm the water table rises much more slowly than the lake level because, over much of the drainage basin, rainfall must infiltrate through about 15 to 25 feet (5 to 8 m) of surficial material before reaching the water table. In the Lake Johio drainage basin, 2 to 4 days apparently are required to complete this process for rainfalls of substantial magnitude. When rainfalls are closely spaced in time, therefore, the leading edge of the infiltrating water from one rainfall may overlap or blend with the trailing edge of the infiltrating water from the immediately preceding rainfall. This overlapping effect sometimes obscures the impact of individual rainfalls on the level of the water table. The same overlapping effect is evident in the response of the potentiometric surface of the Floridan aquifer; however, the impact of small rainfalls on the potentiometric surface also is partly obscured by the effects of earth tides and atmospheric pressure variations. Similarly, the effect of intermittent pumping from the Floridan aquifer at times obscures or distorts the rise in water level that results from rainfall.

Near the lake, where the water table is close to the land surface, the water table responds rapidly to rainfall. For example, figure 14 shows that the water level of well F (location shown in figs. 3, 4) rose abruptly as a result of several small rainfalls between August 30 and September 7, 1967. The edge of the lake at the time was about 75 feet (23 m) from well F. The water table at well F was about 1.5 feet (0.5 m) below land surface. The cyclic nature of the water-level fluctuations between storm periods appears to be shaped significantly by evapotranspiration. This suggests that the capillary fringe is at or near the land surface. The rate of decline in the level of the water table at well F, after a rapid rise in level, indicates a surge of ground-water inflow to the lake that occurs within 4 to 6 hours of the time of the rainfall. The quantity of water involved in this surge apparently is relatively small. For example, the larger rises shown in figure 14 correspond to rainfalls of about 0.04 foot (0.01 m). For the purpose of this discussion it is presumed that all of the rainfall infiltrated to the water table. A 75-foot (23 m) wide strip around Lake Johio would contain about 6 acres (2 ha). Thus, the surge of ground-water inflow following each of the larger rainfalls would equal a volume of about 0.2 acre-foot (0.2×10^{-3} hm^3), equivalent to a depth of about 0.007 foot (0.002 m) over the 28-acre (11 ha) lake. Not all the rainfall would immediately reach the lake as ground-water inflow because some of it would contribute to the general rise of the ground-water level.

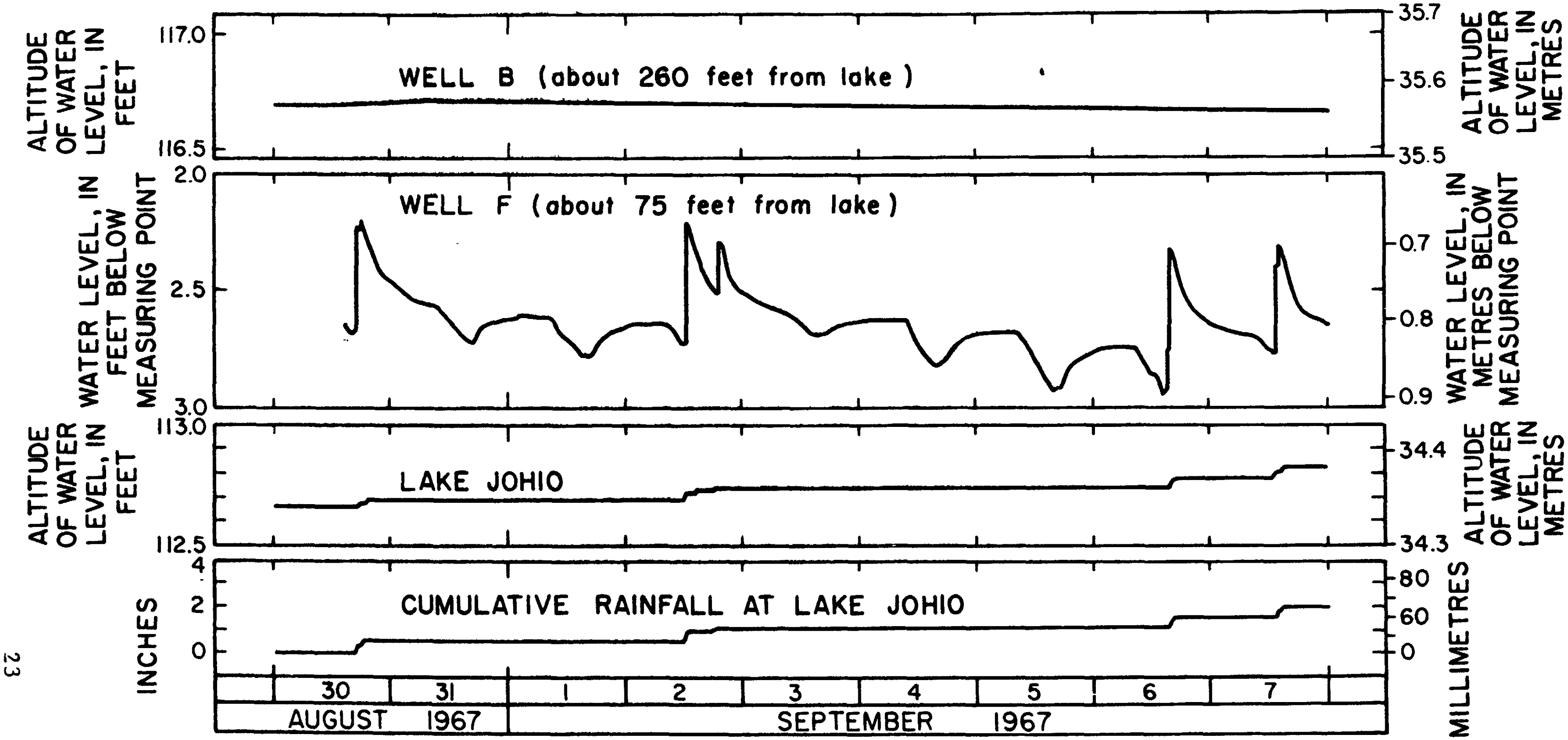


FIGURE 14.--CUMULATIVE RAINFALL AT LAKE JOHIO AND WATER LEVELS OF LAKE JOHIO AND WELLS B AND F THAT TAP THE WATER-TABLE AQUIFER NEAR THE LAKE, AUGUST 30 TO SEPTEMBER 7, 1967.

At well J (fig. 3), which was driven several feet into the lake bottom near the lake gage, the water level in the well was consistently above the lake level by a foot or so. This confirms that near the shore of the lake, at least, ground water is entering the lake from the water-table aquifer through the lake bottom. On the assumption that this same condition persists around the lake, any ground-water outflow to the Floridan aquifer that occurs probably does so near the center of the lake.

Determining Net Seepage

The net effect of ground-water movement into and out of Lake Johio was determined by the water-budget method for periods of 7 to 14 days. The intent was to work with computational periods of about 10 days but the time span of the periods was varied so that, insofar as possible, the entire effect of a storm could be included within a single period. A total of 49 computational periods were used.

For each of the computational periods, net seepage was taken as the algebraic sum of the change in lake stage, rainfall on the lake, overland flow into the lake, and evaporation from the lake. Rainfall on the lake and overland inflow to the lake were assumed to occur almost simultaneously during the rapid rise of the lake level, and the combined magnitude of the two was determined by scaling the full extent of the rapid rise in level from the lake-level recorder chart for each distinguishable rise. Such determinations are in error to the extent that corrections were not made for net seepage that occurred during the time span of the individual rises in level; however, in relation to the time spans of the computational periods, the total time taken up by rapid rises in level within each computational period was less than 1 percent for 32 periods, and ranged from 2 to 5 percent for 12 periods and 6 to 8 percent for 4 periods, and was greater than 10 percent for only 1 period (June 3-10, 1968). Hence, the error introduced by neglecting the effect of net seepage during the rapid rise in lake level was of no appreciable consequence for about 44 of the 49 computational periods, and probably had no measurable effect on the outcome of the study as a whole.

Lake evaporation was estimated from National Weather Service records of daily pan evaporation at Lisbon, about 25 miles (40 km) northwest of the study area. A pan coefficient of 0.85 was used for all days in a deliberate attempt to make the estimate of lake evaporation slightly too large. This was done because lake evaporation and ground-water outflow both work in the same direction in water-budget computations. If the estimate of lake evaporation is too small, then ground-water outflow is indicated to be too large. Inasmuch as the results of this study ultimately indicate that ground-water outflow is sizeable, it seemed desirable to remove or reduce the uncertainty as to whether the results were unduly influenced by an estimate of lake evaporation that was too small.

Net seepage was determined in units of depth (feet per day) and converted to units of volume (acre-feet per day) by multiplying the depth by the average surface area for the computational period. The lake area varied slightly with stage. The water-budget data are given in table 1.

Determining Inflow and Outflow Components of Net Seepage

Net seepage was assumed to consist of a component of inflow to the lake from the water-table aquifer, and a component of outflow from the lake to the Floridan aquifer. Figure 14-a shows the general relation between the lake level, water table, and potentiometric surface of the Floridan aquifer. The outflow component was assumed to vary directly with the difference between the lake level and the level of the potentiometric surface of the Floridan aquifer measured at well A. The inflow component was assumed to vary directly with the difference (H) between the lake level and the level of the water table at well B, divided by the distance (L) between well B and the edge of the lake. Thus, net seepage can be represented by the following equation:

$$S = AX + BY \qquad (1)$$

wherein S = net seepage, in acre feet per day,

X = an index of the hydraulic gradient of the water table towards the lake (H/L; see text above),

Y = difference between the lake level and the level of the potentiometric surface of the Floridan aquifer,

A = a coefficient representing the product of the hydraulic conductivity and cross-sectional area of materials in the flow section of the water-table aquifer that relates to X, and

B = a coefficient representing the product of the vertical hydraulic conductivity and area of materials between the lake bottom and the top of the Floridan aquifer divided by the thickness of these same materials.

Values of X are considered positive if the water table is above the lake level; values of Y are considered negative if the lake level is above the potentiometric surface of the Floridan aquifer. The coefficients A and B were treated as lumped parameters because information was lacking as to the saturated thickness of the water-table aquifer and the thickness and area of materials between the lake bottom and the top of the Floridan aquifer.

