STATE OF FLORIDA
STATE BOARD OF CONSERVATION

DIVISION OF GEOLOGY
Robert O. Vernon, Director

REPORT OF INVESTIGATIONS NO. 49

HYDROLOGIC EFFECTS OF GROUND-WATER PUMPAGE IN THE PEACE AND ALAFIA RIVER BASINS, FLORIDA, 1934-1965

By
Matthew I. Kaufman

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT
and the
DIVISION OF GEOLOGY

1967

FLORIDA STATE BOARD OF CONSERVATION

LETTER OF TRANSMITTAL

Division of Geology
Tallahassee
July 27, 1967

Honorable Claude R. Kirk, *Chairman*
State Board of Conservation
Tallahassee, Florida

Dear Governor Kirk:

The Division of Geology, of the State Board of Conservation, is publishing in its regular series of publications a report prepared by Matthew I. Kaufman entitled "Hydrologic Effects of Ground-Water Pumpage in the Peace and Alafia River Basins, Florida, 1934-1965.

This report was prepared as part of the cooperative program to study the water resources of Florida in cooperation with the United States Geological Survey.

The pollution problems of the Peace and Alafia rivers have become alarmingly large. This study was undertaken to try to relate the reaction of surface streams to ground water pumpage and to understand the cause of lowered artesian water levels and the effacts on the total hydrologic system. It was found that there was opportunity for an upward migration of saline water from the subsurface; that a dewatering of the subsurface resulted in the formation of sinkholes; that there were increased costs due to a loss of suction and increased pumping lifts; and that some sections of the rivers changed from ground water discharge to ground water recharge.

The facts developed in this study will be needed in the full understanding of the total hydrologic system of this area.

Respectfully yours,

Robert O. Vernon
Director and State Geologist

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HYDROLOGIC EFFECTS OF GROUND-WATER PUMPAGE IN THE PEACE AND ALAFIA RIVER BASINS, FLORIDA, 1934-1965

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ABSTRACT

Accelerated industrial and agricultural growth in the Peace and Alafia River basins, east-southeast of Tampa, Florida, has led to an increased use of water from the Floridan aquifer, causing a progressive decline of artesian water levels. The largest declines underlie the phosphate industrial area of southwest Polk County, where concentrated pumpage has lowered artesian water levels more than 50 feet since 1934.

A regional decline of artesian levels, centered in the phosphate industrial complex, and extending over an area of approximately 1,000 square miles, has deepened and has expanded until it presently (1965) reaches the ridge and sinkhole lake region to the northeast. Preliminary evidence indicates retardation of the growth of the cone in this direction, probably as a result of recharge from the lakes. Pumpage from the Floridan aquifer has increased the hydraulic gradient between the lake surfaces and the piezometric surface and may be responsible in part for lowered lake levels in this area.

Additional effects of lowered artesian water levels on the hydrologic system include: (1) loss of suction and increased pumping lifts in wells; (2) reversal of hydrologic conditions along the Peace River between Bartow and Ft. Meade in Polk County from one of discharge from the Floridan aquifer in 1934 to one of potential recharge in 1965; (3) opportunity for upward migration of the saline-fresh water interface; and (4) collapse of the subsurface resulting in the formation of sinkholes. A quantitative evaluation of the Floridan aquifer within the Peace and Alafia basins, especially in the heavily pumped areas, is needed in order to provide information required to develop efficiently the water resources.

INTRODUCTION

PURPOSE AND SCOPE

The Floridan aquifer, composed of formations of Tertiary age, is the major source of water in the Peace and Alafia River basins in west-central Florida. Within the basins, the increasing needs of industry, agriculture, and municipalities have resulted in an increasing rate of withdrawal of water from the artesian Floridan aquifer. Ground-water pumpage increased approximately tenfold during the period 1934-65. An estimated minimum rate of withdrawal of 350 mgd (million gallons per day) in 1965 attests to the importance of the ground-water resources to the growth and economy of the Peace and Alafia River basins. Located within the basins are one of the major phosphate industrial complexes in the United States, numerous citrus canning plants, and extensive citrus acreage.

The long-term pumpage increase in the Peace and Alafia River basins has resulted in declines of artesian water level over most of the area. The largest declines are centered in the phosphate industrial complex of southwestern Polk County, where pumpage has lowered artesian water levels more than 50 feet since 1934.

Phenomena which occurred in the northeastern Peace River basin in the spring of 1965 and which may be closely related to the heavy ground-water pumpage and declining artesian water levels include lowered lake levels, occurrence of sinkholes, and the loss of suction in wells in the Floridan aquifer. Questions which arise include the adequacy of the long-term water supply, future trends in ground-water conditions, and the effects on the hydrologic system of a progressively increasing demand for ground water.

The purposes of this report are to: (1) determine the effects of ground-water pumpage on the hydrologic system for the period 1934-65, with special reference to artesian water levels; (2) determine the areal pattern and magnitude of seasonal water-level fluctuations and long-term water-level trends; (3) predict possible future trends in ground-water conditions; (4) portray some of the hydrologic effects of lowered artesian water levels with respect to lake levels, sinkhole occurrence, position of the saline-fresh water interface, and (5) provide hydrologic information that will assist in the planning and development of the area's water resources and which will serve as a brief hydrologic background for more detailed studies, such as a quantitative evaluation of the aquifer system.

This report is not an intensive study, but rather a summary in order to portray the problem and help determine what additional information is needed to insure the maximum development and utilization of the area's abundant water resources.

The investigation was carried out in cooperation with the Alafia and Peace River Basin Boards of the Southwest Florida Water Management District as part of the cooperative program with the Division of Geology, Florida Board of Conservation, to evaluate the water resources of Florida.

The investigation was under the direct supervision of J. W. Stewart, Hydrologist-in-Charge of the U. S. Geological Survey Tampa Field Office, and under the general supervision of C. S. Conover, District Chief, Water Resources Division, U. S. Geological Survey, Tallahassee, Florida.

ACKNOWLEDGMENTS

The author is grateful to L. Johnson, consultant to the Southwest Florida Water Management District, and to W. S. Wetterhall, J. W. Stewart, R. N. Cherry, and N. P. Dion of the U. S. Geological Survey for helpful advice and suggestions in the preparation of this report.

Special thanks are extended to the phosphate companies for their cooperation in furnishing pumpage data. Appreciation is expressed to the U. S. Department of Agriculture, Florida Citrus Mutual, and the various county agents for their assistance in determining the total and irrigated citrus acreage figures, and to the city of Lakeland and other municipalities for providing pumpage data.

The author also wishes to thank the many well owners who allowed access for water-level measurements. Without the cooperation of those mentioned above, this report would not have been possible.

LOCATION AND EXTENT OF AREA

The Peace and Alafia River basins, east-southeast of Tampa, encompass an area of approximately 3,000 square miles in west-central Florida, figure 1. The basins include parts of Polk, Hillsborough, and Charlotte counties and all of Hardee and DeSoto counties. The Peace and Alafia River basins are part of the Southwest Florida Water Management District and their boundaries approximate the natural drainage basin divides.

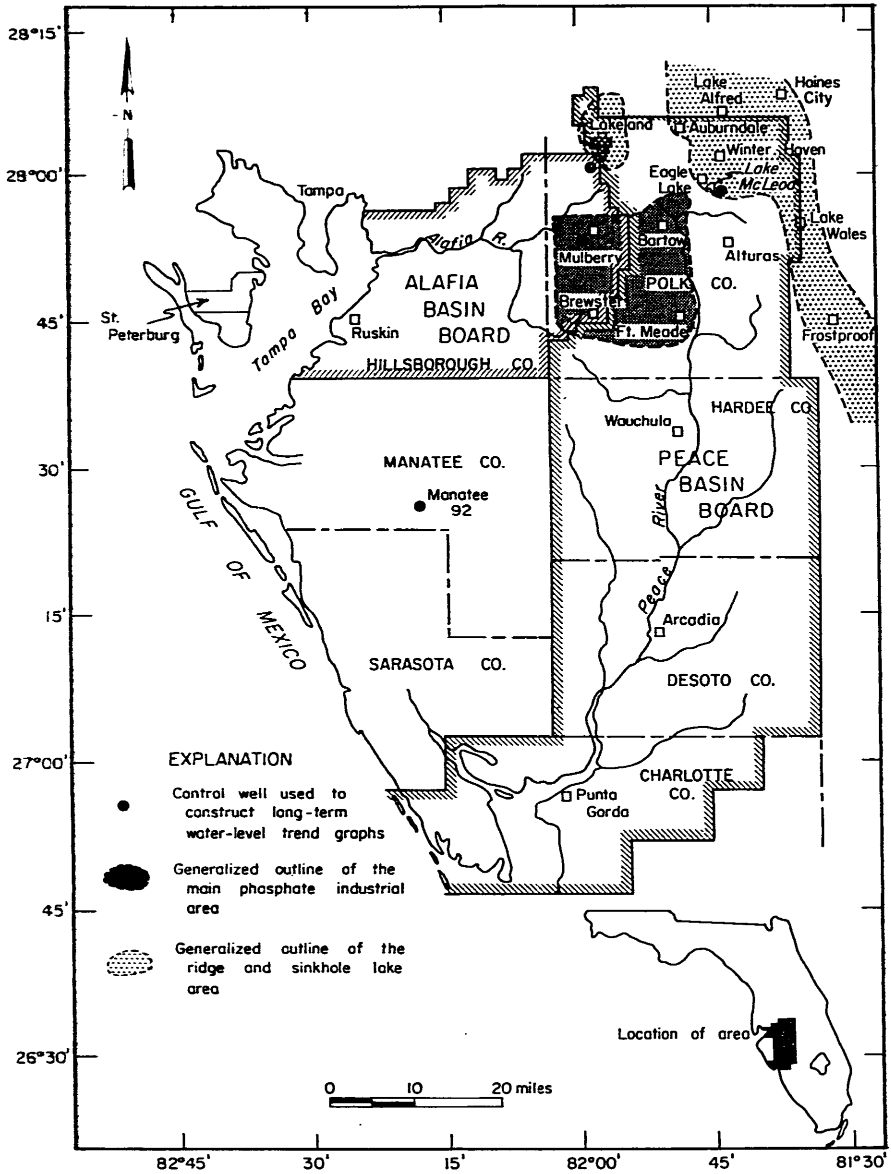

Figure 1.—Location of area, control wells, and generalized outline of main phosphate industrial area, and ridge and sinkhole lake area.

