STATE OF FLORIDA
DEPARTMENT OF NATURAL RESOURCES
Randolph Hodges, *Executive Director*

DIVISION OF INTERIOR RESOURCES
J. V. Sollohub, *Director*

BUREAU OF GEOLOGY
Robert O. Vernon, *Chief*

Report of Investigations No. 58

SEEPAGE BENEATH HOOVER DIKE SOUTHERN SHORE OF LAKE OKEECHOBEE, FLORIDA

By
Frederick W. Meyer

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
FLORIDA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF INTERIOR RESOURCES
BUREAU OF GEOLOGY
and the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT
U. S. ARMY CORPS OF ENGINEERS

TALLAHASSEE, FLORIDA
1971

DEPARTMENT
OF
NATURAL RESOURCES

REUBIN O'D. ASKEW
Governor

RICHARD (DICK) STONE
Secretary of State

ROBERT L. SHEVIN
Attorney General

THOMAS D. O'MALLEY
Treasurer

FRED O. DICKINSON, JR.
Comptroller

FLOYD T. CHRISTIAN
Commissioner of Education

DOYLE CONNER
Commissioner of Agriculture

W. RANDOLPH HODGES
Executive Director

LETTER OF TRANSMITTAL

Bureau of Geology
Tallahassee
May 6, 1971

Honorable Reubin O'D. Askew, Chairman
Department of Natural Resources
Tallahassee, Florida

Dear Governor Askew:

The Bureau of Geology is publishing as its Report of Investigation, a paper, "Seepage Beneath Hoover Dike, Southern Shore of Lake Okeechobee, Florida", written by Mr. Frederick W. Meyer, a Geophysicist of the U.S.G.S.

The needs for the future of water in Southern Florida requires that the levee of Lake Okeechobee be increased to obtain additional storage of water for needs of the future. This study involved determining what the rate of seepage beneath the dike would be when the gradient was increased across the dike.

It is anticipated that toe ditches around the levee section must be constructed in order to control the amount of water that would be permitted to seep beneath the dikes.

Some additional pumpage back into the lake may be required utilizing the toe ditches as sumps.

Sincerely yours,

R.O. Vernon, Chief

Completed manuscript received
May 6, 1971
Printed for the Florida Department of Natural Resources
Division of Interior Resources
Bureau of Geology
by Rose Printing Company
Tallahassee, Florida

Tallahassee
1971

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS - continued

ILLUSTRATIONS - continued

TABLES

SEEPAGE BENEATH HOOVER DIKE, SOUTHERN SHORE OF LAKE OKEECHOBEE, FLORIDA

By
Frederick W. Meyer

ABSTRACT

Future water needs in southern Florida call for an increase in the storage capacity of Lake Okeechobee. Seepage from the lake is expected to increase as a result of raising the lake level. Data concerning the occurrence and amounts of seepage are needed for the design and operation of flood-control works which will remove excess water from the rich agricultural lands along the southern shore. Intensive studies at five sites along the southern shore of Lake Okeechobee between the Caloosahatchee Canal and the St. Lucie Canal indicate that seepage occurs chiefly through beds of shell and limestone which underlie the Hoover Dike at shallow depth. Seepage rates at the five sites range from about 0.1 to 0.9 cfs per mile per foot of head across the dike. Seepage beneath the 50-mile length of dike should increase from about 22 to 50 cfs if the average stage of the lake is raised from 14 to 16.5 feet. Seepage is greatest between Moore Haven and Clewiston, where deep borrows have been excavated on the landward and lakeward sides of the dike. Most of the seepage from the lake can be controlled by properly spaced toe ditches which would intercept the seepage and return it to the lake.

INTRODUCTION

With the beginning of land reclamation in the Everglades at the turn of the century, it became evident that the key to successful utilization of the rich organic soil lay in the control of Lake Okeechobee, figure 1. In the early 1920's attempts at flood control were undertaken by the Everglades Drainage District and low levees were built around the southern shore of the lake to protect nearby towns and agricultural lands from flooding. However, the attempt proved futile, for in 1926 and 1928 hurricanes swept waters over the levees and about two thousand people were drowned.

In 1929, the Florida Legislature created the Okeechobee Flood Control District which overlapped and augmented the Everglades Drainage District and efforts were made to involve the Federal Government in providing flood protection. With the help of President Herbert Hoover, Congress adopted the Okeechobee project under the Rivers and Harbors Act as a navigation feature

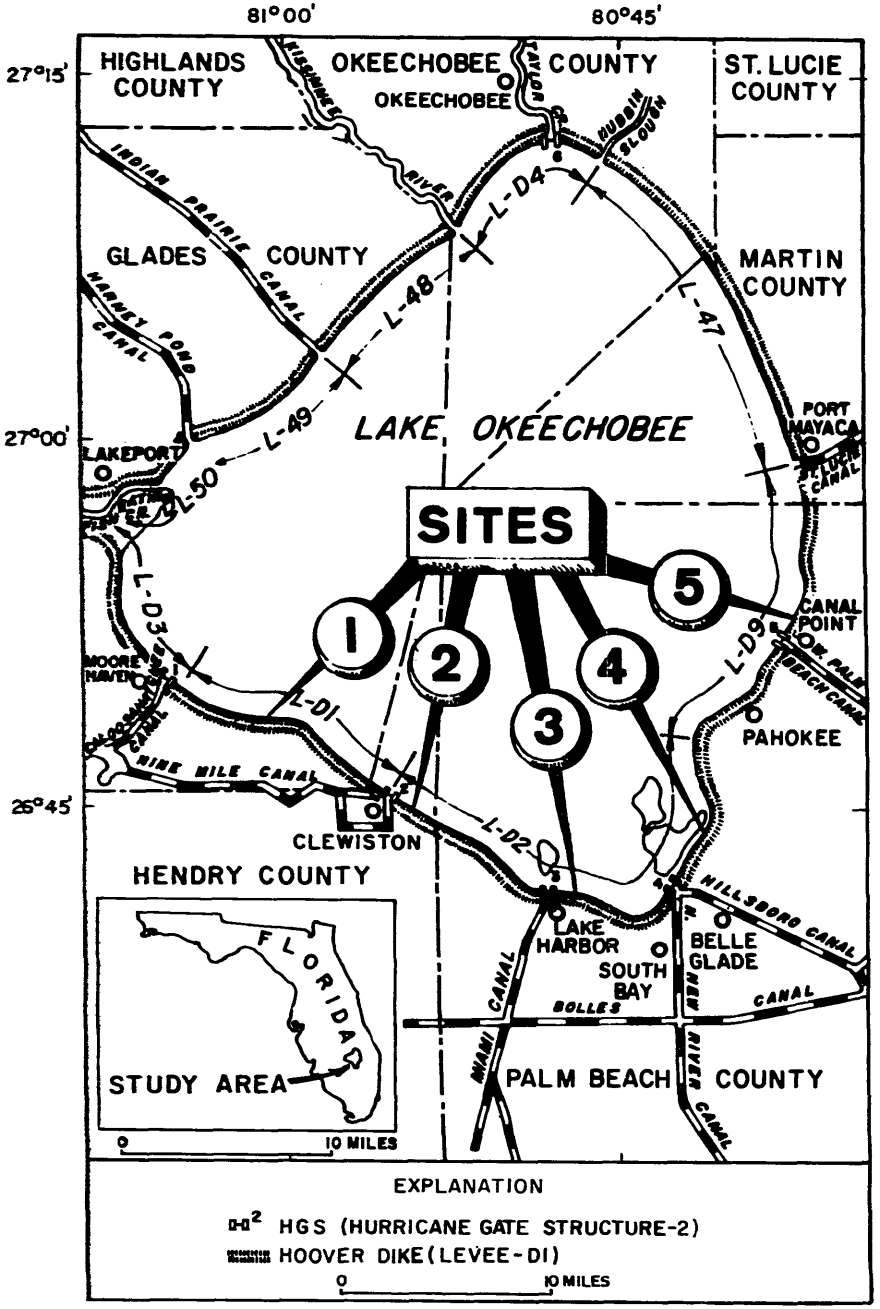

Figure 1. Map of the Lake Okeechobee area showing locations of investigation and test sites.

with due consideration for flood control, and the U.S. Army Corps of Engineers began work on the project in November 1930. By 1937 the Hoover Dike had been constructed around the southern perimeter of Lake Okeechobee from Fisheating Creek to the St. Lucie Canal.

Subsequent land reclamation in the Everglades south of Lake Okeechobee led to overdrainage, which threatened the water supplies of the rapidly expanding coastal cities. In 1948, Congress authorized the project "Central and Southern Florida Project for Flood Control and Other Purposes" which, among other things, would utilize Lake Okeechobee as a reservoir. In 1949, the State Legislature designated the C&SFFCD (Central and Southern Florida Flood Control District) as the agency responsible for state and local cooperation and participation in the project. Part of the project called for increasing the storage capacity of the lake by raising existing portions of the Hoover Dike and for extending it around the entire shoreline. The project also called for a higher regulation schedule for the lake.

Enlargement of the existing portions of the dike was started in 1960 and completed in 1964. Extension of the dike around the northern perimeter is scheduled for completion in 1970. Upon completion, the lake level (U.S. Corps of Engineers, 1961, p.6) will be changed from that ranging between approximately 12.5 to 15.5 feet above msl (mean sea level) to that ranging between 15.5 and 17.5 feet above msl, figure 2. Therefore the change in regulation would theoretically raise the average lake stage from 14 to 16.5 feet.

Seepage beneath the Hoover Dike was expected to increase as a result of raising the lake level and agriculturists became increasingly concerned about the effects that additional seepage would have on production in rich farmland along the southern shore adjacent to the dike. Little was known, however, of the existing seepage rates and the C&SFFCD and the U.S. Corps of Engineers needed reliable data to predict the effects that raising the lake level would have on seepage so that adequate drainage might be planned.

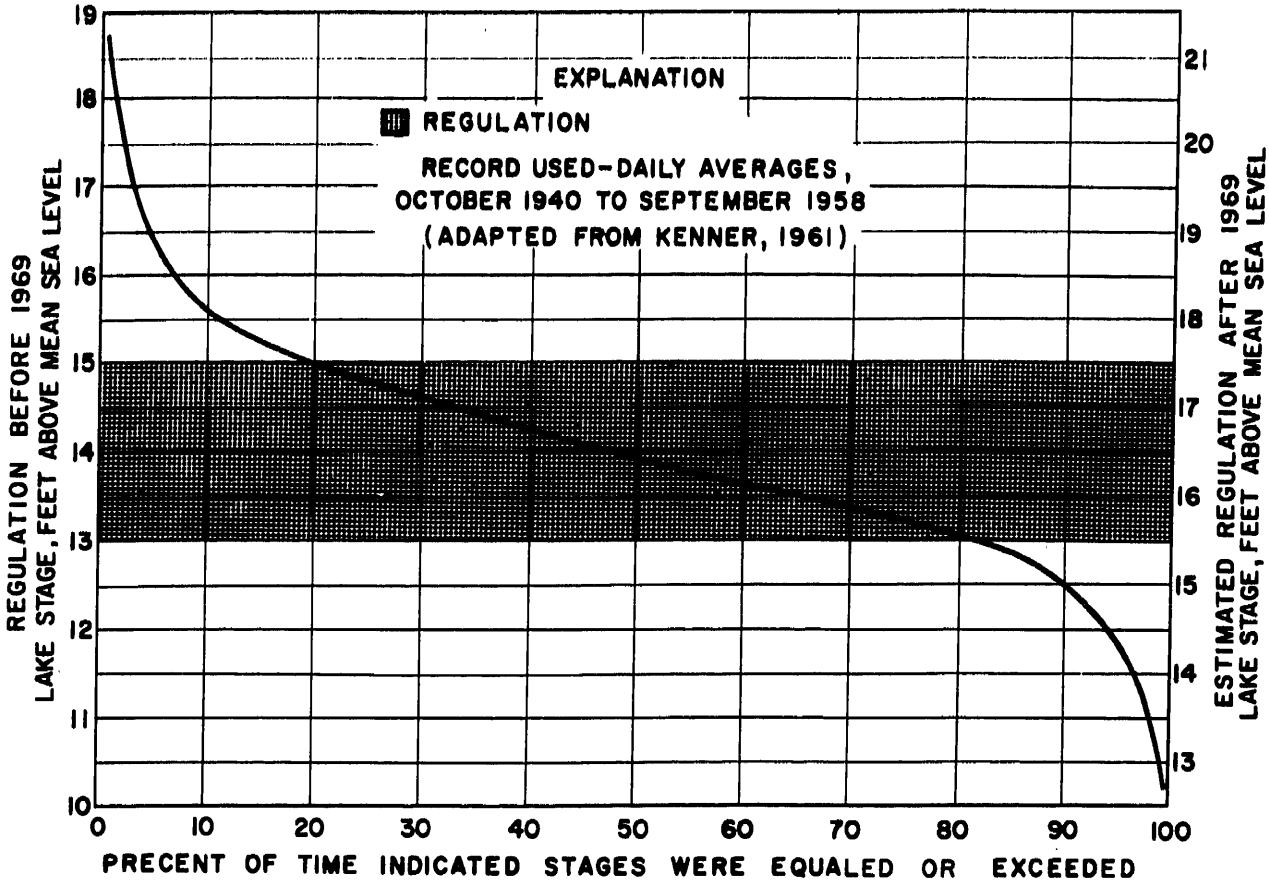

Figure 2. Stage-duration curve for Lake Okeechobee showing present and future regulation.

LOCATION OF INVESTIGATION

The area studied is located in south central Florida along the southern shore of Lake Okeechobee between the Caloosahatchee Canal on the west and the St. Lucie Canal on the east (fig. 1). Intensive studies were made at the following five sites:

Site No.	County	Township (south)	Range (east)	Section	Levee[1])	Station[1])
1	Glades	42	33	15	D1	180+00
2	Hendry	43	34	14	D2	60+18
3	Palm Beach	43	35	36	D2	480+95
4	Palm Beach	43	36	13	D2	980+00
5	Palm Beach	41	37	27	D9	390+06

[1] U.S. Corps of Engineers base line survey.

PURPOSE AND SCOPE

In 1962, the C&SFFCD requested the U.S. Geological Survey to study the seepage around the southern perimeter of the lake. The objective was to describe the manner in which seepage occurred and to develop a relation between the lake level and water levels landward of the dike, so predictions of seepage at a lake level 2.5 feet higher than the existing level might be made.

Because the study involved about 50 miles of dike it was decided that the estimates of seepage would be based upon detailed studies at five sites (fig. 1), on the premise that they would be representative of the average hydraulic conditions. The length of dike that was assumed to be represented by each site is as follows:

Site No.	Length of Dike (miles)
1	9.0
2	8.5
3	8.5
4	10.0
5	14.0

Field studies began in the fall of 1963 and ran concurrently with the raising of the dike and re-routing of U.S. Highway 27 along the landward toe of the dike between Clewiston and South Bay. As a result of the construction the progress of the study was impeded and field work continued until the spring of 1966. During the period December 1967 through March 1968 verification tests were performed at site 1 near Moore Haven at the request of C&SFFCD and the U.S. Sugar Corporation. The results of those tests (Meyer, 1969) confirmed seepage data collected during the period 1963-66.

METHODS OF INVESTIGATION

Observation wells were drilled in a line perpendicular to the dike at each site in order to determine the extent, thickness, and character of the subsurface materials and to define the hydraulic gradients. The wells ranged from about 4 to 50 feet deep and were constructed of either 2- or 4-inch diameter steel casing. Measuring points were established at each observation well to reference changes in water-levels. Fluctuations of ground-water levels on the landward side of the Hoover Dike were continuously recorded in at least one observation well at each of the 5 sites.

Observation points (OP's) were established in nearby canals and in the lake to reference changes in surface-water levels. Fluctuations in the stage of Lake Okeechobee were continuously recorded at HGS 3 (Hurricane Gate Structure 3) at Lake Harbor and at HGS 5 at Canal Point.

Data concerning water levels, chloride content of water, and water temperature were collected at monthly intervals. Hydrologic profiles were constructed from these data to analyze ground-water movement (seepage) relative to the stage of the lake. Aquifer coefficients were determined by pumping tests, slug tests, and/or by relating seepage gains or losses in canals to hydraulic gradients.

Wells used in this report were numbered consecutively at each site and are cross referenced to a county numbering system and a national numbering system. Observation points (OP's) in the lake and canals were numbered consecutively.

PREVIOUS STUDIES

No detailed studies of seepage along the southern shore of Lake Okeechobee were made prior to this study. However, the U.S. Corps of Engineers (1963, p. 10) estimated that the seepage from Lake Okeechobee into the L-D1 Borrow Canal, located at site 1 near Moore Haven, would be about 12.7 cfs (cubic feet per second) per mile, per foot of head between the lake and the canal. The Corps (1953) estimated the seepage through similar strata at four

sites along the alignments of proposed levees remote from the Hoover Dike. Seepage for test sites 6, 7, 9, and 10 ranged from about 0.5 to 3 cfs per mile of levee, per foot of head across the base of the proposed levees. However, the width of the proposed levees was about half that of the Hoover Dike, therefore, the rates of seepage under a levee equivalent in size to the Hoover Dike would be about half the estimated rates.

Schroeder, Milliken and Love (1954, p. 12-14) reported that the transmissivity of a sand and shell aquifer at Delray Beach, in eastern Palm Beach County, was about 70,000 gpd/ft (gallons per day per foot). Similar aquifers occur at shallow depth in the vicinity of Lake Okeechobee.

Parker, Ferguson, Love, and others (1955) described the geomorphology, geology, and general hydrology of the Everglades including Lake Okeechobee. They reported that the hydraulic conductivity (permeability) of terrace sands at the north end of the lake ranged from 10 to 800 gpd/ft^2 (gallons per day per square foot) and might exceed 3,000 gpd/ft^2 in well-sorted sand. Studies made by the U.S. Geological Survey in cooperation with the Soil Conservation Service indicated that there was no substantial gain or loss by the lake through underground flow (op. cit., p. 107, 185), that the permeability of organic soils is low (op. cit., p. 109), and that areas of low permeability generally have water of poor quality (op. cit., p. 183-184).

Water-budget studies of Lake Okeechobee by Langbein (op. cit., p. 551-560) suggest that as much as 6 inches, or 250,000 acre-ft. could have been lost annually from the lake by seepage. However, Langbein concluded that the apparent 6-inch loss was probably due to an error in the pan coefficient used in computing evaporation.

Other studies relating to the hydrogeology of the area were made by Greene (1966); Klein, Schroeder, and Lichtler (1964); Kenner (1961); Lichtler (1960); Matson and Sanford (1913); Meyer and Hull (1969); Parker (1942); Stringfield (1933); and the U.S. Corps of Engineers (1955, 1961, 1962, 1963). Studies pertaining to the geology of the area were made by Cooke (1945); Dall (1887, 1893); Dubar (1958); Heilprin (1887); Mansfield (1931a, 1931b, 1939); Olsson (1964); Parker (1944); Perkins (1968); Puri and Vernon (1964); Roland (1969); and Schroeder, Millikin, and Love (1954). Historical information on the hydrology of the area is presented in reports by Herr (1943), Wallis (1942), and Jones (1948).

ACKNOWLEDGMENTS

This report was prepared by the U.S. Geological Survey as part of the cooperative water resources program with the Central and Southern Florida Flood Control District and the U.S. Corps of Engineers. The investigation was conducted under the direct supervision of Howard Klein, former subdistrict

chief, Water Resources Division, Miami, Florida, and under the general supervision of C.S. Conover, district chief, Water Resources Division, Tallahassee, Florida.

The author thanks the following people for assistance rendered during the investigation: Messrs. W. V. Storch and R. L. Taylor of the Central and Southern Florida Flood Control District; Messrs. J. J. Koperski, O. G. Rawls, Angelo Tabita, J. H. Grimes, and A. R. Broadfoot of the U. S. Corps of Engineers; Mr. C. W. Knecht of the U. S. Sugar Corporation; Mr. J. D. Rogers of the Pahokee Drainage District; Mr. W. M. Jeffries of South Florida Conservacy District; Dr. D. R. Moore, paleontologist of the Institute of Marine Science, University of Miami; and Dr. A. A. Olsson, retired consulting geologist of Coral Gables, Florida.

GEOGRAPHIC SETTING

LAKE OKEECHOBEE

Lake Okeechobee, in the southern part of the Florida Peninsula (fig. 1), is the second largest fresh-water lake wholly within the conterminous United States. The lake includes parts of Glades, Hendry, Martin, Okeechobee, and Palm Beach Counties. It is nearly circular, measuring about 35 miles from north to south and about 30 miles from east to west. The shoreline, approximately 105 miles long, is rimmed by the Hoover Dike. The surface area of the lake, including three small islands, is about 680 square miles (4.35 million acres) at average stage of 14 feet above msl as shown by the area-capacity curves on figure 2A. The average depth is 7 feet and the maximum depth is about 15 feet at average stage. Approximately 3.5 million acre-ft (acre-feet) of fresh water are stored in the lake at average stage 14 feet (fig. 2A). The useable storage between 10.5 and 15.5 feet is about 2 million acre-ft of which 0.6 million are used annually for irrigation. Future water needs, however, call for increasing the storage capacity of the lake by raising the average stage from 14 to about 16.5 feet, which will increase both the average storage capacity and the useable storage (between 10.5 and 17.5 feet) by about a million acre-ft.

The lake water is generally hard and highly colored. The total dissolved solids in the water seldom exceeds 300 mg/l (milligrams per liter). The temperature of the water ranges from 60°F (16°C) in the winter to about 90°F (32°C) in the summer. A few municipalities and industries use the lake as a source of water supply.