Table 1.--Water-budget data for Lake Johio

Period	No. days	Altitude of mean water level: Lake	Well B	Well A	Mean lake area	Mean distance lake to Well B	Pan evaporation	Lake evaporation	Rainfall plus overland flow	Change in lake level	Net seepage by water budget			water level Well B minus lake level	X^b	Y^c	Net seepage by equation 4	Computed inflow to lake from water-table aquifer	Computed outflow from lake to Floridan aquifer
		(ft)			(acres)	(ft)	(in)	(ft)	(ft)	(ft)	(ft)	(ft/day)	(ac-ft/d)	(ft)	(ft/ft)	(ft)	(ac-ft/day)		
1967																			
April 31-23[a]	11	111.01	113.38	64.2	26.01	298	2.94	0.21	0.02	-0.25	-0.06	-0.00545	-0.1418	2.37	0.00795	-46.8	-0.177	0.679	0.856
April 24 to May 4[a]	11	110.70	113.14	63.1	26.70	305	2.74	.20	0	-.31	-.11	-.01000	-.2670	2.44	.00800	-47.6	-.188	.683	.871
May 5-17[a]	13	110.51	112.93	62.7	26.51	309	3.47	.25	.13	-.21	-.09	-.00692	-.1834	2.42	.00783	-47.8	-.206	.669	.875
May 18-31[a]	14	110.25	112.71	62.3	26.25	316	3.49	.25	.13	-.20	-.08	-.00571	-.1499	2.46	.00728	-47.9	-.212	.665	.877
June 1-9	9	110.31	112.82	62.5	26.31	316	1.50	.11	.45	+.32	-.02	-.00222	-.0584	2.51	.00794	-47.8	-.197	.678	.875
June 10-20	11	110.41	113.55	62.9	26.41	313	2.24	.16	.20	+.03	-.01	-.00091	-.0240	3.14	.01003	-47.5	-.012	.857	.869
June 21-30	10	110.52	113.68	63.4	26.52	309	1.86	.13	.29	+.17	+.01	+.00100	+.0265	3.16	.01023	-47.1	+.012	.874	.862
July 1-9	9	110.89	114.60	64.3	26.89	300	1.58	.11	.54	+.50	+.07	+.00778	+.2092	3.71	.01237	-46.6	+.204	1.057	.853
July 10-20	11	111.14	115.54	64.4	27.14	296	2.39	.17	.04	-.04	+.09	+.00818	+.2220	4.40	.01486	-46.7	+.414	1.269	.855
July 21-29a	9	111.32	115.34	65.1	27.32	291	1.87	.13	.38	+.37	+.12	+.01333	+.3642	4.02	.01381	-46.2	+.335	1.180	.845
July 30 to Aug.10[a]	12	111.52	115.50	65.8	27.52	287	2.11	.15	.10	+.08	+.13	+.01083	+.2980	3.98	.01387	-45.7	+.349	1.185	.836
Aug. 11-20[a]	10	112.00	116.21	67.2	28.00	276	1.69	.12	.64	+.70	+.18	+.01800	+.5040	4.21	.01525	-44.8	+.507	1.327	.820
Aug. 21-31[a]	11	112.47	116.67	67.7	28.47	265	2.60	.19	.36	+.44	+.27	+.02455	+.6989	4.20	.01585	-44.8	+.534	1.354	.820
Sept. 1-12[a]	12	112.82	116.68	67.7	28.82	253	1.94	.14	.20	+.23	+.17	+.01417	+.4084	3.86	.01526	-45.1	+.479	1.304	.825
Sept. 13-26	14	112.93	116.44	67.5	28.93	249	2.30	.16	0	0	+.16	+.01143	+.3307	3.51	.01410	-45.4	+.373	1.204	.831
Sept. 27 to Oct.10	14	113.02	116.16	67.2	29.02	245	2.16	.15	.18	+.13	+.10	+.00714	+.2072	3.14	.01282	-45.8	+.257	1.095	.838
Oct. 11-20	10	112.97	115.93	66.7	28.97	245	1.60	.11	.01	-.10	0	0	0	2.96	.01208	-46.3	+.185	1.032	.847
Oct. 21-31	11	112.88	115.68	66.2	28.88	249	1.52	.11	0	-.10	+.01	+.00091	+.0263	2.80	.01124	-46.7	+.105	.960	.855
Nov. 1-10	10	112.76	115.42	65.7	28.76	253	1.42	.10	.01	-.15	-.06	-.00600	-.1726	2.66	.01051	-47.1	+.036	.898	.862
Nov. 11-20	10	112.62	115.23	65.1	28.62	261	1.29	.09	0	-.10	-.01	-.00100	-.0286	2.61	.01000	-47.8	-.021	.854	.875
Nov. 21-30	10	112.53	114.99	64.7	28.53	265	1.07	.08	0	-.09	-.01	-.00100	-.0285	2.46	.00928	-47.8	-.082	.793	.875
Dec. 1-10[a]	10	112.42	114.82	64.4	28.42	267	.89	.06	.03	-.09	-.06	-.00600	-.1705	2.40	.00899	-48.0	-.110	.768	.878
Dec. 11-20	10	112.49	114.68	64.7	28.49	265	.90	.06	.12	+.08	+.02	+.00200	+.0570	2.19	.00826	-47.8	-.169	.706	.875
Dec. 21-31[a]	11	112.38	114.49	64.6	28.38	267	1.03	.07	.05	-.14	-.12	-.01091	-.3096	2.11	.00790	-47.8	-.200	.675	.875
1968																			
Jan. 1-10	10	112.28	114.34	64.4	28.28	269	0.93	0.07	0.01	-0.11	-0.05	-0.00500	-0.1414	2.06	.00766	-47.9	-0.223	0.654	0.877
Jan. 11-20[a]	10	112.14	114.16	64.3	28.14	274	.79	.06	0	-.15	-.09	-.00900	-.2533	2.02	.00737	-47.8	-.245	.630	.875
Jan. 21-31[a]	11	112.02	113.96	64.0	28.02	276	.99	.07	.05	-.10	-.08	-.00727	-.2037	1.94	.00703	-48.0	-.277	.601	.878
Feb. 1-13[a]	13	111.86	113.81	63.7	27.86	278	1.46	.10	.01	-.25	-.16	-.01231	-.3430	1.95	.00701	-48.2	-.283	.599	.882
Feb. 14-26[a]	13	111.73	113.66	63.6	27.73	283	1.15	.08	.17	-.01	-.10	-.00769	-.2132	1.93	.00682	-48.1	-.279	.583	.880
Feb. 27 to Mar. 19	22	-	-	-	-	-	3.05	.26	.17	-	-	-	-	-	-	-	-	-	-
Mar. 20-30[a]	11	111.47	113.55	62.6	27.47	287	2.15	.15	0	-.23	-.08	-.00727	-.1997	2.08	.00725	-48.9	-.276	.619	.895
Mar. 31 to Apr. 19	10	111.26	113.37	61.9	27.26	291	1.98	.14	0	-.19	-.05	-.00500	-.1363	2.11	.00725	-49.4	-.285	.619	.904
Apr. 10-20[a]	11	111.05	113.17	61.2	27.05	298	2.56	.18	.03	-.25	-.10	-.00909	-.2459	2.12	.00711	-49.8	-.304	.607	.911
Apr. 21-30[a]	10	110.78	113.00	60.7	26.78	302	2.40	.17	.01	-.25	-.09	-.00900	-.2410	2.22	.00735	-50.1	-.289	.628	.917
May 1-11	11	110.46	112.78	60.3	26.46	309	2.76	.20	.01	-.47	-.28	-.02545	-.6734	2.32	.00751	-50.2	-.277	.642	.919
May 12-23[a]	11	110.11	112.61	60.3	26.11	318	2.85	.20	.15	-.22	-.17	-.01545	-.4034	2.50	.00786	-49.8	-.240	.671	.911
May 24 to June 2	10	110.03	112.53	61.2	26.03	320	2.12	.15	.21	+.03	-.03	-.00300	-.0781	2.50	.00781	-48.8	-.226	.667	.893
June 3-10	8	110.46	114.00	63.3	26.30	314	1.16	.08	.67	+.58	-.01	-.00125	-.0329	3.54	.01127	-47.2	+.099	.963	.864
June 11-17	7	110.80	115.09	64.2	26.90	300	1.31	.10	.31	+.31	+.10	+.01428	+.3841	4.29	.01430	-46.6	+.369	1.222	.853
June 18-30[a]	13	111.20	115.65	65.1	27.20	294	2.57	.18	.65	+.67	+.20	+.01538	+.4183	4.45	.01514	-46.1	+.449	1.293	.844
July 1-10[a]	10	111.65	116.15	65.8	27.65	285	1.98	.14	.19	+.21	+.16	+.01600	+.4424	4.50	.01579	-45.8	+.511	1.349	.838
July 11-20[a]	10	111.83	116.02	66.5	27.83	280	1.91	.14	.10	+.13	+.17	+.01700	+.4731	4.19	.01496	-45.3	+.449	1.278	.829
July 21-29	9	111.97	115.90	66.7	27.97	276	2.16	.15	.08	+.05	+.12	+.01333	+.3728	3.93	.01424	-45.3	+.387	1.216	.829
July 30 to Aug. 6[a]	8	112.05	115.78	66.4	28.05	276	1.55	.11	.24	+.21	+.08	+.01000	+.2805	3.73	.01351	-45.6	+.320	1.154	.834
Aug. 7-19[a]	13	112.16	115.67	66.6	28.16	272	2.66	.19	.08	+.03	+.14	+.01077	+.3033	3.51	.01290	-45.6	+.268	1.102	.834
Aug. 20-30	11	112.33	115.61	66.8	28.33	269	1.82	.13	.44	+.38	+.07	+.00636	+.1802	3.28	.01219	-45.5	+.208	1.041	.833
Aug. 31 to Sept 7[a]	8	112.61	116.16	67.3	28.61	261	1.68	.12	.06	+.06	+.12	+.01500	+.4292	3.55	.01360	-45.3	+.333	1.162	.829
Sept. 8-15[a]	8	112.82	116.18	67.6	28.82	253	1.19	.09	.27	+.29	+.11	+.01375	+.3963	3.36	.01328	-45.2	+.307	1.134	.827
Sept. 16-24	9	112.91	116.15	67.8	28.91	249	1.55	.11	.03	-.02	+.06	+.00667	+.1928	3.24	.01301	-45.1	+.286	1.111	.825
Sept. 25 to Oct. 2	8	112.91	116.06	67.6	28.91	249	1.41	.10	.03	-.03	+.04	+.00500	+.1446	3.15	.01265	-45.3	+.252	1.081	.829

a Data for this period used in determination of coefficients A and B in equation 1.
b "X" is difference between water levels in lake and Well B divided by distance from lake to Well B.
c "Y" is difference between water levels in lake and Well A.
Note: The water level in Well B represents the water table; that in Well A represents the potentiometric surface of the Floridan aquifer.

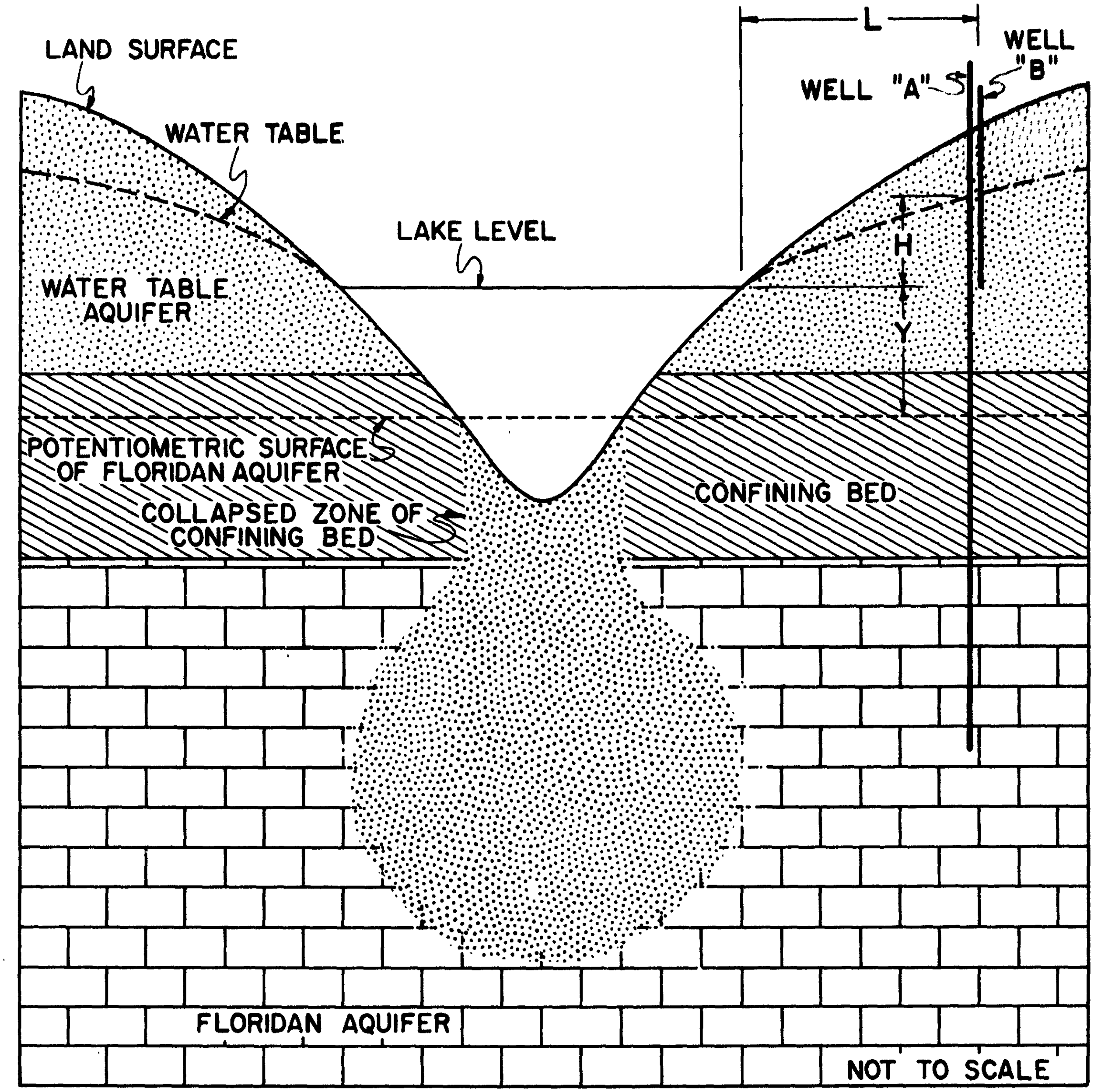


FIGURE 14-A.--GENERALIZED DIAGRAM SHOWING STATIC HEADS USED IN FORMULATION OF EQUATION 1 FOR LAKE JOHIO.

If values of S, X, and Y are obtained for each of two contrasting water-level conditions, equation 1 can be written for each condition:

$$S_1 = AX_1 + BY_1 \qquad (2)$$

$$S_2 = AX_2 + BY_2 \qquad (3)$$

Inasmuch as the coefficients A and B are the only unknowns, their values are determinable by the solution of two simultaneous equations.

Implicit in this approach is the assumption of steady-state ground-water flow. In other words, it is assumed that the surficial aquifer gradient as determined from Well B and lake level is in linear proportion to the gradient at the ground-water-lake interface. In theory, a ground-water-recharge event (or change in lake stage) has a depletion characteristic in the aquifer based on the ratio of Transmissivity to Storage Coefficient (Diffusivity), the distance to the ground-water divide, and the distance from the lake to the observation point (well).

For a period of time (whose length is controlled by these parameters) after such an event, the relationship between the gradient at a well some distance from the lake and that at the interface is non-linear. After this period of time the relationship does approach linearity. If the time period is short, or if the recharge events are small and cause only slight changes in the gradient at the interface, or if the well is very close to the lake, the steady-state assumption should have only slight effect on the computed seepage. The same reasoning can be applied to the relationship between the lake and the Floridan aquifer with the thickness of the confining bed being an additional controlling parameter.

Although a single solution of equations 2 and 3 would provide a valid estimate of the true values of the coefficients A and B, values based on the average of results for several such solutions generally would be considered more reliable because of the vagaries that are inherent in any set of hydrologic data and because of inherent simplifying assumptions. Thus, the coefficients A and B were evaluated by selecting data for 28 computational periods, 14 of which represented times when net seepage <u>into the lake</u> was large and 14 of which represented times when net seepage <u>out of the lake</u> was large. The selected periods are identified in table 1. The computational periods of one group were randomly paired with the computational periods of the other group; this provided contrasting data for 14 independent solutions. The same procedure was repeated 3 times. Representative values of the coefficients A and B were then obtained by averaging the median values of each set of solutions. The final values of A and B were substituted in equation 1 as follows:

$$S = 85.42\,X + 0.0183\,Y \qquad (4)$$

The reasoning involved in selecting and pairing data to obtain a reasonable contrast of conditions for each individual solution of equations 2 and 3 is much the same as would pertain to a determination of the slope of a straight line on graph paper. To reduce the chance or effect of error, one normally would determine the coordinates of two points that are far apart on the line rather than close together.

The representativeness of the values obtained for the coefficients A and B was tested by making a regression analysis of the data for the same 28 computational periods used in the determination of the coefficients. The resulting regression equation was:

$$S = 1.193 + 75.91 X + 0.0414 Y \qquad (5)$$

wherein S, X, and Y are the same as previously defined for equation 1. Net-seepage values obtained from equation 5 differed only slightly from those obtained from equation 4, as shown in figure 15.

Net seepage as computed from equation 4 and net seepage as computed from water-budget data follow the same general trends, but, as figure 16 shows, they differ appreciably for some computational periods. The difference is exceptionally large for May 1-11, 1968. Examination of the lake-level record, as reproduced in figure 17, shows that on 3 days the decline in level was unusually large: 0.08 foot (0.024 m) on May 8 and May 10, and 0.05 foot (0.015 m) on May 11. Although these days were windy--the recorder trace indicates a surging water level--and high evaporation rates therefore might be expected, other days in this same period appear to have been equally windy without an exceptionally large decline in lake level. Pan evaporation in the region was not exceptionally large on these days. Possibly water was pumped from the lake on these days to irrigate surrounding groves; the period in question was near the end of an extended dry period. Because of the uncertainty as to the cause of these unusually large declines in lake level, the data of May 1-11, 1968, was arbitrarily excluded from the determination of the coefficients A and B.