Shaded patterns show the generalized outlines of the ridge and sinkhole lake region, believed to be a major source of recharge for the Floridan aquifer in this area, and the area of the main phosphate industrial complex, representing an area of heavy ground-water withdrawals from the Floridan aquifer.

SOURCE OF WATER AND MAGNITUDE AND TRENDS OF GROUND-WATER PUMPAGE

The Floridan aquifer, one of the most productive in the United States, is the major source of water in the report area. The aquifer is composed of about 1,000 feet of limestone and dolomite, consisting of several geologic formations which range in age from Eocene to Miocene.

Throughout most of the area, these formations act as a gross aquifer system. Formations included within the aquifer are the upper part of the Lake City Limestone, the Avon Park Limestone, the Ocala Group (Crystal River, Williston, and Inglis Formations), the Suwannee Limestone, the Tampa Formation, and the lower part of the Hawthorn Formation. The nomenclature used in this report is that of the Florida Geological Survey and not necessarily that of the U. S. Geological Survey.

The major water-producing formation within the aquifer in the Peace and Alafia River basins is the Avon Park Limestone. Wells penetrating this formation yield as much as several thousand gpm (gallons per minute). For recent geologic and hydrologic discussions pertaining to parts of the report area and immediately adjacent areas, see Bishop (1956), Menke, et al (1961), Pride, et al (1966), and Stewart (1966).

Ground water is estimated to account for approximately 90 per cent of the water used in the Peace and Alafia River basins. A partial inventory of water users, which included municipalities, irrigators of citrus, and phosphate industries, indicated an average ground-water use of approximately 350 mgd (million gallons per day) in 1965. The 350 mgd does not include water used for the citrus canning industry, other industries, irrigation (excluding citrus), and domestic use, and hence represents a minimum figure for total water use in the basins.

Owing to the seasonal nature of ground-water pumpage by irrigators of citrus, by municipalities, and by the canning industry, the quantity of water used may vary considerably for any given period. The municipal water use of about 27 mgd in 1965 accounts for less than 8 per cent of the minimum total ground water used in the area.

Increases in citrus acreage, phosphate rock production, and municipal use from 1934 through 1965 have resulted in large increases in ground-water withdrawals as shown in figure 2. The city of Lakeland uses about 50 per cent of the total ground water pumped by municipalities in the Peace and Alafia River basins. The insignificance of the municipal demand with respect to the ground-water demands of industry and agriculture is readily seen in figure 2.

The phosphate rock production data are from Florida Board of Conservation biennial reports and U. S. Bureau of Mines Minerals Yearbooks, and represent production for the entire State of Florida. However, the bulk of the State's phosphate is mined and produced within the Peace and Alafia River basins, and the data are believed to be a good measure of the production in these basins.

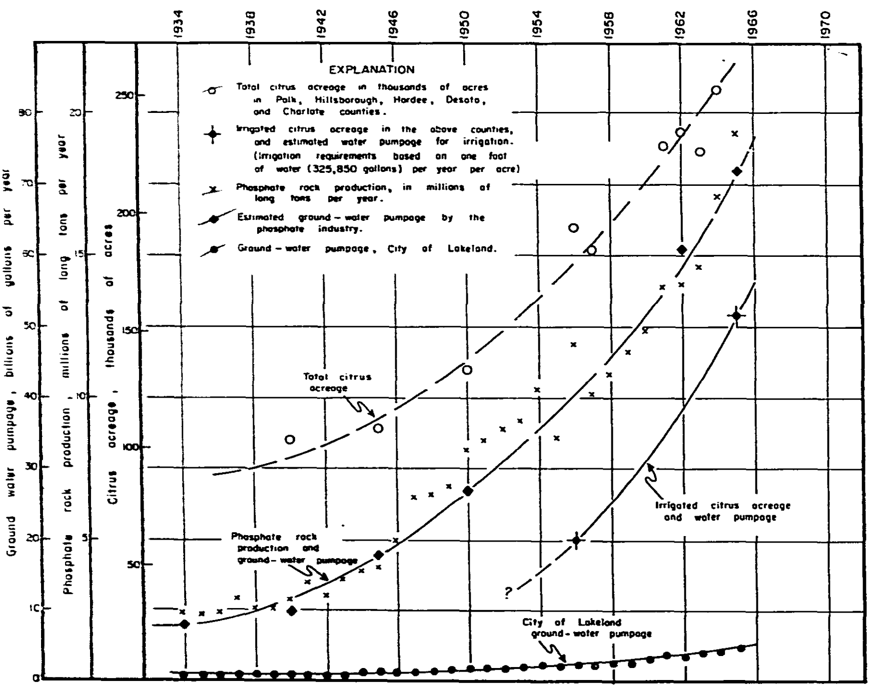

Figure 2.—Total and irrigated citrus acreage, phosphate rock production, and estimated ground-water pumpage—1934 to 1965.

The estimated ground-water pumpage by the phosphate industry from 1934 to 1950 is after Peek (1951, p. 79). The pumpage data for 1962 was furnished by the phosphate industry. The accuracy of the pumpage estimates is shown by the close agreement of the rock production curve and the ground-water pumpage curve. On the basis of these curves, the production of 1 million long tons of phosphate requires approximately 4 billion gallons of ground water under present operating conditions; that is, processing of 1 long ton of phosphate rock requires 4,000 gallons of ground water. Ground water use by the phosphate industry has increased from about 8 bgy (billion gallons per year) in 1934 to about 72 bgy in 1965.

In a recently published study (Florida Board of Conservation, 1966) water use data for the area under discussion are reported. Polk County is shown to have the highest industrial use of water. The high demand for water reflects the presence of the phosphate and electric power generating industries. Total industrial water use in Polk County was reported to be 133.5 bgy (366 mgd) in 1962. Most of this use of water occurs within the Peace and Alafia River basins. According to the Florida Board of Conservation, projection to 1980 indicates an industrial water use of 316 bgy (868 mgd), an increase of 2.3 times the 1962 demand.

Estimates of water requirements for citrus irrigation vary. According to personnel at the citrus experiment station in Lake Alfred, an average of 1 foot of water per acre (325,850 gallons) per year is required for irrigation. This figure is based on studies covering different kinds of citrus and soil types, including soil moisture tests to determine the optimum requirements (Johnson, 1965). Based on data compiled by the Soil Conservation Service (U. S. Department of Agriculture, 1965), 1.95 acre feet of water per acre is used for citrus irrigation under average conditions in west-central Florida. The water-use data for irrigated citrus acreage shown in figure 2 are based on the value of 1 acre foot per acre. An estimated 82 per cent of the water used for citrus irrigation is derived from ground-water sources, and the remaining from surface-water sources. Water use for citrus has increased from about 20 bgy in 1956 to about 52 bgy in 1965. According to the Soil Conservation Service, the projected agricultural water use by 1980 will be 2.4 times the present (1965) demand in the 5-county area included in the Peace and Alafia River basins, or approximately 125 bgy. As parts of Polk and Hillsborough counties lie outside the Peace and Alafia River basins, the quantities presented above are too large, however, the trends are significant.

The total fresh water use by industry, agriculture, and municipalities within the Peace River basin during 1963 was estimated at 196 bgy (Florida Board of Conservation, 1966). In addition, projections to 1980 indicated a total water use of 478 bgy, an overall increase of approximtely 2.4 times over the 1963 water use.

With respect to the availability of water in Polk County, Stewart (1966, p. 119) states:

> "The tabulation of recharge to the limestone aquifers in 1959 shows that runoff exceeded recharge in the various drainage basins by amounts ranging upward from a factor of 3. Thus it is clear that the water available for recharge is vastly more than that required by the ground-water system to supply present (1959) demands."

It must be borne in mind in evaluating the above statement that 1959 was the wettest year on record during the past 30 years, with rainfall almost 20 inches above normal over the basins as a whole and almost 27 inches above normal at Bartow, site of one of the gaging stations in Polk County; consequently, conditions in 1959 did not represent a picture of long-term average conditions. Runoff was excessive and ground-water pumpage was considerably reduced.

In contrast to Stewart's conclusions, the Florida Board of Conservation (p. 146, op. cit) using the assumption that water available for use is equal to the runoff from the basins, and using the total industrial, agricultural, and municipal water use states:

> "The most critical water short area indicated by these studies appears to be the Polk County area where approximately 860 mgd will be available. The projected water need for the area is 1,200 mgd for 1980 .... This would mean a water shortage in the area of 340 mgd by 1980 .... "

In summary, the above discussion and figure 2 illustrate the increasing rate of ground-water withdrawal in the Peace and Alafia River basins during the period 1934-65 and point out the expected increases in demand in the future. A correlation between ground-water use and phosphate production and citrus acreage is shown to exist.