The lake is chiefly used as a flood-control storage basin for excess waters and for irrigation of the large sugar plantations, truck farms, and cattle ranches

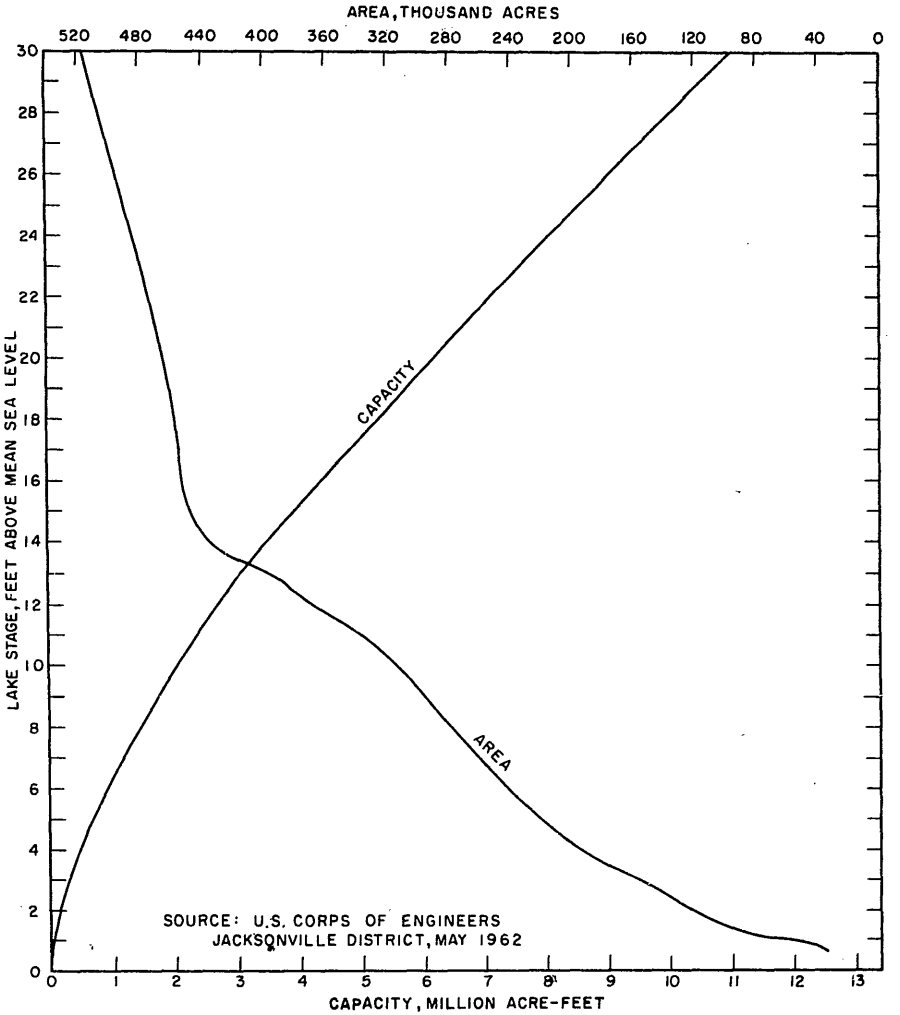

Figure 2A. Area-capacity curves for Lake Okeechobee, 1962.

that surround the lake. It is also used for cross-state navigation, commercial fishing, and recreation. Water from the lake also replenishes supplies to the growing coastal cities.

TOPOGRAPHY

The most prominent topographic feature in southern Florida is the Everglades-Lake Okeechobee basin (Davis, 1943, p. 41). Lake Okeechobee, which lies at the northern extent of the basin, is a shallow saucer-like depression within the broad flat plain. The deepest point in the lake is slightly below sea-level, figure 3. The northern half of the lake is almost completely surrounded by sandy prairies that range in altitude from 20 to 30 feet above msl. The southern half of the lake lies in the Everglades where the altitude of land surface ranges from 14 to 20 feet above msl.

Studies by Stephens (1951) indicated that the surface of the Everglades agricultural area had subsided several feet due chiefly to drainage and resultant shrinkage of organic soils. He reported (op. cit. p. 13) that during 1912-1950 the average thickness of organic soils in the upper Evergaldes had shrunk about 40 percent, at an average rate of about one foot in ten years. Thus the altitude of land surface in the agricultural area, prior to reclamation, was about 18 to 20 feet above msl.

DRAINAGE

Runoff from about 5,650 square miles drains southward into the lake. Largest of the inflowing streams is the Kissimmee River (fig 3) which discharges about 1.6 million acre-feet (0.5 cubic mile) into the lake annually. Other principal inflowing streams or canals are Fisheating Creek, the Harney Pond and Indian Prairie Canals, Taylor Creek, and Nubbin Slough.

The principal canals that drain the lake are the Caloosahatchee and St. Lucie which together with the lake comprise the Okeechobee Waterway inland navigation route between the Gulf of Mexico and the Atlantic Ocean. Other large canals that drain the lake are the Hillsboro, North New River, West Palm Beach, and Miami, which are also used for routing excess water during the rainy season into the lake by back-pumping from the agricultural area.

In pristine times the natural flow from the lake was chiefly southward through the Everglades but some flow occurred westward through the Caloosahatchee Swamp. Parker, Ferguson, Love, and others (1955, p. 332) estimated that overflow occurred at stage 15 feet and reached sizeable proportions between stages 17 and 18 feet.

CLIMATE

The climate of the Lake Okeechobee region is subtropical and is characterized by warm, humid summers and moderately cool winters. Climatological data presented herein are based on the mean of data collected by

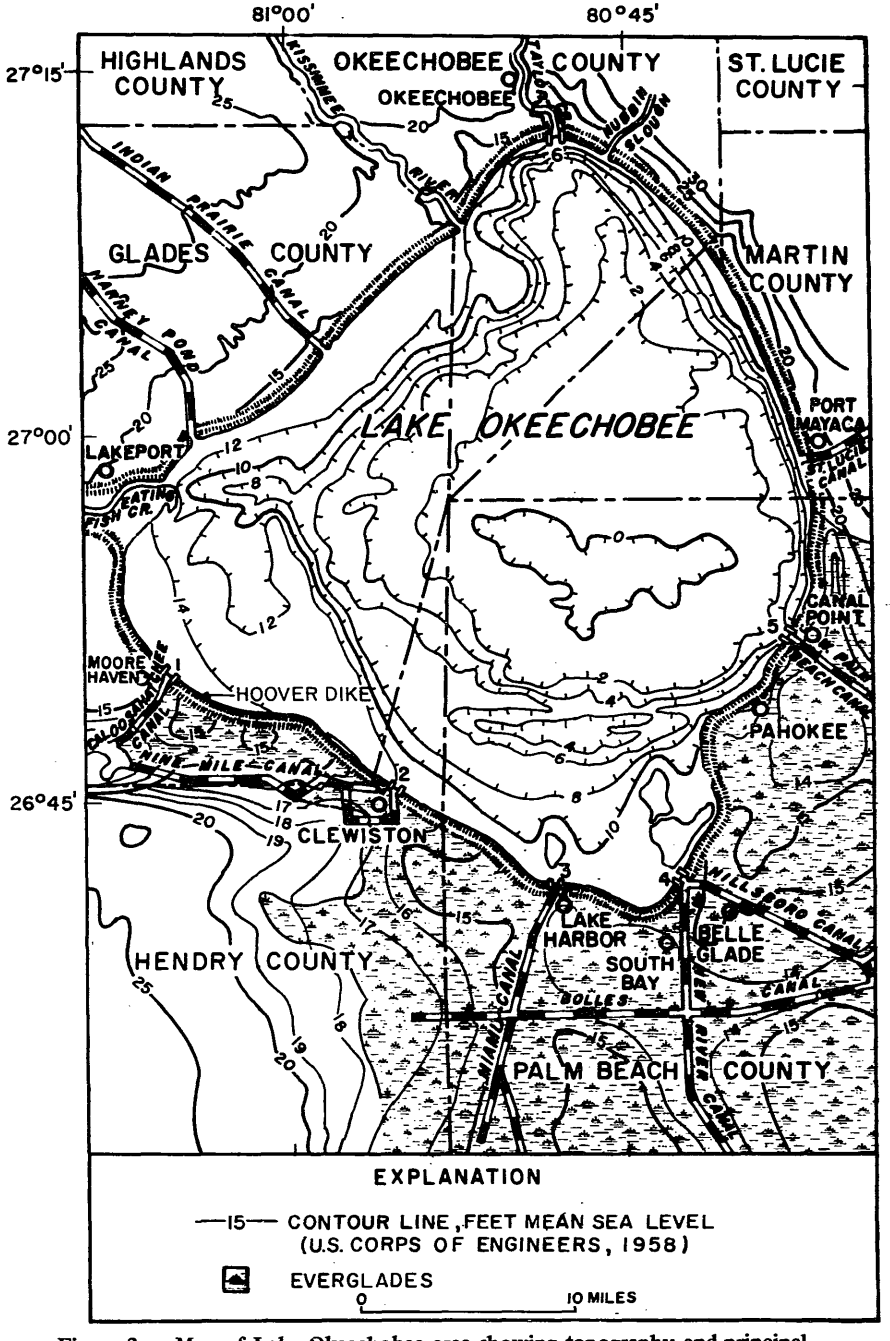

Figure 3. Map of Lake Okeechobee area showing topography and principal drainage.

the U. S. Weather Bureau at Moore Haven Lock 1 and Belle Glade Experiment Station. The average annual rainfall during 1931-1960 was 54.50 inches. Rainfall is seasonal with about 75 percent of the yearly total occurring during May through October. Mean monthly rainfall ranges from 1.56 inches in December to 8.46 inches in September, figure 4. The maximum daily rainfall recorded at the Belle Glade Experiment Station was 10.90 inches in November 1931, and the maximum monthly rainfall there was 24.11 inches in June 1945. Rainfall during 1963-65, figure 5, was below normal despite severe weather conditions that accompanied the passage of three hurricanes. On August 27, 1964, Hurricane Cleo passed a few miles east of Lake Okeechobee. Winds associated with Cleo ranged from 80 mph on the east shore to 40 mph on the west shore. Rainfall during the period August 27-28 was 1.89 inches at Belle Glade and 0.68 inch at Moore Haven. On October 14, 1964, Hurricane Isabell, a small but wet hurricane, passed a few miles southeast of the lake; 5.09 inches of rainfall were measured at Belle Glade and 0.50 inch was measured at Moore Haven. On September 8, 1965, Hurricane Betsy crossed the southern tip of Florida; and rainfall for September 8-9 was 2.08 inches at Belle Glade and 1.99 inches at Moore Haven.

Rainfall during 1966 was above average. Hurricane Alma skirted the west coast of Florida during June 8-9 dumping 3.01 inches of rain at Belle Glade and 3.12 inches of rain at Moore Haven.

The average annual temperature during 1931-1960 was 72.7°F. Mean monthly temperatures ranged from 63.3°F in January to 81.1°F in August (fig. 5). Killing frosts occur infrequently. The lowest temperature recorded at Belle Glade was 24°F in January 1940 and the highest was 100°F in July 1931. Temperatures were slightly below normal during 1963 and 1966 but were slightly above normal during 1964 and 1965 (fig. 5).

GEOLOGIC SETTING

The Lake Okeechobee area lies within the Coastal Lowlands of Florida (Cooke, 1939, p. 14). The Lake Okeechobee-Everglades basin probably was a shallow embayment, or depression, formed on an ancient sea floor during, or prior to, Pleistocene time. Seas covered the area during the Pleistocene interglacial stages and marine calcareous materials were deposited. During glacial stages the seas retreated and the area was eroded, but fresh-water marls were deposited in shallow depressions. The Lake Okeecobee-Everglades basin probably was a lake or a swamp during a part of each glacial stage.

The formations[1] that underlie the area at shallow (less than 50 feet) depth range from Miocene to the Holocene in age as shown in table 1. The oscillations

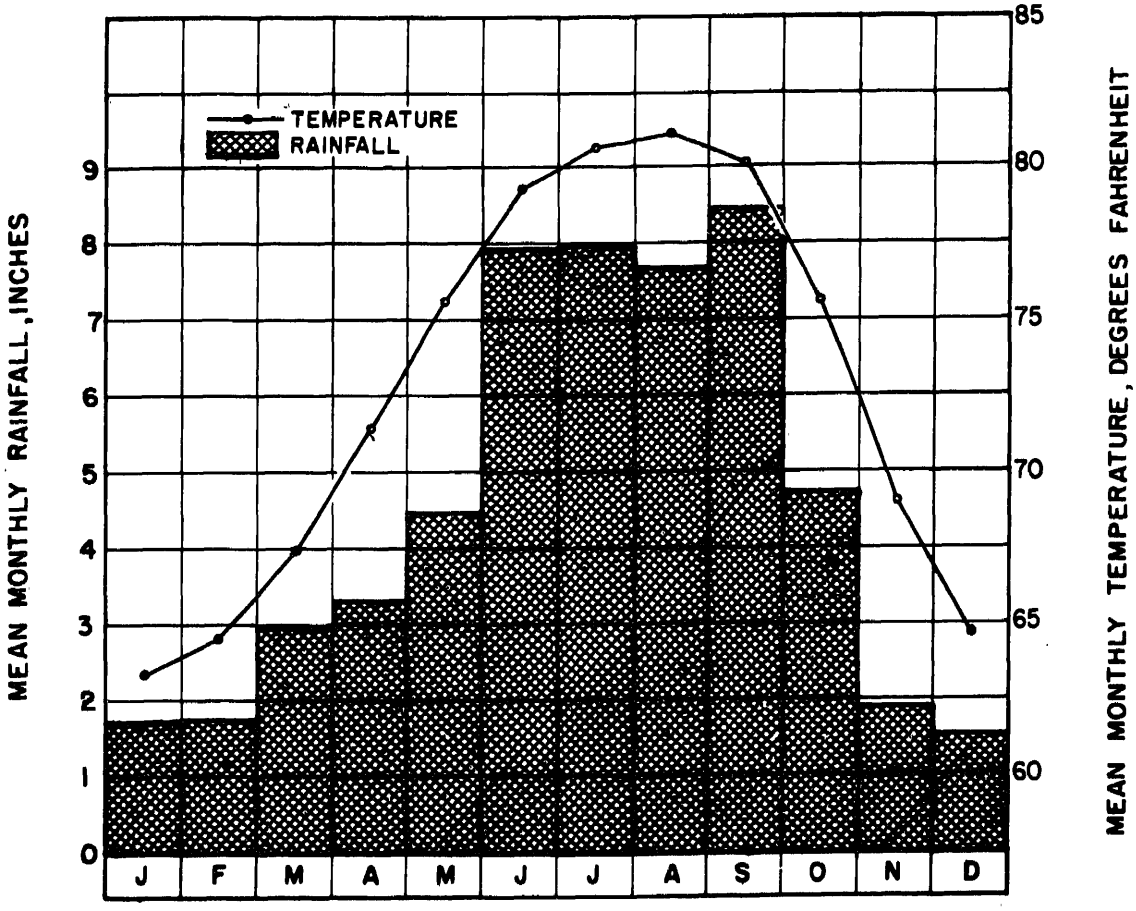

Figure 4. Graph showing mean monthly rainfall and temperature, south shore of Lake Okeechobee, 1931-60.

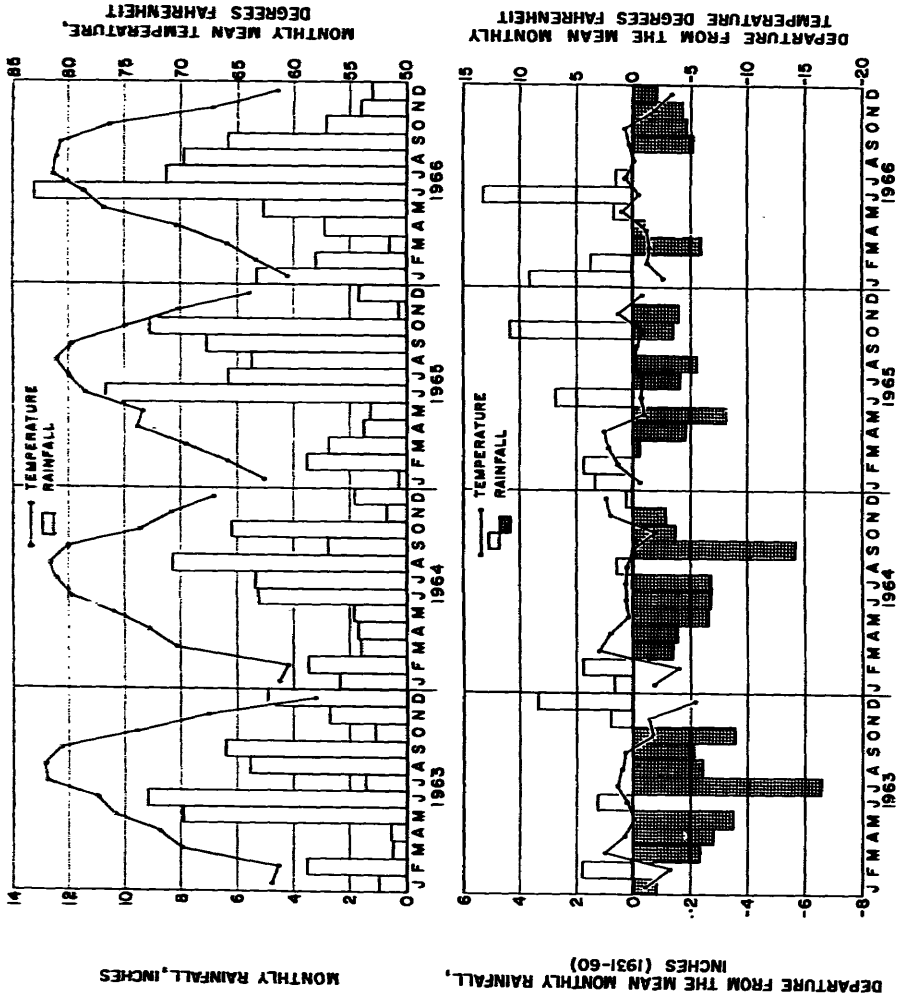

Figure 5. Graphs showing monthly rainfall and departure from the mean monthly rainfall; monthly mean temperature and departure from the mean monthly temperature; south shore of Lake Okeechobee, 1963-66.

TABLE 1. – FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS IN THE LAKE OKEECHOBEE AREA.

Series	Formation[1])	Range in thickness (feet)	Lithology	Water-bearing property
Holocene	Organic soil	0-10	Peat.	Low permeability.
Pleistocene	Lake Flirt Marl	0-10	Sandy marl.	Low permeability.
	Terrace deposits	0-10	Quartz sand.	Low permeability.
	Fort Thompson Formation	0-30	Alternating marine and fresh-water limestones and/or marls.	Variable permeability; low in dense crystalline limestones and high in shelly limestone.
	Caloosahatchee Marl	0-30	Shell, sand, clay, and sandy limestone.	Variable permeability; high in shell beds and low in clay.
Miocene	Tamiami Formation	30-110	Clay, sand, and sandy limestone.	Variable permeability; high in sandstone beds and low in sands and clay.

[1]) The nomenclature and stratigraphy used herein are based on that used by the Florida Geological Survey (Puri and Vernon, 1964).

of sea level are permanently recorded by alternating marine and fresh-water strata. The shallow geology is complex due to relatively rapid depositional and environmental changes. Consequently, few geologists agree on the ages of the shallow formations.

[1] The nomenclature and stratigraphy used herein are based on that used by the Florida Geological Survey (Puri and Vernon, 1964).

SURFACE DEPOSITS

Surface deposits include organic soil, which is chiefly comprised of peat that accumulated in the Lake Okeechobee-Everglades basin during Holocene time, and sand of late Pleistocene-Holocene age. Figure 6 shows the type and distribution of surface deposits in the Lake Okeechobee area. Parker, Ferguson, Love and others (1955, p. 109) reported that samples of peat from depths ranging from 5 to 6 feet in the upper Everglades were determined to be about 5,000 years old by Carbon 14 dating. In 1945, the organic soil ranged in thickness from 8 feet on the southeastern side of the lake to a feather edge on the southwestern side.

Sand that mantles the area on the north, east, and west sides of the lake is probably part of the Pamlico Formation of late Pleistocene age. This sand, probably not more than 10 feet thick, was derived from the higher Terrace deposits when sea level was about 25 feet higher than present sea level. The sand has been classified by the U. S. Soil Conservation Service as being poorly-drained or well-drained. The well-drained sand occupies areas of slightly higher topography suggesting that the drainage characteristic is related to topographic position rather than to the permeability of the sand.

SUBSURFACE DEPOSITS

Underlying the surface deposits are beds of shell, clay, marl, and sand, which range from Miocene through Pleistocene in age. These beds are referred to herein as subsurface deposits and their distribution is shown in figure 7.

The Tamiami Formation (Parker, 1951, p. 823), of Miocene age, is composed of silty shelly sands and silty shelly marls that occasionally contain thin beds of limestone or sandstone. Schroeder and Klein (1954, fig. 5) reported that the top of the formation lies at a depth of about 60 feet in the Belle Glade area. Klein, Schroeder, and Lichtler (1964, Table 3) reported that the Tamiami occurs at depth of about 35 feet near Moore Haven and that the formation

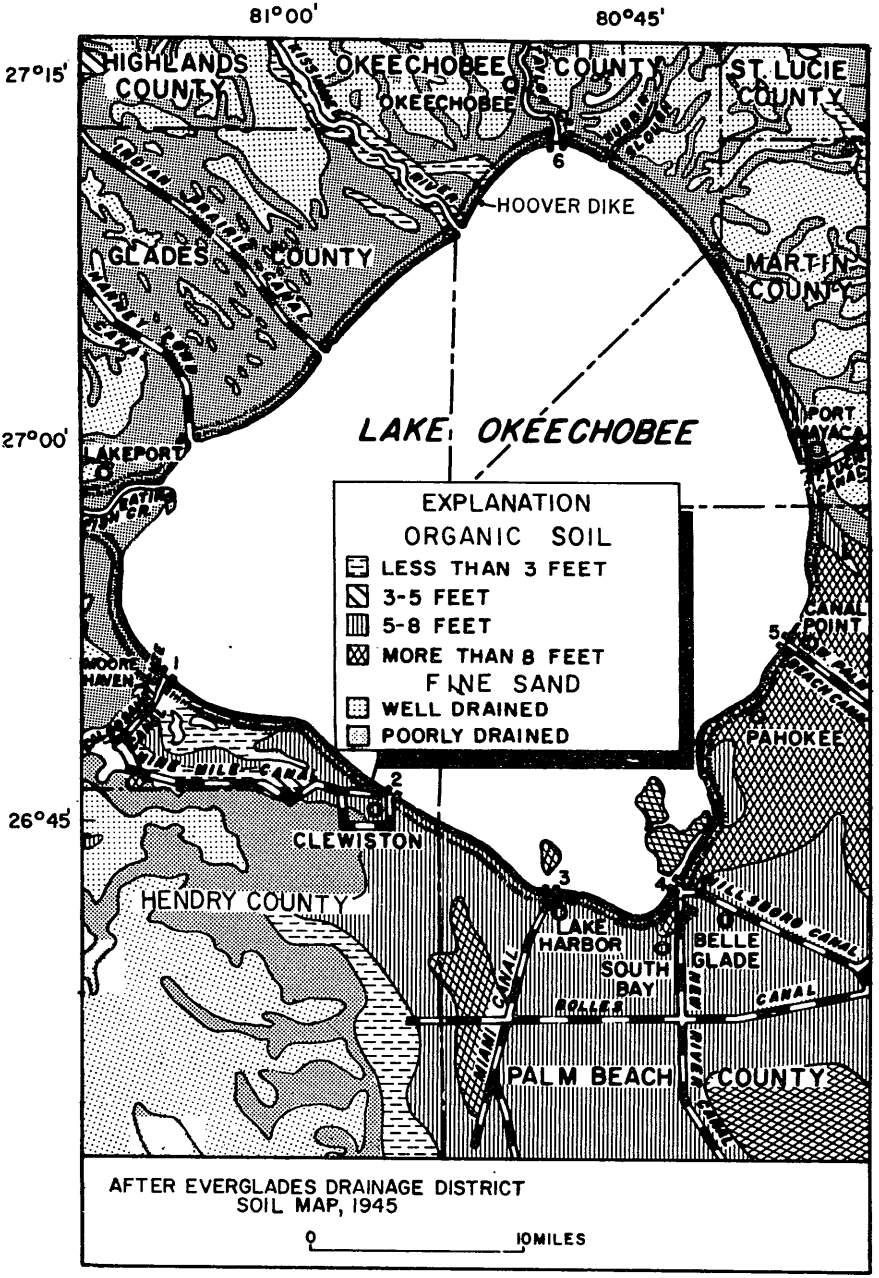

Figure 6. Map of Lake Okeechobee area showing surface deposits.