Inflow and outflow components of net seepage, as represented by the individual terms on the right side of equation 4, are listed in table 1 and also are shown in figure 18. A comparison of figures 16 and 18 clearly shows that the variations in net seepage are due primarily to variation in ground-water inflow from the water-table aquifer. The computed ground-water outflow from the lake is fairly steady because the variation in the difference between the lake level and the level of the potentiometric surface of the Floridan aquifer is small in relation to the total difference. For example, on basis of the average values for computational periods in table 1, the maximum difference between

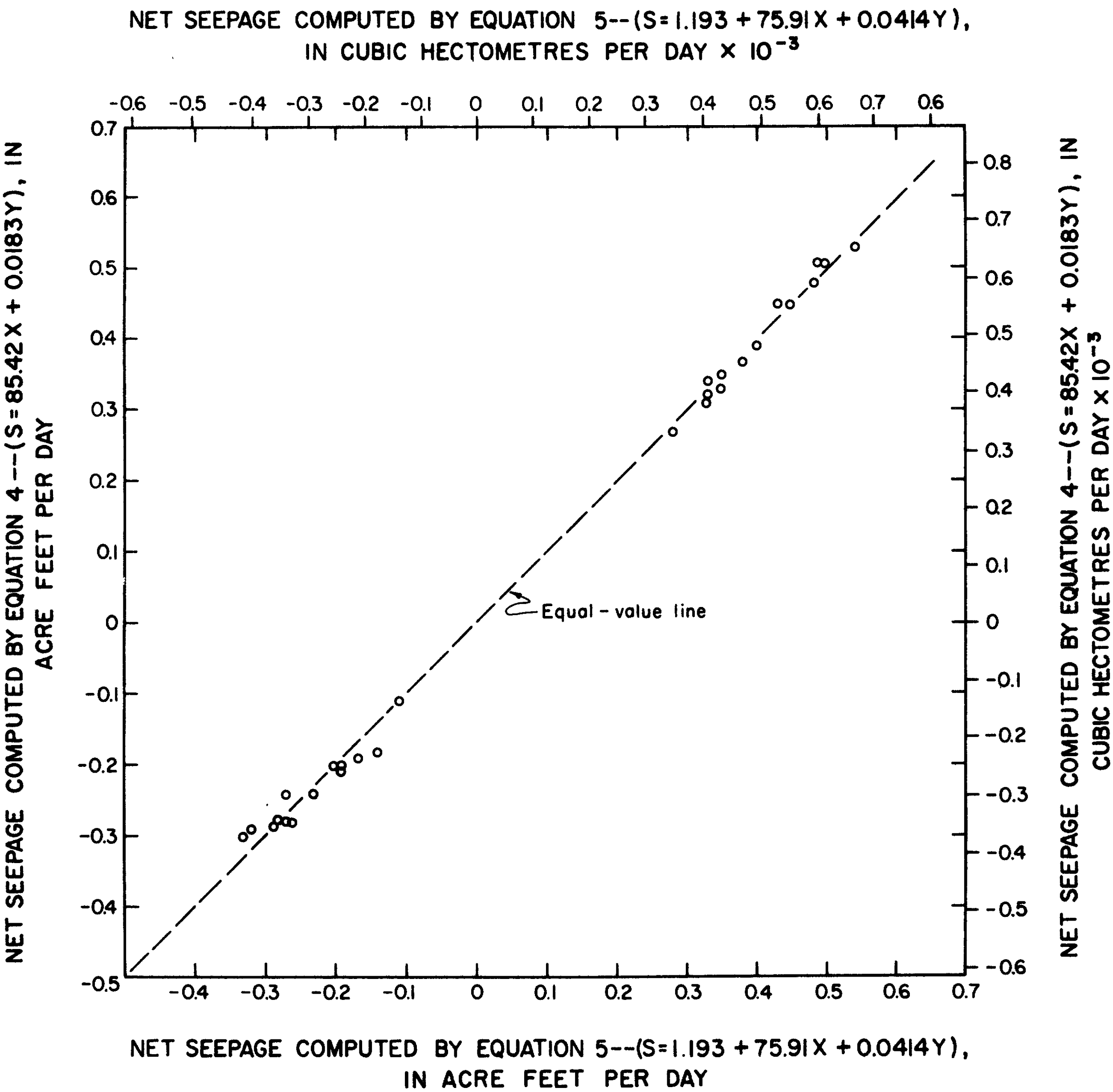


FIGURE 15.--RELATION BETWEEN NET SEEPAGE COMPUTED BY A MULTIPLE REGRESSION EQUATION (EQUATION 5) AND NET SEEPAGE COMPUTED BY AN EMPIRICAL EQUATION (EQUATION 4) BASED ON THE SAME SELECTED DATA.

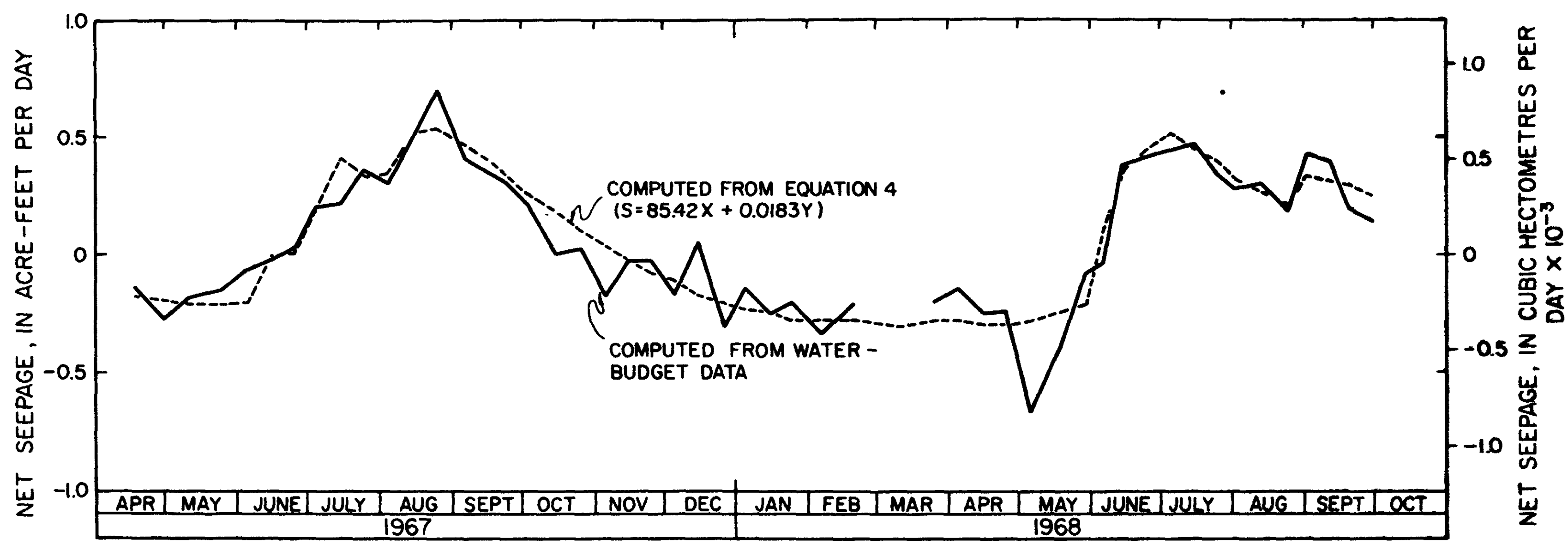


FIGURE 16.--NET SEEPAGE INTO (+) AND OUT OF (-) LAKE JOHIO AS COMPUTED FROM WATER-BUDGET DATA AND AS COMPUTED BY EQUATION 4, APRIL 13, 1967 TO OCTOBER 2, 1968.

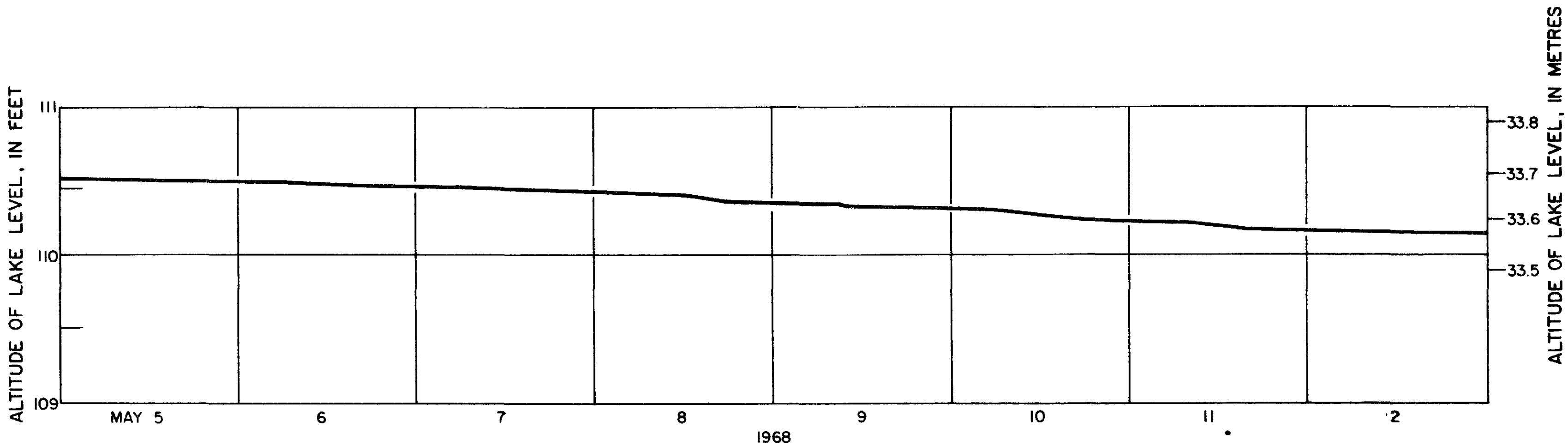


FIGURE 17.--UNUSUALLY LARGE DECLINE OF WATER LEVEL OF LAKE JOHIO ON MAY 8, 10, 11, 1968.

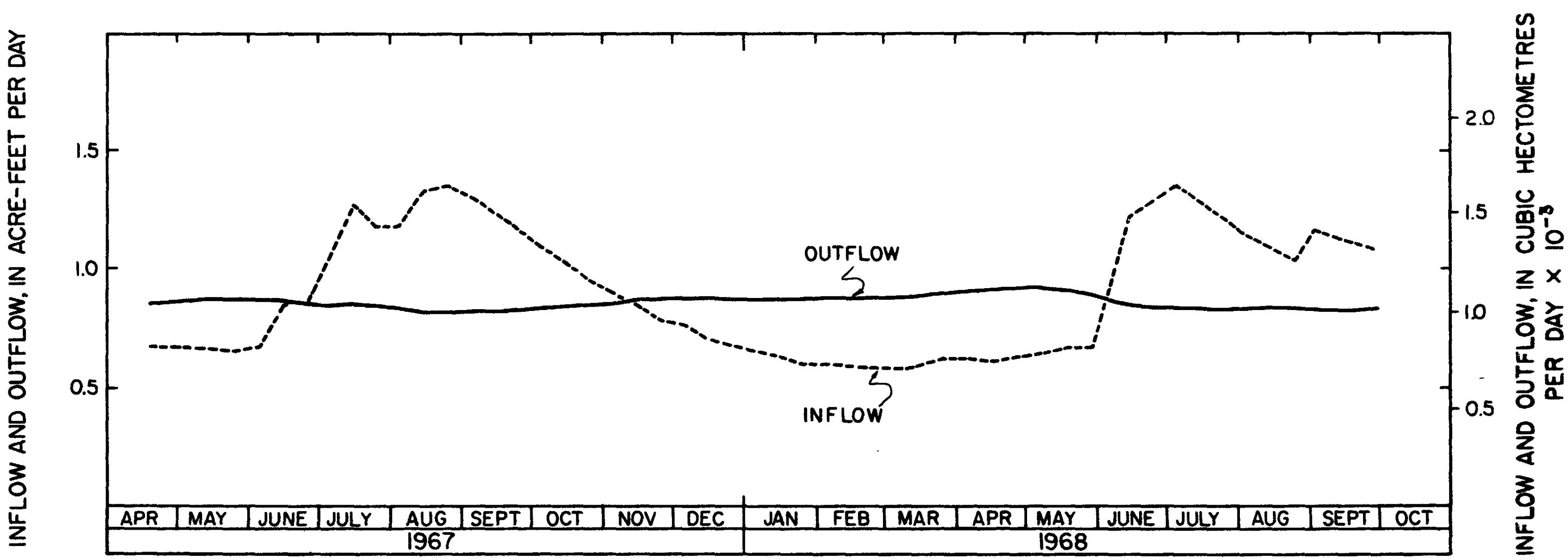


FIGURE 18.--SEASONAL VARIATION IN INFLOW AND OUTFLOW COMPONENTS OF COMPUTED NET SEEPAGE (EQUATION 4) INTO AND OUT OF LAKE JOHIO, APRIL 13, 1967 to OCTOBER 2, 1968.

the lake level and the potentiometric surface of the Floridan aquifer exceeds the minimum difference by only about 12 percent, whereas the maximum hydraulic gradient between the lake and the water-table aquifer exceeds the minimum by about 230 percent.

For the 341 days when the lake-level record was complete between April 13, 1967 and April 9, 1968, the computed ground-water inflow to Lake Johio totaled 297.9 acre-feet (367 x 10^{-3} hm^3) and computed ground-water outflow totaled 292.5 acre-feet (361 x 10^{-3} hm^3). The difference of 5.4 acre-feet (7 x 10^{-3} hm^3) represents a net-seepage gain of 0.19 foot (0.058 m) over the average lake area of 27.8 acres (11 ha). For the same period a net-seepage gain of 0.09 foot (0.027 m) was obtained by the water-budget method. Rainfall plus overland flow into the lake was 4.12 feet (1.26 m) compared to an estimated 3.98 feet (1.21 m) of lake evaporation. The net change in the quantity of water stored in the water-table aquifer was small for the near 12-month period.

For 349 days when the lake-level record was complete between September 27, 1967 and October 2, 1968, the computed ground-water inflow to Lake Johio was 308.0 acre-feet (380 x 10^{-3} hm^3) and computed ground-water outflow was 302.1 acre-feet (372 x 10^{-3} hm^3). The difference of 5.9 acre-feet (7 x 10^{-3} hm3) represents a net-seepage gain of 0.21 foot (0.065 m) over the average lake area of 27.9 acres (11 ha). Net seepage computed by the water-budget method was -0.05 foot (-0.015 m) for the same period. Rainfall plus overland flow into Lake Johio was 4.20 feet (1.28 m) compared to 4.04 feet (1.23 m) of estimated lake evaporation. Again, the net change in the quantity of water stored in the water-table aquifer was small.

During the 22 days between February 27 and March 19, 1968, when the lake-level record was incomplete, about 2 inches (51 mm) of rainfall was measured at Lake Johio. On the assumption that overland flow into Lake Johio averaged about 8 percent of the rapid rise in lake level, rainfall during the investigation was about 49 inches (1,200 mm) or slightly less than normal for the general area. Computed ground-water inflow to Lake Johio during this same 22-day period was about 0.55 acre-foot (0.68 x $10^{-3}hm^3$) per day, which would add about 12 acre-feet (14.8 x $10^{-3}hm^3$) to the yearly totals previously mentioned.

Thus, for a complete year the computed ground-water inflow to Lake Johio was about 315 acre-feet (388 x $10^{-3}hm^3$), which is about equal to 1.5 feet (0.46 m) or 18 inches (457 mm) of water over the 212-acre (86 ha) contributing area of the drainage basin (total area of lake basin minus the area of the lake). If about 30 inches (760 mm) of the year's rainfall of 49 inches (1,200 mm) was consumed by evapotranspiration from the upland area of the drainage basin, and storage in the water-table aquifer was about the same at the beginning and end of the year, then virtually all the rainfall that infiltrated to the water-table aquifer during the 12-month span moved into the lake. The lake gained some additional water inasmuch as rainfall plus overland flow was slightly in excess of lake evaporation. As the lake level was nearly the same at the beginning and end of the 12-month span, the net gain in water from rainfall, overland flow, and lake evaporation, and the inflow to the lake from the water-table aquifer presumably moved downward through the lake bottom to recharge the Floridan aquifer. Hence, within its own drainage basin, Lake Johio is by far the most important point source of recharge to the Floridan aquifer.

Test for Reasonableness of Results

A simple calculation was made to determine whether the magnitude of the computed ground-water inflow to Lake Johio (315 acre-feet or 388 x $10^{-3}hm^3$ per year) was consistent with reasonable estimates of the hydrologic parameters involved. From Darcy's law, the hydraulic conductivity of material through which ground-water moves is equal to the quantity of flow divided by the product of the cross-sectional area of the aquifer (through which water moves toward the lake), and the hydraulic gradient at the point where the cross section is taken.