HYDROLOGIC EFFECTS OF THE INCREASING WITHDRAWAL OF GROUND WATER

LONG-TERM ARTESIAN WATER-LEVEL TRENDS AND SEASONAL WATER-LEVEL FLUCTUATIONS

Within the Peace and Alafia River basins, artesian water levels show a declining trend attributable to the increasing withdrawal of ground water from the Floridan aquifer. Hydrographs of wells tapping the Floridan aquifer in four areas are plotted in figure 3. Only the annual high and low water levels are plotted. These hydrographs depict the long-term declines of ground-water levels in four selected areas (Eagle Lake, Lakeland, Mulberry, and south-central Manatee County) for the period 1934 to 1965. Water-level data were compiled from Stringfield (1936), and U. S. Geological Survey and U. S. Army Corps of Engineers records. Locations of the wells are shown in figure 1.

Examination of the hydrographs indicate that the annual rate of ground-water level decline is progressively increasing. The period 1957-60 was a notable exception to the general downward trend in water level. Water levels generally rose from their 1956 lows and remained relatively steady. The rise was due primarily to excessive rainfall and consequent increased recharge and concomitant decreased demand for ground water. Stewart (1966, p. 104) concluded that pumpage was nearly equal to recharge in southwestern Polk County in 1959-60. At the end of the wet cycle, water levels again declined. By the spring of 1965, water levels at Lakeland and Mulberry were considerably below their 1956 levels.

In order to better assess the effects of precipitation on water levels, three records of long-term rainfall are plotted in figure 4. Calculations of average rainfall for three successive 10-year periods are as follows:

Station	10-Year Period	Average Rainfall in Inches
Lakeland	1935-44	49.3
	1945-54	50.9
	1955-64	49.5
Bartow	1935-44	52.3
	1945-54	55.9
	1955-64	58.4

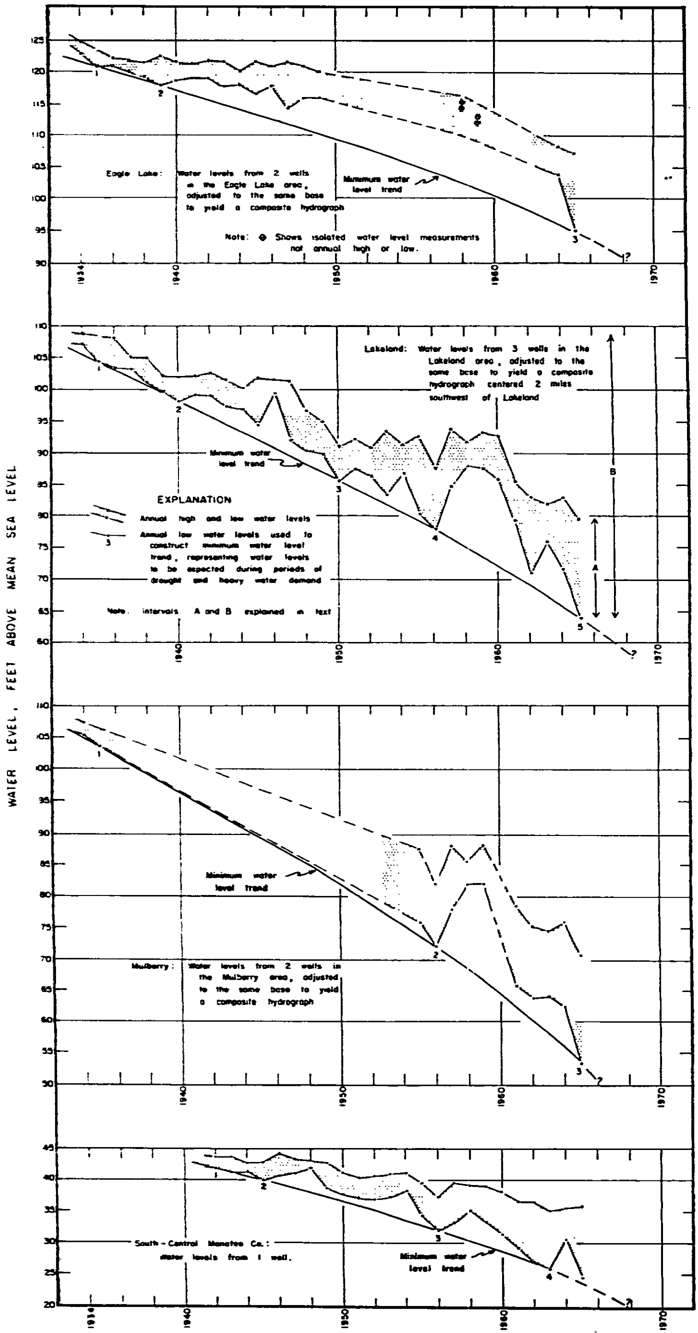

Figure 3.—Long-term water-level trends in four selected areas—1934 to 1965.

Brewster	1935-44	53.0
	1945-54	54.4
	1955-64	54.6

Figure 4 and the above data indicate that although the rainfall is highly erratic from year to year or for a series of years to series of years, no apparent long-term change in rainfall has occurred during the past 30 years. Deficient precipitation thus is not a major cause for long-term declines of the artesian water levels. The cyclic wet and dry periods, however, contribute to short-term water-level fluctuations, as evidenced by the sharp rise in ground-water levels during the 1957-60 wet period following the dry period of 1954-56.

As brought out by Stewart (1966), observed declines of artesian water levels do not necessarily constitute dewatering of the aquifer. Nevertheless, water is being removed from the aquifer and the overall effects on the hydrologic system of the lowered artesian water-levels must be taken into account.

Periods of severe drought are associated with greatly increased water demand and consequent lowering of water levels. These periods of drought are the most critical for the water user. The numbered points on figure 3 represent the annual low-water levels which occurred during drought periods. Connecting these points results in "minimum water-level trends." By projecting these trends, an estimation of the low ground-water levels to be expected during future critical periods of peak water demand may be obtained.

The minimum annual water-level data presented in the above graphs along with data from three other areas are listed in table 1.

The magnitude of the annual water-level fluctuations has increased with time for most of the wells studied, reflecting the increased effect of seasonal pumpage on the hydrologic system.

The seasonal relation between rainfall, pumpage, and ground-water levels in the Lakeland area is shown in figure 5. The correlation between water level and pumpage appears to be better than that between water level and rainfall. The amount of rainfall probably affects the magnitude of pumpage in the area; increased rainfall resulting in decreased pumpage and vice-versa. Water levels in turn respond most directly to pumpage. A rise in water level corresponds primarily to reduced pumpage and a lowering of water level to increased pumpage.

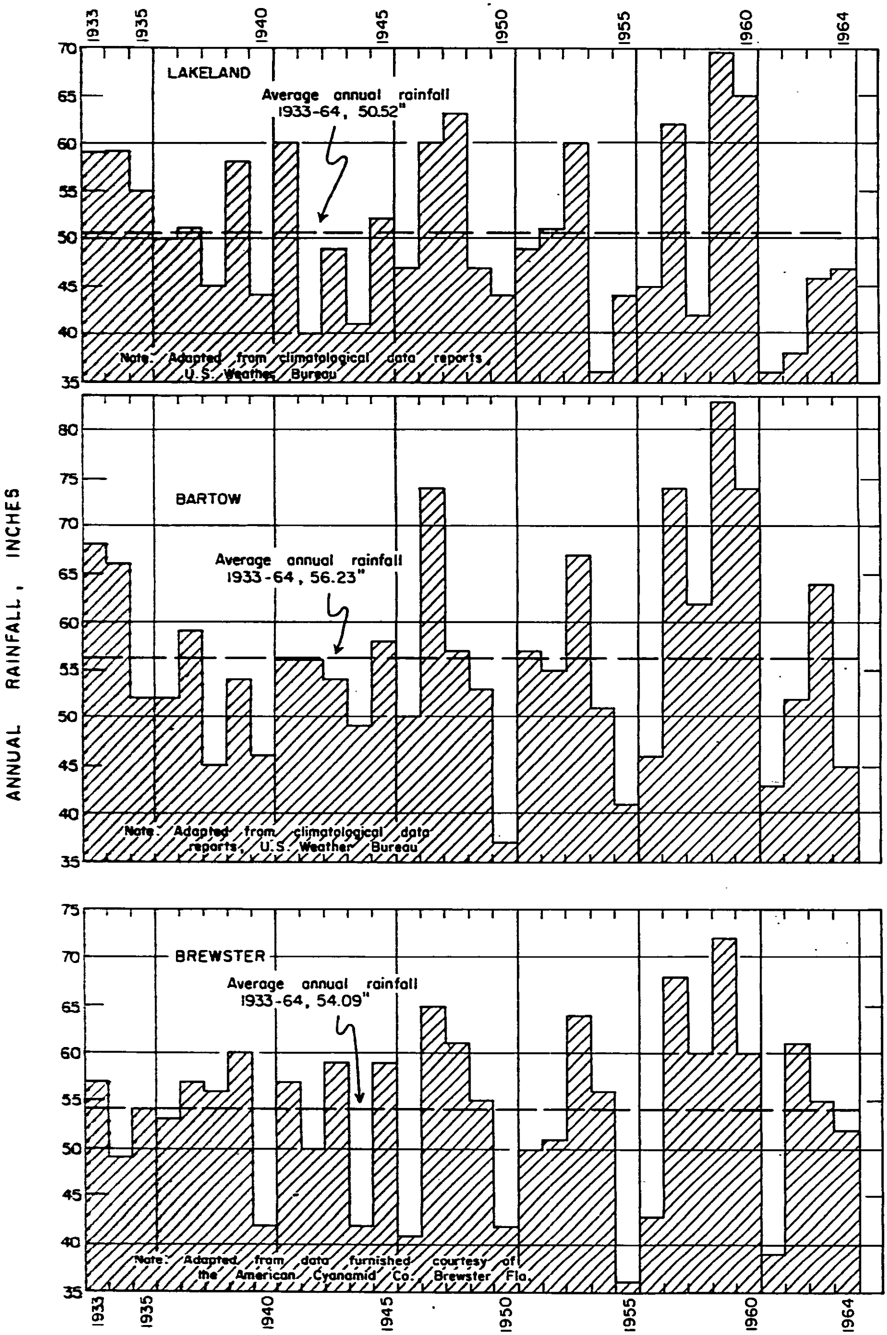

Figure 4.—Annual rainfall at Lakeland, Bartow, and Brewster—1933 to 1964.