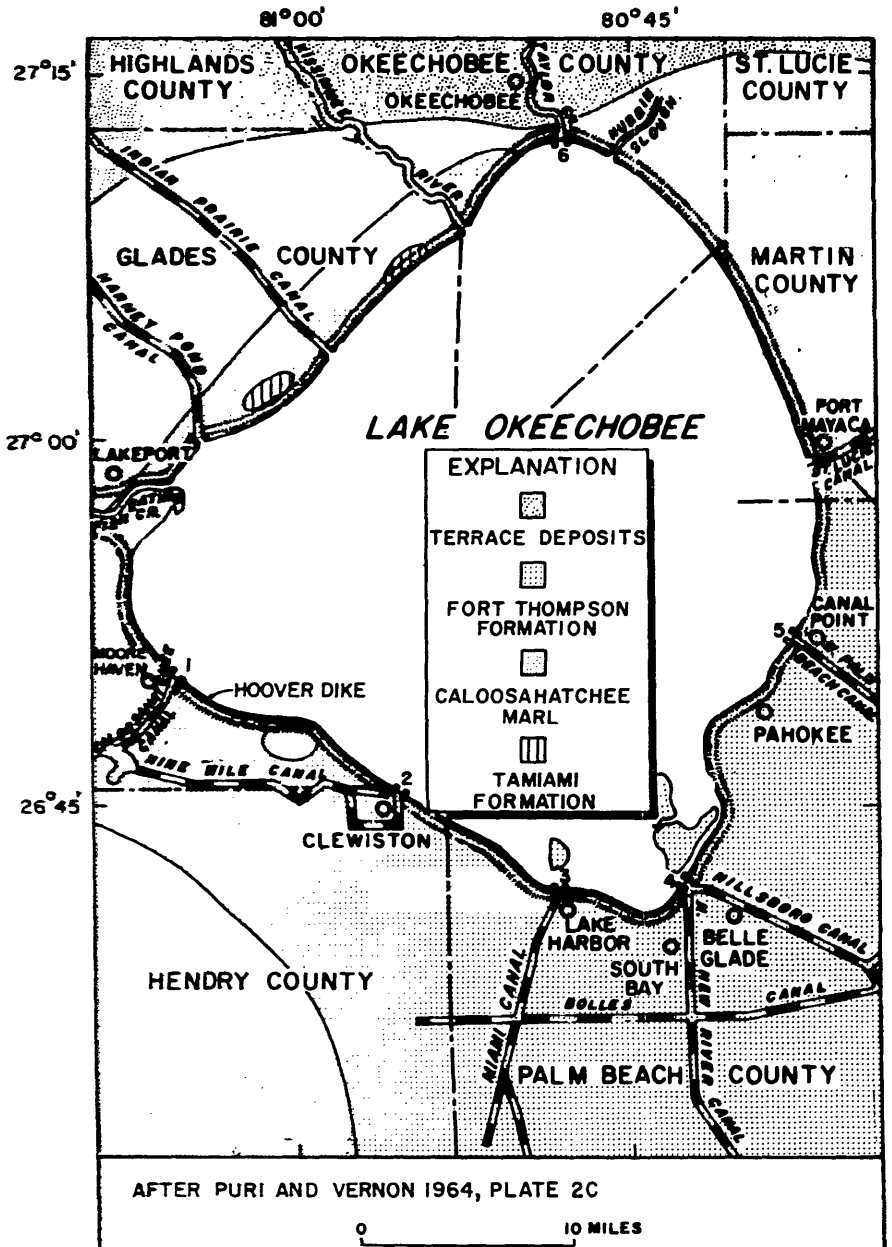

Figure 7. Map of Lake Okeechobee area showing shallow subsurface deposits.

ranges from 30 to 110 feet thick. Puri and Vernon (1964, plate 2C) mapped a small patch of green clay which occurs near the surface on the northwest side of the lake as the Tamiami (see fig. 7). Klein, Schroeder, and Lichtler (1964, p.26), however, included a similar bed of clay in the overlying Caloosahatchee Marl because it seemed to be restricted to the flanks of eroded hills of the Tamiami.

During this study the top of the Tamiami Formation was located by test drilling at a depth of about 40 feet at sites 1 and 2 near Moore Haven and Clewiston, respectively. The Tamiami is chiefly composed of fine to very coarse quartz sand with some limestone, sandstone, and phosphate. Principal fossils found in the Tamiami are *Balanus* sp., *Cymatosyrinx lunata* Dall, *Ringincula* sp., *Hanetia (Solenosteira) mengeana* (Dall), and *Nassarius (Uzita) bidentata* (Emmons). A bed of green clay occurs in the overlying Caloosahatchee Marl.

The Caloosahatchee Marl (Dall, 1887) unconformably overlies the Tamiami Formation. The formation underlies the surface deposits in much of the area surrounding the northeastern, northwestern, and southwestern shores of the lake; and underlies the younger Fort Thompson Formation in the area beneath the lake and southeastward thereof (fig. 7). The Caloosahatchee Marl is composed chiefly of shelly sand and shelly sandy marl and an occasional bed of limestone. DuBar (1958, p.35) assigned the Caloosahatchee to the Pleistocene and reported a maximum thickness of about 50 feet. However, the formation generally ranges between 15 and 30 feet thick in the study area. The fossils contained in the formation are too numerous to list here but *Cyprea problematic* is generally considered to be a good index fossil. DuBar (op. cit.) reported that the Caloosahatchee Marl cropped out in a small area between Moore Haven and Clewiston. The same area was mapped by Parker (1955) as Fort Thompson.

The Fort Thompson Formation (Cooke, 1929, p. 211-215) is composed of alternating beds of fresh-water and marine marls and/or fresh-water and marine limestone. The formation does not exceed 30 feet in thickness and underlies most of the lake. The formation is unconformable to beds above and below. The most common fossil in the fresh-water beds is *Helisoma scalare.*

After intensive studies of the type localities of the Caloosahatchee Marl and the Fort Thompson Formation, DuBar (1958) assigned the Caloosahatchee Marl to the Pleistocene Series rather than the Pliocene Series primarily on the basis of vertebrate fossils, and to a lesser degree on mollusks and stratigraphic relationship. Most investigators have accepted DuBar's biozonation but not all agree on the age of the Caloosahatchee.

Figure 8 is a comparison of the stratigraphic columns of principal investigators at the type locality of Fort Thompson located 21 miles west of Moore Haven on the Caloosahatchee River. Parker (1955) presented the stratigraphy at Fort Thompson originally proposed by Parker and Cooke (1944). DuBar (1958) mapped the biozones along the Caloosahatchee River, subdivided the Caloosahatchee Marl and the Fort Thompson Formation into members,

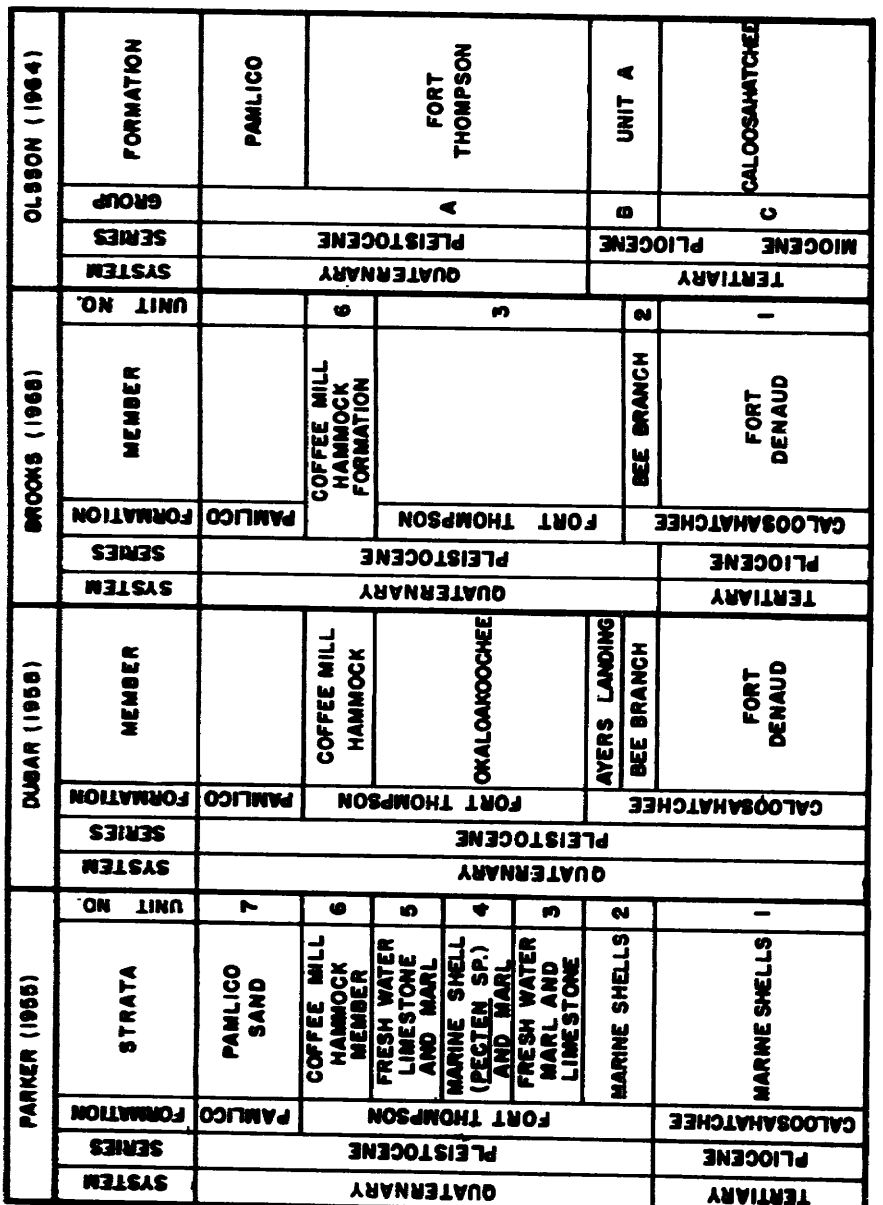

Figure 8. Comparison of stratigraphic columns at Fort Thompson.

assigned the Fort Thompson Formation and the Caloosahatchee Marl to the Pleistocene and included the lower part of the Fort Thompson Formation in the Caloosahatchee Marl. Olsson (1964) assigned the Caloosahatchee Marl to upper Miocene and assigned the lower part of the Fort Thompson to "Unit A" of Pliocene age. Brooks (1968) included the lower part of the Fort Thompson Formation in the Caloosahatchee Marl, reassigned the Caloosahatchee Marl to Pliocene and lower Pleistocene, retained part of DuBar's subdivision of the Caloosahatchee Marl and part of Parker's original Fort Thompson Formation, and upgraded the Coffee Mill Hammock Member to a formational rank. However, DuBar's stratigraphic designations are presently recognized and used by the Florida Geological Survey (Puri, and Vernon 1964, p.232).

Terrace deposits, which are composed chiefly of quartz sand, underlie the surface deposits in a band across the northernmost part of the lake (fig. 7). These deposits are only a few feet thick and are pre-Pamlico (Pleistocene) in age.

GEOHYDROLOGY

This study is principally concerned with the source, direction and rate of seepage through the materials underlying the Hoover Dike and to a lesser extent with the quality of the water. Test drilling at each of the five sites yielded data on the depth, thickness, lithology, and hydraulic characteristics of aquifers (permeable strata) and of confining beds (relatively impermeable strata). In some cases it was difficult to identify separate aquifers because differences in lithologies and in permeabilities were not pronounced. However, measurements of water levels and their fluctuations in selected observation wells yielded the data needed to prepare hydraulic profiles (flow nets) that ultimately aided in the identification of aquifers and confining beds and of points of recharge and discharge.

The hydraulic profiles of the five sites were generally similar in that seepage from the lake initially moved inland from a deep borrow (the Navigation Canal) in the lake. Seepage moved through a filtercake, which lined the borrow, into an aquifer (or aquifers) underlying the Hoover Dike toward discharge points, such as canals and ditches, where water levels were controlled at optimum levels for farming. Water-level fluctuations indicated that steady-state flow from the lake to discharge points in the nearby agricultural areas was usually attained within a few days after periods of unsteady water levels. Therefore, the steady-state seepage from the lake may be reasonably estimated by using the hydraulic gradients during periods of relatively stable water levels.

During steady-state conditions, the seepage from the lake is equivalent to the flow through the filtercake and the flow through the aquifers beneath the dike. At those sites where the filtercake is missing, or has about the same

permeability as the continguous aquifers, the seepage from the lake is about equivalent to the flow through the aquifers.

Obviously it would have been difficult to determine the flow through the filtercake because of the difficulty in obtaining data from the deep borrow (Navigation Canal) in the lake. On the other hand it was relatively easy to determine the flow through the aquifers underlying the dike at each site. Once the hydraulic characteristics of the aquifer(s) and the average hydraulic gradient in the aquifers were determined, it was possible to compute the amount of seepage from the lake through each aquifer using the modified form of the Darcy equation.

$$Q = T\,I\,L \tag{1}$$

where Q is the seepage in gallons per day, T is the transmissivity of the aquifer in gallons per day per foot, I is the average hydraulic gradient (steady state) in the aquifer; and L is the length of dike or, canal, along which T was effective. The gradient, I, was determined by the equation

$$I = \frac{h}{d} \tag{2}$$

where h is the head, in feet, between the steady-state water levels, hence equipotential lines, in two observation wells in the same aquifer, and d is the distance, in feet, between the wells.

The hydraulic characteristics of the aquifers were determined by relating observed water-level fluctuations caused by natural or artificial discharge and recharge to suitable equations. The characteristics are commonly referred to as transmissivity and hydraulic conductivity (field). Transmissivity, T, is the rate of flow, in gallons per day, at the prevailing water temperature, through a vertical strip of aquifer, 1 foot wide having a height equal to the saturated thickness, m, of the aquifer, under a unit hydraulic gradient. Hydraulic conductivity (field), K_f, is the rate of flow, in gallons per day, at the prevailing temperature, through a one square foot section of aquifer under a unit hydraulic gradient. If T is known, K_f may be determined by dividing T by the thickness of the aquifer (m). Conversely, if K_f is known, T may be determined by multiplying K_f by the thickness of the aquifer (m).

Pumping tests and slug tests were performed on selected wells in order to determine the transmissivity of the various aquifers. The pumping test (nonequilibrium) method involved pumping a well at a constant rate and recording the rate of drawdown or recovery in the pumped well and/or in nearby observation wells. The slug test (nonequilibrium) method involved injecting a known volume of water (a slug) into an observation well and recording the rate of decline of head in the well. The data were subsequently analyzed to determine T using standard methods presented in reports by Ferris and others (1962) and by Cooper, Bredehoeft, and Papadapulos (1967).

Seepage tests were also used to determine T whenever it was possible to relate measured seepage into or out of a canal to hydraulic gradients in aquifers. Generally, the method involved measuring the discharge entering or leaving a specified reach of canal at the landward toe of the Hoover Dike and then relating the discharge to ground-water gradients which were determined by water-level measurements (equipotential lines) in the line of observation wells normal to the dike at the respective site.

The analysis of the test data depended upon the following conditions: 1) that the transmissivity and the gradients were uniform along the reach of the canal affecting the seepage, and 2) that the seepage tests had continued for sufficient time for the waters levels to stabilize, or to reach a steady state.

Under steady state conditions, the measured discharge leaving or entering the reach of canal. Q_c, is related to the seepage by the equation

$$Q_c = Q_1 + Q_a - E \tag{3}$$

where Q_1 is the seepage from or into the lake, Q_a is the seepage from or into the agricultural area, and E is the loss imposed by evaporation.

Actually, none of the seepage tests continued long enough for water levels to stabilize completely. Therefore part of the measured flow (Q_c) was caused by changes in both canal and ground-water storage. Thus compensation for change in storage is expressed in the equation

$$Q_c = Q_1 + Q_a + \Delta S_c + \Delta S_g - E \tag{4}$$

where ΔS_c is the change in canal storage and ΔS_g is the change in ground-water storage; and both terms are expressed in terms of daily mean discharge. Elements Q_c, Q_1, Q_a, ΔS_c, and ΔS_g are positive when, 1) seepage is toward the canal, 2) discharge is leaving the reach of canal, and 3) water levels in the canal and aquifers are falling.

The seepage tests, however, were continued sufficiently long that the magnitude of the terms E and ΔS_g became very small in relation to other terms and they were dropped from the equation. Thus the following equation was used to determine the approximate seepage relationship for a steady state condition.

$$Q_c = Q_1 + Q_a + \Delta S_c \tag{5}$$

Equations 6 and 7 below are expressions of steady state seepage related to the lake and agricultural area, where I_1 is the hydraulic gradient related to the lake and I_a is that related to the agricultural area.

$$Q_1 = TLI_1 \tag{6}$$

$$Q_a = TLI_a \tag{7}$$

Equation 8 below is obtained by substituting equations 6 and 7 in equation 5; and equation 9 is obtained by solving equation 8 in terms of T.

$$Q_c = TL(I_1 + I_a) + \Delta S_c \tag{8}$$

$$T = \frac{Q_c - \Delta S_c}{L(I_1 + I_a)} \tag{9}$$

Usually the data collected during seepage tests were concerned with the terms on the right hand side of equation 9. Once the transmissivity of the aquifer (s) was determined it was possible to determine the lake seepage (Q_1) associated with hydraulic gradients beneath the Hoover Dike using equation 6.

Because a single aquifer test is merely a guidepost to aquifer transmissivity, several tests were usually performed at each site in order to obtain values of transmissivity that were consistent with the geologic and hydrologic setting.

Once the proper magnitude of seepage (Q_1) was determined at each site it was possible to relate the value to the hydraulic gradient across the Hoover Dike because a linear relationship exists between the gradient across the dike and the gradient in the aquifer(s) beneath the dike during steady-state conditions. For convenience, seepage (Q_1) is expressed in terms of a seepage factor, S_e, which is defined herein as the steady-state rate of seepage per length of recharge section per foot of head between the recharge boundary and the discharge boundary. It is determined by using the equation

$$S_e = \frac{Q_1}{L(h_1 - h_c)} \tag{10}$$

where Q_1 is the seepage rate expressed in cubic feet per second (cfs), L is the length of the recharge section in miles, h_1 is the elevation of the water level at the recharge boundary in feet, and h_c is the elevation of the water level at the discharge boundary in feet.

In most cases the lakeside Navigation Canal was considered the recharge boundary and the landside borrow canal, or toe ditch, was considered the discharge boundary. However, in places that lacked a close, well-defined discharge boundary on the landward side of the dike, the seepage factor was related to the lake level and the ground-water level in an observation well located at the landside toe of the dike. In the latter case the seepage factor was related to the head between the lake and a specific point in the aquifer (the well); and future estimates of seepage using the seepage factor (S_e) will require a knowledge of the steady-state water level in the well. Therefore, it would be advantageous to retain those wells as permanent observation wells.

The value of the seepage factor for each site can be expected to decrease in the future as the filtercake continues to form in the lakeside borrows but there are insufficient data at present to determine the rate of reduction in the seepage factor. However, effects of the filter-cake buildup may be determined in the future by comparing the seepage computed using the seepage factor with the seepage determined by gradients in aquifer(s) beneath the dike. Therefore, long-term water-level data are needed at each site to detect future changes in seepage factors.

Measurements of chloride content and temperature of both surface and ground water were used to supplement the hydraulic data. The chloride content of water in shallow aquifers beneath the southern shore of the lake is in many places high (Parker, 1955, p. 818 and Klein, 1964, p. 73), whereas the chloride content in lake waters is relatively low. Thus, high chloride content in aquifers that underlie the dike would indicate that the aquifers convey relatively little seepage from the lake; whereas low chloride content in the aquifers would indicate that they convey significant amounts of seepage from the lake. Temperature variations were also helpful in determining zones which convey seepage from the lake.

Because the geohydrology at each of the sites is somewhat different, the sites will be discussed separately in the sections that follow.

SITE 1

DESCRIPTION

Site 1 is in Glades County on the southwest shore of Lake Okeechobee about 5 miles east of Moore Haven, as shown in figure 9. The site consists of data collection stations along a line about 820 feet long, which constructed normal to the Hoover Dike, as shown by figure 10. The stations consist of 19 test wells, of which 14 were used to obtain data on ground-water levels. Two observation points (OP's) were used to obtain water-level data in the lake and in the L-D1 Canal. North of the dike is the Navigation Canal which was excavated in the thirties to construct the Hoover Dike. South of the dike is the L-D1 Canal which was excavated in 1962 to raise the dike to its present height (39 feet above mean sea level) and to construct a smaller dike along the southern (landward) bank of the L-D1 Canal.