As determined from the difference between the lake level and the water level in well B, the hydraulic gradient corresponds to flow through a vertical section that encircles the lake and passes midway between the lake and well B, which on the average is about 300 feet (91 m) from the lake. On the assumptions that the slope of the water table is the same on all sides of the lake, and that the lake is basically circular and has a diameter of 1,200 feet (366 m), the vertical section encloses a circular area 1,500 feet (457 m) in diameter; hence, the area of the vertical section (in square feet) is 1,500 feet x π x the thickness (or depth) of the aquifer (in feet).

From table 1 the hydraulic gradient corresponding to an average flow of 0.863 acre-foot (1.06 x $10^{-3}hm^3$) per day (315 acre-feet or 388 x $10^{-3}hm^3$ divided by 365 days) through the vertical section is about 0.01 foot per foot (0.003 m/m). The saturated thickness of the water-table aquifer is not known but it is probably less than 50 feet. If the saturated thickness of the water-table aquifer is as little as 25 feet (8 m), the required hydraulic conductivity would be 32.1 feet per day (9.8 m/d). This value is well within the range of hydraulic conductivities given by Morris and Johnson (1967, p. 20, table 5) for fine sand (particle diameter, 0.125 to 1.250 mm) and substantially less than the average hydraulic conductivity of 45 feet per day (14 m/d) given for medium sand (partical diameter, 0.250 to 0.500 mm). On this basis, the magnitude of the computed ground-water inflow to Lake Johio appears reasonable.

Analysis of Errors

In the mathematical solution for the coefficients A and B of equation 1, neither the cross sectional area nor the hydraulic conductivity of the water-table aquifer was determined, but the product of the two was implicitly assumed to be constant. In fact, however, both of these factors vary: The cross sectional area varies with the saturated thickness of the aquifer which in turn varies with the level of the water table; and, the hydraulic conductivity varies with the viscosity of water which in turn varies with the temperature of the water in the aquifer.

Effect of Variation in Aquifer Thickness

During the investigation the level of the water table at Well B fluctuated about 4.2 feet (1.2 m). The effect of this fluctuation on the computed ground-water inflow to the lake probably would be minimal for a thick aquifer but might be of great consequence for a thin aquifer. The probable extent of this effect was examined.

The coefficients A and B were redetermined with a minimum value of 25 feet (8 m) assigned for the saturated thickness of the water-table aquifer; that is, the depth of the vertical section through which ground-water flow was computed was allowed to vary from 25 feet (8 m) to about 29 feet (9 m) in accordance with the fluctuation in water levels. As part of this adjustment, the length of the vertical section encircling the lake also was allowed to vary, inasmuch as the distance between the lake and well B varies with the lake level. The result of these two adjustments was to make the area of the vertical section about 20 percent greater at high water levels than at low water levels. This would affect the solution for the coefficients A and B because the contrast between the quantities of ground water entering the lake at high and low water levels would be enhanced. The net effect was to reduce the coefficients A and B--and, hence, ground-water inflow to the lake--by 10 percent.

Effect of Variation in Hydraulic Conductivity

The seasonal variation in temperature of ground water 10 to 20 feet (3 to 6 m) below land surface probably is less than 10°F (5.6°C). The mean annual temperature of shallow ground water probably is close to the mean annual air temperature, which in the general area of Lake Johio is about 72°F (22°C). At this temperature the kinematic viscosity of water changes about 1.3 percent per degree F or about 13 percent for a range of 10°F (5.6°C). Previously it was shown that the effect of a 20-percent variation in the area of the vertical flow section caused a change of 10 percent in the computed ground-water inflow to the lake, provided that the minimum saturated thickness of the aquifer is 25 feet (8 m). Thus, adjustments for a 13-percent variation in the viscosity of ground water would change the computed ground-water inflow by less than 10 percent.

The extent to which the adjustments for variations in hydraulic conductivity and saturated thickness of the water-table aquifer might be additive would depend on the phase relation between the seasonal fluctuation of water levels and the seasonal variation in temperature of the shallow ground water. If the phase relation were such that the two effects were directly additive, the computed ground-water inflow would be reduced by less than 20 percent (for the assumed conditions examined herein).

The variation in the hydraulic conductivity of the confining layer beneath the lake also could affect the solution for the coefficients A and B. The range of fluctuation in temperature of the lake water is about the same as the range of the average monthly air temperature, which in the vicinity of Lake Johio is about 22°F (12.2°C). For such a temperature variation the kinematic viscosity of the lake water would vary about 29 percent. The range of temperature variation would tend to decrease as the water moves through the confining layer; however, if water moves rather freely through the confining layer the range of temperature variation would probably approach that of the lake water and the hydraulic conductivity of the confining layer would vary accordingly. The extent to which the variation in the hydraulic conductivity of the confining layer would affect the solution for the coefficients A and B was not investigated in detail. However, in view of the size of the effect that was attributable to the variation in the thickness of the water-table aquifer, the coefficients A and B probably would not be altered by more than 15 percent by this factor acting alone.

Although the effects of variations in the temperatures of the lake and shallow ground water and in the saturated thickness of the water-table aquifer probably would not be directly additive, the cumulative effect in some instances could be large enough to alter the coefficients A and B appreciably. Thus, if a precise determination of the coefficients A and B is desired, the solution of equation 1 should include corrective factors for such variations.

Effect of Pumping from Lake

At the outset of the investigation, pumping of water from the lake was thought to be of little importance in the water budget of Lake Johio; consequently, pumpage was not monitored. Except possibly on May 8, 10, and 11, 1968, the lake-level recorder trace did not indicate that larger quantities of water were ever pumped from the lake; however, residents around the lake probably pumped some water to maintain lawns, shrubbery, gardens, and so forth.

An attempt was made to evaluate the extent to which an accounting of such pumping in the water budget of the lake might have affected the magnitude of the computed ground-water inflow to the lake. The coefficients A and B of equation 1 were re-determined with net seepage adjusted for pumpage at an assumed rate of 0.1 acre-foot (0.123 x 10^{-3} hm^3) per day or 22.6 gallons per minute (1.4 l/s). The pumpage adjustment was arbitrarily assumed to apply only to computational periods which fell in the warm months of the year (March through September) and which had less than about 1.5 inches (37 mm) of rainfall. The re-evaluation of the coefficients A and B was based on data for the same 28 computational periods previously used in the determination of the coefficients of equation 4; the periods were paired exactly as before.

Only 12 of the 28 periods were affected by adjustments for pumpage. Based on the average of the median values of the coefficient A, derived from 3 solution sets, computed ground-water inflow to the lake was 4 percent less than previously determined. The different values of the coefficient B are not comparable because the computed ground-water outflow from the lake to the Floridan aquifer obviously had to be reduced by the pumpage adjustment.

The assumed rate of pumpage (0.1 acre-foot per day or 0.123 x 10^{-3} hm^3/d may or may not be representative of the magnitude of pumpage that occurred during the investigation of this lake; however, pumping from the lake probably was intermittent rather than continuous for days on end. In other words, the capacities of the pumps used probably were several times greater than would be indicated by the average rate of pumping. If so, the effect of intermittent pumping probably would have been detectable in the trace of the lake-level recorder had the pumpage averaged substantially more than 0.1 acre-foot per day (0.123 x 10^{-3} hm^3/d).

Effect of Errors in Net Seepage Computed by Water-budget Method

In a water-budget analysis a residual term represents the net effect of any factors whose magnitudes have not been determined plus the net of errors in determinations of the magnitudes of those factors included in the analysis. If the magnitudes of all but one of the factors have been determined, the significance of the residual term depends largely on the relation between the magnitude of the residual term and the magnitude of possible errors in the estimates of the other factors.

At Lake Johio the change in lake content could be accurately determined for periods of 10 days to so. The rise in lake level owing to rainfall and overland inflow also could be accurately determined. Although the effect of net seepage during the time of the rise in level was neglected, the rises in level in the aggregate represented only a small part of the time span of most computational periods. Hence, for most computational periods, the residual of the water-budget equation was several times greater than the probable error contained in the estimates of change in contents or the rise in level owing to rainfall and overland inflow. Thus, the extent to which the residual term might represent net seepage into or out of the lake relies almost entirely on the validity of the estimate of lake evaporation.

According to the pan-evaporation map of Kohler and others (1959, plate 1) the evaporation from the Class A pan at Lisbon is representative of pan evaporation in the general area. For short time spans, such as an hour a day, pan evaporation at Lisbon would not always be equally representative of evaporation from a lake some 25 miles away; however, over a period of 10 days the pan evaporation probably would represent lake evaporation with fair consistency. Furthermore, errors owing to variation in the degree of representativeness would not necessarily be biased always in the same direction.

In table 1, the values of computed net seepage for 9 computational periods fall within a range of $\pm$ 0.02 foot (5 mm), whereas the estimated lake evaporation ranged from 0.06 to 0.16 foot (15 to 41 mm) and averaged 0.09 foot (23 mm) for the same 9 periods. Obviously, the apparent significance of such small residuals could be influenced greatly by the choice of the pan-to-lake coefficient which conceivably could range from 0.6 to 1.0. However, for most of the other computational periods, the magnitudes of the computed net seepage and the estimated lake evaporation were more nearly the same. In several instances the computed net seepage was greater than the estimated lake evaporation. For these periods the estimated lake evaporation could not contain an error large enough to alter appreciably the apparent significance of the residual term. To do so would be to require a totally unreasonable adjustment of the pan-to-lake coefficient. Thus, while each value of the water-budget residual may contain an element of error stemming from an erroneous estimate of lake evaporatiom, the magnitude of the residual in general is large enough in relation to the probable magnitude of the error that the residual can be called net seepage. The conclusion is strengthened by the distinct seasonal reversal in the sign of the residual because of the improbability that the pan-to-lake coefficient could be grossly too large in one instance and grossly too small in the other.

Basic Requirements of the Method

The solution of equation 1 provides a valid estimate of net seepage into and out of a lake because the X and Y parameters are related to the ground-water flow system and they are also related to the water-budget data, much as would be done by regression methods. However, the inflow and outflow components of net seepage are not uniquely determined unless the X and Y parameters are equally representative of water-level conditions on all sides of a lake. For example, if the X parameter--which represents the hydraulic gradient between the lake and the water-table aquifer--indicates that water moves into the lake from the water-table aquifer, then water must move into the lake from the water-table aquifer on all sides of the lake. Further, if the range of water-level fluctuation is such that the water table at times declines below the lake level, then the water table must decline below the lake level simultaneously on all sides of the lake. If it were otherwise, that is, if water were to move into the lake from the water-table aquifer on one side of a lake and out of the lake to the water-table aquifer on the other side of the lake, the solution of equation 1 in no way could distinguish between water which moves from the lake to the water-table aquifer and that which moves from the lake to the Floridan aquifer. The same limitation also would apply to the Y parameter, which represents the head difference between the lake and the Floridan aquifer.

The representativeness of the X parameter depends largely on the symmetry of the lake basin, the homogeneity of the water-table aquifer, and the areal distribution of the permeability of the confining bed between the water-table aquifer and the Floridan aquifer. If the confining bed is relatively permeable directly under a lake and relatively impermeable elsewhere in the lake basin, the water level in a well tapping the water-table aquifer on one side of the lake probably would be always representative of the water table at other points around the lake. However, if the relatively permeable area of the confining bed extends outward from the lake for some distance on one side of the lake, but not on the other, then the water level in a well tapping the water-table aquifer likely would not be equally representative of the water table on all sides of the lake throughout the range of water-level fluctuation.

The Y parameter generally will reflect the head difference between the lake and the Floridan aquifer equally well on all sides of a lake if the lake surface is always far above or below the potentiometric surface of the Floridan aquifer. If the two surfaces differ only slightly in altitude, then the size of the lake and the regional slope of the potentiometric surface come into play. For example, if a lake is relatively large and the regional slope of the potentiometric surface is relatively steep, then the potentiometric surface can be simultaneously above the lake surface in one part of the lake and below the lake surface in another part of the lake.

LAKE SHERWOOD

Description of Study Site

Lake Sherwood--about 6 miles (10 km) west of Orlando and 2 miles (3 km) southwest of Lake Johio--is the terminus of a chain of lakes that interconnect only during extraordinary wet spells. State Highway 50 passes through Lake Sherwood and divides it into two parts of about equal size. The two parts of the lake interconnect through a bridge opening above a lake stage of about 71 feet (22 m) above sea level. At a near normal lake stage of 68 feet (21 m) above sea level, Lake Sherwood has a surface area of about 120 acres (49 ha). The lake drainage area is about 1,100 acres (450 ha), of which about 55 percent is planted in citrus groves. The surficial materials are relatively sandy.

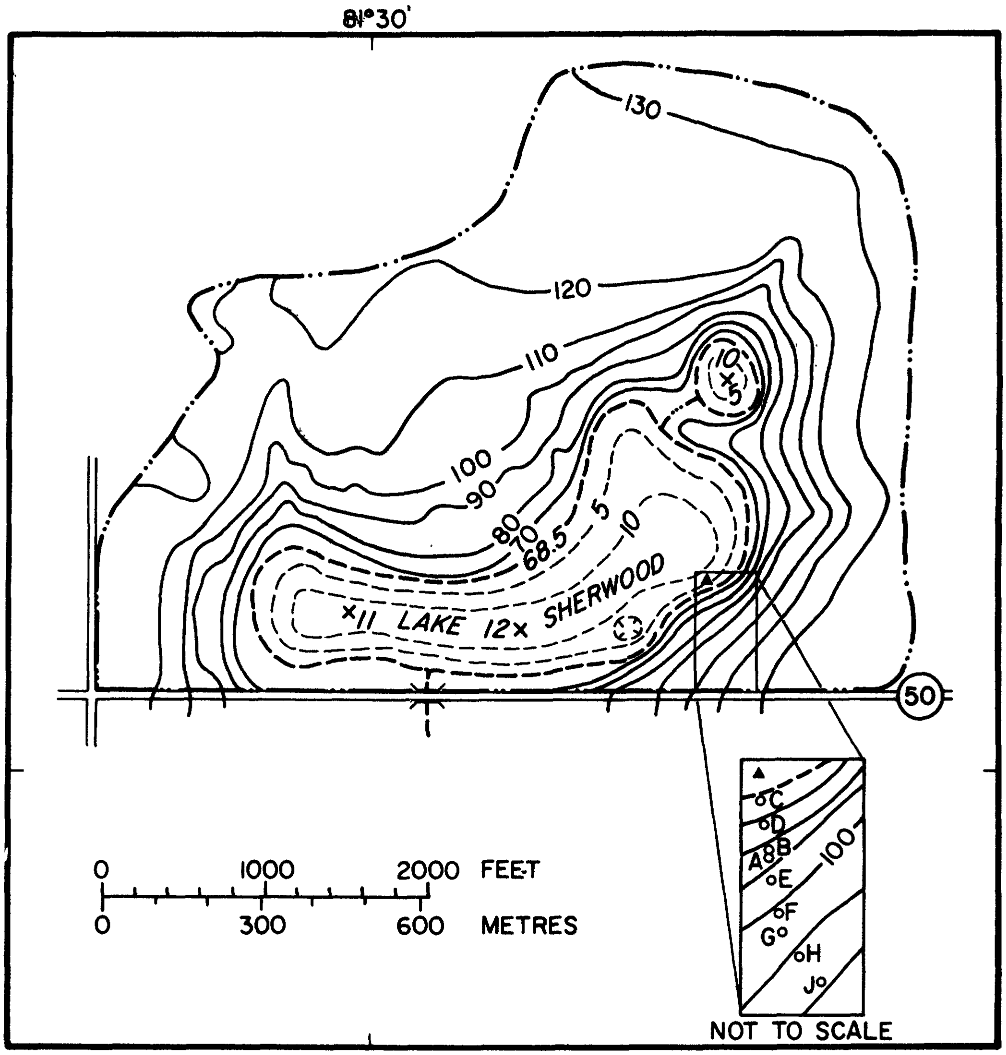
Lake Sherwood has the largest range of fluctuation recorded for lakes in Orange County. The maximum recorded lake stage was 88.4 feet (26.9 m) in 1960; the minimum, 64.1 feet (19.5 m) in 1963. During high water in 1960 numerous homes on the north side of the lake and a tourist court on the east side of the lake were flooded. Some of the homes were partly inundated for almost a year.