Table 1.—Minimum ground-water levels in feet above sea level.

Year	Eagle Lake	Alturas	Lakeland	Mulberry	Brewster	Frostproof	S.-Central Manatee Co.
1934/35	121	112[1]	105	104	101	92	—
1939/40	118	—	98	—	—	—	—
1942	—	—	—	—	—	—	42
1945	—	—	—	—	—	—	40
1950	—	—	86	—	—	—	—
1953	—	—	—	—	—	84	—
1955/56	—	87	78	72	72	83	32
1963	—	—	—	—	—	—	26
1965	95	68	64	53	54	78	—

[1] Estimated from 1934 piezometric map.

The areal pattern and magnitude of seasonal water-level fluctuations for 1965, as exemplified by extremes in water-level fluctuations, is shown in figure 6. The fluctuation represents the general seasonal fluctuation of levels which is a reflection of changes in pumpage and recharge and not a change in water level from non-pumping to pumping levels (drawdown) in pumped wells. The magnitude of the fluctuations is greatest in the highly developed central area. Figure 6 was constructed by taking the difference between the highest and lowest water levels in 1965 in selected wells as illustrated by interval A on figure 3.

The range in fluctuations reflects primarily the influence of seasonal pumpage for irrigation and for municipal use. As the amount of pumpage is expected to increase, the magnitude of the annual fluctuations also is expected to continue to increase.

AREAL PATTERNS OF LONG-TERM ARTESIAN WATER-LEVEL CHANGES

The areal effects of ground-water withdrawal can be portrayed by changes in the piezometric surface over a period of time. (The piezometric surface is an imaginary surface that coincides with the static water level in the artesian aquifer). Figure 7 is a map

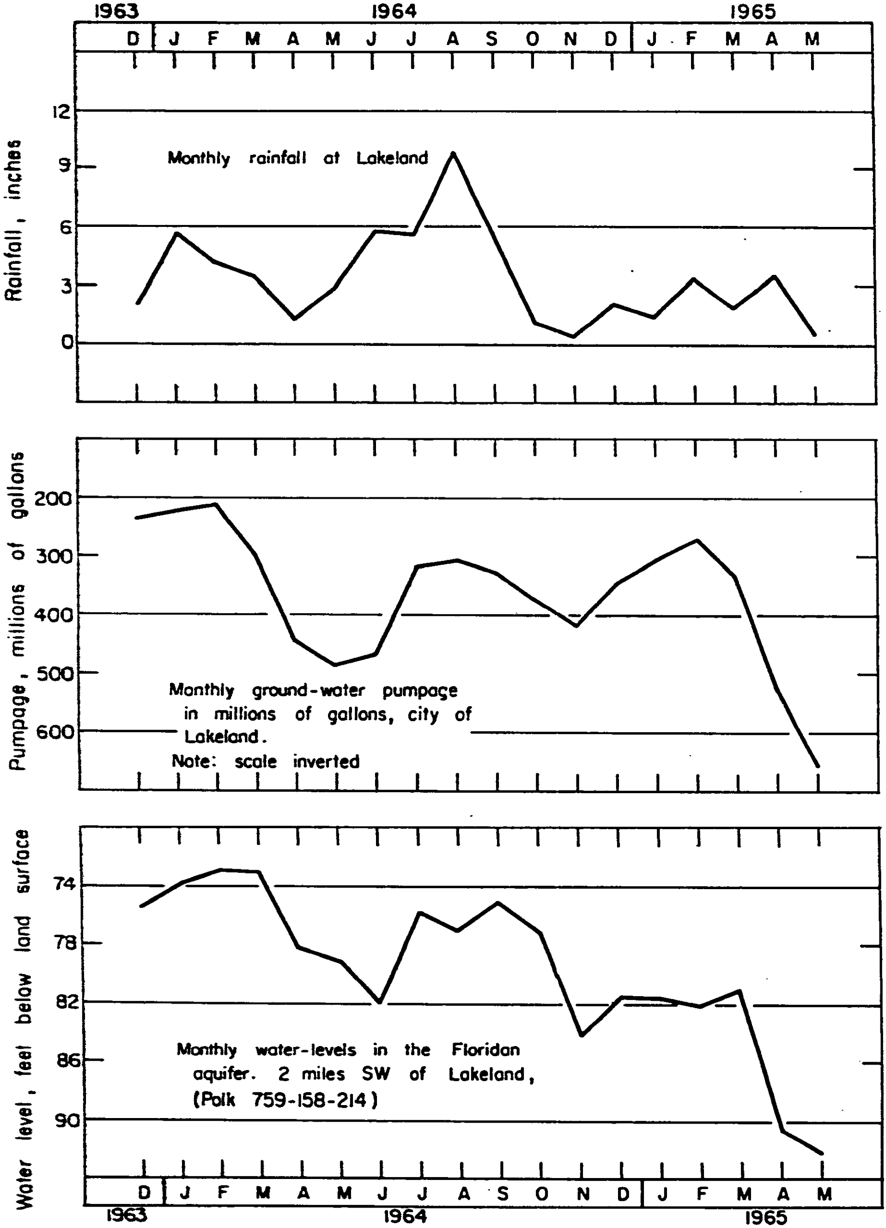

Figure 5.—Rainfall, pumpage, and ground-water levels in the Lakeland area (December 1963-May 1965).

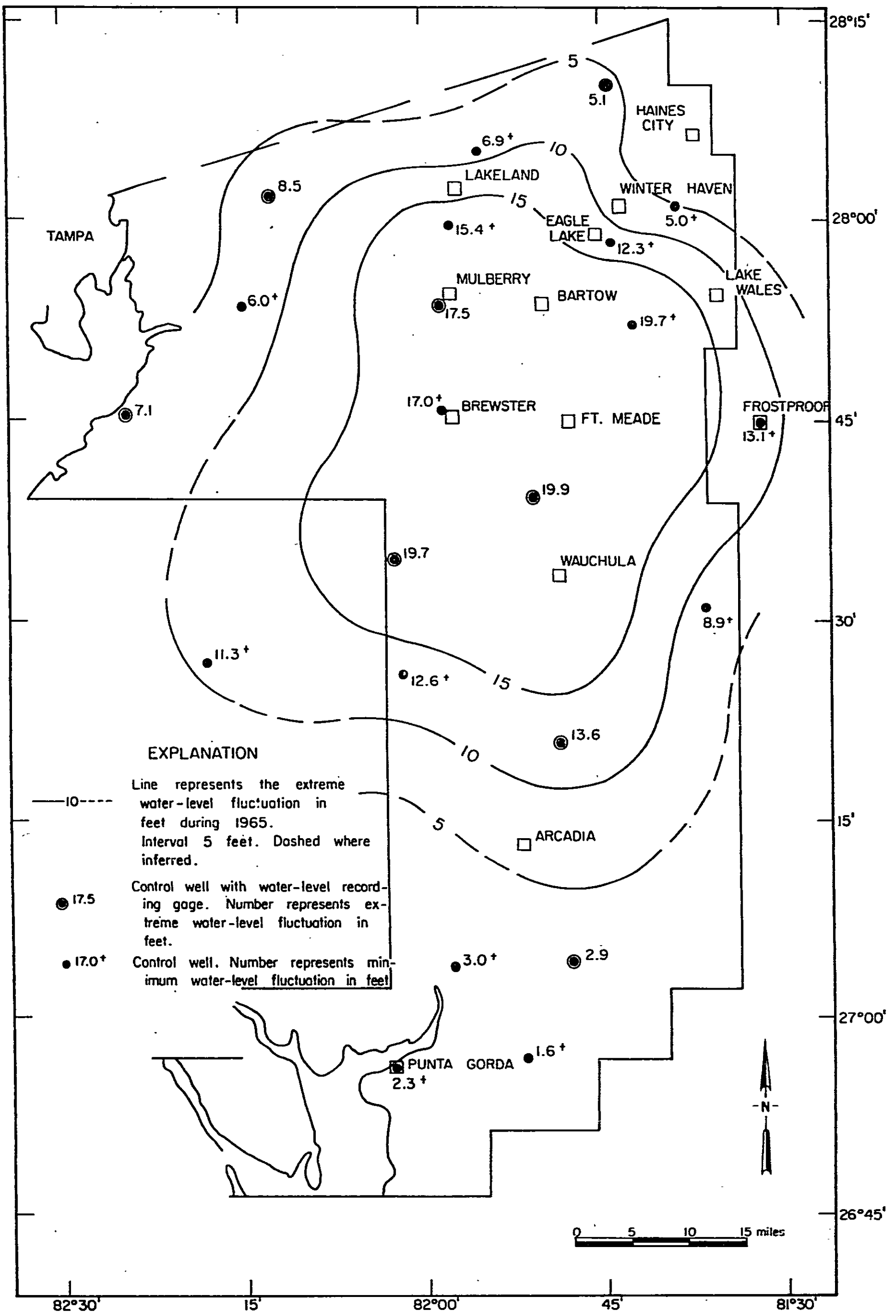

Figure 6.—Extremes in fluctuation of water levels in the Floridan aquifer, 1965.