Natural land surface at the site is about 13 feet above msl and is underlain by about 2 to 3 feet of organic soil (see profile in fig. 10). The area south of the L-D1 Canal is devoted chiefly to agriculture (sugar cane) and water levels there are controlled by the Diston Island Drainage District. The district is drained by a series of north-south lateral canals (not shown in fig. 9)

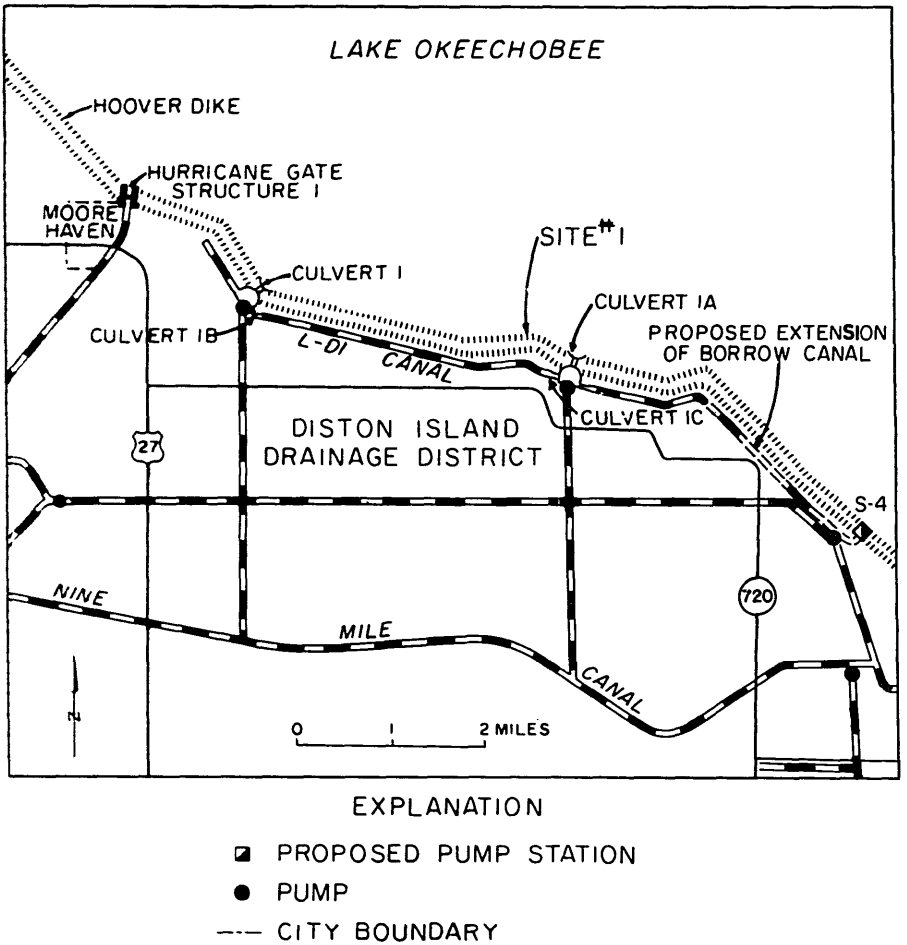

Figure 9. Map showing location of site 1 near Moore Haven.

about 25 feet wide and 5 feet deep. The lateral canals are spaced at half-mile intervals and connect to main canals which are about 60 feet wide and 7 feet deep. The main canals are equipped with pumping facilities and gated controls to provide drainage and to route water from the lake for irrigation.

At site 1 the flow of a 3½-mile reach of the L-D1 Borrow Canal is regulated by automatic flap gates on two 72-inch culverts (culverts 1B and 1C in fig. 9) at the intersection with the main pump pools near culverts 1 and 1A. The flap gates on culverts 1B and 1C close when the water level in the pump pool is higher than that in the borrow canal. The flap gates are usually closed during the rainy season when the Diston Island Drainage District pumps into the lake. The flap

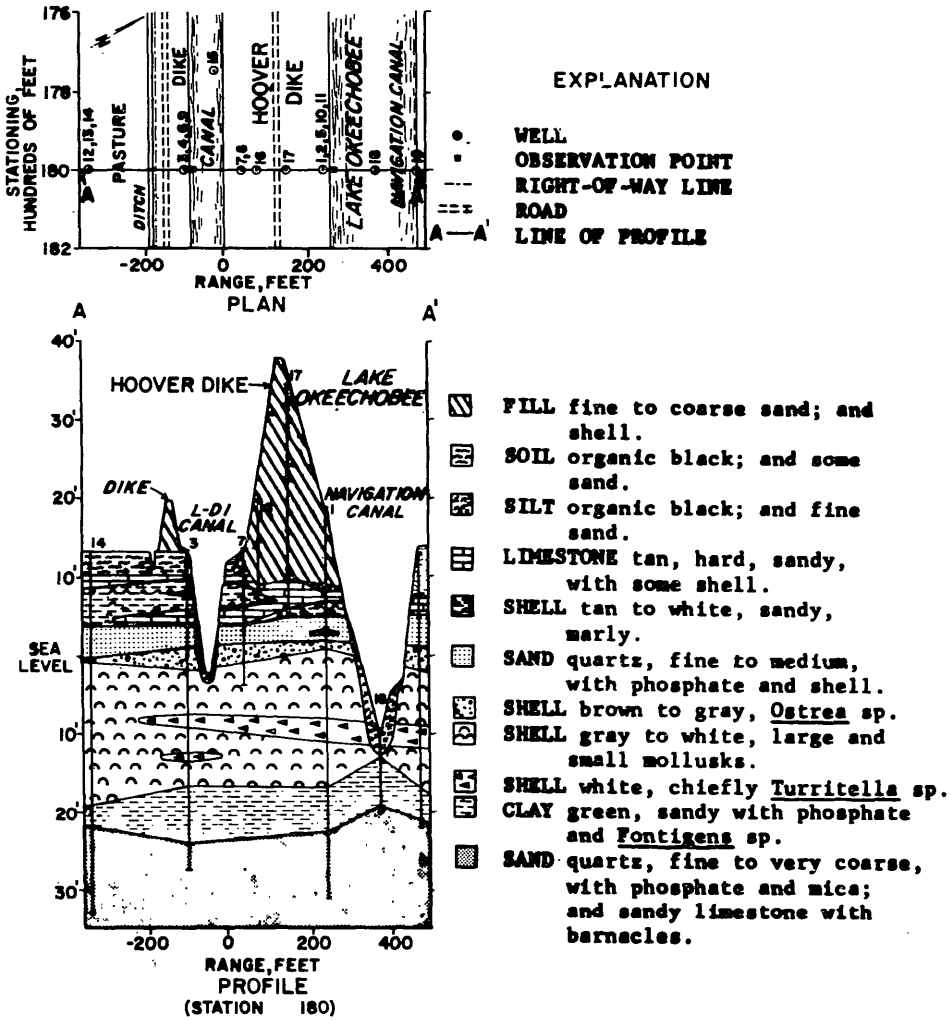

Figure 10. Plan and profile along line A-A′ at site 1.

gates are usually open during the dry seasons when the seepage from the lake into the L-DI Canal supplements the regulated flow of irrigation water from the lake through culvert 1A into the district.

The profile along line A-A′ at site 1 (fig. 10) shows that the materials to a depth of about 32 feet below msl are sand, marl, shell, and limestone which grade laterally and vertically into each other. Generally beds of limestone and shell are considered aquifers and beds of marl, fine sand, and clay are considered confining beds. Seepage is greatest through shell beds within the Caloosahatchee Marl, which ranges between 10 feet above msl to 20 feet below msl.

AQUIFERS AND CONFINING BEDS

The aquifers, confining beds, and depths of the observation wells along line A-A' at site 1 are shown on figure 11. The aquifers and confining beds are

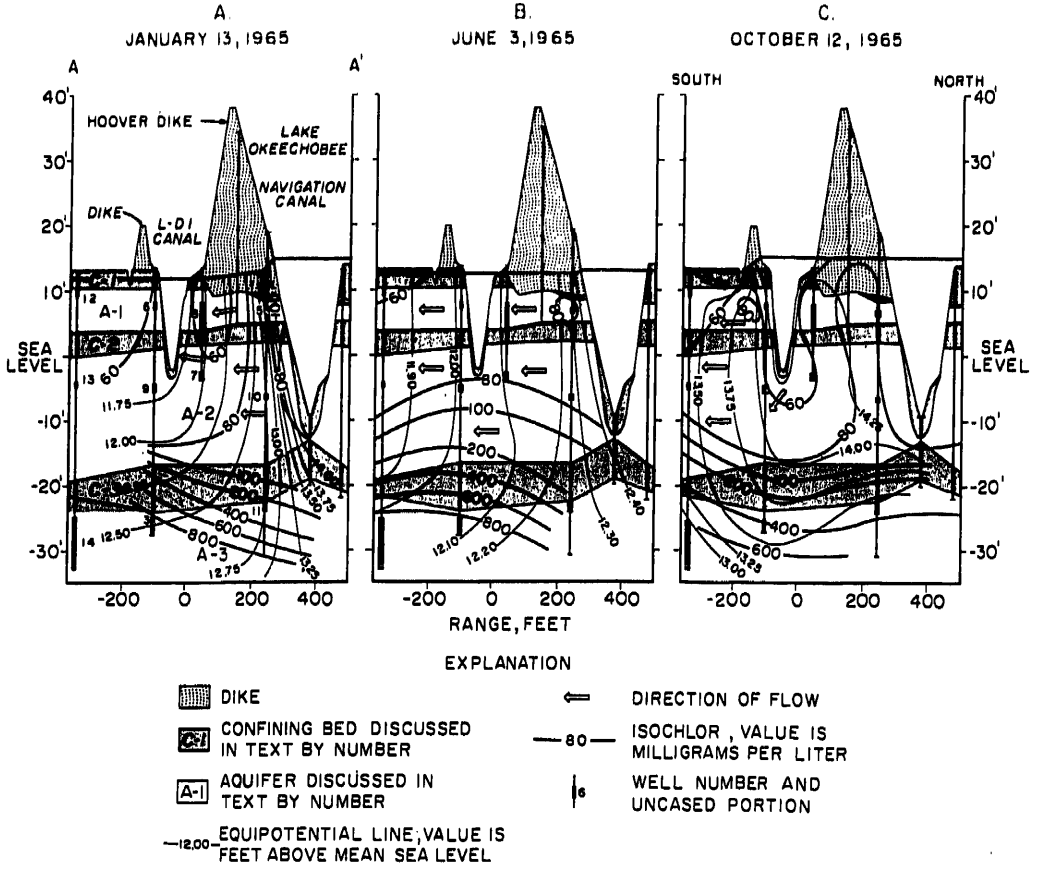

Figure 11. Selected hydraulic profiles along line A-A' showing aquifers, confining beds, and depths of observation wells at site 1.

numbered consecutively with increasing depth, and the numbers are peculiar only to site 1.

Confining bed C-1 is composed of relatively impermeable black organic soil. The bed retards the movement of water between the surface and the underlying beds, but its confining ability is locally ineffective where the bed is cut by many canals and ditches. Aquifer A-1 is chiefly a sandy marly limestone. The upper surface of the bed is well cemented and relatively impermeable, however, locally occurring solution holes account for zones of high permeability, Confining bed C-2 is composed of shelly sand. The bed is only slightly less permeable than the overlying aquifer but it probably contains zones of very low permeability. Aquifer A-2 is chiefly shell and is highly permeable. Confining bed C-3 is composed of green clay and it is relatively impermeable. Aquifer A-3 is composed of sand and sandstone and it is moderately permeable.

Some seepage occurs through all the beds but most seepage occurs through aquifers A-1, A-2, and A-3. However, aquifers A-1 and A-2 and perhaps confining bed C-2 are the chief sources of seepage from the lake because they are breached by deep borrow canals on the lakeward and landward sides of the dike. The Navigation Canal is the perennial recharge boundary. The L-D1 Canal is the chief dry season discharge boundary and the network of ditches in the fields nearby is the chief wet season discharge boundary.

Silt deposits that line the sides and bottoms of the borrow canals play an important part in seepage. These deposits were formed chiefly by the settling of the fine fractions from the excavated material and by the accumulation of organic sediments derived from dead vegetation and the erosion of nearby surface materials. Because the level of the lake is usually higher than the water level in the Diston Island Drainage District, hydrostatic pressure has probably caused these deposits to form a filtercake on the bottom and walls of the Navigation Canal; and the buildup of the filtercake probably has caused a progressive reduction in the rate of seepage from the lake over the years. The loss in head across the filtercake is an important factor in analyzing aquifer coefficients because more head is required to move water at a given rate through the filtercake than to move water at the same rate through a like thickness of aquifer. Therefore, the determination of seepage through an aquifer must be related to the transmissivity and hydraulic gradients within the aquifer itself, and not to gradients which include the head across the filtercake.

WATER MOVEMENT AND FLUCTUATIONS

The principal direction of water movement at site 1 is from Lake Okeechobee to the Diston Island Drainage District as shown in the hydraulic profiles (fig. 11) by the arrows representing flow lines. Short seasonal reversals occur however when the stage of the lake is routinely lowered prior to the rainy

season. Profiles A-C were constructed from data collected on January 13, 1965, June 3, 1965, and October 12, 1965, respectively, to show the distribution of equipotential lines and chloride content for selected high and low stages of the lake. Although the profiles depict the instantaneous conditions of flow normal to the Hoover Dike, that is, along a stream line, the equipotential lines generally represent the steady state hydraulic gradients in the flow system.

On January 13, 1965, a period of high water levels, the stage of Lake Okeechobee at the Navigation Canal was 14.18 feet and the stage of the L-Dl Canal was 11.69 feet. The principal direction of water movement in aquifers A-1 and A-2 was from the Navigation Canal to the L-Dl Canal. The principal direction of water movement in aquifer A-3 was southward toward an undetermined point of discharge in the Diston Island Drainage District, but some upward movement probably occurred through confining bed C-3 in the area immediately south of the L-Dl Canal. Most of the seepage occurred through aquifers A-1 and A-2. Of the measured 10.5 cfs discharging through culvert 1C from the 3½-mile reach of the L-Dl Canal, about 7.5 cfs was estimated to have seeped from the lake. The close, even spacing of equipotential lines and the low chloride content in aquifers A-1 and A-2 beneath the Hoover Dike suggests that locally the upper 25 to 30 feet of strata act as a unit aquifer. The high chloride content in water in aquifer A-3 suggested that relatively little water seeped from the lake through that unit.

On June 3, 1965, a period of low water levels, the stage of Lake Okeechobee at the Navigation Canal was 12.44 feet, the stage of the L-Dl Canal was 12.09 feet, and the principal direction of ground-water movement in aquifers A-1, A-2, and A-3 was from the Navigation Canal into the Diston Island Drainage District. No losses occurred from the L-Dl Canal other than seepage and evaporation. Hydraulic gradients were low indicating that the rate of seepage was lower than it was on January 13, 1965.

On October 12, 1965, a period of high water level, the stage of Lake Okeechobee at the Navigation Canal was 14.37 feet and the stage of the L-Dl Canal was 14.32 feet. About 8.5 cfs was flowing from the lake through culvert 1 into the 3½-mile reach of the L-Dl Canal because of a malfunction of culvert 1B after the passing of Hurricane Betsy in September. This condition caused a landward shift in the principal recharge boundary from the Navigation Canal to the L-Dl Canal, which resulted in a significant decrease in the chloride content in aquifer waters beneath the L-Dl Canal.

A comparison of the daily mean stage of the lake with the daily highest water level in well 8, on figure 12, shows that during 1964-65 the stage of the lake was higher than the stage of the water level in well 8 except for a few days in June 1965. Fluctuations of the lake level are chiefly caused by seiche, winds, seasonal rainfall on the basin, and water-management practices of the nearby drainage districts and the U. S. Corps of Engineers. Fluctuations of the water

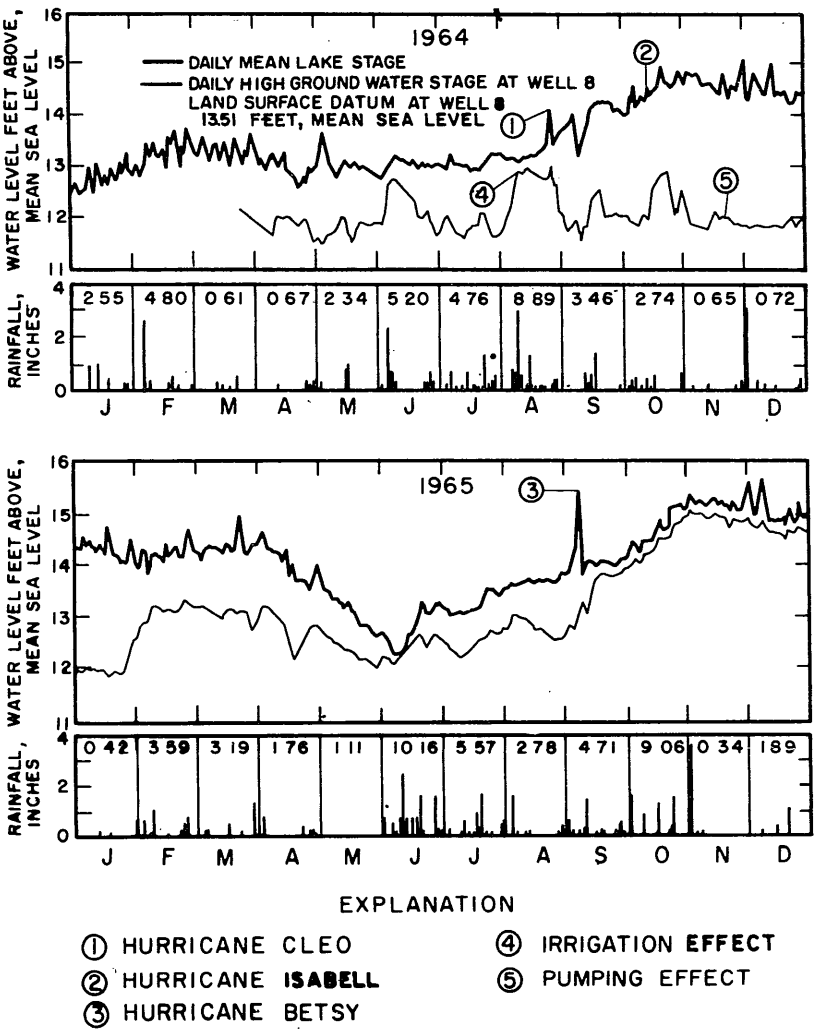

Figure 12. **Graphs showing daily stages of Lake Okeechobee and ground-water levels in well 8 at site 1; and daily and monthly rainfall at Moore Haven, 1964-65.**

level in well 8 are chiefly caused by fluctuations of the water level in the L-D1 Canal which is presently controlled by the water-management practices of the Diston Island Drainage District.

Water-level fluctuations in the lake that generally lasted only a few days were usually caused by winds. In some instances short-term peaks (waves), such as those caused by hurricanes or low waves from large boats, were transmitted

through aquifer A-1 and were recorded in well 8. The location of well 8 is such that its water level is closely related to the water level in the L-DI Borrow Canal. The water level in the L-DI Canal is controlled by two 6-foot gated culverts (1B and 1C) which connect to the pump bays at culverts 1 and 1A (see locations on fig. 9). The water levels in the pump bays are in turn controlled by gates on culverts 1 and 1A, which lead to the lake, and by rectangular concrete controls with removable stop logs, which lead from the pump bays to the main canals of the Diston Island Drainage District.

When the district needs water from the lake for irrigation during dry periods, the gates on culverts 1 and 1A are partly opened and the stop logs in the controls are removed, thereby allowing water to flow from the lake into the district. This operation causes the automatic flap gates in culverts 1B and 1C to open, allowing water to drain from the L-DI Canal into the pump bays until the level in the L-DI Canal reaches a level slightly above that in the pump bays, or until the level in the L-DI Canal falls below the bottom invert of culverts 1B and 1C (invert elevation 10.2 feet).

When the district needs to remove excess water from the fields after heavy rains the stop logs are replaced in the controls, the gates on culverts 1 and 1A are opened, and water is pumped from the main canals into the lake. This operation causes the water levels in the pump bays to exceed that in the L-DI Canal, thereby closing the automatic flap gates in culverts 1B and 1C. Then the water level in the L-DI Canal rises to a static level between the lake level and the water level in the district.

Thus, the peaks on the hydrograph of well 8 (fig. 12) during 1964 usually represented periods when the district was pumping excess water into the lake and the troughs usually represented periods when the district was withdrawing irrigation water from the lake.

During April and May, 1965, the U. S. Corps of Engineers routinely lowered the stage of Lake Okeechobee and the regional water level to about 12 feet above msl prior to the wet season (fig. 12). After heavy rains in early June, water levels in the district rose above the lake level and reverse seepage, that is seepage from the district to the lake, occurred for a few days. After a normal landward gradient was reestablished, the gates on culverts 1B and 1C were closed due to pumping from the district to the lake and the water levels in well 8 (and in the L-DI Canal) rose to a level between the lake level and the water level in the district.

On September 11, 1965, shortly after the passing of Hurricane Betsy, some debris became lodged under the automatic flap gate at culvert 1B, permitting water to flow from the lake through culvert 1 (which was open) and culvert 1B into the L-DI Canal, and the water level in well 8 (and in the L-DI Canal) approached that of the lake (fig. 12). If no water was seeping from the L-DI Canal into the district, then the water levels in the L-DI Canal and well 8

would have equalled that of the lakes and the flow into the L-Dl Canal would have ceased. However, the water level in well 8 (and in the L-Dl Canal) was lower than the lake level. Therefore, it follows that water was seeping from the L-Dl Canal into the district and the flow through culvert 1B represented the seepage losses along the 3½-mile reach from culvert 1B to culvert 1C, assuming that evaporation losses were insignificant. This condition existed through December, 1965, and the inland shift in the distribution of flow is shown by the hydraulic profile on October 12, 1965, in figure 11. Thus operations of the landside drainage works in the Diston Island Drainage District has a significant effect on the relationships between the stage of the lake and the stage of the L-Dl Canal, the hydraulic gradients from the lake, and the seepage from the lake.

Figures 13 through 15 are graphs comparing water levels, chloride content, and water temperature in wells that tap the three aquifers with data for the lake and the L-D1 Canal. The lines representing the well data are coded by numbers of dots; the line with the least dots represents the well nearest the lake.

A comparison of the data in figures 13 and 14 suggest that locally aquifers A-1 and A-2 are hydraulically connected and function as a unit aquifer. The data in figure 15 suggest that confing bed C-3 separates aquifer A-3 from the shallower aquifers. The data in figures 13 and 14 also indicate that near the dike water levels in aquifers A-1 and A-2 are highly influenced by the operational stage of the L-D1 Canal. Of particular importance is the fact that most of the time the water levels in the wells 5, 10, and 11 were closely related to fluctuations in the water levels in the L-Dl Canal despite their close proximity to the recharge boundary (the Navigation Canal). This relationship suggest that the head loss between the lake and the water levels in the nearby wells is caused by a layer of silt, or a filtercake, on the walls of the lakeside Navigation Canal.