Instrumentation

Water-level recording gages were installed in the northern part of Lake Sherwood and in two wells about 200 feet (60 m) from the lake. One of the wells (well B) was developed in the water-table aquifer; the other (well A) in the Florida aquifer. In addition, seven 1¼-inch (32 mm) diameter sand-point wells were installed in a line extending radially from the southeast side of the northern part of the lake. The general layout of wells and water-level recording gages is indicated in figure 19.

Water levels in the sand-point wells were measured periodically to determine the general slope of the water table near the lake. Slope profiles for two different water-table conditions are shown in figure 20. In May and June 1967, the water table declined below the bottoms of well B (on which the water-level recorder was installed) and one of the nearby sand-point wells.

Evaporation from Lake Sherwood was estimated from National Weather Service records of pan evaporation at Lisbon, Fla.; a pan coefficient of 0.85 was used. Rainfall at Lake Sherwood was measured by a weighing-type recording gage except from July 18 to November 30, 1967, when daily rainfall measurements were recorded by a local observer. The



EXPLANATION

A○	Observation well.
▲	Lake-level recorder.
12×	Point of maximum depth; number is depth in feet, with lake surface 68.5 feet above sea level.
--*68.5*--	Outline of lake surface at stage 68.5 feet above sea level.
—100—	Land-surface contour -- Shows altitude of land surface. Contour interval is 10 feet. Datum is mean sea level.
---*5*---	Line of equal depth to lake bottom. Interval 5 feet. Datum is lake surface at 68.5 feet above sea level.
-··——··—	Basin boundary.

FIGURE 19.--LOCATION OF LAKE GAGE AND GROUND-WATER OBSERVATION WELLS IN NORTHERN PART OF LAKE SHERWOOD DRAINAGE BASIN.

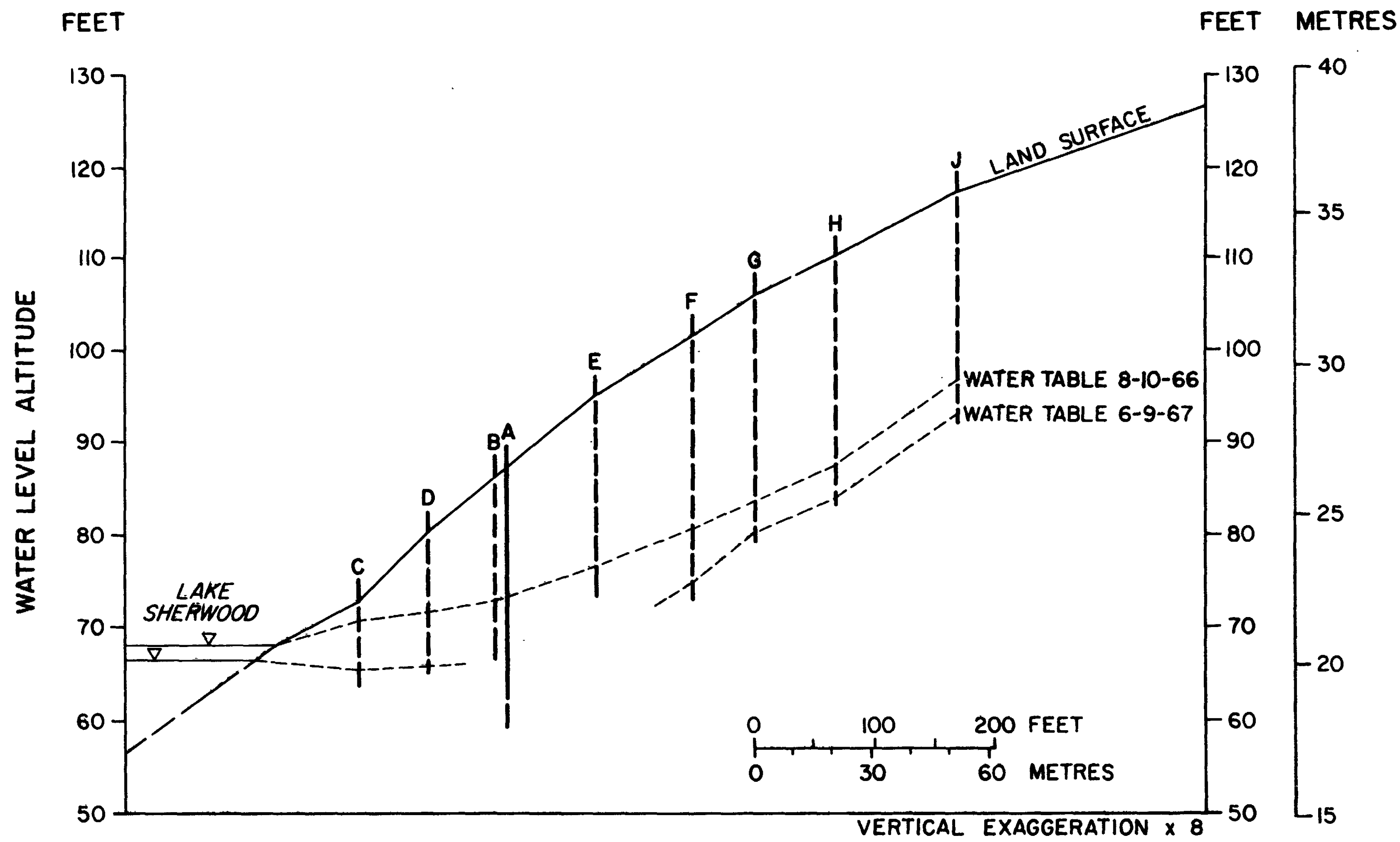


FIGURE 20.--GENERAL SLOPE OF LAND SURFACE AND WATER TABLE ALONG LINE OF OBSERVATION WELLS NEAR LAKE SHERWOOD; WELL A TAPS FLORIDAN AQUIFER; ALL OTHERS TAP WATER-TABLE AQUIFER. (WATER TABLE BELOW BOTTOM OF WELLS B AND E ON JUNE 9, 1967.)

hydraulic connection between the lake and the stilling well of the lake-level recorder was poor during the last 6 months of the study; during this period determinations of changes in lake stage are subject to small errors.

Data Analysis

Data for the investigation at Lake Sherwood were collected from September 1966 to December 1967. The lake level was relatively high in September 1966 because rainfall was abundant in the several preceding months. From October 1965 to September 1966 rainfall at Orlando totaled almost 60 inches (1,500 mm). Surface inflow from the upstream lakes entered Lake Sherwood until November 1966. The surface inflow was not measured.

Rainfall was less than average during the period of investigation. After October 1966 the lake level trended downward as shown in figure 21. In January 1967 the lake level declined below the level where the two parts of the lake are inconnected; hence, the data for Lake Sherwood were analyzed only for the period January 15 to December 31, 1967, when the northern part of the lake basically was a separate landlocked lake having a contributing drainage area of 268 acres (108 ha) as outlined in figure 19. The findings of the study pertain only to the northern part of the lake.

Determining Net Seepage

Net seepage into and out of the northern part of Lake Sherwood was determined by the water-budget method for bimonthly periods in the manner already described of Lake Johio. The water-budget data are given in table 2.

The coefficients A and B, which are required to compute net seepage by equation 1, were determined by the solution of two simultaneous equations as previously described. Data for 10 computational periods were used: 5 periods selected to represent times when net seepage out of the lake (in units of feet) was greatest, and 5 periods selected to represent times when net seepage into the lake was greatest. These periods are identified in table 2. The resulting equation for computing net seepage into and out of the northern part of Lake Sherwood was:

$$S = 44.60\ X + 0.178\ Y \qquad (6)$$

where S, X, and Y are as previously defined for equation 1.

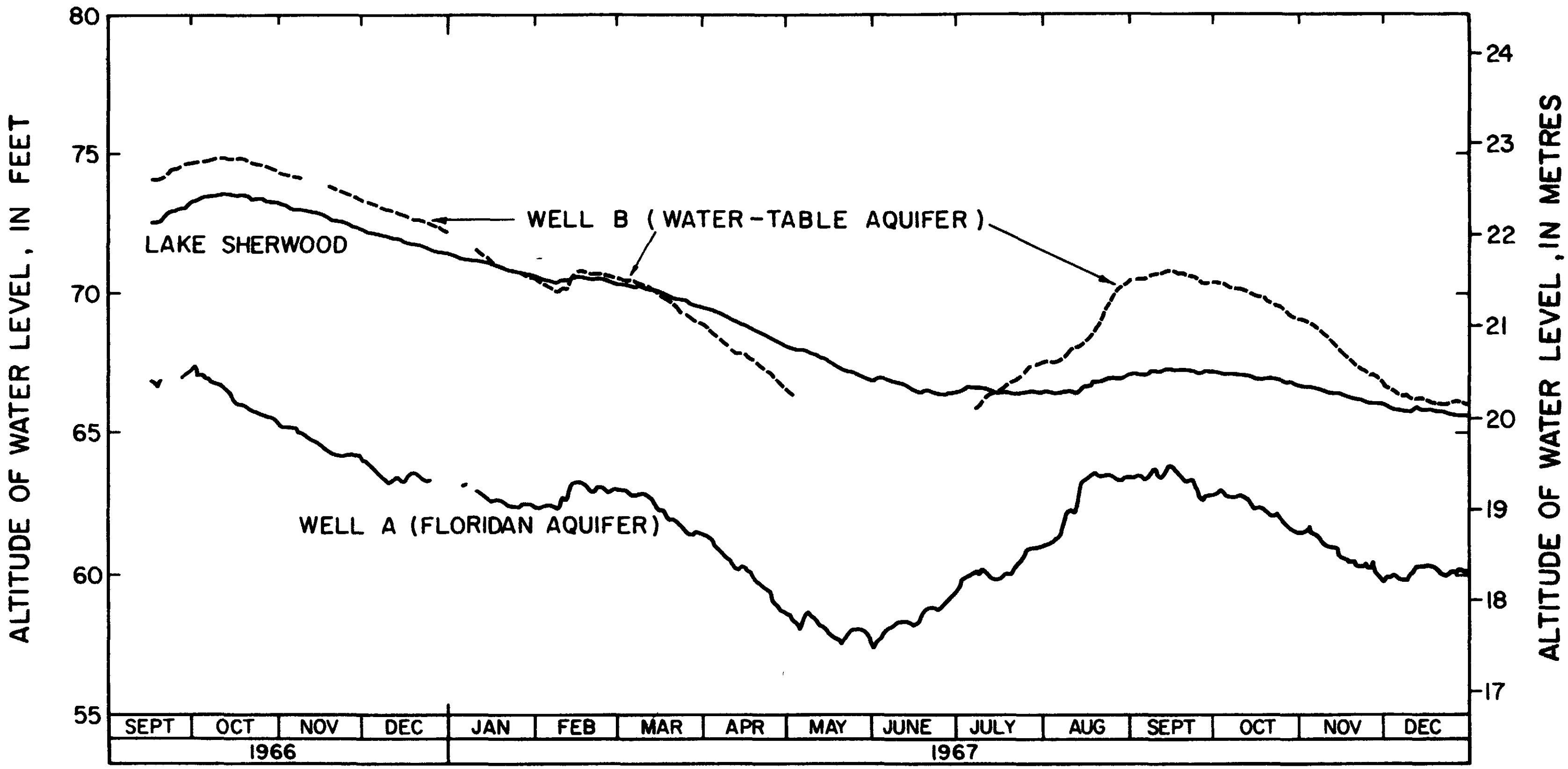


FIGURE 21.--WATER LEVELS OF LAKE SHERWOOD, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELL B, TAPPING THE WATER-TABLE AQUIFER, SEPTEMBER 1966 TO DECEMBER 1967.