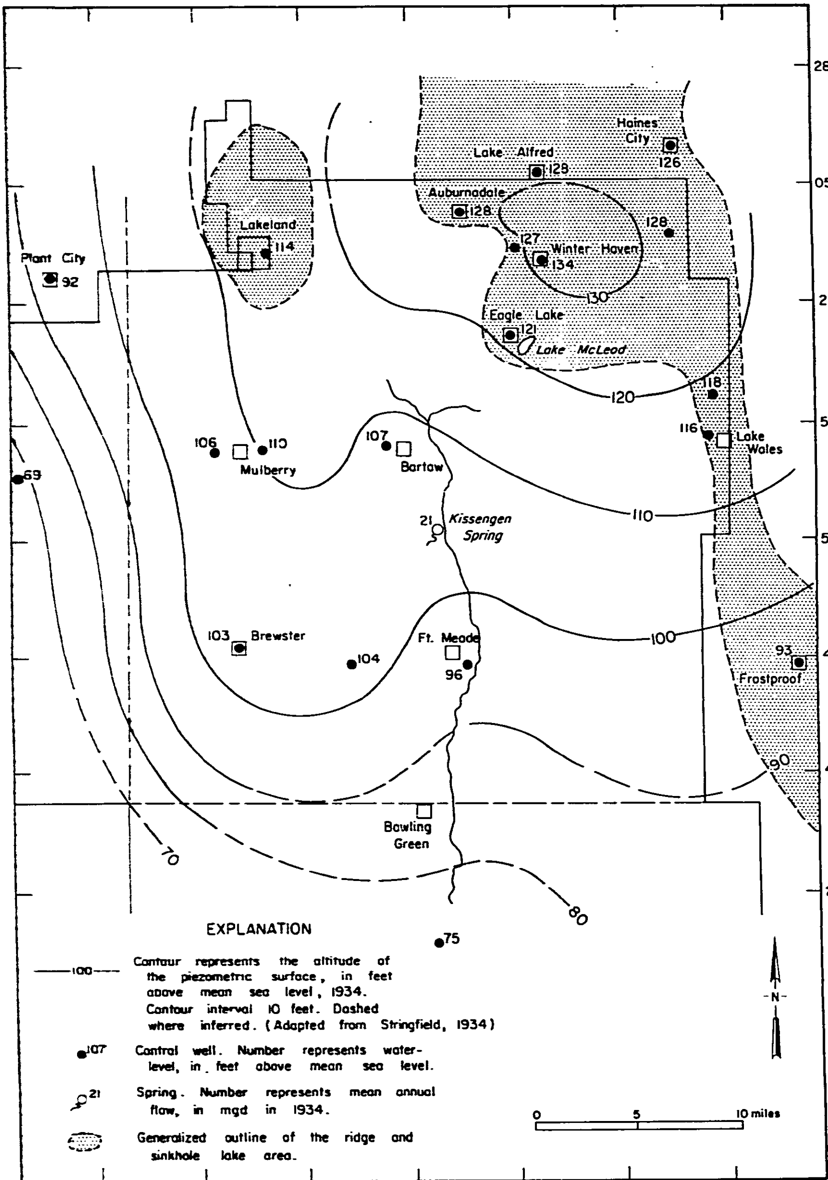

Figure 7.—Piezometric surface of the Floridan aquifer in southwest Polk County—1934.

of the piezometric surface in 1934 (after Stringfield, 1936) before significant development of the aquifer occurred. This figure shows a piezometric-high centered near Winter Haven. Stringfield (1936) considered that the piezometric-high and sinkhole lake region represented a major recharge area for the Floridan aquifer. The direction of ground-water flow is generally downgradient, perpendicular to the contours in an isotropic aquifer.

The piezometric surface in early May 1965 and major centers of ground-water pumpage (greater than 5 mgd) are shown in figure 8.

A comparison of figure 8 with figure 7 shows the persistence of the piezometric high near Winter Haven and a sharpening of a ridge, or ground-water divide, running from Lake Alfred to Frostproof. The piezometric high and ground-water divide underlie the sinkhole lakes and indicate the ridge and sinkhole lake area to be a major source of recharge to the Floridan aquifer in the Peace and Alafia River basins. Under natural conditions, ground water moves through an aquifer from areas of recharge, where water levels are high, to areas of discharge, where water levels are low. In general, the average rate of movement is slow, possibly a few feet per day, and is controlled by the permeability of the aquifer materials, by the temperature of the water, and by the hydraulic gradient, or slope, of the piezometric surface. Additionally, in limestone aquifers, progressive solution enlarges the subsurface conduits, thus changing the flow characteristics of the water. According to Stewart (1966), horizontal flow through fracture controlled cavern systems may result in troughs in the piezometric contours due to the reduction of pressure head.

The piezometric high and the southeastward trending ground-water ridge extend into Highlands County underlying the Highlands Ridge. According to Bishop (1956), the entire ridge section of Highlands County is in the recharge area for the Floridan aquifer; he states (p. 60) ". . . . . Most of the recharge to the aquifer occurs north of Sebring (located 20 miles southeast of Frostproof). Cuttings from wells in the area north of Sebring indicate that the beds overlying the limestones of the Floridan aquifer are thin and fairly permeable. The recharge area extends northward into Polk County where the principal recharge to the aquifer occurs." Stewart (1966 p. 72) reports "the entire length of the Lake Wales Ridge in this county is packed with and flanked by innumerable closed basin lakes. There are also many sinkhole basins without lakes . . . . It seems likely that

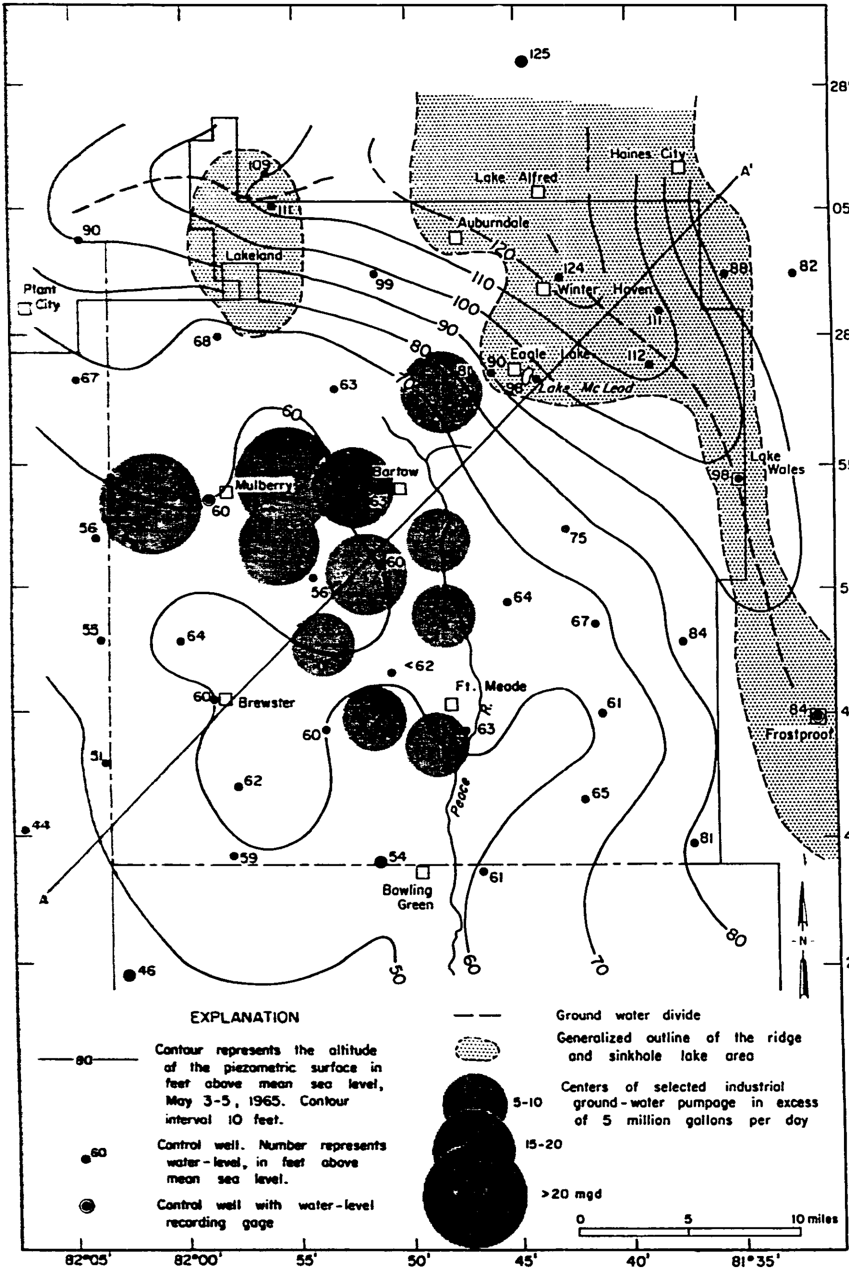

Figure 8.—Piezometric surface of the Floridan aquifer showing centers of selected pumpage in southwest Polk County—early May 1965.

in much of this area, ground water percolating down the slopes of these dry basins is going into the artesian limestone aquifers as recharge." In a detailed investigation of the hydrology of the Green Swamp area, bordering the Peace River basin on the north, Pride, et al (1966, p. 82) states "the drawdown is confined to the southern boundary of Green Swamp, suggesting that the area of the sinkhole-riddled ridges around southern Green Swamp is a recharge area."