Generally, waters in the lake, the L-Dl Canal, and in aquifers A-1 and A-2, contained chloride concentrations ranging between 50 and 100 mg/1 (milligrams per liter) as shown on figures 13 and 14. Chloride content was slightly lower in the wells farthest from the lake suggesting that aquifers A-1 and A-2 were recharged by local rainfall as well as by seepage from the lake.

Waters in aquifer A-3 (fig. 15) contained chloride concentrations ranging from 100 to more than 800 mg/1. Concentrations in aquifer A-3 were lowest in the area near the Navigation Canal where infiltration of fresh water from the lake was greatest. Concentrations were highest in the district south of the L-Dl Canal, which suggests that seepage through aquifer A-3 from the lake into the district is of minor importance.

However, infiltration from the L-Dl Canal into aquifer A-3 was induced by pumping nearby well 14 (fig 15). The chloride content in well 3 decreased from about 800 mg/1 in February 1965 to 500 mg/1 in April 1965 after well 14 was pumped at a rate of about 80 gpm (gallons per minute) on March 4. In August 1965, well 14 was again pumped and the water in well 3 was freshened to about

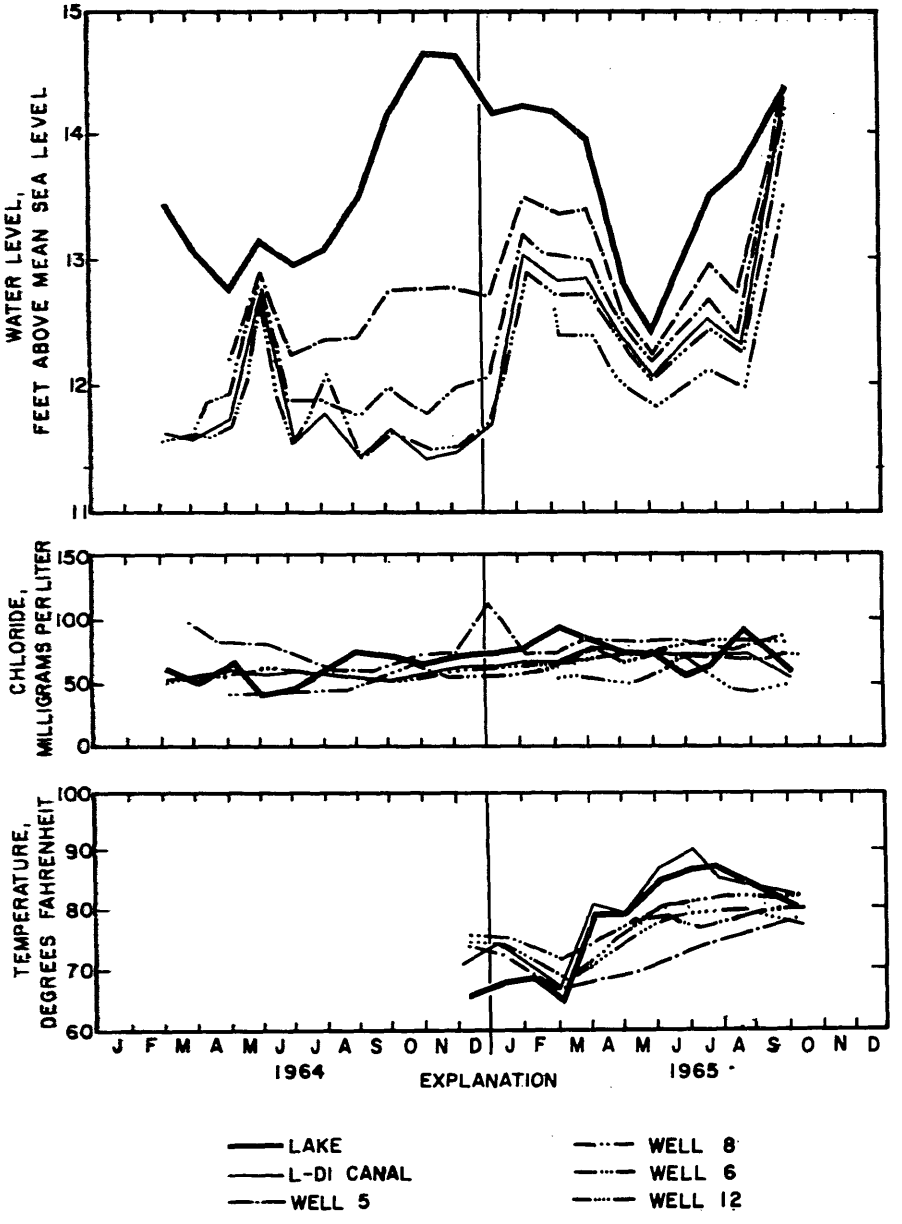

Figure 13. Graphs comparing water levels, chloride content and water temperature in wells that tap aquifer A-1 at site 1 with data for the lake and the L-D1 Canal, 1964-65.

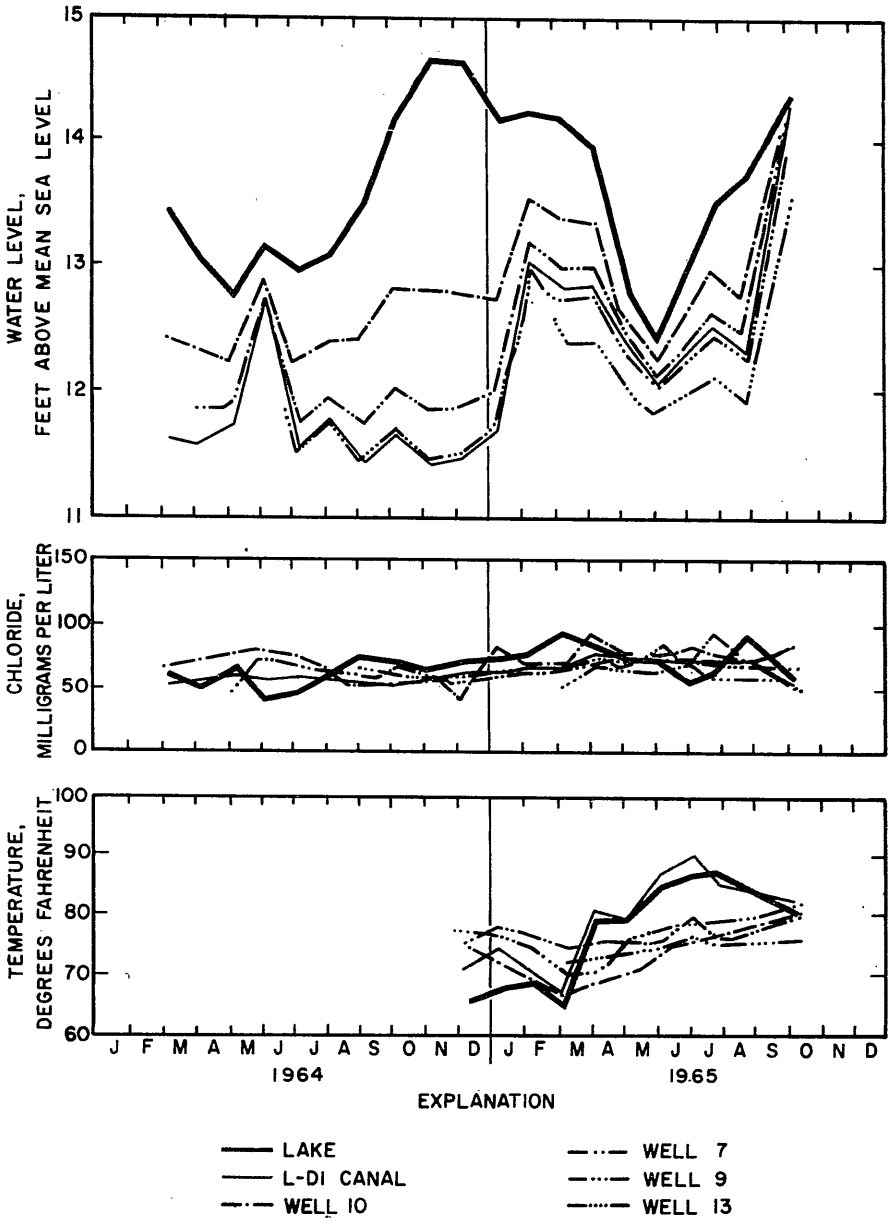

Figure 14. Graphs comparing water levels, chloride content and water temperature in wells that tap aquifer A-2 at site 1 with data for the lake and the L-D1 Canal, 1964-65.

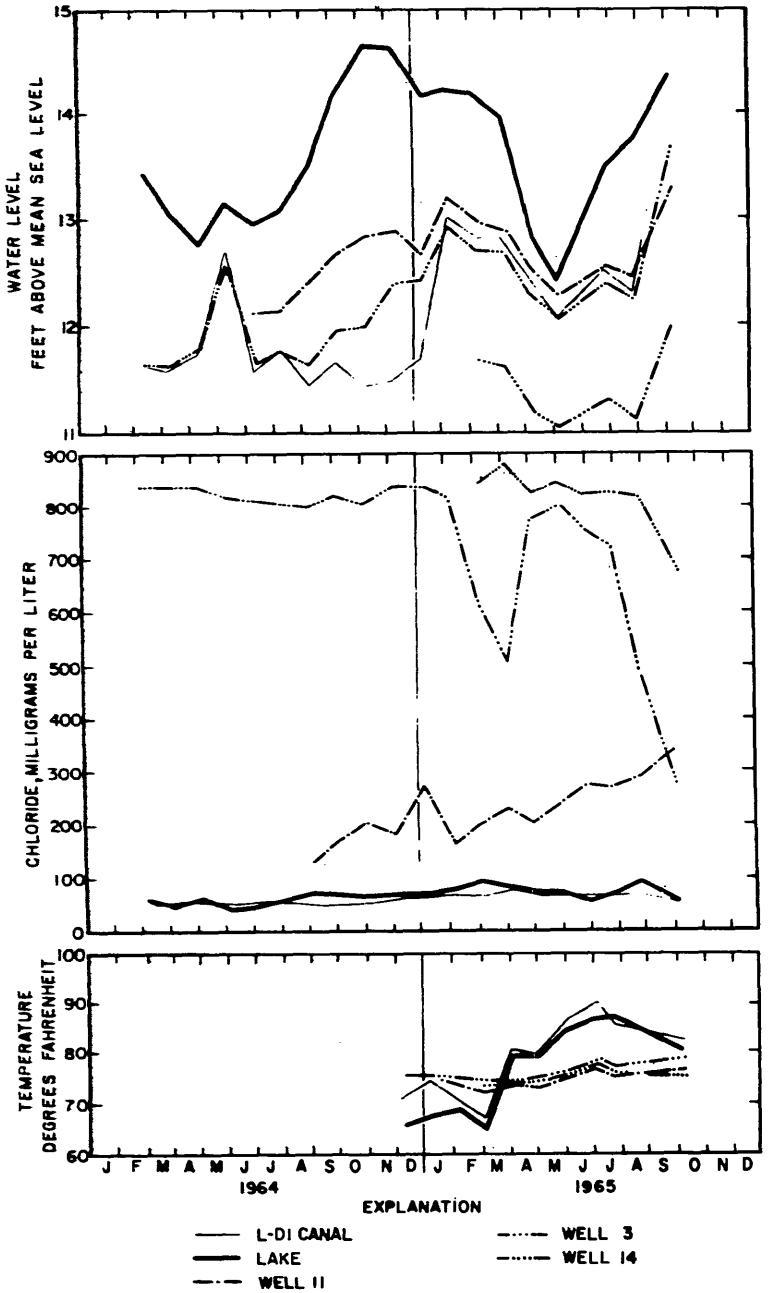

Figure 15. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-3 at site 1 with data for the lake and the L-D1 Canal, 1964-65.

500 mg/1. Well 3 was further freshened to less than 300 mg/1 after the malfunction of culvert 1B during Hurrican Betsy in September 1965, which caused the recharge boundary to shift from the Navigation Canal to the L-Dl Canal.

The temperature (°F) of water in the L-Dl Canal and in the lake side Navigation Canal ranged from the high sixties during the winter to high eighties during the summer. The seasonal variation in temperature of ground water decreased with depth. Temperatures in aquifer A-3 were least affected by seasonal variations in temperature.

During 1964-65, monthly observations of water levels and of operations of the drainage works at site 1 suggested that three generalized relations could be recognized between the stages of the lake and the L-Dl Canal. Monthly measurements of the stages in the lake were plotted against the stages in the L-Dl Canal, figure 16, and the plots were then related to the physical operations of the drainage works. The first line (1) represents the relationship caused by the malfunction of culvert 1B and the resultant shift in the recharge boundary from the Navigation Canal to the L-Dl Canal. The second line (2) represents the approximate relationahip that occurs when the L-Dl Canal is ponded by pumping operations. The third line (3) represents the relationship when the L-Dl Canal is draining into the Diston Island Drainage District during irrigation operations. Because seepage from the lake is closely related to the head between the lake and the L-Dl Canal, the relationship in line 2 can be used to estimate water levels in the L-Dl Canal when the canal is ponded by operations of the drainage works during wet periods if no physical changes occur in the system.

QUANTITATIVE STUDIES

Aquifer tests were performed at site 1 to determine the transmissivity (T) and/or the hydraulic conductivity (K) of the aquifers which are the chief conveyers of seepage from the lake. Pumping tests were conducted on wells 9 and 10 which tap aquifer A-2, and on well 3 which taps aquifer A-3 (see locations of wells on profile in fig. 11A).

Well 9 was pumped for 60 minutes at a rate of 90 gpm while water-level fluctuations were recorded in wells 3, 6, 7, 10, 13, and in the pumped well (9). Well 10 was pumped for 40 minutes at a rate of 122 gpm while fluctuations of water levels were recorded in wells 5, 7, 8, and 11. The data indicated that recharge from the L-Dl Canal, from the Navigation Canal and from vertical leakage, caused the drawdowns in the observation wells to be suppressed early in the tests. However, an analysis of a few data which were collected early in the tests and therefore least affected by recharge, suggests that the value of T could be in the magnitude of 100,000 gpd/ft. The tests also indicated that locally beds A-1, C-2 are essentially a unit aquifer, that water flows from the borrow canals

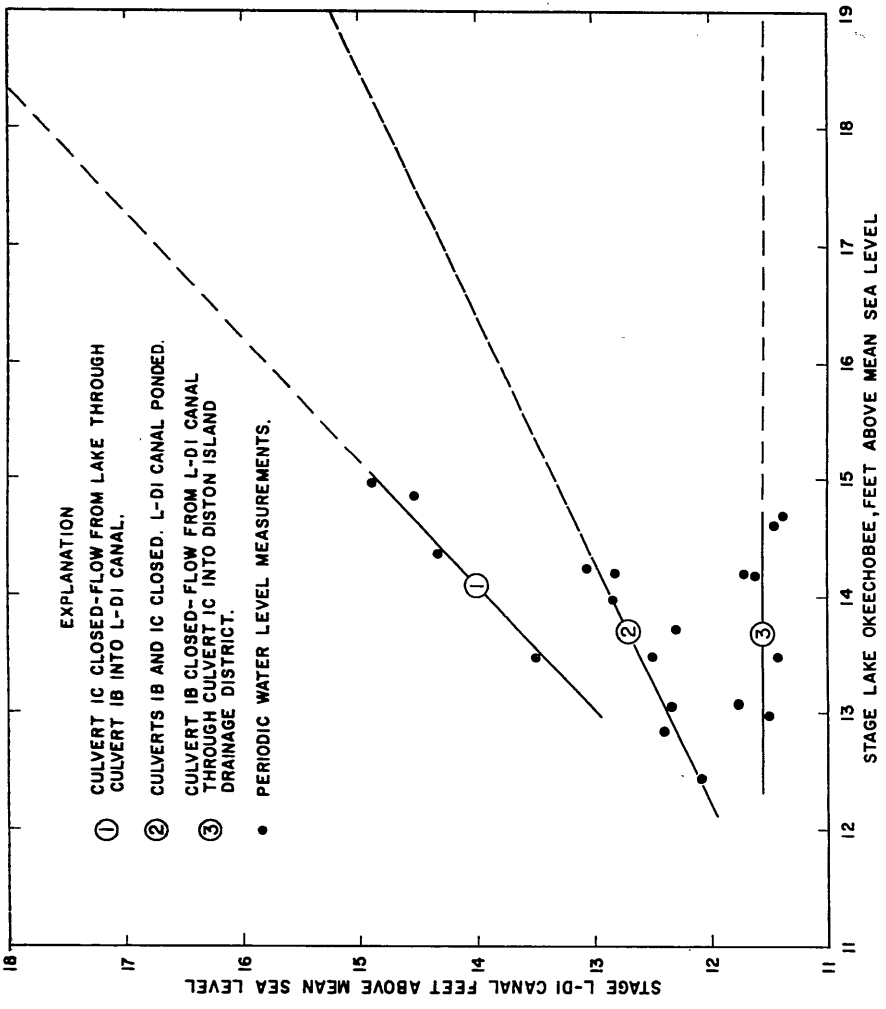

Figure 16. Stage correlation curves for the L-D1 Canal and Lake Okeechobee for various drainage operations in the Diston Island Drainage District.

into the aquifers A-1 and A-2, and that some leakage (minor amounts) occurs through bed C-3.

Well 3 was pumped for 62 minutes at a rate of 12½ gpm while fluctuations of water levels were recorded in wells 11 and 14, and in the pumped well. The

data suggest that the transmissivity of aquifer A-3 in about 7,000 gpd/ft and that some leakage occurs through confining end C-3.

Slug tests were conducted in wells 1 through 3 at 9 different zones during drilling operations. The results of the slug tests are presented in table 2. The analysis of the slug tests generally required a great deal of subjective judgement, therefore the results only suggest the magnitude of values that might be expected. The estimated value of T for the saturated zone of flow beneath the dike between 13.5 feet above msl and 17 feet below msl is about 28,500 gpd/ft; and that for the zone between 17 and 31 feet below msl is about 6,900 gpd/ft. Probably the minimum T value that might be expected for the total flow zone would be about 35,000 gpd/ft.

TABLE 2. – RESULTS OF SLUG TESTS AT SITE 1.

Bed	Thickness (feet)	K_f (gpd/ft^2)	T (gpd/ft)
Dike Fill	3[1]	20	60
C-1	1	2	2
A-1	5	1,200[1]	6,000[2]
C-2	3	70	210
A-2	18.5	1,200	22,200
C-3	6	20	120
A-3	8	850	6,800
TOTAL	44.5		35,392

[1] Saturated

[2] Estimated

On January 13, 1965 a seepage test was conducted in the 3½-mile reach of the L-D1 Canal between culverts 1B and 1C (see location on fig. 9). Water levels were measured in the observation wells and at observation points at site 1 in order to relate hydraulic gradients to the measured discharge (10.5 cfs) flowing eastward from the L-Dl Canal through culvert 1C. The waterlevel data were used to construct the hydraulic profile at site 1 (see profile A in figure 11) and the hydraulic gradients at site 1 were assumed to be uniform along the L-Dl Canal from culvert 1B to culvert 1C. Culvert 1B was closed, so that the flow through culvert 1C represented most of the seepage from the lake to the L-Dl Canal. Seepage from the lake was assumed to have reached a steady-state condition because the water level in well 8 (thus the stage of the L–Dl Canal) had stabilized for a period of at least 2 weeks prior to the test (fig. 12). The

transmissitivity along the 3½-mile reach was assumed to be uniform because geologic conditions along the reach (U. S. Corps of Engineers 1961, plate 13) are similar to those at site 1, therefore, the hydraulic gradient between wells 10 and 7 was assumed to be representative of the gradient across the aquifer beneath the Hoover Dike along the reach. The hydraulic gradient, I_1, between wells 10 and 7 was determined by equation 2.

$$I_1 = \frac{h\ 0.71\ \text{foot}}{d\ 200\ \text{feet}} = 0.00355$$

The hydraulic gradient across the aquifer from the L-D1 Canal southward to the Diston Island Drainage District was almost flat at site 1, therefore the I was assumed to be zero.

Transmissivity, T, was computed using equation 9.

$$T = \frac{Q_c - \Delta S_c}{L\,(I_1 + I_a)}$$

where Q_c was the measured discharge from the L-D1 Canal at culvert 1C, 10.5 cfs (6.8 mgd); ΔS_c was determined to be equivalent to 1.7 cfs (1.1 mgd); L was 18,800 feet; I_1 was 0.00355; and I_a was assumed to be an insignificant factor.

$$T = \frac{6.8\ \text{mgd} - 1.1\ \text{mgd}}{18{,}800\ \text{ft}\ (0.00355) + 18{,}800\ \text{ft}\ (0.00000)}$$

$$T = 85{,}400\ \text{gpd/ft}$$

Thus, the transmissivity of the strata that convey the seepage from the lake was estimated to be about 85,400 gpd/ft; and the value of T obtained by the seepage test was considered to be more representative of the actual T than those obtained by the pumping tests and the slug tests.

In 1968, however, three additional seepage tests were conducted at site 1 at the request of the C&SFFCD in order to verify the results of the January 13th test. Test 3 (Meyer, 1969, p. 20-26) involved the lowering of the water level in the 3½-mile reach of the L-D1 Canal several feet below the lake level by pumping; and the results of test 3 suggested that the transmissivity of the water-bearing strata beneath the dike was about 64,600 gpd/ft. However, the results of the three tests indicated that T is probably about 72,300 gpd/ft (op. cit., p. 27); therefore, the value 72,300 gpd/ft was used to compute seepage at site 1.

SEEPAGE

Seepage from the lake at site 1 can be estimated using the transmissivity of the water-bearing strata that underlie the dike and the hydraulic gradient

between wells 10 and 7. On the other hand, it would be more convenient to estimate the seepage using the water levels in the lake and the L-D1 Canal, but the loss in head across the filtercake on the walls of the Navigation Canal prevents a direct computation of seepage from the lake (Q_1) using equations 6 or 9, and the aquifer transmissivity. However, a comparison of water-level data indicated that there is a direct relationship between the water levels in wells 10 and 7 and the water levels in the lake and the L-D1 Canal. Therefore, the seepage through the aquifer(s) can be related directly to the head between the lake and the L-D1 Canal by using equation 10, assuming that the relationships will not change appreciably in the future due to the slow buildup of the filtercake.