Table 2.--Water-budget data for Lake Sherwood

Period	No. days	Altitude mean water level: Lake	Well B	Well A	Mean lake area	Mean distance lake to Well B	Pan evaporation	Lake evaporation	Rainfall plus overland flow	Change in lake level	Net seepage by water budget			Water level Well B minus lake level	X^b	Y^c	Net seepage by equation 6	Computed inflow to lake from water-table aquifer	Computed outflow from lake to Floridan aquifer
		(ft)			(acres)	(ft)	(in)	(ft)	(ft)	(ft)	(ft)	(ft/day)	(ac-ft/d)	(ft)	(ft/ft)	(ft)	(ac-ft/day)		
1967																			
Jan. 16-31[a]	16	70.82	70.81	62.50	80	143	1.55	0.11	0.06	-0.43	-0.38	-0.023	-1.90	-0.01	-0.0001	-8.32	-1.48	0	-1.48
Feb. 1-15	15	70.53	70.35	62.68	78	153	1.66	.12	.37	+.03	-.22	-.014	-1.14	-.18	-.0012	-7.85	-1.45	-.05	-1.40
Feb. 16-28	13	70.54	70.72	63.09	78	153	1.69	.12	.08	-.25	-.21	-.016	-1.26	+.18	+.0012	-7.45	-1.27	+.05	-1.33
March 1-15	15	70.25	70.37	62.84	77	157	2.14	.15	.05	-.31	-.21	-.014	-1.08	+.12	+.0008	-7.41	-1.28	+.04	-.132
March 16-31[a]	16	69.78	69.44	61.76	75	163	2.77	.20	.02	-.55	-.37	-.023	-1.73	-.34	-.0021	-8.02	-1.52	-.09	-1.43
April 1-15[a]	15	69.24	68.29	60.72	73	171	3.61	.26	.02	-.58	-.34	-.023	-1.65	-.95	-.0056	-8.52	-1.77	-.25	-1.52
April 16-30[a]	15	68.59	67.27	59.41	70	180	4.03	.29	0	-.75	-.46	-.031	-2.15	-1.32	-.0073	-9.18	-1.96	-.33	-1.63
May 1-15	15	67.92		58.34	63	189	3.89	.28	.12	-.60	-.44	-.029	-1.85			-9.58			-1.71
May 16-31	16	67.25		57.83	64	199	4.00	.28	.12	-.69	-.53	-.033	-2.12			-9.42			-1.68
June 1-15	15	66.86		58.06	62	204	3.00	.21	.26	-.34	-.39	-.026	-1.61			-8.80			-1.51
June 16-30	15	66.49		58.83	60	209	2.60	.18	.29	-.17	-.28	-.019	-1.12			-7.66			-1.36
July 1-15	15	66.61		59.92	61	208	3.02	.21	.50	+.11	-.18	-.012	-.73			-6.69			-1.19
July 16-31	16	66.50	67.13	60.36	60	209	3.13	.22	.33	-.05	-.16	-.010	-.60	+.63	+.0030	-6.14	-.96	+.13	-1.09
Aug. 1-15[a]	15	66.53	67.85	61.92	60	209	2.26	.16	.41	+.22	-.03	-.002	-.12	+1.32	+.0063	-4.61	-.54	+.28	-.82
Aug. 16-31[a]	16	66.95	69.50	63.52	62	202	3.83	.27	.51	+.47	+.23	+.014	+.89	+2.55	+.0126	-3.43	-.05	+.56	-.61
Sept. 1-15[a]	15	67.24	70.71	63.62	63	199	2.24	.16	.30	+.19	+.05	+.003	+.21	+3.47	+.0174	-3.62	+.13	+.78	-.64
Sept. 16-30[a]	15	67.28	70.67	63.22	64	197	2.75	.19	.09	-.09	+.01	+.001	+.04	+3.39	+.0172	-4.06	+.04	+.77	-.72
Oct. 1-15[a]	15	67.16	70.32	62.78	63	199	2.21	.16	.02	-.19	-.05	-.003	-.21	+3.16	+.0159	-4.38	-.07	+.71	-.78
Oct. 16-31	16	66.92	69.64	61.99	62	201	2.32	.16	.01	-.30	-.15	-.009	-.58	+2.72	+.0135	-4.93	-.28	+.60	-.88
Nov. 1-15	15	66.60	68.66	61.24	61	208	2.10	.15	.02	-.33	-.20	-.013	-.81	+2.06	+.0099	-5.36	-.51	+.44	-.95
Nov. 16-30	15	66.25	67.41	60.30	59	213	1.68	.12	0	-.35	-.23	-.015	-.90	+1.16	+.0054	-5.95	-.82	+.24	-1.05
Dec. 1-15	15	65.95	66.46	59.99	58	216	1.34	.09	.15	-.17	-.23	-.015	-.89	+.51	+.0024	-5.96	-.95	-.11	-1.06
Dec. 16-31[a]	16	65.80	66.16	60.14	57	219	1.49	.11	.03	-.33	-.25	-.016	-.89	+.36	+.0016	-5.66	-.94	+.07	-1.01

a Data for this period used in determination of coefficients A and B in equation 1.

b "X" is difference between water levels in lake and Well B divided by distance from lake to Well B.

c "Y" is difference between water levels in lake and Well A.

Note: The water level in Well B represents the water table; that in Well A represents the potentiometric surface of the Floridan aquifer.

Figure 22 shows that net seepage as computed by equation 6 follows the general trend of net seepage as computed by the water-budget method; differences between values computed by the two methods are large for some computational periods but overall they are about balanced. From January 16 to April 30 and from July 16 to December 31, 1967, computed net seepage from the lake was 224 acre-feet ($274 \times 10^{-3} hm^3$) by the water-budget method and 238 acre-feet ($291 \times 10^{-3} hm^3$) by equation 6. Net seepage by equation 6 consisted of 300 acre-feet ($370 \times 10^{-3} hm^3$) of ground-water outflow from the lake to the Floridan aquifer (based on the "Y" term of equation 6) and 62 acre-feet ($76 \times 10^{-3} hm^3$) of net ground-water inflow to the lake from the water-table aquifer (based on the "X" term of equation 6). Seasonal variations of the two components are shown in figure 23.

On basis of the lake-level decline shown in figure 21, most of the seepage from the lake to the Floridan aquifer apparently came from water stored in the lake at the start of the study. Much of the lake water probably was surface inflow from the upstream chain of lakes. Thus, the water balance of the northern part of Lake Sherwood during the study was not entirely the product of hydrologic conditions within the 268-acre (108-ha) area that contributes water directly to the northern part of the lake.

The northern part of Lake Sherwood leaks freely to the Floridan aquifer yet much of the time it is isolated from the southern part of the lake and hence, is cut off from the only source of any appreciable surface-water inflow. Under the climatic conditions that cause the northern and southern parts to remain separate, rainfall and overland flow into the northern part are hardly sufficient to offset the effect of lake evaporation. If during dry spells the level of the northern part is to stabilize short of the lake going dry, inflow to the lake from the water-table aquifer at some time must almost equal the outflow from the lake to the Floridan aquifer. For this condition to develop the lake would have to decline relative to both the water table and the potentiometric surface of the Floridan aquifer. This would increase the inflow to the lake from the water-table aquifer and decrease the outflow from the lake to the Floridan aquifer. The relation between the lake and ground-water levels did shift in this direction from the start to the end of the study (fig. 21). If the level of the northern part of Lake Sherwood tends to stabilize during prolonged dry spells, then (1) the ground water inflow to the lake from the water table must be appreciable and (2) leakage through the lake bottom must account for an appreciable part of the total recharge to the Floridan aquifer from the 268-acre (108-ha) drainage basin contributing to the northern part of the lake.

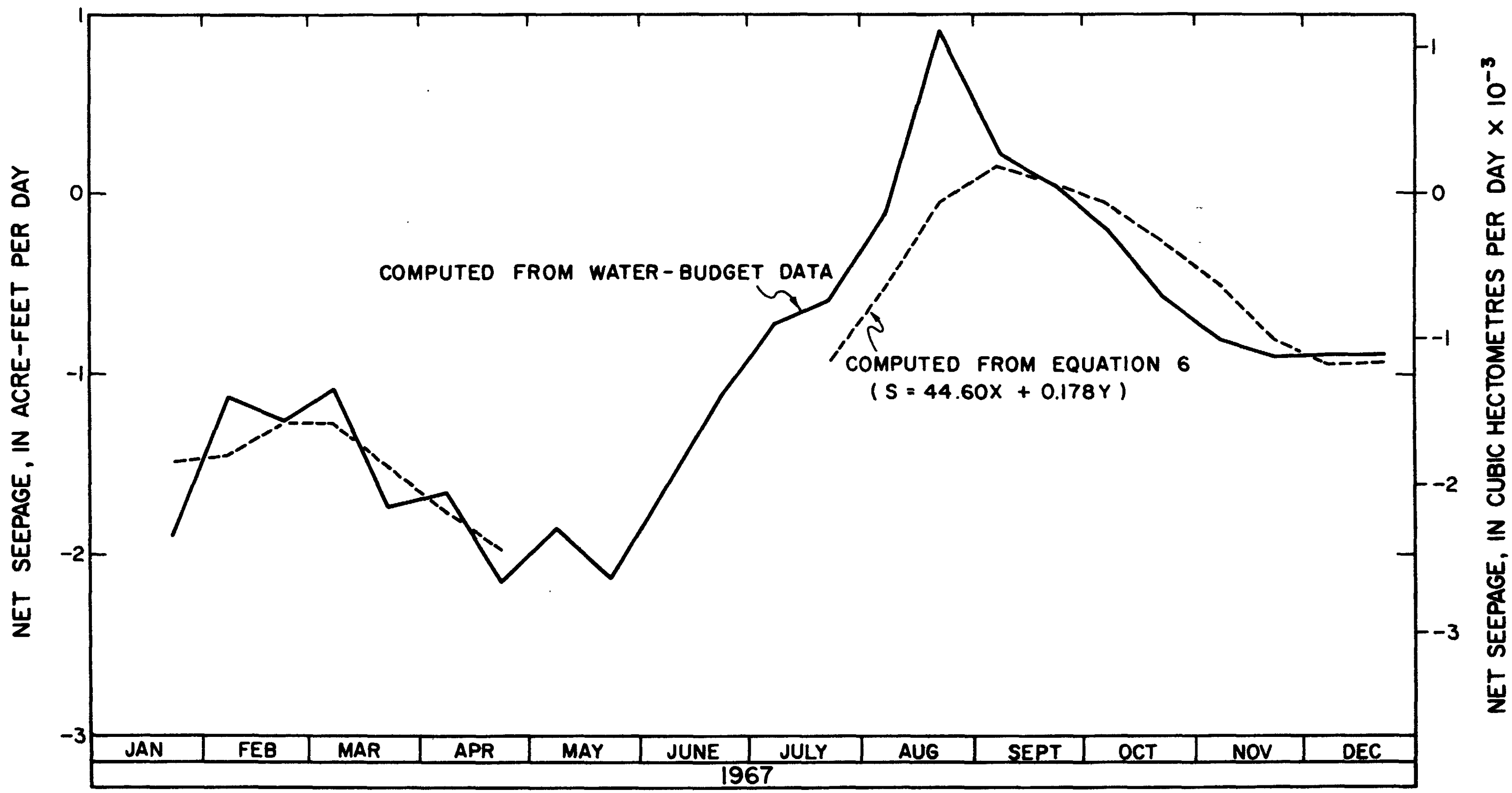


FIGURE 22.--NET SEEPAGE INTO (+) AND OUT OF (-) LAKE SHERWOOD AS COMPUTED FROM WATER-BUDGET DATA AND AS COMPUTED BY EQUATION 6, JANUARY 16 TO DECEMBER 31, 1967.

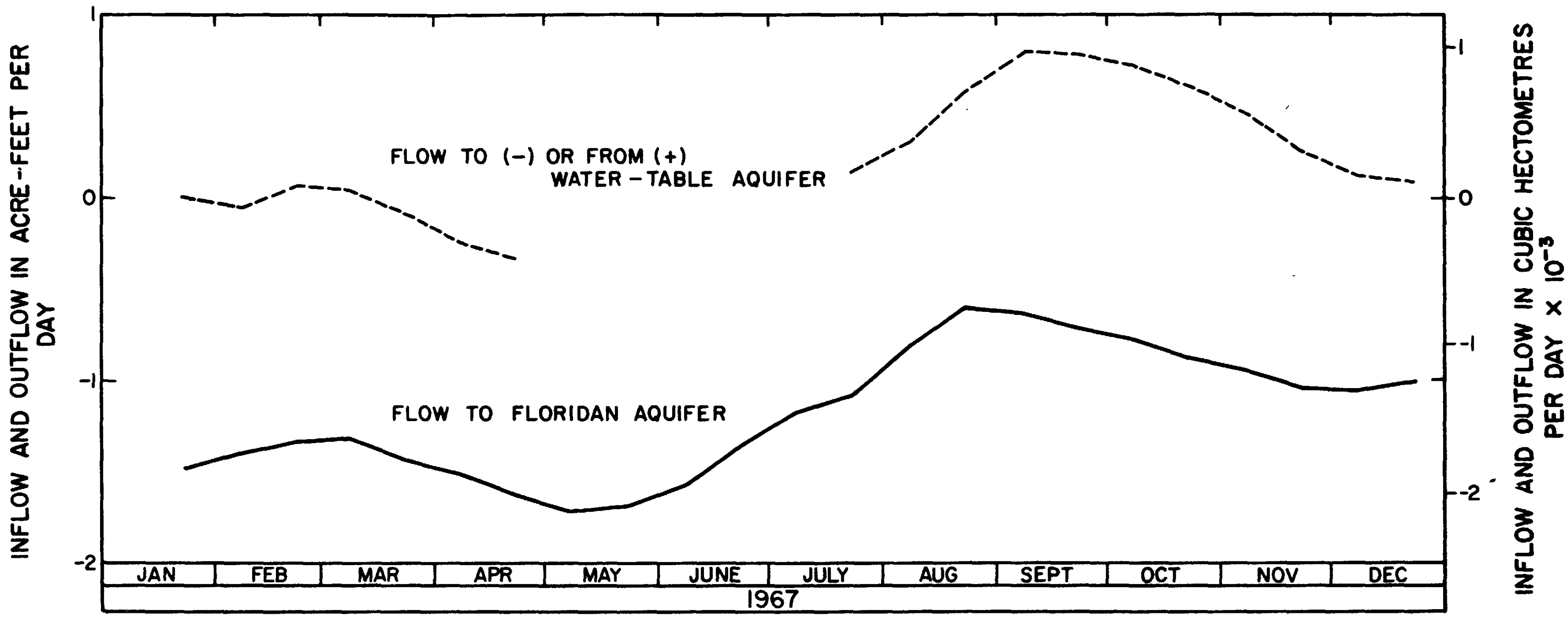


FIGURE 23.--SEASONAL VARIATION IN INFLOW AND OUTFLOW COMPONENTS OF COMPUTED NET SEEPAGE (EQUATION 6) INTO AND OUT OF THE NORTHERN PART OF LAKE SHERWOOD.

Also some water must move from the water-table aquifer directly to the Floridan aquifer; otherwise, the water table would not have declined below the level of the lake as it did at times from January to July 1967. The shape of the water-table profile (dated 6-9-67) in figure 20 suggests that water moves downward to the Floridan aquifer near the lake. The clay layers of the confining bed probably collapsed for some distance from the lake at the time the lake basin was formed. If the collapsed zone is fairly extensive, then much of the recharge to the water-table aquifer--that is, recharge from rainfall on the 268-acre (108-ha) drainage basin--may reach the Floridan aquifer either through the bottom of the northern part of Lake Sherwood or through the zone of relatively permeable material within a short distance from the lake.

The apparently collapsed zone of the confining bed may or may not extend completely around the lake. If the collapsed zones does not extend somewhat symmetrically around the lake, the estimates of the inflow and outflow components of net seepage as computed by equation 6 probably are invalid.

LAKE HERRICK

Description of Study Site

Lake Herrick is about 5 miles (8 km) west of Orlando, about 3/4 mile (1.2 km) east of Lake Sherwood, and about 2½ miles (4 km) southeast of Lake Johio. The drainage basin of the lake is a closed depression covering about 300 acres (121 ha). The altitude of the basin rim ranges from about 115 to 140 feet (35 to 43 m). About 80 percent of the basin is planted in citrus groves; the basin is otherwise undeveloped except for a clay road that skirts the east side of the lake. The surficial material is sand that is relatively permeable.

The maximum recorded stage of Lake Herrick was 81 feet (25 m) above sea level in November 1960; the lake was dry for several weeks in 1967 and 1968 but according to local residents is not known to have been dry before that time. Maximum lake stage during the study (September 1966 to December 1967) was about 68.2 feet (20.8 m) above sea level; the maximum lake area was about 25 acres (10 ha). Most of the time the lake consisted of two pools connected by a narrow ditch.

Instrumentation

Water-level recording gages were installed in Lake Herrick and in two wells that tapped the water-table aquifer (well B) and the Floridan aquifer (well A) about 200 feet (60 m) from the east side of the lake. Thirteen 1¼-inch (30 mm) diameter sand-point wells were installed in a line along the clay road that skirts the east side of the lake. Well screens were placed a few feet below the water table and at most sites only a few feet above a clay layer of yellow to brown to gray-green clay. The general layout of wells and water-level gages is shown in figure 24.