Runoff from the northeastern Peace River basin, containing the areas of the ridge and sinkhole lake complex, is considerably lower than runoff from the remainder of the basin. The Florida Board of Conservation (1966, p. 32) reports that the headwater region of the Peace River is "composed of many sinkhole lakes which limit surface runoff and provide storage and avenues for recharge of the aquifers.......... Runoff is least (5 to 10 inches annually) in the northeastern part of the area because of the high evaporation losses from the many lakes and recharge to the aquifers. It is greatest (nearly 15 inches annually) in the lower part of the area because of the small number of lakes and because of discharge from the aquifers."

Additional data indicating that the sinkhole dotted ridges represent significant areas of recharge are the relatively low hardness of water from the Floridan aquifer underlying the Winter Haven and Lake Wales ridges (personal communication, A. E. Coker and N. P. Dion) and a calcium carbonate per cent saturation map (Pride, et al., 1966, p.91). This map shows waters from the Floridan aquifer to be undersaturated with respect to calcium carbonate (thus implying a recharge area), in part extending south and southeast from Winter Haven, in general conformance with the piezometric high and ground-water ridge as portrayed by figure 8.

Recharge to the Floridan aquifer, however, is not restricted to the ridge and sinkhole lake region. As pointed out by Stewart (1966) recharge occurs over all areas of the county (Polk) where hydrologic conditions are favorable for the downward leakage of water through the semi-permeable confining beds. Evidence supporting this view arises from the studies of Pride et al (1966). They report that total mineral content and calcium carbonate saturation in water in the Floridan aquifer indicate that recharge is occuring over much of central Florida.

Based in part on water-budget computations and the existence of piezometric troughs underlying some sinkhole lakes in the

Lakeland area, Stewart (1966) further concluded that recharge through sinkholes was a relatively small part of the total annual recharge to the aquifer and that the amount of recharge in the principal sinkhole areas did not necessarily equal or exceed the amount of recharge in adjacent nonsink areas of comparable size.

This conclusion appears questionable for several reasons:

1. In calculating recharge values of approximately 5 inches over the 650 sq. mi. of the Peace River basin within Polk County in 1959, Stewart assumed uniform runoff over the basin. However, published data indicate that runoff is significantly lower in the sinkhole lake region than the remainder of the basin (Florida Board of Conservation, 1966, p. 32, and U. S. Geological Survey, 1963, pp. 132, 134). The gaging station at Bartow, used by Stewart in his computations, reflects runoff from both the sinkhole and nonsink areas. In oder to assess the runoff from the different areas of the drainage basin, it is necessary to separate the contributions from the different areas. To accomplish this separation, data from the gaging station north of Alturas which reflects the runoff from the sinkhole lake area must be used and the data from the Bartow gaging station must be corrected so as to reflect only the runoff from the remainder of the area. Reworking the water budget for the year 1959 in the same general manner as Stewart, but in accordance with the above discussion, calculations show 9.4 inches of recharge over the 150 sq. mi. ridge and sinkhole lake area and 4 inches of recharge over the remaining 500 sq. mi. of the basin. This indicates recharge values 2.3 times as great in the sinkhole area as in the nonsink area per unit area.

2. The occurrence of piezometric troughs underlying some sinkhole lakes in the Lakeland area (Stewart, 1966) appear to be caused in part by the contouring of pumping water levels. Hence, these troughs are artificial and not related to recharge aspects. Other troughs may be due to the reduction in pressure head caused by localized high flow velocities in solution channels and the rate of downward leakage of lake water may be insufficient to counterbalance this. It is pertinent to observe that figure 8 of this report shows a well defined-linear piezometric

high underlying the main ridge and sinkhole lake complex extending from Winter Haven to Frostproof.

3. Water budget studies made on four different lakes all indicate downward leakage to the underlying limestone aquifers during periods of declining piezometric levels. These studies will be discussed in detail in a subsequent section of this report.

It appears therefore that a large amount of recharge to the Floridan aquifer in the Peace and Alafia River basins does occur in the ridge and sinkhole lake area and that recharge values in the principal sinkhole areas exceed those in nonsink areas per unit area. As the nonsink areas are of much greater areal extent, significant quantities of recharge can occur outside the main sinkhole areas.

More detailed work is needed to assess with greater accuracy the relative quantities of recharge from the different areas. Studies presently underway by the U. S. Geological Survey utilizing calcium carbonate saturation and age-dating of ground water by carbon-14 may prove valuable in this respect.

Concentrated heavy ground-water pumpage, the effects of which are shown by a shift in the contours on the piezometric surface map depicted in figure 8, has resulted in a considerable lowering of the piezometric surface southwest of Bartow. The increased hydraulic gradient between Winter Haven and Bartow from about 2 ft/mile in 1934 to 5 ft/mile in 1965 is the result of the increasing withdrawal of ground water in southwest Polk County during the above period. The resultant changes in hydraulic gradients have altered the direction of ground-water movement and increased the rate of movement toward the centers of pumpage. Also, Kissengen Spring (figure 7) which had a mean annual flow of 21 mgd in 1934, ceased to flow in 1950 (Peek, 1951) when the piezometric surface declined below the spring outlet. The 1965 ground-water flow pattern, as portrayed by figure 8, is a result of both the regional gradient and heavy pumpage.

A hydrologic profile across Polk County, from northeast to southwest, showing the changes that have occurred in the piezometric surface from 1934 to 1965 in relation to land surface and sea level is shown in figure 9. Lowered water levels caused the piezometric surface in May 1965 to fall below the bottom of Lake McLeod and increased the head differential between lake levels and the piezometric surface of the Floridan aquifer in the sinkhole-

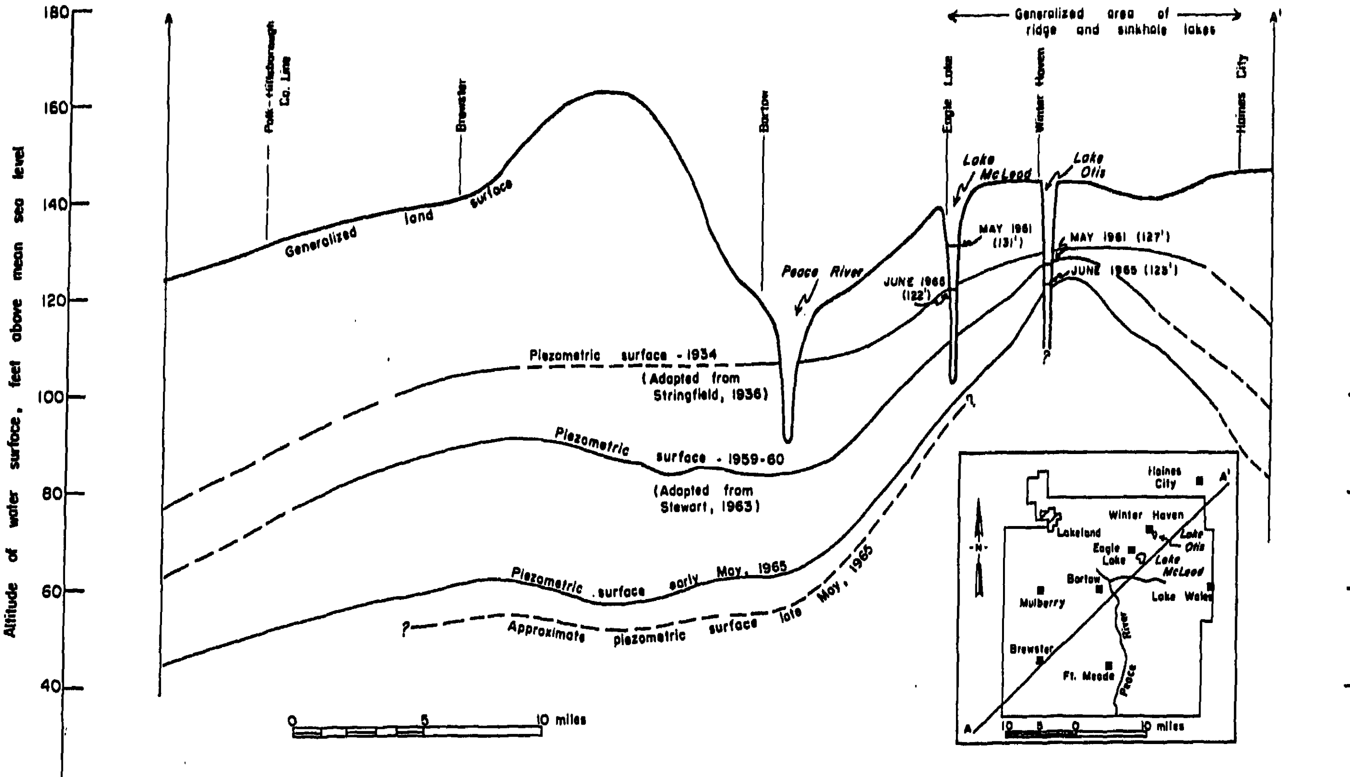

Figure 9.—Profiles of the piezometric surface of the Floridan aquifer across Polk County—1934, 1959-60, and May 1965.

lake area south of Winter Haven. The level of Lake Otis, at Winter Haven, appears to correspond closely to the decline in the piezometric surface.

Pumping creates a depression in the piezometric surface. The decline in water levels is essentially directly proportional to the rate of pumping and inversely proportional to the logarithm of the distance from the center of pumping. When many wells within an area are pumped, the depressions overlap to cause a regional lowering of water levels (i.e. regional decline in the piezometric surface). The extent of the individual or regional declines in water levels is a function of pumping rate, aquifer characteristics, and resultant changes in discharge and recharge.

Ground-water pumpage within the Peace and Alafia River basins has produced a large regional depression in the piezometric surface, figure 10, of more than 50 feet. The depression is centered southwest of Bartow and covers an area of about 1,000 square miles out to the 20-foot contour. Thousands of wells tap the Floridan aquifer within this area and mutually contribute to the lowering of the piezometric surface. Beyond the 20-foot line, it is difficult to distinguish between seasonal and long-term effects. The greatest decline in water levels is the result of concentrated ground-water pumpage in the phosphate mining area southwest of Bartow.