The seepage factor, S_e, was therefore computed using equation 10 and the data for the seepage test on January 13, 1965. The length of canal section (L) was 18,800 feet, or 3.56 miles; the seepage pickup (Q_1) was assumed to be 8.8 cfs; the stage of the lake (h_1) was 14.18 feet; and the stage of the L-D1 Canal (h_c) was 11.69 feet.

$$S_e = \frac{Q_1}{L(h_1 - h_c)} = \frac{8.8 \text{ cfs}}{3.56 \text{ mi. } (14.18 \text{ ft.} - 11.69 \text{ ft.})}$$

$$= 1.0 \text{ cfs/mi/ft}$$

Thus, the seepage factor, S_e, at site 1 was estimated to be about 1.0 cfs per mile per foot of head between the lake and the L-D1 Canal; and this value was considered representative for design purposes.

On the basis of the 1968 tests, the seepage for the test on January 13, 1965, was re-evaluated using 72,300 gpd/ft as the value of T. Equation 9 was used to evaluate the gradients related to the seepage into the L-D1 Canal.

$$72{,}300 \text{ gpd/ft} = \frac{6.8 \text{ mgd} - 1.1 \text{ mgd}}{18{,}800 \text{ ft. } (0.00355 + I_a)}$$

$$I_a = 0.00064$$

The result suggested that some seepage was derived from the Diston Island Drainage District. Equation 7 was used to determine the amount that seeped from the district into the L-D1 Canal.

$$Q_a = 72{,}300 \text{ gpd/ft} \times 0.00064 \times 18{,}800 \text{ ft.}$$

$$= 0.87 \text{ mgd or } 1.3 \text{ cfs}$$

Thus the earlier assumption that the gradient I_a on the south side of the canal was equal to zero was erroneous, and a net 1.3 cfs seeped from the district into

the L-Dl Canal along the 3½-mile reach. This condition was later confirmed by test 2 of the 1968 tests.

On the basis of the 1968 value of T, the distribution of seepage during the test on January 13, 1965, was re-evaluated using equation 5.

$$Q_c = Q_1 + Q_a + \Delta S_c$$
$$10.5 \text{ cfs} = 7.5 \text{ cfs} + 1.3 \text{ cfs} + 1.7 \text{ cfs}$$
$$10.5 \text{ cfs} = 10.5 \text{ cfs}$$

Thus, the seepage from the lake (Q_1) was about 7.5 cfs and not 8.8 cfs as originally determined.

The seepage factor (S_e) was recomputed using equation 10, where Q_1 is 7.5 cfs, L is 3.56 miles, h_c (lake) is 14.18 feet, and h_c (L-Dl Canal) is 11.69 feet.

$$S_e = \frac{Q_1}{L\,(h_1 - h_c)}$$

$$S_e = \frac{7.5 \text{ cfs}}{3.56 \text{ mi } (14.18 \text{ ft.} - 11.69 \text{ ft.})}$$

$$S_e = 0.8 \text{ cfs/mi/ft.}$$

Thus the seepage factor (S_e) for the January 13, 1965 test is about 0.8 cfs per mile per foot of head between the stage of the lake and that of the L-Dl Canal; and the results of the January 13 test are within the order of magnitude of both the original estimate which was used for design purposes and the average value of 0.9 cfs/mi/ft which was determined by the 1968 tests. However, the 1968 value is considered the more reliable of the three values. Therefore, the seepage factor (S_e) at site 1 is about 0.9 cfs per mile per foot of head between the stage of Lake Okeechobee and that of the L-Dl Canal.

The present effect of the filtercake in the Navigation Canal is included in the value of the seepage factor but the value can be expected to decrease as the filtercake continues to build up and the lake level is raised. The data suggest that the filtercake causes a 68 percent reduction in seepage from the lake. If the filtercake has formed uniformly since the excavation of the Navigation Canal in the early thirties then the buildup of the filtercake has reduced the seepage about 2 percent per year, however, there are no data to support this conclusion. Therefore no attempt was made to relate the seepage factor to future changes in the filtercake, but it is apparent that the value of the seepage factor will decrease in the future.

Seepage from the lake into the Diston Island Drainage District is related to the lake level and the operational water levels of the district and the L-Dl Canal.

If the average stage in the L-D1 Canal were maintained at, or slightly below, the average stage of water table in the Diston Island Drainage District then the L-D1 Canal would intercept most of the seepage from the lake. For example, if the average stage of the L-D1 Canal were maintained at about 11.0 feet (that is below the average stage in the district) by pumping the seepage back into the lake, then the average annual rate of seepage into the L-D1 Canal would be the product of the seepage factor (0.9 cfs/mi/ft) and the average head between the lake and the L-D1 Canal (14 ft. - 11 ft. = 3 ft), or 2.7 cfs per mile. If the average stage of the lake were raised to 16.5 feet then the average rate of seepage into the L-D1 Canal would be about 5.0 cfs per mile. If the L-D1 Canal were ponded, that is, closed off at both ends, then the seepage would pass from the lake through the canal southward into the Diston Island Drainage District; and the seepage would be approximately proportional to the head between the lake and the L-D1 Canal. For example, if the culverts at the ends of the L-D1 Canal were closed so that the canal were ponded, then the stage of the canal that would correspond to an average lake stage of 14 feet would be about 12.8 feet (from line 2 in figure 16); and the corresponding average rate of seepage into the Diston Island Drainage District would be about 1.1 cfs per mile (1.2 ft x 0.9 cfs/mi/ft). If the average stage of the lake were increased to 16.5 feet then the average stage of the L-D1 Canal would be 14.1 feet and the average seepage to the Diston Island Drainage District would be about 2.2 cfs per mile.

In order to estimate the average increase in seepage that would result from raising the average stage of the lake from 14 to 16.5 feet, one would have to know the long-term water levels in the L-D1 Canal and in the District. The only data available, however, were those collected during 1964-65, but they suggest that the long-term water levels in the L-D1 Canal and the adjacent fields are regulated slightly below 11.5 feet during the dry (irrigation) season, and that the forementioned water levels are regulated slightly above 12 feet during the wet season. If it is assumed that the future regulation of the water levels will be the same, that is, drainage operations will occur 50 percent of the time and irrigation operations will occur the other 50 percent, then it is possible to estimate the increase in seepage that will result from raising the average stage of the lake.

During the 1964 dry season, most of the seepage from the lake was intercepted by the L-D1 Canal, which discharged the seepage southward into the Diston Island Drainage District. The water level in the L-D1 Canal was controlled at a stage of about 11.5 feet by the irrigation practices of the Diston Island Drainage District regardless of the stage in the lake. Therefore, during irrigation periods; the long-term average head between the lake and the L-D1 Canal is estimated to be about 2.5 feet (14 ft - 11.5 ft = 2.5 ft) and the resultant seepage is about 2.2 cfs per mile (2.5 ft x 0.9 cfs/mi/ft). If the average stage of the lake is raised to 16.5 feet, the average head should be about 5.0 feet and the resultant seepage should be about 4.5 cfs per mile.

During the 1964 wet season, the drainage practices of the Diston Island Drainage District usually caused the water in the L-Dl Canal to pond. When the average stage of the lake is 14 feet, the average stage of the L-Dl Canal is about 12.8 feet. Therefore, during the wet seasons the long-term average gradient between the lake and the L-Dl Canal is estimated to be about 1.2 feet and the resultant seepage is about 1.1 cfs per mile. If the average stage of the lake is raised to 16.5 feet, then the average stage of the L-Dl Canal will rise to 14.1 feet and the average seepage will be about 2.2. cfs per mile. If the irrigation and drainage seasons are about equal in duration, then the average annual seepage rates are about 1.6 and 3.4 cfs per mile for the corresponding average lake stages of 14 and 16.5 feet and the average increase in seepage will be about 1.8 cfs per mile.

Thus, raising the average stage of Lake Okeechobee from 14 feet to 16.5 feet should increase the average seepage rate at site1 from 1.6 to 3.4 cfs per mile; and the seepage beneath the 9-mile section of dike represented by site 1 should increase from 14.4 to 30.6 cfs.

SITE 2

DESCRIPTION

Site 2 is located in Hendry County on the southwestern shore of Lake Okeechobee about 1 mile east of Clewiston as shown on Figure 17. The site consists of data-collection stations along a line about 470 feet long, which was constructed normal to the Hoover Dike, as shown in plain view of figure 18. The data-collection stations include 16 test wells, of which 11 were used to obtain data on ground-water levels, and two observation points (OP's) which were used to obtain data on water-levels in the lake and in the L-D2 Canal.

North of the Hoover Dike is the Navigation Canal which was used in the early thirties for borrow to construct the dike. South of the Hoover Dike is the L-D2 Canal from which borrow was taken in 1962 to raise the dike to its present height. The L-D2 Canal is about 9,700 feet long and is not connected to the flood control works in the agricultural area or to the Industrial Canal at Clewiston, just south of the L-D2 Canal on U.S. Highway 27 which parallels the length of the canal. Beyond U. S. Highway 27 the land is locally uncultivated and poorly drained. The nearest controlled drainage at site 2 is located in the agricultural area about one quarter mile south of the dike. Canals in the agricultural area, which are equipped with pumping facilities and gated controls, provide drainage during wet periods and route water from the lake for irrigation during dry periods. Water levels in the agricultural area are locally regulated by the Clewiston Drainage District.

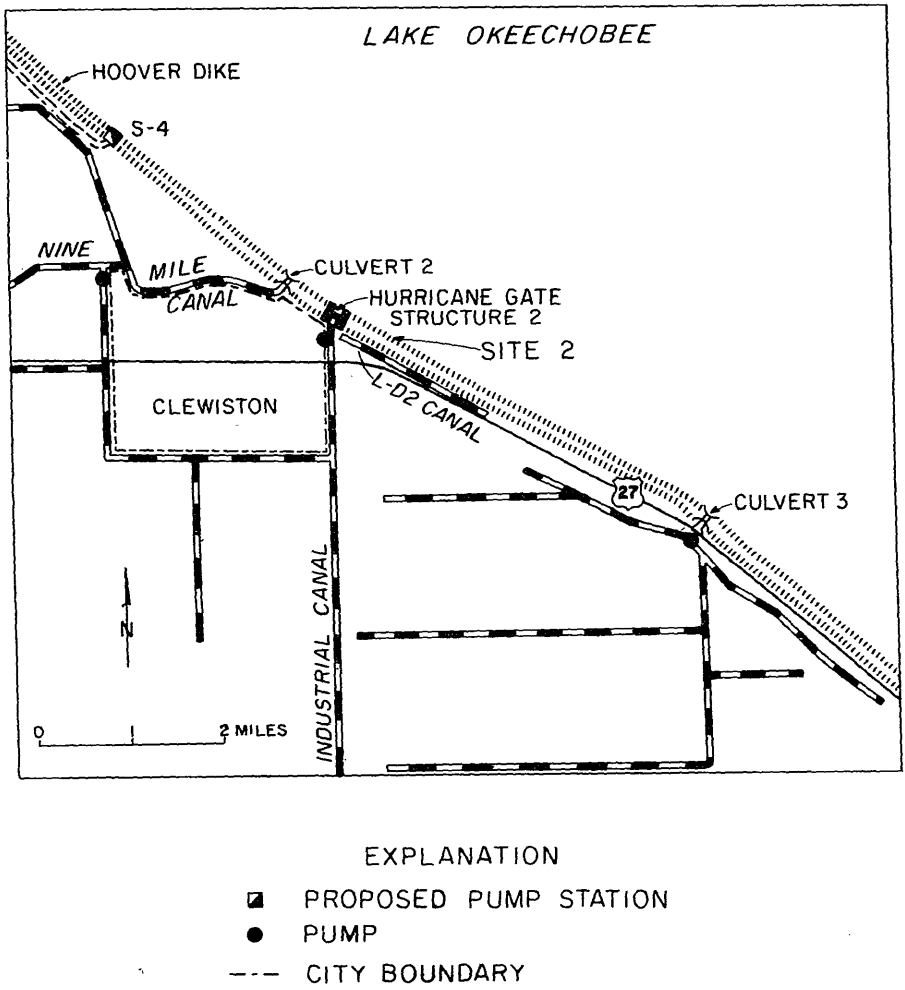

Figure 17. Map showing location of site 2 near Clewiston.

Natural land surface at site 2 ranges from 14 to 15 feet above msl and it is underlain by about a foot of organic soil (see profile in fig. 18). Beneath the soil are beds of sand, limestone, marl, clay, and shell which grade vertically and laterally into each other. Generally beds of shell and limestone are permeable and beds of organic soil, sand, marl and clay are relatively impermeable. Seepage is probably greatest through solution holes in the limestone which ranges from 4 to 12 feet (above msl) in what appears to be the upper part of the

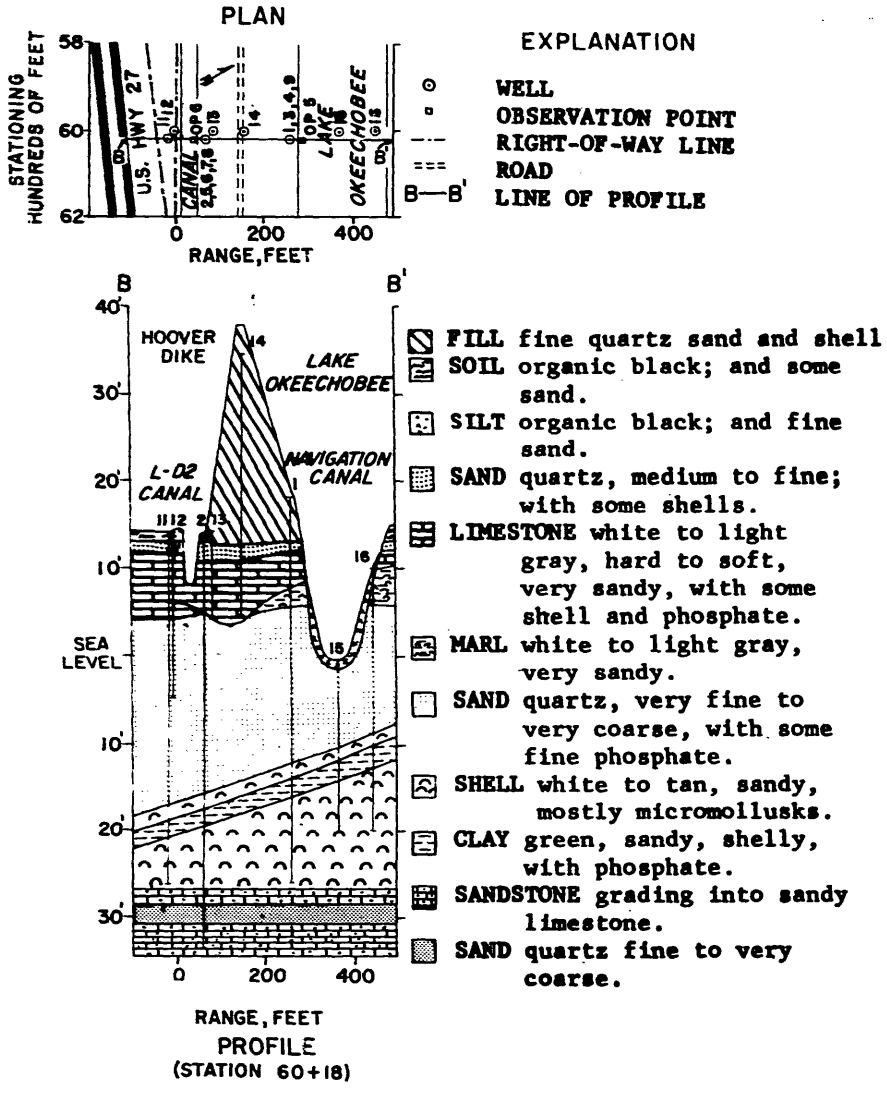

Figure 18. Plan and profile along line B-B′ at site 2.

Caloosahatchee Marl. Permeable beds of shell, which range from 8 to 27 feet below msl in the lower part of what also appears to be Caloosahatchee Marl, are potential conveyers of large amounts of seepage if penetrated by deep borrow canals on the landward and lakeward sides of the dike.

AQUIFERS AND CONFINING BEDS

The aquifers, confining beds, and depths of observation wells along line B-B′ at site 2, are shown on figure 19A. The aquifers and confining beds are

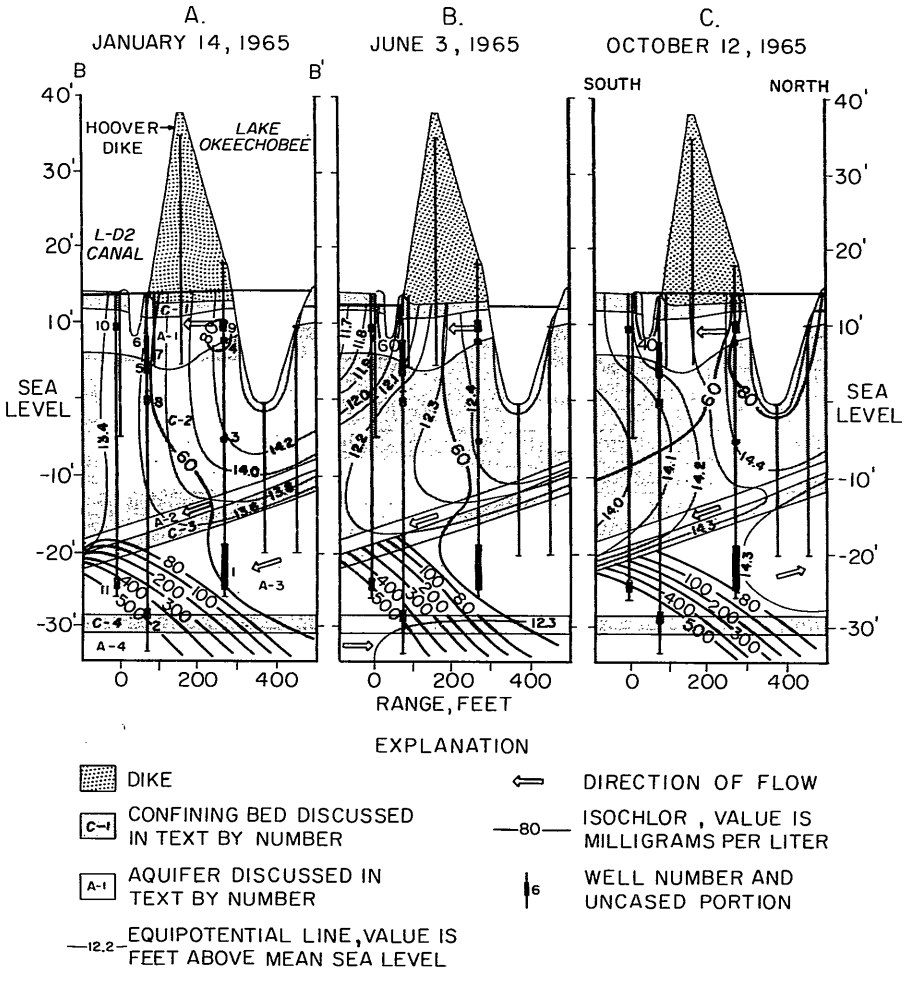

Figure 19. Selected hydraulic profiles along line B-B′ showing aquifers, confining beds and depths of observation wells at site 2.

numbered consecutively with increasing depth and the unit numbers are peculiar only to site 2.

Confining bed C-1 is 2 to 3 feet thick and it is composed of a bed of sandy organic soil and a bed of medium to fine quartz sand. Aquifer A-1 ranges from 2 to 7 feet in thickness and it is a hard, sandy, limestone that locally contains solution holes. Confining bed C-2 is about 17 feet thick beneath the center of the dike and the thickness of the bed increases southward. The upper 3 feet is composed of clayey sandy marl and the lower 14-feet is composed of fine to coarse quartz sand. Aquifer A-2 is about 2 feet thick and is chiefly shell. Confining bed C-3 is about 2 feet thick and consists of sandy green clay that grades vertically into the shell in aquifers A-2 and A-3. Aquifer A-2 and confining bed C-3 dip southward from the lake toward the agricultural area. On the other hand aquifer A-3 is a wedge-shaped bed of shell that appears to increase in thickness northward beneath the lake. Aquifer A-3 is about 10 feet thick beneath the center of the dike and the shell is similar to that in aquifer A-2. The upper part of aquifer A-3 contains clay and the lower part contains sandy limestone. Confining bed C-4 is about 2 feet thick and it is composed chiefly of fine to coarse quartz sand. Aquifer A-4 is more than 4 feet thick and it is composed of sandy limestone.

Some seepage occurs through each bed that underlies the dike but seepage is greatest through aquifer A-1 which has been breached by borrow canals. Aquifers A-2, A-3, and A-4 are permeable but they are overlain by at least 10 feet of "tight" sand which retards the movement of water from the Navigation Canal into the aquifers, therefore, seepage through aquifers A-2, A-3, and A-4 is considered to be a relatively unimportant factor in the analysis. Silt deposits that line the bottom and sides of the borrow canals at site 2 are also considered to be relatively unimportant factors in determining seepage because the data indicate that the loss in head across the deposits is relatively small. The principal recharge boundary for the upper 30 feet of strata that underlies the dike is the Navigation Canal and the principal discharge boundary is the network of drainage canals located one-quarter mile south of the dike in the agricultural area. The recharge and discharge boundaries for the deeper strata are underfined.

WATER MOVEMENT AND FLUCTUATIONS

The principal direction of seepage at site 2 is southward from the lake toward the drainage works in the agricultural area. Short reversals occur seasonally, however, when the stage of the lake is routinely lowered by the Corps of Engineers prior to the rainy season, or when heavy rains cause water levels in the agricultural area to abruptly rise above the lake level during the wet season. Hydraulic profiles for January 14, 1965, June 3, 1965, and October 12, 1965 were constructed to show the direction of flow and the distribution of

equipotential lines (water levels) and isochlors for selected high and low stages of the lake (fig. 19).

On January 14, 1965, a period of high water levels, the stage of Lake Okeechobee at site 2 was 14.29 feet and the stage of the L-D2 Canal was 13.53 feet. Seepage through aquifers A-1 and A-2, and through confining bed C-2, was southward from the lake toward the agricultural area. The low chloride content and inferred steep hydraulic gradients in aquifers A-1 and A-2, and in confining bed C-2, suggest that most of the seepage occurred there. The high chloride content and the inferred low hydraulic gradient in aquifer A-3 (and perhaps A-4) suggest that it conveys insignificant amounts of seepage. Water levels in bed A-3 were lower than those in bed A-2 indicating that bed C-3 retards the vertical movement of water between overlying and underlying beds.

On June 3, 1965, a period of low water levels, the stage of the lake was 12.44 feet and the stage of the L-D2 Canal was 11.94 feet. The equipotential lines show that seepage through aquifers A-1 and A-2, and confining bed C-2, was southward from the Navigation Canal to the L-D2 Canal and to the agricultural area. Hydraulic gradients in aquifer A-3 (and perhaps A-4) was low therefore water movement there was probably insignificant. The slight lakeward shift in chloride content in aquifer A-3 suggest that water movement there was northward.