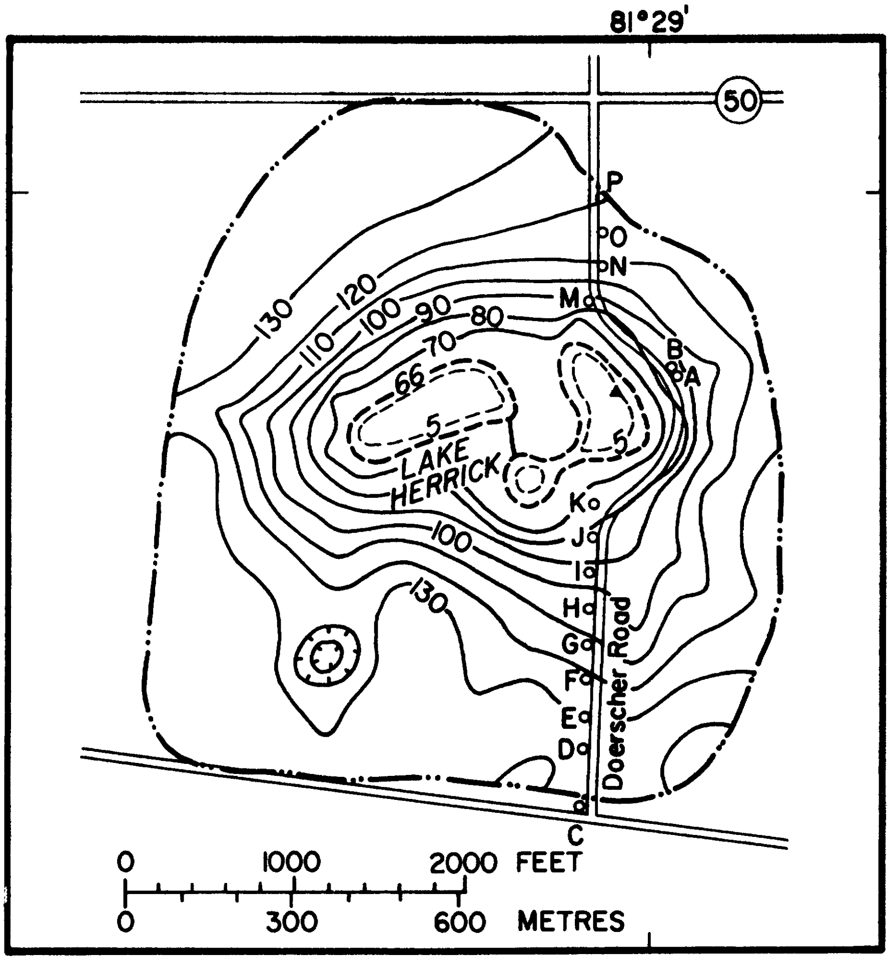
The water levels in the sand-point wells were measured periodically to determine the general slope of the water table near the lake. Slope profiles for 3 different water-table conditions are shown in figure 25. The water level in one of the sand point wells near the lake (well K) was recorded during two brief periods in March-April 1967.

At times the water-level recorders on wells A and B failed to operate for brief periods. Gaps in the record for well A were filled in with reasonable accuracy on basis of the level of the potentiometric surface of the Floridan aquifer at Lake Sherwood. Short gaps in the record of the water level in well B were filled in with reasonable accuracy on basis of occasional tape readings and the trend of other water levels at times when recessions were relatively steady. The water table dropped below the bottom of well B from April 8 to August 17, 1967 and from October 29 to December 31, 1967. No attempt was made to estimate the level of the water table during these periods.

Evaporation from Lake Herrick was estimated from National Weather Service records of pan evaporation at Lisbon, Fla., about 25 miles northwest of the lake; a pan coefficient of 0.85 was used. Rainfall was measured by a weighting-type recording gage.

Data Analysis

The water-level data collected for the study of Lake Herrick covered the same time span (September 1966 to December 1967) as that collected for Lake Sherwood. The water levels at the two lakes followed the same general trend, as is evident from comparison of figures 21 and 26. Lake Herrick was dry from May 22 to July 31, 1967. At Lake Herrick the lake level usually was from 2 to 4 feet (0.6 to 1.2 m) above the potentiometric surface of the Floridan aquifer; however, the potentiometric surface was slightly above the lake level in September 1966 and in August 1967. The water table at well B usually was about 1 to 2 feet (0.3 to 0.6 m) below the level of Lake Herrick but it was slightly above the lake level for a brief time at the start of the study, and possibly again in August 1967. The tendency seemed to be for the potentiometric surface of the Floridan aquifer and the water table at well B to rise above the lake level when water levels were rising rapidly during the rainy season.



EXPLANATION

○A	Observation well.
▲	Lake-level recorder.
--66--	Outline of lake surface at stage 66 feet above sea level.
—100—	Land-surface contour -- Shows altitude of land surface. Contour interval is 10 feet. Datum is mean sea level.
---5---	Line of equal depth to lake bottom. Interval 5 feet. Datum is lake surface at 66 feet above sea level.
—··——··—	Basin boundary.

FIGURE 24.--LOCATION OF LAKE GAGE AND GROUND-WATER OBSERVATION WELLS IN LAKE HERRICK DRAINAGE BASIN.

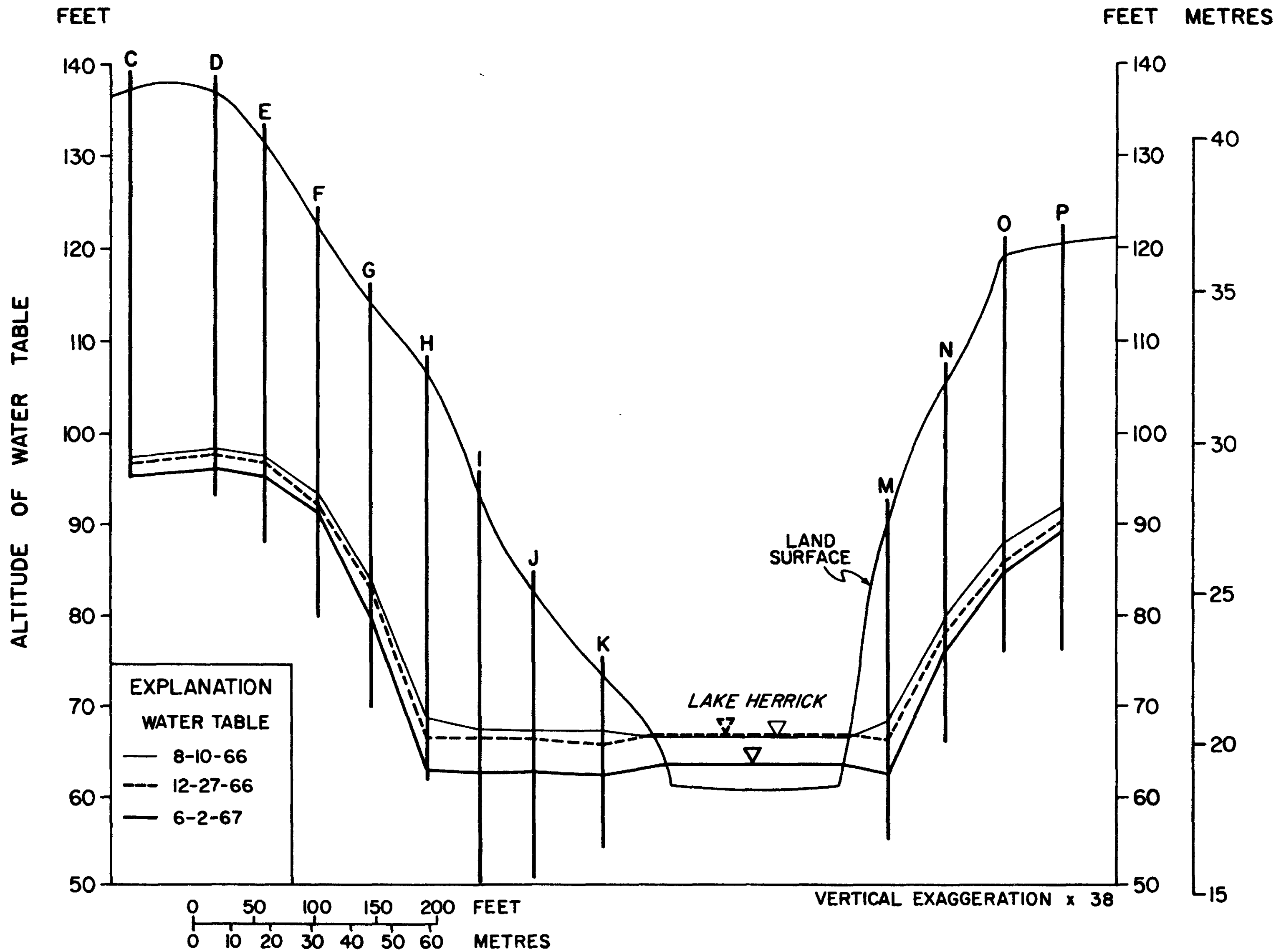


FIGURE 25.--GENERAL SLOPE OF LAND SURFACE AND WATER TABLE ALONG A LINE OF OBSERVATION WELLS AT LAKE HERRICK.

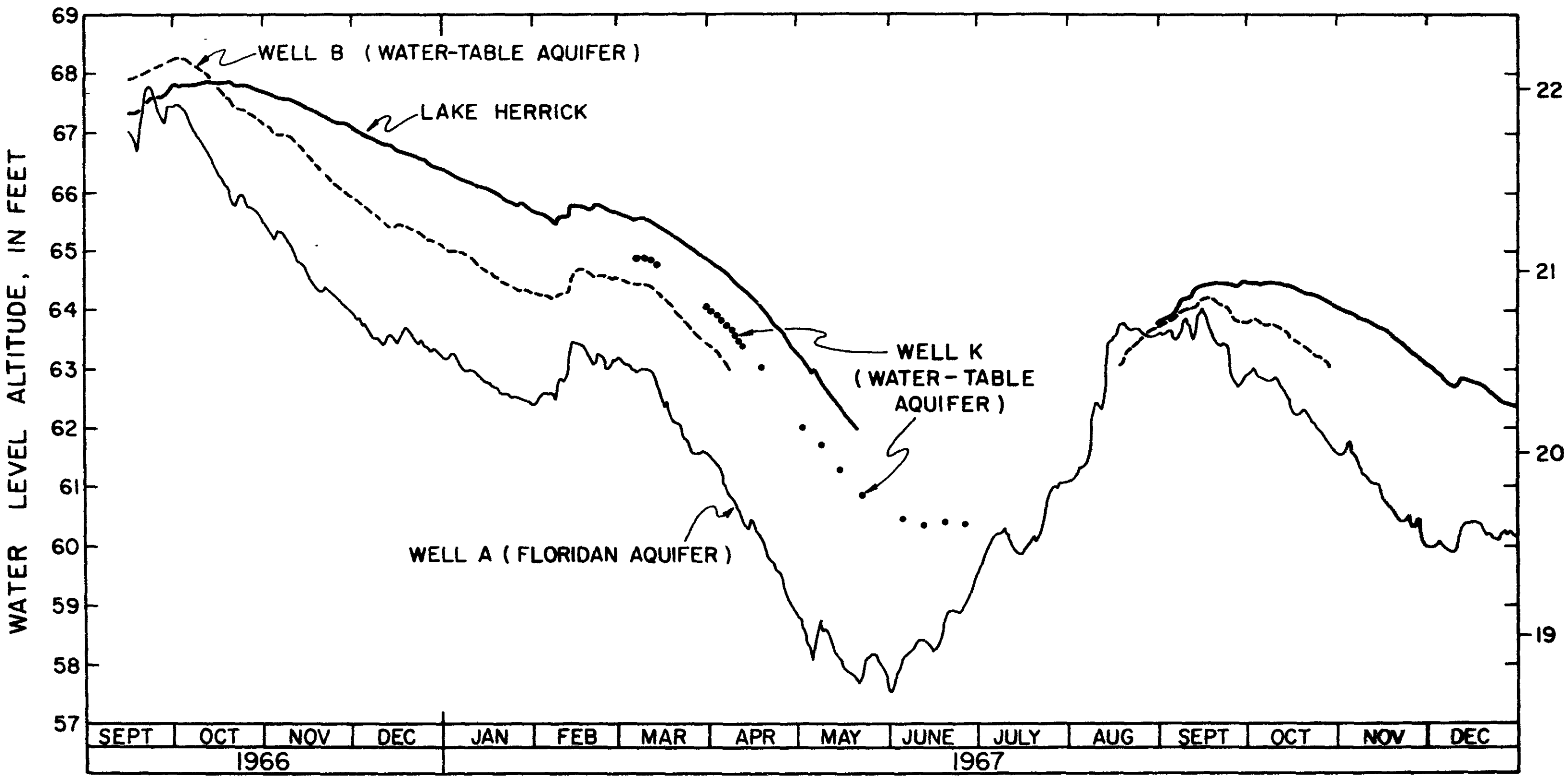


FIGURE 26.--WATER LEVELS OF LAKE HERRICK, WELL A, TAPPING THE FLORIDAN AQUIFER, AND WELLS B AND K, TAPPING THE WATER-TABLE AQUIFER, SEPTEMBER 1966 TO DECEMBER 1967.

On basis of the slope profiles in figure 25, and also the relation between the water levels in wells B and K indicated in figure 26, the water table near Lake Herrick is relatively flat for a considerable distance from the lake on the north, south, and east sides of the lake. As represented in figure 25, the configuration of the water table suggests that within the lake-drainage basin water moves generally from the water-table aquifer towards Lake Herrick, and also, that much of the water moves directly downward from the water-table aquifer to the Floridan aquifer in the area contiguous to the lake where the water table is flat. This suggests that the collapsed zone of the confining bed extends outward from the lake for a considerable distance in some directions, perhaps as much as 1,000 feet (305 m) along the line of observation wells (fig. 25). Within this zone the materials underlying the water-table aquifer and those underlying the lake appear to be about equally conductive for water moving downward to the Floridan aquifer.

Determining Net Seepage

Net seepage into and out of Lake Herrick was determined by the water-budget method for bimonthly periods in the manner described for Lake Johio. Because the lake was dry from May 22 to July 31, 1967, and, also, because the lake-level record was incomplete for most of August 1967, the water-budget computations covered only the periods spanning September 16, 1966 to May 15, 1967, and September 1 to December 31, 1967. The water-budget data are summarized in table 3.

The water-budget data for September 1 to October 15, 1967 (table 3) show that net seepage was into the lake at a time when both the potentiometric surface of the Floridan aquifer and the water-table at well B were below the lake level; consequently, part of the water-level data was adjusted before attempting to compute net seepage by the solution of equation 1.

In September 1967 the potentiometric surface of the Floridan aquifer on the the east side of Lake Herrick (at well A) was only slightly below the level of Lake Herrick. Conceivably, therefore, the potentiometric surface of the Floridan aquifer might have been higher than the lake level somewhere aroud the lake. However, a comparison of figures 21 and 26 suggest that the potentiometric surface of the Floridan aquifer slopes slightly downward from the east side of Lake Herrick to Lake Sherwood, which is about 3/4 mile (1.2 km) west of Lake Herrick. Thus, during this period of concern, the level of the potentiometric surface probably was everywhere below the level of Lake Herrick; hence, the net seepage into the lake could not have been caused by water from the Floridan aquifer.