Figure 10 was prepared by plotting changes in water level in individual deep wells and by comparing the 1934 piezometric map (Stringfield, 1936) with well measurements in late May 1965 and with the 1965 piezometric map. The decline in water levels mapped in figure 10 is defined by the interval "B" on figure 3, that is the decline is the difference in water levels from 1934 to the lowest levels in May 1965.

Pumpage of ground water necessitates that water levels progressively decline until enough water is diverted toward the areas of concentrated pumpage from areas of recharge or natural discharge to balance the rate of withdrawal. When this balance occurs, water levels in the Floridan aquifer will tend to remain steady and a state of equilibrium can be said to exist. Should the pumping rate be increased, either before or after equilibrium conditions are reached, water levels will decline, reflecting the adjustment to the new pumping rate. Equilibrium conditions in general do not exist at the present time (1965) within the Peace and Alafia River basins.

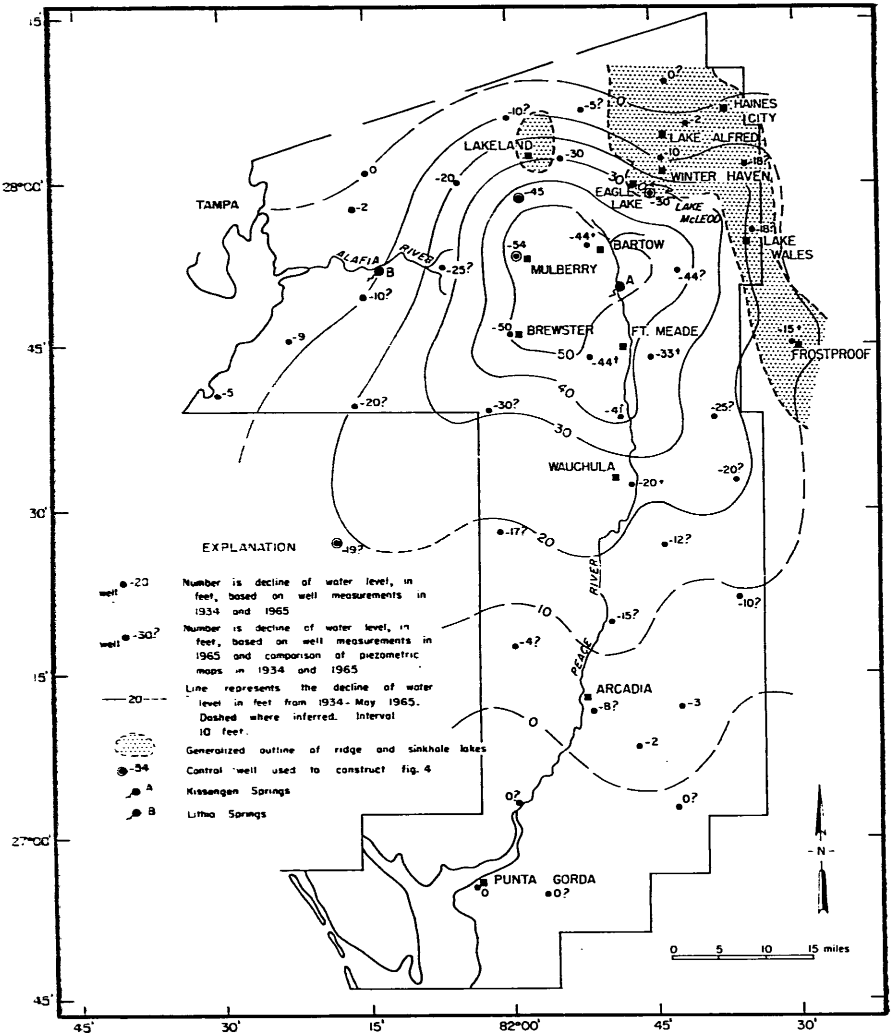

Figure 10.—Decline of water levels in the Floridan aquifer, 1934 to late May 1965.

It is pertinent to observe the relative steepness of the gradient of decline northeast from Bartow. The lowering of water levels apparently is being retarded in this area, possibly by increased recharge from the sinkhole lake region around Winter Haven. The increased pumpage from the Floridan aquifer may therefore be one of the causes of declines in some lake levels in this area. Also, the steep gradients of decline, west and northwest of

Mulberry, indicate that the lowering of water levels also is being retarded in this direction, possibly by a reduction in the natural discharge occurring along the Alafia River. This natural discharge manifests itself, in part, in the flow of Lithia Springs, one of the large limestone springs of Florida with a total flow of 72.2 cubic feet per second (46.7 mgd) on September 30, 1958.

The continuing increase in pumpage will cause further artesian pressure declines. In addition, the distribution of pumpage is expected to expand southward owing to the increased use of water for irrigation and possible migration of phosphate mining to the southern Peace River basin. This shift in the pumpage pattern may cause additional water-level declines to the south and southwest.

RELATION BETWEEN THE PIEZOMETRIC SURFACE AND LAKE LEVELS IN THE LAKE McLEOD AREA

Record low ground-water levels throughout most of the area occurred during the spring of 1965. Lake levels in the northeastern Peace River basin also declined, leading to complaints from residents, especially in the vicinity of Lake McLeod in Polk County, about the extreme low water levels in several lakes. Lake McLeod, for example, declined from 131 feet above msl (mean sea level) in May 1961 to 122 feet above msl in June 1965.

Lake McLeod, because of its circular shape and location, appears to be a sinkhole lake. The progressive decline of the piezometric surface near the lake (from approximately 110 feet above msl in 1961 to 95 feet above msl in late May 1965) has increased the head differential between the lake level and the piezometric surface, thereby contributing to an increase in downward leakage from the lake and apparently a consequent lowering of lake level.

A water budget for Lake McLeod was computed for the period May 1, 1961 to June 4, 1965 (Johnson, 1965). While the values obtained are approximate, they do provide an indication of the quantities of water involved and the cause of the decline in lake level. Johnson's results indicate that about 7 feet of water was unaccounted for in the four years. He attributed this to leakage to the underlying aquifers. This means that the average downward leakage of water from the lake was about 0.8 mgd during the above 4-year period.

Kohout and Meyer (1959) investigated the hydrologic features of Lake Placid (located to the southeast of Lake McLeod in Highlands County in a similar hydrogeologic setting) and concluded that downward leakage from the lake during the first half of 1956 (a drought period) amounted to about 2 to 3 inches per month (6.4 to 9.5 mgd).

They noted that the recession curve for Lake Placid for 1955-56 deviated from those for previous years and attributed this to increased downward leakage from the lake because of lowered water levels in the Floridan aquifer.

Studies to determine the relations between the lakes of Polk County and the underlying limestone aquifers were conducted by Stewart (1966), who reports (p. 1):

> "Water budget analyses for two lakes near Lakeland, during the first 6 months of 1956, show that the lakes recharged the underlying limestone aquifers. Lake Parker recharged water to the Floridan aquifer at a rate of about 2.5 inches per month and Scott Lake recharged water to the limestones of the Hawthorn Formation at a rate of about 5 inches per month. Data suggest that other lakes in the county may also recharge the aquifers at slow rates."

LOSS OF SUCTION IN DEEP WELLS

In the spring of 1965 many "deep" wells "went dry" (that is the pumps lost suction when water levels declined below the pump intake) in parts of the study area. The city of Eagle Lake in Polk County lost its water supply for several days and water had to be transported by truck to meet the needs of the residents.

These occurrences are expected to continue in the future and many well owners will need to lower their pump intakes in order to obtain water. Lowered water levels increase the lift and power required to pump water and thereby increase the cost.

REVERSAL OF THE HYDROLOGIC CONDITIONS ALONG THE PEACE RIVER IN POLK COUNTY

In 1934 an area of artesian flow existed along the Peace River from just north of Bartow southward to the Polk-Hardee county line. The water levels in the Floridan aquifer were about 10 to 20 feet above land surface along the Peace River between Bartow and Ft. Meade. This area of artesian flow from the Floridan aquifer manifested itself in the flow of Kissengen Springs, southeast of Bartow. This spring ceased to flow in 1950 (Peek, 1951) when the piezometric surface declined below the spring outlet.

In May 1965 the water level in the Floridan aquifer was about 20 to 25 feet below land surface along the Peace River between Bartow and Ft. Meade. This decline in the water level has caused a reversal of the hydrologic conditions, in that a potential now (1965) exists for water to move from the Peace River and the shallow water table to the Floridan aquifer, as opposed to the flow of water from the Floridan aquifer into the river in 1934.

SALT-WATER ENCROACHMENT

The entire study area is underlain by saline water (greater than 1,000 ppm total dissolved solids) at varying depths below the fresh water in the aquifer. The depth at which this saline water occurs and the conditions governing its movement are not adequately known but depend upon the characteristics of the aquifer. The altitude of the piezometric surface above msl is one of the factors which appears to govern the depth to saline water.

Using the approximate relation that for every foot of fresh water above mean sea level, there is 40 feet of fresh water below sea level, that is 40 feet of fresh water above the saline water, a depth to saline water underlying Mulberry and Brewster of 2,140 feet below msl is calculated to exist in late May 1965. Information pertaining to the actual depth of the saline fresh-water interface underlying southwest Polk County is not available. An oil exploratory well, located north of the Peace and Alafia River basins in southern Lake County, encountered saline water at approximately 2,300 feet (personal communication: R. N. Cherry and B. F. Joyner). Pride, et al (1966, p. 92) report "Data from a few scattered deep wells indicate that fresh water extends to about 1,500 feet below sea level in much of the interior of central Florida from Marion County to Highlands County."