On October 12, 1965, a period of high water levels, the stage of the lake was 14.54 feet and the stage of the L-D2 Canal was 14.20 feet. The data were collected during a period of slightly unsteady water-level conditions which were caused by locally occurring rains and strong winds. Water movement in aquifers A-1 and A-2 and confining bed C-2, was southward from the lake toward the agricultural area. The equipotential lines in aquifer A-1 infer a low hydraulic gradient from the lake toward the agricultural area. The equipotential lines in bed C-2 suggests that the permeability of bed C-2 is lower than bed A-1. The curvature of the lines suggests that some water moved downward through bed C-2 from the Navigation Canal and the L-D2 Canal and some water moved upward through bed C-2 from aquifer A-2. A lakeward shift in chloride content and hydraulic gradient in aquifer A-3 suggest that water movement there was northward from the agricultural area toward the lake.

Figure 20 is a graph comparing the daily mean stage of the lake with the daily highest water level in well 7 which taps aquifer A-1 and is located on the landward berm of the Hoover Dike (see location on figure 18). The water level in well 7 is about the same as that in the L-D2 Canal. During 1964-65, the lake level was generally higher than the water level in well 7 except during April through June 1964, June through August 1965, and September 1965, when heavy rains caused local water levels south of the dike to rise higher and faster than the level of the lake.

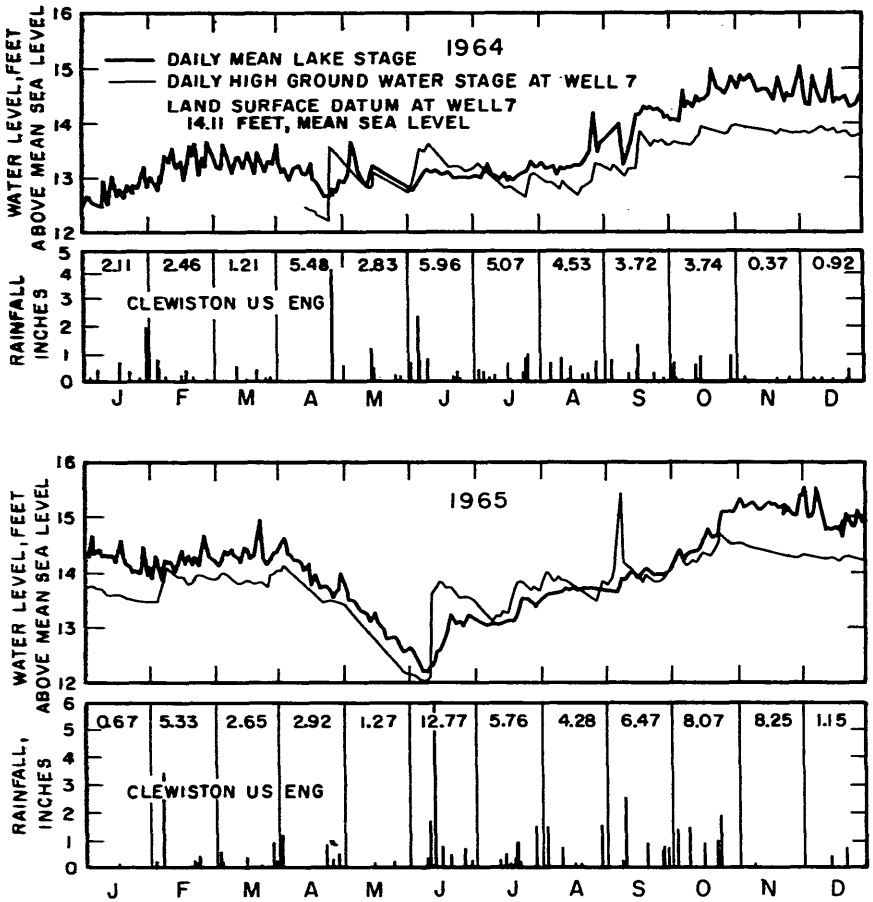

Figure 20. Graphs showing daily stages of Lake Okeechobee and ground-water levels in well 7 at site 2; and daily and monthly rainfall at Clewiston; 1964-65.

Generally the water level in well 7 rose in response to local rainfall and to corresponding fluctuations of the lake. However, when the stage of the lake was below 13.5 feet, fluctuations of the water level in well 7 were chiefly caused by local rainfall. Short-term fluctuations of the lake level had relatively little affect on the water level in the well, which suggested that the hydraulic connection (the permeability of the aquifer) between well 7 and the lake is poor. The water level in well 7 appears to be only slightly affected by drainage because the drainage works (network of canals) are relatively far from the well and the hydraulic connection is relatively poor. The water-level recession during April and May 1965 was caused by the routine lowering of regional water levels by the Corps of Engineers prior to the wet season.

Figures 21 through 23 are graphs comparing water levels, chloride content, and water temperature in wells that tap selected aquifers and confining beds

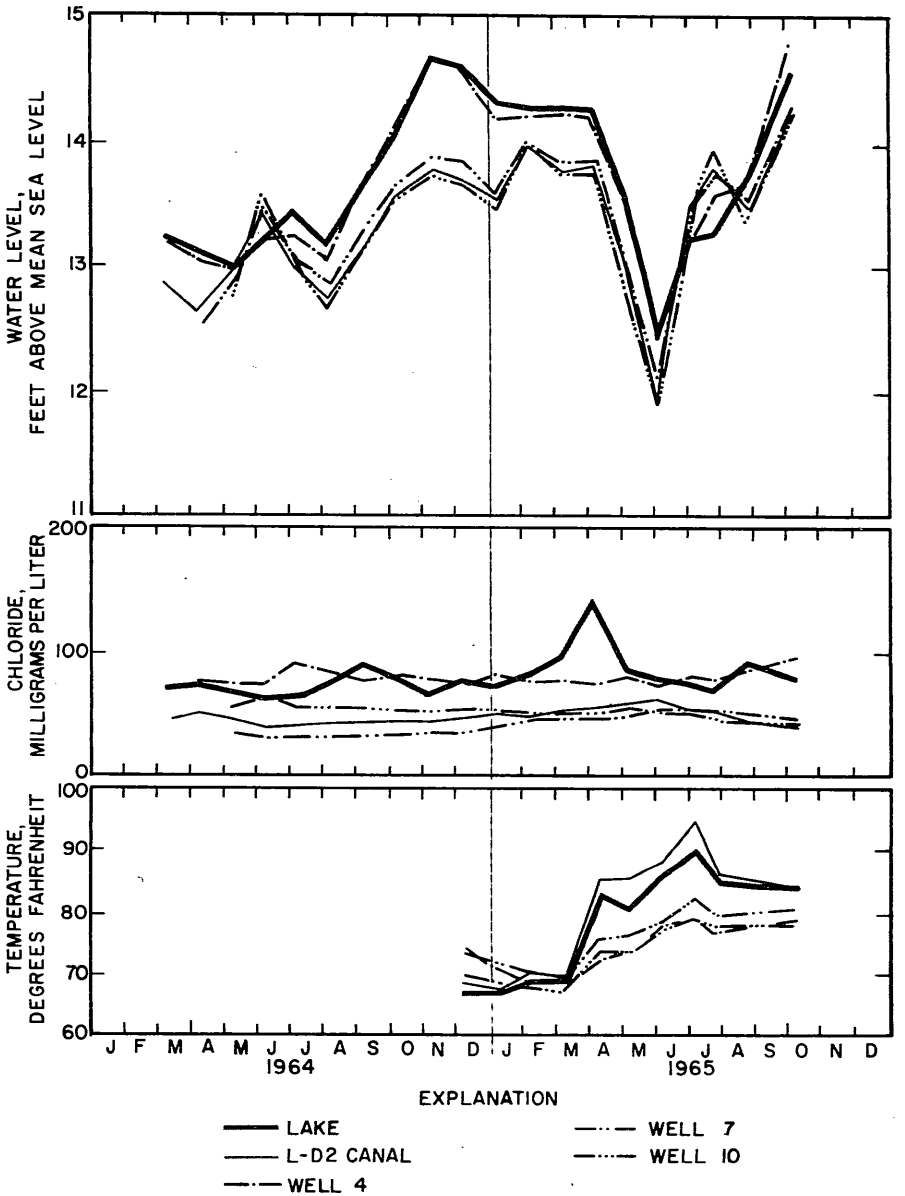

Figure 21. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-1 at site 2 with data for the lake and the L-D2 Canal, 1964-65.

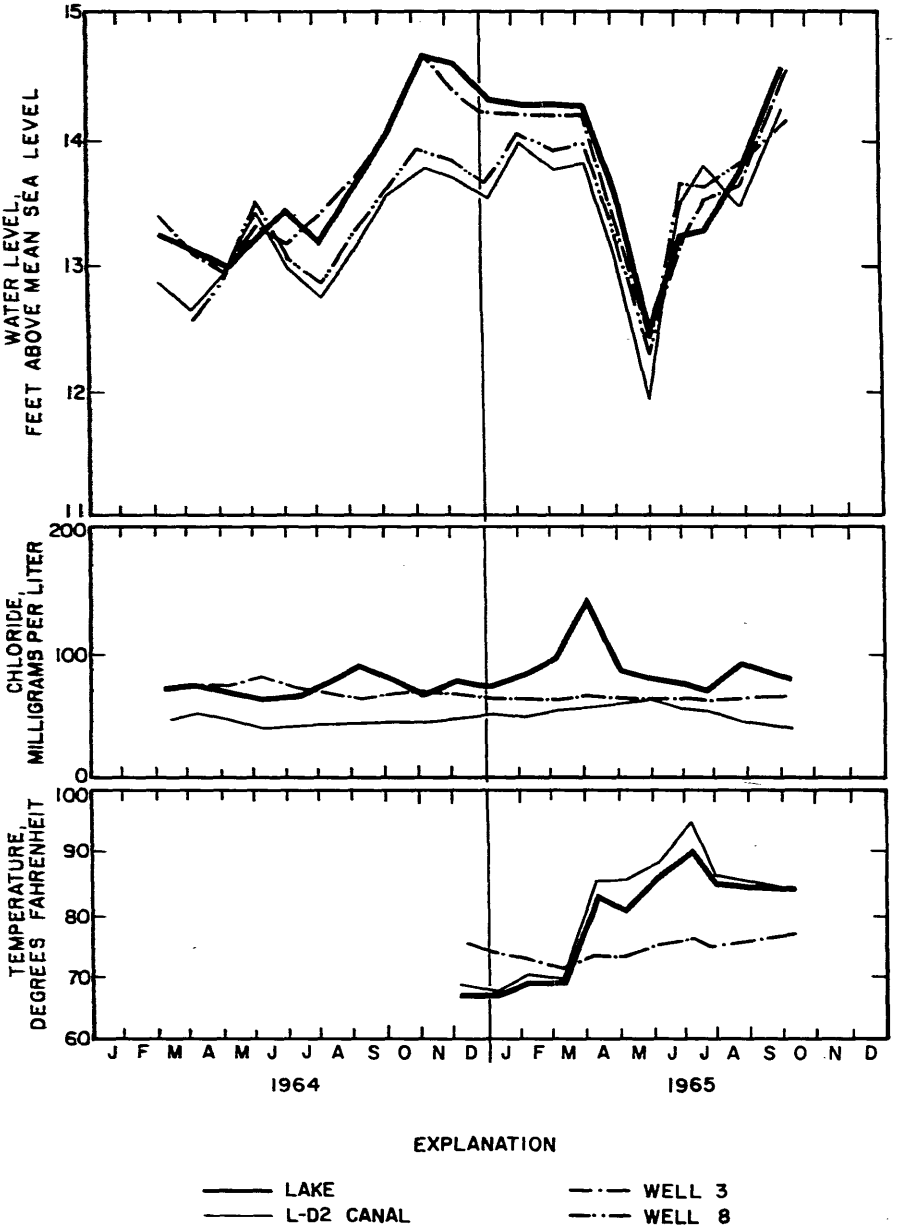

Figure 22. Graphs comparing water levels, chloride content, and water temperature in wells that tap confining bed C-2 at site 2 with data for the lake and the L-D2 Canal, 1964-65.

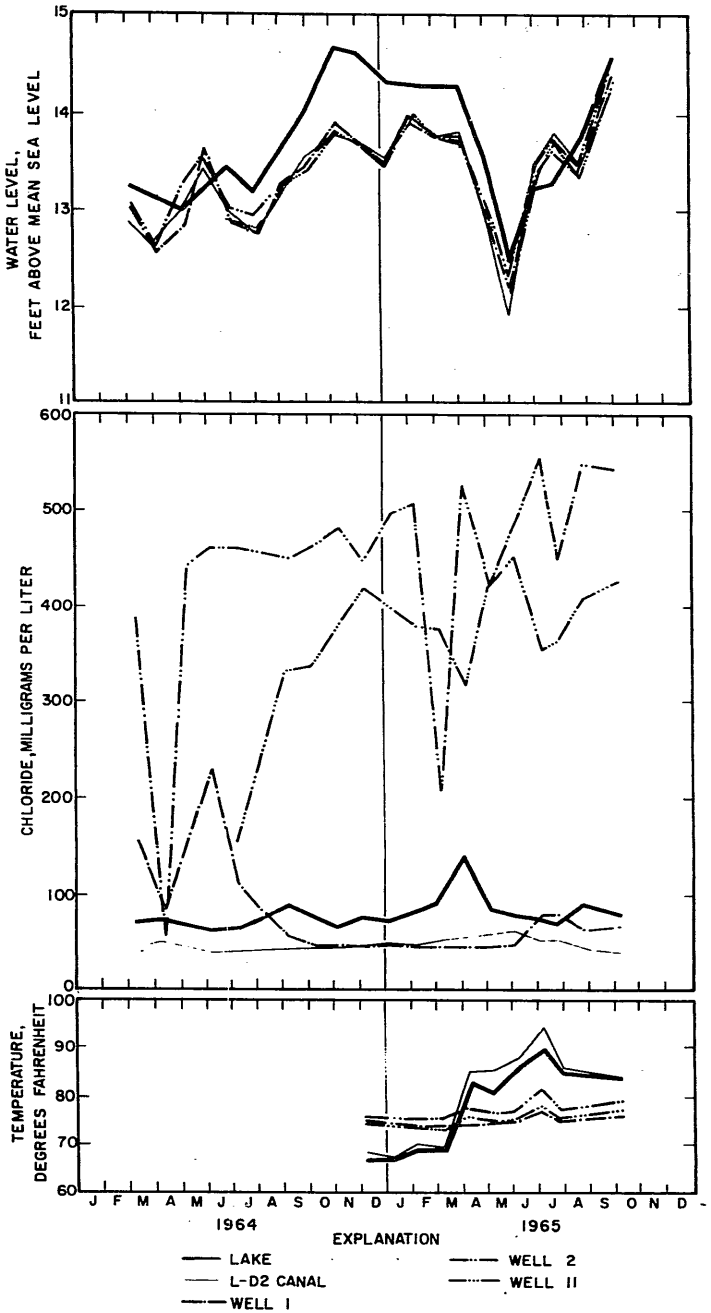

Figure 23. Graphs comparing water levels, chloride content and water temperature in wells that tap aquifer A-3 at site 2 with data for the lake and the L-D2 Canal, 1964-65.

with data for the lake and the L-D2 Canal. The lines representing well data are coded by a number of dots. The line with the least dots represents the well nearest to the lake.

Water levels nearest the lake in aquifer A-1 are closely related to the lake level (fig. 21). This relationship indicates that the permeability of aquifer A-1 is about the same as the permeability of the filtercake in the Navigation Canal. The hydraulic gradient, which is shown by water levels in the line of wells, indicates that water moved southward from the lake through the L-D2 Canal toward the agricultural area. Chloride content in water in well 4, which is nearest the lake, is closely related to that of the lake. The lag in time between peak chloride content in the lake and peak chloride content in the L-D2 Canal suggest that seepage through the aquifer occurs at a slow rate. For example, the peak chloride concentration in the lake water occurred in April 1965 while the peak chloride concentration in the L-D2 Canal occurred about 2 months later. Chloride content in the landward wells and the L-D2 Canal was lower than that in the lake, suggesting that some dilution by local recharge (rainfall) occurs there. The temperature of the water in aquifer A-1, in the lake, and in the L-D2 Canal varies seasonally, and the range in temperature of ground water is less than that of the surface water but the data suggest that there is a general relation between water movement and temperature in the lake and in aquifer A-1.

Water levels in confining bed C-2 near the lake are also closely related to the water level in the lake (fig. 22). The similarity between the graphs in figures 21 and 22 suggest that the permeabilities of aquifer A-1 and confining bed C-2 are probably similar.

Water levels in aquifer A-3 are closely related to the water level in the L-D2 Canal (fig. 23). The hydraulic gradient, which is inferred from the differences between the water levels in the wells, is low, therefore the rate of water movement in aquifer A-3 is probably slow even if the permeability of the material is relatively high. Chloride content is highest in the water in wells which are the deepest and farthest from the lake suggesting that seepage through A-3 is relatively insignificant. The decrease in the chloride content in well 2 during 1964 and 1965 was probably caused by the movement of fresh water into the aquifer from the Navigation Canal after well 2 and other nearby wells in aquifer A-3 were pumped during sampling. The high chloride content and occasional reverse gradient in aquifer A-3 suggest that aquifer A-3 is unimportant in the analysis of seepage from the lake. The temperature of the water in aquifer A-3 fluctuates through a relatively narrow range and the data suggest that there is slight relationship between water movement and temperature in aquifer A-3.

QUANTITATIVE STUDIES

Aquifer tests were performed at site 2 to determine the transmissivity (T) and/or the hydraulic conductivity (K_f) of the beds which are the chief conveyors of seepage from the lake.

A pumping test was conducted on well 2 which taps aquifer A-3. The well was pumped for 74 minutes at a rate of 75 gpm and water level fluctuations were recorded in wells 1 and 11, and in the pumped well. Data from the test indicated that recharge suppressed the drawdown in the observation wells early in the test, therefore, it was not possible to accurately determine the transmissivity of aquifer A-3. A few early data, however, suggested that the T of aquifer A-3 does not exceed 70,000 gpd/ft, but the transmissivity obtained by the slug tests was considered to be in the correct order of magnitude for aquifer A-3. Slug tests were performed in wells 1 through 4, 7, 10, and 11 in order to determine the magnitude of the hydraulic conductivities of various beds beneath the dike. The results of the test are shown in table 3.

TABLE 3. – RESULTS OF SLUG TESTS AT SITE 2.

Bed	Thickness[1] (feet)	K (gpd/ft^2)	T (gpd/ft)
Dike Fill	1	100[2]	100[2]
C-1	2	100[2]	200[2]
A-1	8	384	3,040
C-2	17	50	850
A-2	2	2,000[2]	4,000[2]
C-3	2	<1	<1
A-3	10	1,340	13,400
Total	42		21,590

[1] Measured below center of dike
[2] Estimated

No data were obtained in confining bed C-3 and in aquifer A-4, but the seepage there is considered to be a minor factor in the total analysis. The total transmissivity of the 42-foot section beneath the center of the dike is about 22,000 gpd/ft. However, the distribution of hydraulic gradients in the various beds is not uniform, therefore seepage should be computed for each bed.

SEEPAGE

Seepage from the lake at site 2 can be estimated best by determining the flow through the 42 feet of saturated material down to confining bed C-4 underlying the dike rather than the flow through the filtercake in the Navigation Canal. The flow through the materials for a given period can be determined from

the transmissivities of the individual beds and the hydraulic gradients within the beds. If the flow through the materials is steady state and the hydraulic gradients in the aquifer are directly related to the hydraulic gradient across the dike, that is, between the Navigation Canal and the L-D2 Canal, then the seepage through the materials can be related to the long-term head across the dike. A comparison of water levels in wells at various depths in the materials suggest that a direct relationship between the hydraulic gradients does in fact exist. Therefore, the flow, hence the seepage, beneath the dike was computed for January 14, 1965, a period of steady-state water levels and above average lake levels (see profile A in fig. 19) and the seepage from the lake was related to the head across the dike by the seepage factor S_e.

Seepage on January 14, 1965 is related to the transmissivities which were presented in table 3 of the preceeding section, and to the hydraulic gradients in the hydraulic profile in figure 19. The seepage through the upper 28 feet of the materials was computed using equation 1, where T is the sum of the transmissivities of the dike fill (saturated part), confining bed C-1, aquifer A-1, and confining bed C-2; and I was the hydraulic gradient in aquifer A-1.

$$Q = TIL$$
$$= 4{,}190 \text{ gpd/ft} \times 0.00292 \times 1 \text{ ft.}$$
$$= 12.2 \text{ gpd per foot of width of aquifer}$$

Seepage through 2-foot thick aquifer A-2 (fig. 19) was computed using equation 1 where T is the transmissivity of aquifer A-2 and I was the hydraulic gradient in aquifer A-2.

$$Q = TIL$$
$$= 4{,}000 \text{ gpd/ft} \times 0.0014 \times 1 \text{ ft.}$$
$$= 4.6 \text{ gpd per foot of width of aquifer}$$

Seepage through 2-foot thick bed C-3 was very low and was therefore omitted in the analysis. Seepage through the 12-foot thick aquifer A-3 was computed using equation 1 where T is the transmissivity of aquifer A-3 and I was the hydraulic gradient in aquifer A-3.

$$Q = TIL$$
$$= 13{,}400 \text{ gpd/ft} \times 0.00014 \times 1 \text{ ft.}$$
$$= 1.9 \text{ gpd per foot of width of aquifer}$$

Seepage through the basal materials shown in figure 19, confining bed C-4 and aquifer A-4, was considered an insignificant factor in the analysis. Thus, the seepage from the lake through the saturated material (42 ft deep) is equal to the sum of the computed seepages.

$$Q_1 = 12.2 \text{ gpd} + 4.6 \text{ gpd} + 1.9 \text{ gpd}$$
$$= 18.7 \text{ gpd per foot of width of aquifer}$$

However, the geologic section prepared by the Corps of Engineers (1961, plate 16) indicates that aquifer A-1, which is the chief source of seepage at site 2, is discontinuous along the dike, therefore the seepage at site 2 is probably higher than the average value along the section of dike assigned to site 2. However, the seepage at site 2 is believed to be within the correct order of magnitude and is therefore assumed to be representative of that along 8½ miles of dike.