Table 3.--Water-budget data for Lake Herrick

Period	No. days	Altitude of mean water level			Mean lake area	Mean distance lake to Well B	Pan evaporation	Lake evaporation	Rainfall plus overland flow	Change in lake level	Net seepage by water budget			Adjusted water level Well B minus lake level	X[c]	Y[d]	Net seepage by equation 7
		Lake	Well B	Well A													
		(ft)			(acres)	(ft)	(in)	(ft)	(ft)	(ft)	(ft)	(ft/d)	(ac-ft/d)	(ft)	(ft/ft)	(ft)	(ac-ft/d)
1966																	
Sept. 16 to 30[a]	15	67.57	68.1	67.34	22.3	200	2.49	0.18	0.37	+0.44	+0.25	+0.0167	+0.372	+1.53	+0.00765	-0.23	+0.446
Oct. 1 to 15[a]	15	67.84	68.1	66.95	23.7		2.39	.17	.06	+.07	+.18	+.0120	+.284	+1.26	+.00630	-.89	+.320
Oct. 16 to 31[a]	16	67.78	67.45	65.86	23.4		2.08	.15	0	-.18	-.03	-.0019	-.044	+.67	+.00335	-1.92	+.071
Nov. 1 to 15	15	67.56	66.9	65.09	22.3		1.82	.13	0	-.25	-.12	-.0080	-.178	+.34	+.00170	-2.47	-.065
Nov. 16 to 30	15	67.25	66.2	64.23	20.7		1.89	.13	.01	-.37	-.24	-.0160	-.331	-.05	-.00025	-3.02	-.220
Dec. 1 to 15[a]	15	66.89	65.6	63.63	19.1		1.27	.09	.05	-.33	-.29	-.0193	-.369	-.29	-.00145	-3.26	-.310
Dec. 16 to 31[a]	16	66.56	65.3	63.50	17.7	200	1.19	.08	.01	-.34	-.27	-.0169	-.299	-.26	-.00130	-3.06	-.287
1967																	
Jan. 1 to 15[a]	15	66.24	64.95	63.06	16.5	200	1.36	.10	.05	-.31	-.26	-.0173	-.285	-.29	-.00145	-3.18	-.304
Jan. 16 to 31[a]	16	65.82	64.50	62.60	15.1		1.55	.11	.08	-.36	-.33	-.0206	-.311	-.32	-.00160	-3.22	-.316
Feb. 1 to 15	15	65.65	64.35	62.83	14.8		1.66	.12	.38	+.10	-.16	-.0107	-.158	-.30	-.00150	-2.82	-.283
Feb. 16 to 28	13	65.77	64.60	63.22	15.0		1.69	.12	.08	-.14	-.10	-.0077	-.116	-.17	-.00085	-2.55	-.224
Mar. 1 to 15	15	65.56	64.45	62.97	14.6		2.14	.15	.05	-.27	-.17	-.0113	-.165	-.11	-.00055	-2.59	-.209
Mar. 16 to 31[a]	16	65.11	64.85	61.89	13.7		2.77	.20	.02	-.54	-.36	-.0225	-.308	-.26	-.00130	-3.22	-.298
April 1 to 15[a]	15	64.55	63.0	60.85	12.8		3.61	.26	.02	-.67	-.43	-.0287	-.367	-.55	-.00275	-3.70	-.418
April 16 to 30	15	63.76		59.56	11.6		4.03	.29	.01	-.96	-.68	-.0453	-.525			-3.20	
May 1 to 15	15	62.80		58.42	10.3	200	3.89	.28	.10	-.92	-.74	-.0493	-.508			-4.38	
Sept. 1 to 15[a]	15	64.12	64.0	63.74	12.2	200	2.24	.16	.36	+.60	+.40	+.0267	+.326	+.88	+.00440	-.38	+.240
Sept. 16 to 30[a]	15	64.49	64.1	63.34	12.8		2.75	.19	.07	+.06	+.18	+.0120	+.154	+.61	+.00305	-1.15	+.106
Oct. 1 to 15[a]	15	64.48	63.8	62.90	12.8		2.21	.16	.03	-.10	+.03	+.0020	+.026	+.32	+.00160	-1.58	-.010
Oct. 16 to 31	16	64.28	63.3	62.11	12.4		2.32	.16	.01	-.32	-.17	-.0106	-.131	+.02	+.00010	-2.17	-.142
Nov. 1 to 15	15	63.93		61.36	11.9		2.10	.15	.02	-.40	-.27	-.0180	-.214			-2.57	
Nov. 16 to 30	15	63.43		60.42	11.1		1.68	.12	0	-.54	-.42	-.0280	-.311			-3.01	
Dec. 1 to 15	15	62.92		60.13	10.4		1.34	.09	.17	-.30	-.38	-.0253	-.263			-2.79	
Dec. 16 to 31	16	62.59		60.27	10.1	200	1.49	.11	.02	-.42	-.33	-.0206	-.208			-2.32	

a Data for this period used in determination of coefficients A and B in equation 1.
b Adjusted value is difference between water levels in lake and Well B plus 1 foot.
c "X" is adjusted difference between water levels in lake and Well B divided by the distance from lake to Well B.
d "Y" is difference between water levels in lake and Well A.
Note: The water level in Well B represents the water table; that in Well A represents the potentiometric surface of the Floridan aquifer.

It therefore follows that net seepage into Lake Herrick from September 1 to October 15, 1967, must have been caused by inflow from the water-table aquifer somewhere around the lake. Figure 26 shows that the water table was substantially higher at well K than at well B; thus, conceivably, somewhere around the lake the water table during this period was high enough to cause inflow to Lake Herrick.

In order that the water-level data might be made compatible with net seepage as computed by the water-budget method, the difference between the lake level and the water-level in well B was arbitrarily increased by 1 foot (0.3 m). For the sake of consistency in regard to definitions previously given in connection with equation 1, the adjusted difference in water levels was divided by the 200-foot (61-m) distance between the lake and well B, even though the appropriate distance over which the adjusted difference in levels presumably accrued was indeterminable. In the computations for Lake Herrick the distance between the lake and well B was not varied with lake stage; thus, the same result would have obtained regardless of the distance used to compute the hydraulic gradient between the lake and the water-table aquifer. The equation for estimated net seepage into or out of Lake Herrick resulting from the solution of equation 1 was:

$$S = 60.40 + 0.068\ Y \qquad (7)$$

in which S, X, and Y are as previously defined for equation 1.

Figure 27 compares net seepage as computed by equation 7 with net seepage as computed by the water-budget method for those computational periods when sufficient water-level data were available. Although the adjustment of part of the water-level data was necessary to make the hydraulic gradients compatible with net seepage as computed by the water-budget method, the magnitude of the net seepage as computed from equation 7 is not entirely dependent on the size of the adjustment. If 1.5 feet (0.5 m) rather than 1 foot (0.3 m), had been added to the difference between the lake level and the water level in well B, for example, the solution of equation 1 would have provided different values of the coefficients A and B, but the computed net seepage would have been the same. Inasmuch as the water table was simultaneously above and below the level of Lake Herrick, the two components on the right side of equation 7 do not constitute valid estimates of inflow to the lake from the water-table aquifer and outflow from the lake to the Floridan aquifer.

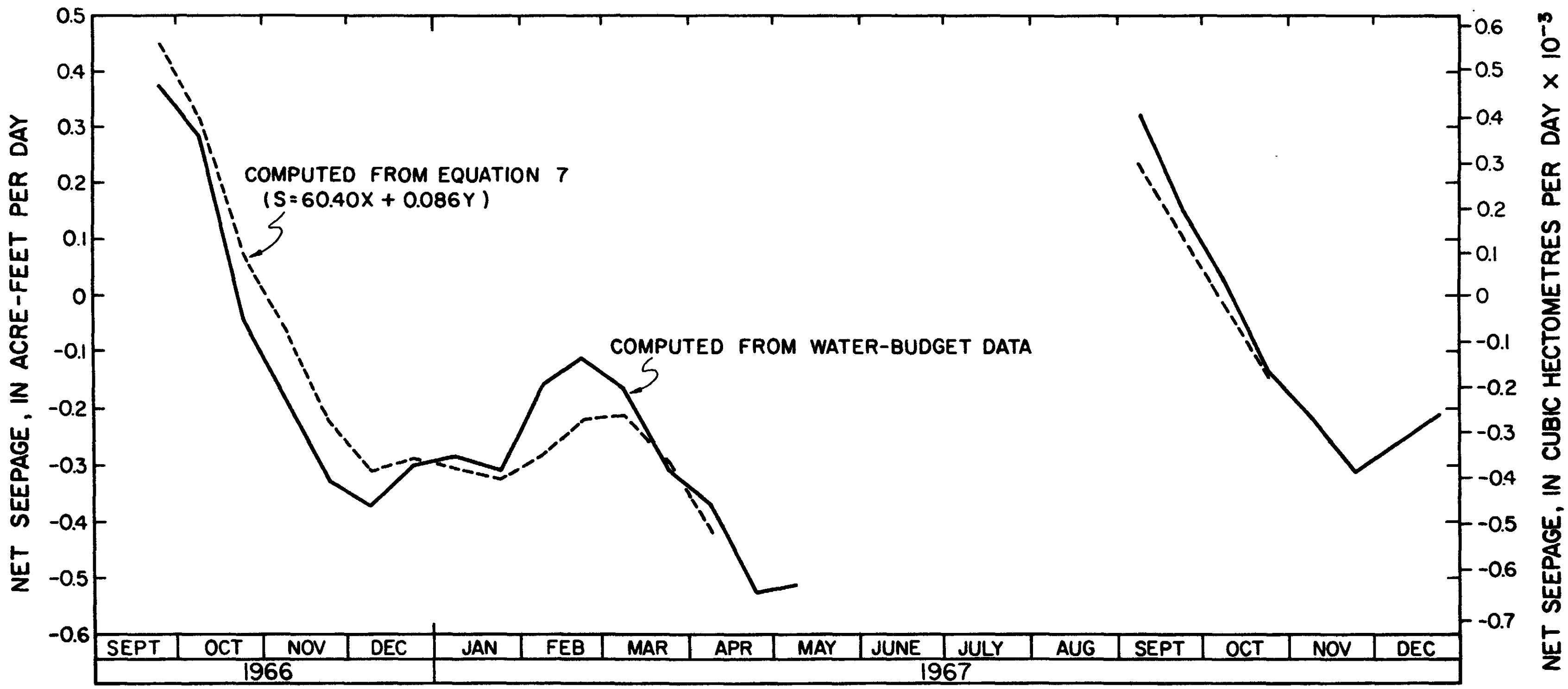


FIGURE 27.--NET SEEPAGE INTO (+) AND OUT OF (-) LAKE HERRICK AS COMPUTED FROM WATER-BUDGET DATA AND AS COMPUTED BY EQUATION 7, SEPTEMBER 1966 TO MAY 1967, SEPTEMBER-DECEMBER 1967.

SUMMARY

The hydrologic relations between lakes and aquifers were documented by hydrologic data collected at three landlocked lakes in a recharge area west of Orlando in 1966-68. The lakes investigated were Lake Johio, the northern part of Lake Sherwood, and Lake Herrick. Data for the three lakes were not entirely concurrent. Rainfall was about normal during the 18-month period when data were collected at Lake Johio, but were less than normal during the 16-month period when data were collected at Lakes Sherwood and Herrick.

In general, the lakes receive water from an adjoining water-table aquifer and lose water to the Floridan aquifer by downward leakage through a collapsed zone in the confining bed beneath the lakes. The lake and ground-water levels follow the same general trend, rising in wet spells and declining in dry spells. Lake levels rise abruptly from rainfall and overland inflow from the drainage basins; overland flow generally is small in these three lake basins because the surficial materials are relatively sandy. At Lake Johio about 8 percent of the abrupt rise in level was attributed to overland inflow.

Ground-water levels also start to rise with rainfall but the response to rainfall is more gradual for aquifers than for lakes. However, the range in water level is greater for the aquifers than for the lakes. Thus, the hydraulic gradient towards the lake from the water-table aquifer tends to increase during wet spells and decrease during dry spells. Inflow to the lake from the water-table aquifer varies accordingly. Conversely, the hydraulic gradient between the lake and the Floridan aquifer decreases in wet spells and increases in dry spells, and the outflow from the lake to the Floridan also varies accordingly.

Water-level conditions varied considerably from lake to lake. At Lake Johio the level of water in a well tapping the water-table aquifer near the lake was always well above the lake level. The lake level in turn was 44 to 50 feet (13 to 15 m) above the potentiometric surface of the Floridan aquifer. The level of Lake Sherwood was only a few feet above the potentiometric surface of the Floridan aquifer and the water table near the lake was sometimes above and sometimes below the lake level. At Lake Herrick the lake level was briefly below the potentiometric surface of the Floridan aquifer during wet spells and during most of the investigation was above the level of water in a well tapping the water-table aquifer near the lake.

Net seepage (the net exchange of water between the lake and adjacent and subjacent aquifers) can be estimated by use of the equation $S = AX + BY$, wherein S is net seepage, X represents the hydraulic gradient between the lake and the water-table aquifer, the coefficient A represents the effect of the hydraulic conductivity and cross-sectional area

of materials in the flow section of the water-table aquifer, Y is the head difference between the lake level and the potentiometric surface of the Floridan aquifer, and the coefficient B represents the effect of the vertical hydraulic conductivity, area, and thickness of materials between the lake bottom and the top of the Floridan aquifer. If values of S, X, and Y are available for each of two contrasting water-level conditions, the coefficients A and B are determinable by the solution of two simultaneous equations. If the pattern of ground-water flow is such that X is always equally representative of the hydraulic gradient between the lake and the water-table aquifer at all points around the lake, and Y is always equally representative of the head difference between the lake and the Floridan aquifer at all points around the lake, the X and Y terms of the equation provide valid estimates of inflow to the lake from the water-table aquifer and outflow from the lake to the Floridan aquifer. For a precise determination of the coefficients A and B, corrections should be made for the variation in the cross-sectional area of the flow section in the water-table owing to fluctuations in the level of the water table especially if the range of the water-table level represents a sizable proportion of the saturated thickness of the aquifer--and, also, for variation in the hydraulic conductivities of the water-table aquifer and of the materials between the lake bottom and the top of the Floridan aquifer owing to variations in temperature (and, hence, viscosity) of the shallow ground water and of the lake.

Most of the recharge to the Floridan aquifer from the 240-acre (97-ha) drainage basin of Lake Johio apparently moves through Lake Johio. Much of the recharge to the Floridan aquifer from the 268-acre (108-ha) drainage basin of the northern part of Lake Sherwood and from the 300-acre (121-ha) drainage basin of Lake Herrick either moves through these lakes or moves downward directly from the water table in the immediate vicinity of these lakes where the collapsed zone of the confining bed apparently extends outward for some distance from the lakes. Because the hydrologic conditions at these three selected lakes do not necessarily span the full range of conditions existing at other lakes in the recharge area, the inferences drawn herein cannot be expected to apply in full to all other lakes in the area.

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