A possible avenue for upward migration of saline water exists along the Peace River. The ground-water circulation pattern is such that upward movement of artesian water occurs. Stewart (1966) reports that piezometric troughs along the Peace River in Polk County are caused by upward leakage along the river and that these troughs extended to the northwest of Bartow during the 1959-60 wet years. In studying the chemical characteristics of artesian water in the southern Peace River basin, Kaufman and Dion (in preparation) mapped a linear zone of relatively warm, highly mineralized calcium-magnesium sulfate water in the vicinity of the Peace River. This appears to reflect the upward movement of waters after relatively deep circulation through the aquifer. North-south trending linear patterns of artesian waters of relatively high mineralization that follow the Peace River in Polk County have recently been mapped (A. E. Coker and N. P. Dion, personal communication).

No vertical saline water encroachment has been observed in the heavily pumped area, however, the possibility exists that with the continued lowering of the piezometric surface, saline water may move upward from depth.

SINKHOLE OCCURRENCE

Within the ridge and sinkhole-lake region of the northern Peace River basin, the Floridan aquifer is overlain predominantly by sand, with some interbedded clays and limestone which range in thickness from less than 50 feet to more than 300 feet. In the spring of 1965 numerous sinkholes developed in the northern Peace River basin. This was a period of extremely low rainfall, maximum ground-water withdrawal, and consequent record low water levels.

The formation of collapse sinkholes represent surficial evidence of solutional activity in the underlying limestone aquifer. Within a limestone aquifer, such as the Floridan, progressive solution enlarges the underground conduits, resulting in extensive cavern systems. As the solutional caverns increase in size or possibly as support of their roofs is reduced by lowered artesian pressures, their roofs may become incapable of supporting the overlying materials and eventually there is a collapse. Although the occurrence of sinkholes is a natural geologic process in buried limestone terranes, the periods of recent major sinkhole activity and the areal distribution of recently formed sinkholes indicate that other factors may be important.

The occurrence and areal distribution of sinkholes in Polk County during the period 1953 to 1960 is discussed by Stewart (1966, p. 65-69). Analyses of the data show that 12 of 18 reported sinkholes occurred during the drought years of 1954-56, a period of generally declining artesian water levels. The areal distribution of these 18 sinkholes was such that 16 out of 18 occurred within the 20-foot line of the northeast quadrant of the regional decline of water levels portrayed in figure 10. This area represents that part of the hydrologic system between the main recharge area to the northeast and the main discharge area to the southwest. The steepest hydraulic gradients and consequently the greatest ground-water velocities occur within this area. (See piezometric map, figure 8).

It appears, therefore, that a causal relation may exist between lowered artesian water levels and the occurrence of sinkholes.

SUMMARY AND CONCLUSIONS

The accelerated industrial and agricultural growth in the Peace and Alafia River basins has resulted in an increasing rate of withdrawal of water from the Floridan aquifer; this in turn has caused an increasing rate of decline of artesian water levels. The largest declines underlie the industrialized area of southwestern Polk County where concentrated pumpage has lowered artesian water levels more than 50 feet since 1934. The demand for water may more than double by 1980 and declines in artesian water level are expected to continue into the future. It should be noted that lowered water levels in themselves may not have an overall adverse effect when the economic, sociological, and political benefits derived from the large scale development of the ground-water resources are taken into consideration.

Seasonal fluctuations of water level within the areas of heavy pumping are large and are increasing and primarily reflect seasonal pumpage rather than precipitation or recharge.

Large scale ground-water pumpage within the Peace and Alafia River basins has produced a large regional lowering of water levels centered in southwestern Polk County. The area of regional decline has deepened and expanded until it presently (1965) reaches the edge of the ridge and sinkhole-lake region to the northeast. Preliminary evidence indicates retardation of the decline of water levels in the direction of the sinkhole region, probably as a result of recharge from the lakes. The declines in some lake levels, such as occurred in the Lake McLeod area in the spring of 1965, may be due in part to the lowered artesian water levels resulting from the increased pumpage from the Floridan aquifer which increased the downward leakage from the lakes. Water budget studies of Lake McLeod in Polk County and Lake Placid in Highlands County indicated downward leakage of 0.80 mgd and 6.4 to 9.5 mgd, respectively. Also water budget analyses for Lakes Parker and Scott near Lakeland show that the lakes recharged the underlying limestone aquifers.

The increasing citrus acreage and related irrigation in the southern Peace River basin coupled with a possible future south and southwestward migration of phosphate mining should cause the distribution of pumpage to increase in this area with additional water-level declines.

Some of the effects of lowered artesian water levels, in addition to the effects on some lake levels as discussed above, are:

(1) The loss of suction in wells when water levels decline below the pump intakes. This entails adding pump column and requires a greater pumping lift, thereby increasing the cost.

(2) The reversal of the hydrologic conditions along the Peace River between Bartow and Ft. Meade in Polk County from one of discharge from the Floridan aquifer in 1934 to one of potential recharge to the aquifer in 1965.

(3) The position of the saline-fresh water interface, which in part depends on the altitude of the piezometric surface, may rise and create the possibility of vertical salt-water encroachment. The depth to saline water underlying the heavily pumped industrial area of southwest Polk County was estimated to be about 2,100 feet below msl in May 1965.

(4) The development of numerous sinkholes, caused by the collapse of the subsurface, in the northern Peace River basin during the spring of 1965 appears to be related to the lowered artesian water levels which increase the effective stress within the confined aquifer system.

Important questions which arise concern the adequacy of the long-term water supply and the long-term effects on the hydrologic system of the progressively increasing demand for ground water. One of the problems of determining the effects of pumping is calculating the ultimate drawdown or change of water level that would result from anticipated rates of pumping. Where knowledge is available on the permeability, storage characteristics, areal extent and thickness of a given aquifer, it is possible to quantitatively calculate how a system of wells will function and what will occur in an aquifer under various assumed patterns of pumping.

A complete appraisal of the Floridan aquifer within the Peace and Alafia River basins is not possible at present (1965). Additional data collection, analyses and interpretation are necessary for a more comprehensive understanding of the aquifer. A quantitative evaluation of the Floridan aquifer within the Peace and Alafia River basins is needed.

Aquifer characteristics such as coefficients of transmissibility, storage, and leakance are available for areas immediately adjacent to the north and northwest and for scattered areas throughout Florida. See for example Menke, et al (1961) and Pride, et al (1966). However, quantitative studies are not available for the Peace and Alafia River basins. Geologic and hydrologic data, including specific information on the amount, distribution, and use of ground water, are especially needed near the center of heavy pumpage in southwest Polk County.

The relation between the level of Lake McLeod and the shallow and deep ground-water system is presently being investigated by the U. S. Geological Survey. Studies to evaluate the relations between lakes and the underlying Floridan aquifer are needed. Additionally, a deep test-well in the center of the phosphate mining area would be of great value. This well should be drilled to the saline-fresh water interface and could serve as a monitor of possible upward salt-water encroachment. It would also determine the thickness and character of the Floridan aquifer and, if drilled in a location so as to take advantage of existing wells as observation wells, could furnish the needed aquifer characteristics through the use of pumping tests. As pumping tests only represent a "spot" sampling of the aquifer, an application of flow net analysis may perhaps provide an integrated and more realistic value of the areal transmissibility.

REFERENCES

Bishop, E. W.
1956 *Geology and ground-water resources of Highlands County, Florida*: Florida Geol. Surv. Rept. Inv. 15.

Cherry, R. N. (see Pride, R. W.)

Florida Board of Conservation
1961-1964 Biennial Reports.
1966 *Florida Land and Water Resources, Southwest Florida.*

Florida Geological Survey
1933-1960 Biennial Reports.

Johnson, L.
1965 *Investigation of Eagle Lake, Lake McLeod, Spirit Lake, Millsite Lake, and Grassy Lake, Polk County, Florida*: Unpublished memorandum report to the Peace River Basin Board.

Kohout, F. A.
1959 (and Meyer, F. W.) *Hydrologic features of the Lake Placid area, Highlands County, Florida*: Florida Geol. Survey Rept. Inv. 19, pt II.

Menke, C. G.
1961 (and Meredith, E. W., and Wetterhall, W. S.) *Water resources of Hillsborough County, Florida*: Florida Geol. Survey Rept. Inv. 25.

Meredith, E. W. (see Menke, C. G.)

Meyer, F. W. (see Kohout, F. A. and Pride, R. W.)

Peek, H. M.
1951 *Cessation of flow of Kissengen Springs in Polk County, Florida*: Florida Geol. Survey Rept. Inv. 7, pt III.

Pride, R.W.
1966 (and Meyer, F. W., and Cherry, R. N.) *Hydrology of Green Swamp area in central Florida*: Florida Geol. Survey Rept. Inv. 42.

Stewart, H. G. Jr.
1963 *Records of wells and other water-resources data in Polk County, Florida*: Florida Geol. Survey Inf. Circ. 38.
1966 *Ground-water resources of Polk County*: Florida Geol. Survey Rept. Inv. 44.

Stringfield, V. T.
1936 *Artesian water in the Florida peninsula*: U. S. Geol. Survey Water-Supply Paper 773-C.

U. S. Bureau of Mines
1964-65 Minerals Yearbooks, Vol. 1.

U. S. Dept. of Agriculture
1965 Appendix to the report of "*Water and related land resources,*" Florida west coast tributaries.

U. S. Geological Survey
1963 *Compilation of records of surface waters of the U. S., Oct. 1950-Sept. 1960, Part 2B*: U. S. Geol. Survey Water Supply Paper 1724.

Wetterhall, W. S. (see Menke, C. G.)