On the basis of the steady-state seepage from the lake on January 14, 1965, the seepage factor (S_e) at site 2 was determined using equation 10 where Q_1 is the January 14 seepage through a one-foot wide segment of the aquifer materials L is 1/5,280 mile, h was the stage of the lake, and h_1 was the stage of the L-D2 Canal.

$$S_e = \frac{Q_1}{L(h_1 - h_c)}$$

$$= \frac{18.7 \text{ gpd/ft} \times 5280 \text{ ft}}{1 \text{ mi } (14.29 \text{ ft} - 13.53 \text{ ft})}$$

$$= 129{,}900 \text{ gpd/mi/ft, or about } 0.2 \text{ cfs/mi/ft.}$$

Thus the seepage factor (S_e) at site 2 is about 0.2 cfs/mi/ft, which includes the retarding effect of the filtercake in the Navigation Canal. However, the effect of the filtercake at site 2, though small compared to that at site 1, will probably cause a further reduction in seepage as the filtercake continues to form and the lake is raised.

A comparison of water-level measurements in the lake with those in the L-D2 Canal during 1964-65 suggested that the rate of seepage varied with the stage of the lake and stage of the L-D2 Canal. Under normal conditions, the head across the dike was about 0.5 foot when the stage of the lake was at or below 14 feet, and the head was about 0.75 foot when the stage of the lake was about 14 feet.

When the stage of the lake was below 14 feet, the stage of the L-D2 Canal was greatly affected by local rainfall which ran off the dike and U.S. Highway 27 and accumulated in the canal. However, during the longer dry periods, the steady seepage from the lake caused a constant head relationship (about 0.5 foot) to exist between the lake and the canal. Therefore the maximum seepage rate that might be expected when the average stage of the lake is 14 feet would be about (0.2 cfs/mi/ft x 0.5 ft) 0.1 cfs per mile.

When the stage of the lake is between 14 and 15 feet, the water level in the L-D2 Canal rises above its banks, but overland flow from the canal is prevented

by U.S. Highway 27 which parallels the southern side of the canal and by fill at the terminuses of the canal. If the relationship between the lake and the L-D2 Canal remains the same for higher stages of the lake and no changes occur in drainage, then the average stage of the L-D2 Canal would be about 15.75 feet if the average stage of the lake is raised to 16.5 feet, and seepage from the lake would be about (0.2 cfs/mi/ft x 0.75 ft) 0.15 cfs per mile. However, if the L-D2 Canal were connected to a drain and controlled at a constant stage of 11.5 feet then the seepage from the lake beneath the dike would be about 0.5 cfs/mi when the average stage of the lake was 14 feet and about 1.0 cfs/mi when the average stage was 16.5 feet.

Thus seepage from the lake at site 2 should increase about 0.05 cfs per mile, if the average stage of the lake is raised from 14 to 16.5 feet, the L-D2 Canal remains isolated from the drainage canals, and the prevailing drainage conditions south of the dike do not change. The seepage beneath the 8½-mile segment of dike represented by site 2 therefore would increase from about 0.8 cfs to about 1.3 cfs if the average stage of the lake were raised from 14 to 16.5 feet.

SITE 3

DESCRIPTION

Site 3, shown in figure 24, is in Palm Beach County on the southern shore of Lake Okeechobee about 0.6 mile east of Lake Harbor.
The site consists of data-collection stations along a line about 860 feet long which was constructed normal to the Hoover Dike, as shown in figure 25. The stations include 11 test wells of which 6 were used to obtain data on ground-water levels, and two observation points which were used to obtain data on water levels in the lake and in the landside toe ditch.

North of the Hoover Dike is the Navigation Canal which was excavated in the early thirties for borrow to construct the dike. In 1964, the north side of the Navigation Canal was deepened for borrow which was used to raise the dike to its present height and for borrow which was used in constructing the roadbed for U.S. Highway 27. South of the dike is a toe ditch which was excavated in 1965 by the South Shore Drainage District to intercept seepage from the lake and to route excess water from the agricultural area south of the highway westward into the Miami Canal where it is pumped into the lake by the C&SFFCD.

Natural land surface at the site ranges from 13 to 14 feet above msl and is underlain by 6 to 8 feet of soft black organic soil. Beneath the soil are beds of clay, limestone and sand which grade vertically and laterally into each other. Generally the beds of shell and limestone are permeable and comprise aquifers; and beds of sand, clay, and organic soil are less premeable and comprise

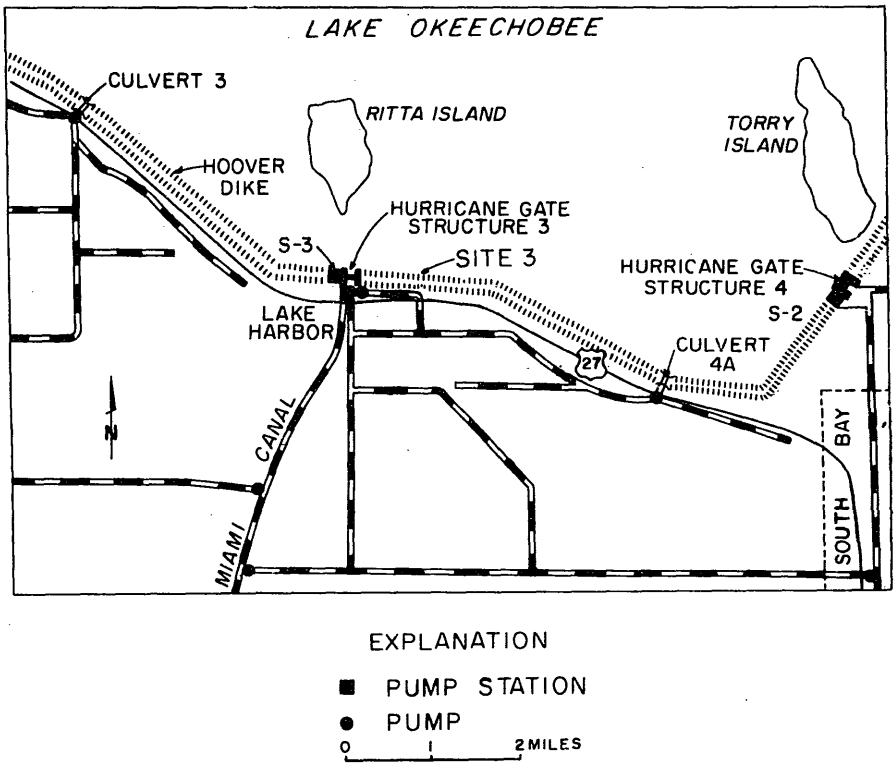

Figure 24. Map showing location of site 3 near Lake Harbor.

confining beds. Seepage is greatest through the beds of limestone and shell which range from 4 feet above to 13 feet below msl in the Caloosahatchee Marl.

AQUIFERS AND CONFINING BEDS

The aquifers, confining beds and depths of observation wells along line C-C′ at site 3 are shown on profile A in figure 26. The aquifers and confining beds are numbered consecutively with increasing depth from land surface and the numbers are peculiar only to site 3.

Confining bed C-1 ranges from 6 to 8 feet in thickness and consists of relatively impermeable organic soil. Confining bed C-2 is about 3 feet thick and consists of relatively impermeable beds of soft shelly marl and hard fresh-water limestone. Aquifer A-1 ranges from 14 to 17 feet in thickness and consists of soft to hard, permeable beds of shell and limestone that locally contain zones of

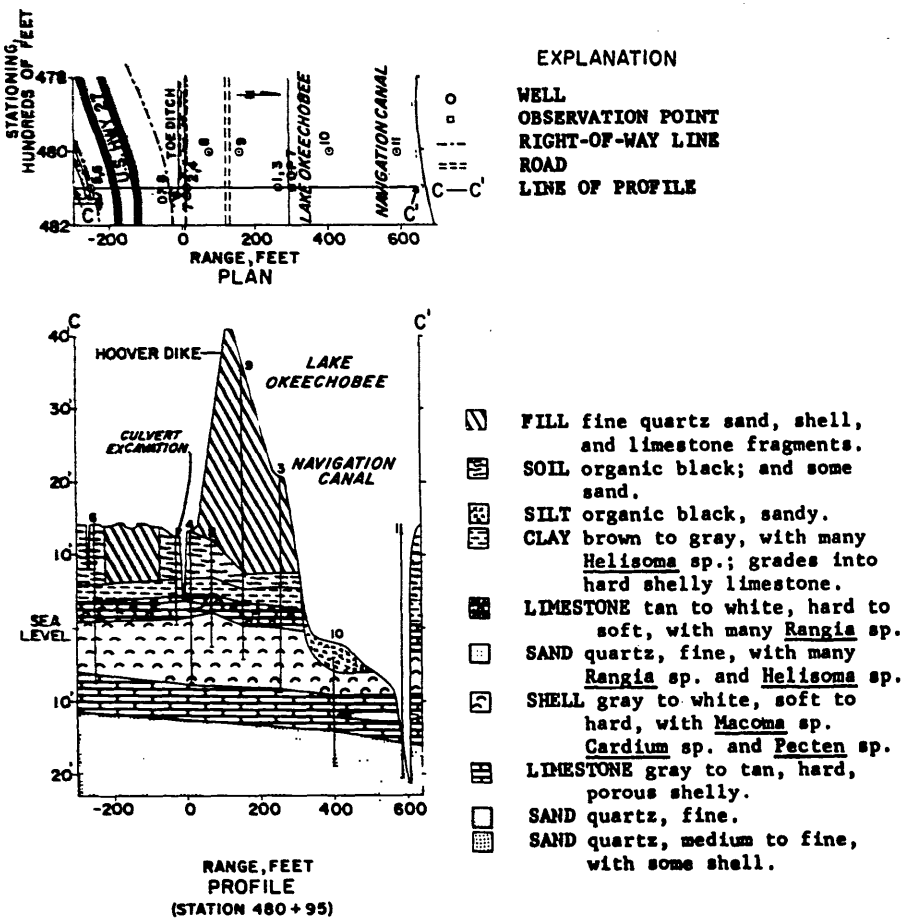

Figure 25. Plan and profile along line C-C′ at site 3.

sand. Confining bed C-3 is at least 10 feet thick and consists of fine sand which is low in permeability. Most of the seepage occurs through aquifer A-1, although some seepage occurs through each bed.

The silt deposits, or the filtercake, that lined walls of the Navigation Canal were partly removed from the north side of the canal when it was deepened for borrow in 1964. The removal of these deposits probably caused seepage to increase; however, the slow redeposition of the silt should cause a reduction in future seepage.

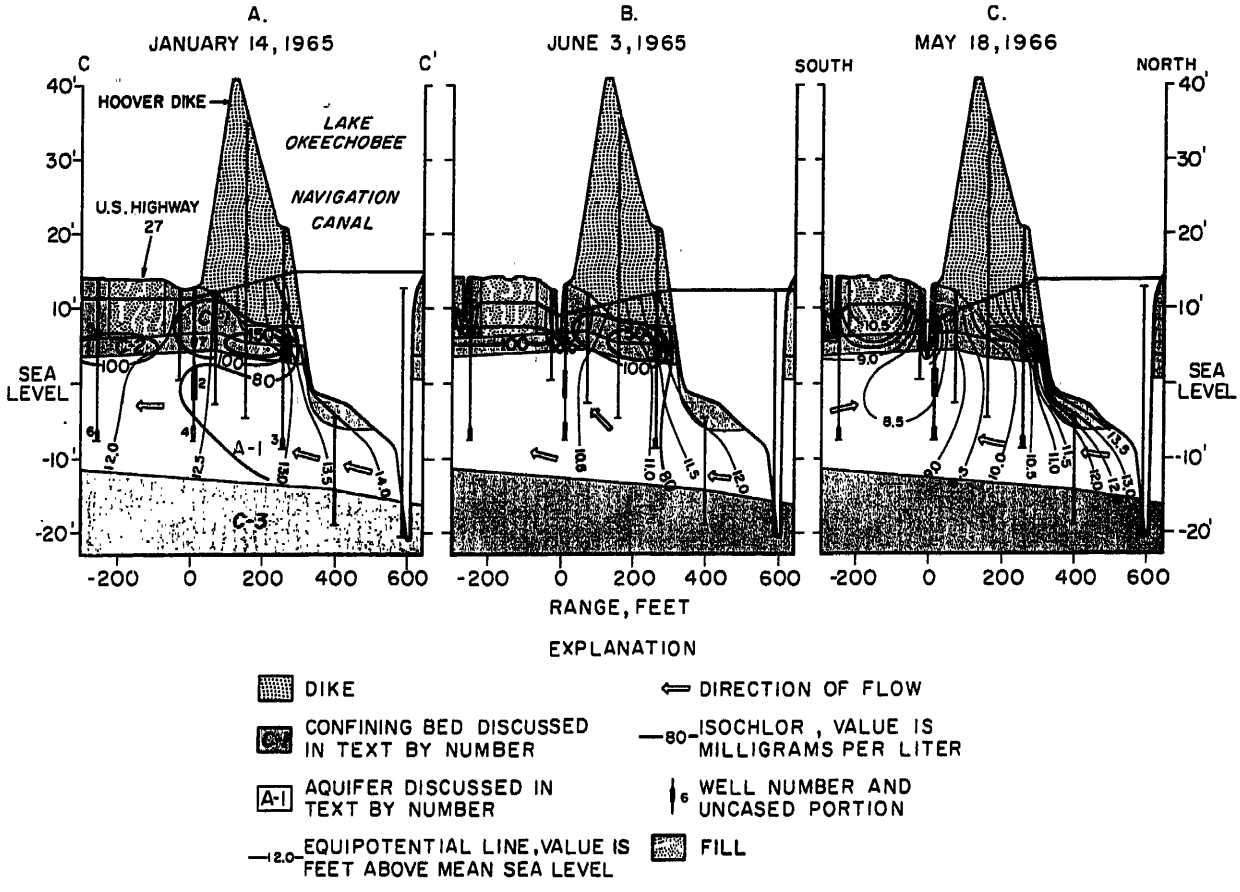

Figure 26. Selected hydraulic profiles along line C-C′ showing aquifers, confining beds, and depths of observation wells at site 3.

WATER MOVEMENT AND FLUCTUATIONS

The principal direction of water movement at site 3 is southward from the lake to the agricultural area. Hydraulic profiles A through C in figure 26 were constructed to show the distribution of equipotentials and isochlors, and the principal direction of water movement on January 14, 1965, June 3, 1965 and May 18, 1966, respectively.

On January 14, 1965, a time of high water levels, the stage of the Navigation Canal was 14.37 feet and the stage of the water table at the southern toe of the dike was 12.06 feet. Seepage was chiefly southward through aquifer A-1 toward the drainage canals in the agricultural area. (see profile A in fig. 26). The chloride content of the water in aquifer A-1 was low near the lake and relatively high in the confining beds, a condition that indicates water movement is greater through aquifer A-1.

During February 1965, a drainage ditch was excavated into bed C-2 along the toe of the dike from a culvert, which underlies U.S. Highway 27 near site 3, to the Miami Canal; and another drainage ditch was excavated from the south side of the culvert southward into the agricultural area and westward along the south side of the highway (see profile B in fig. 26). A pump was installed at the west end of the dike toe ditch to pump excess water from the agricultural area south of the highway into the Miami Canal near HGS-3 at Lake Harbor.

On June 3, 1965, a time of low water levels, the stage of the Navigation Canal was 12.42 feet and the pumping level in the toe ditch was 8.88 feet. Seepage was southward through aquifer A-1 from the lake toward the agricultural area, but most of the seepage was upward into the toe ditch (see profile B in fig. 26). Water from the agricultural area and seepage was flowing westward in the ditch to the pump which was operating at the west end of the toe ditch. The drawdown in the ditch caused water levels in wells at site 3 to decline, which indicated that the hydraulic gradient and seepage from the lake had increased. However, the high chloride content of the ditch water (380 mg/1) indicated that only a small part of the water pumped from the ditch could have originated as seepage from the lake because the chloride content of the lake water was only 70 mg/1.

During December 1965 the toe ditch was deepened so that the bottom of the ditch penetrated the upper part of aquifer A-1. On May 18, 1966, a seepage test was conducted at site 3 and the water-level data shown in profile C, figure 26, was related to the measured seepage in the toe ditch. The pumping level in the ditch was 7.44 feet (msl) and the stage of the lake was 13.75 feet. The closely spaced equipotential lines beneath the dike indicate that the principal direction and rate of water movement was southward from the lake through aquifer A-1 to the toe ditch. South of the highway, water movement in aquifer A-1 was northward toward the toe ditch. However, the hydraulic gradient there

was lower than that beneath the dike indicating that some of the pickup, or seepage, into the toe ditch came from the agricultural area. The seepage through confining beds C-1 and C-2 was considered an insignificant factor in the test.

During 1964, water levels in the area south of the dike were chiefly affected by dewatering operations during the construction of U.S. Highway 27, as shown by the hydrograph of well 2 on figure 27. During February 1965, a toe ditch was excavated along the southern toe of the dike and linked to the drainage system in the fields on the south side of U.S. Highway 27. During the remainder of 1965, the water level in well 2, located a few feet north of the toe ditch, was largely affected by drainage operations of the agricultural area and the stage never exceeded 12 feet. Prior to excavation of the toe ditch, the water level in the aquifer at the toe of the dike probably ranged from 12.0 to 12.5 feet, or about the same as the range in stage of the water level in well 2 during December 1964 through January 1965.

Figures 28 and 29 are graphs comparing water levels, chloride content, and water temperatures in the lake and the toe ditch and in wells that tap aquifer A-1 and confining beds C-1 and C-2. The lines representing well data are coded by dots and the line with the least dots represents the well closest to the lake while the line with the most dots represents the well farthest from the lake.

Graphs of water levels, chloride content, and temperature in wells that tap aquifer A-1 are compared with those in the Navigation Canal and in the toe ditch during 1964-65 in figure 28. Water levels were highest in the well nearest the lake and lowest in the well nearest the agricultural area, thereby indicating that seepage was at all times southward from the lake. During 1964 water levels in the wells were lowered by dewatering operations during the construction of U.S. Highway 27 and by the drainage operations in the agricultural area. During 1965 the drawdown in the toe ditch lowered water levels in the observation wells, indicating that the toe ditch had intercepted some of the seepage from the lake. A comparison of chloride content in the wells in aquifer A-1 with the chloride content in the lake suggests that aquifer A-1 is the principal conveyor of seepage from the lake because the concentrations are about equal. A comparison of the chloride content in the wells with the chloride content in the toe ditch suggests that most of the water that is pumped from the agricultural area is derived from an inland source which is high in chloride content. A comparison of chloride peaks in the lake and chloride peaks in the ditch (fig. 28) suggests that variations in the quality of the lake at site 3 are partly caused by brackish ground water which is pumped from the agricultural area through the Miami Canal into the lake during wet periods. A comparison of the temperature data shows that ground-water temperatures in wells 3 and 6 lag the temperature of the lake by several months, indicating that the movement of water through the aquifer is at best slow.

Water levels, chloride content, and temperatures in confining beds C-1 and C-2 are compared graphically with those in the toe ditch and the lake in figure

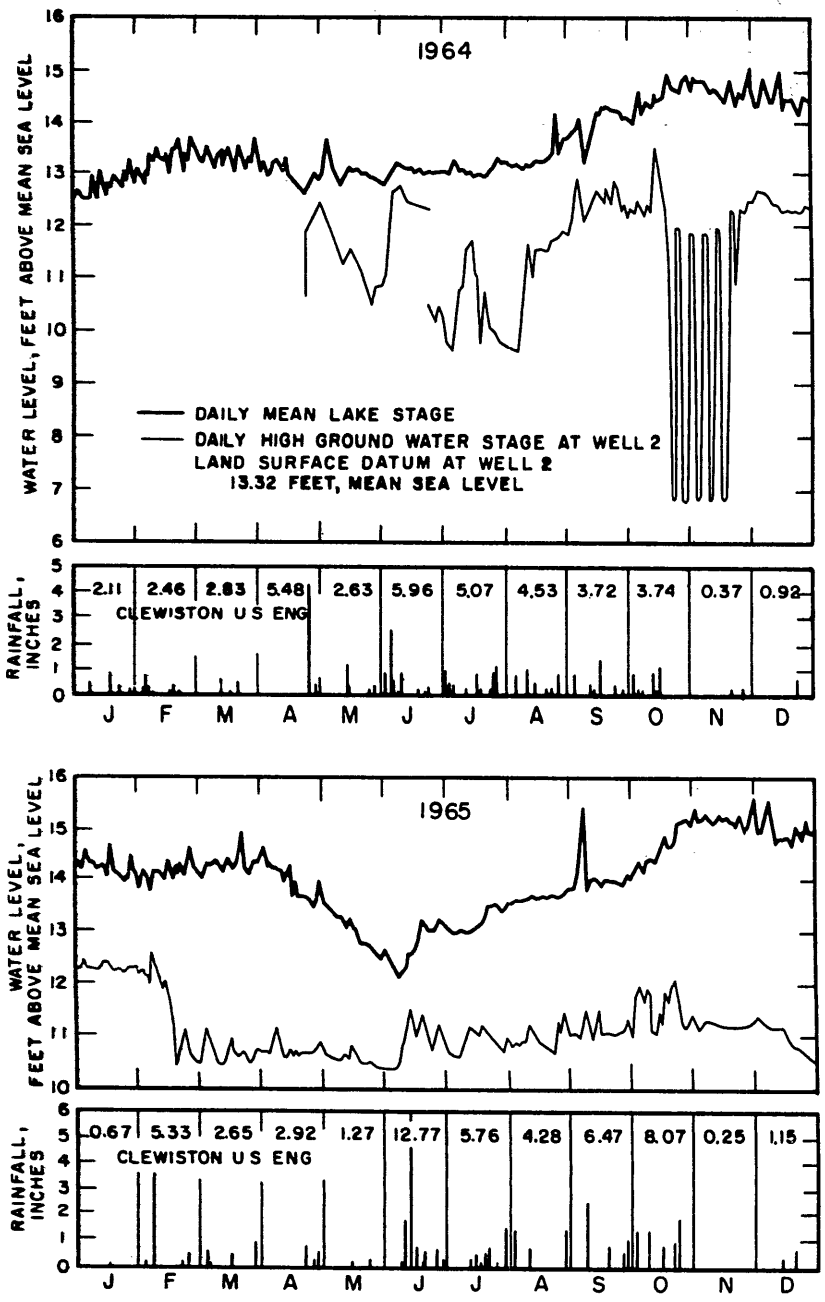

Figure 27. Graphs showing the daily stages of Lake Okeechobee and ground-water levels in well 2 at site 3; and daily and monthly rainfall at Clewiston; 1964-65.

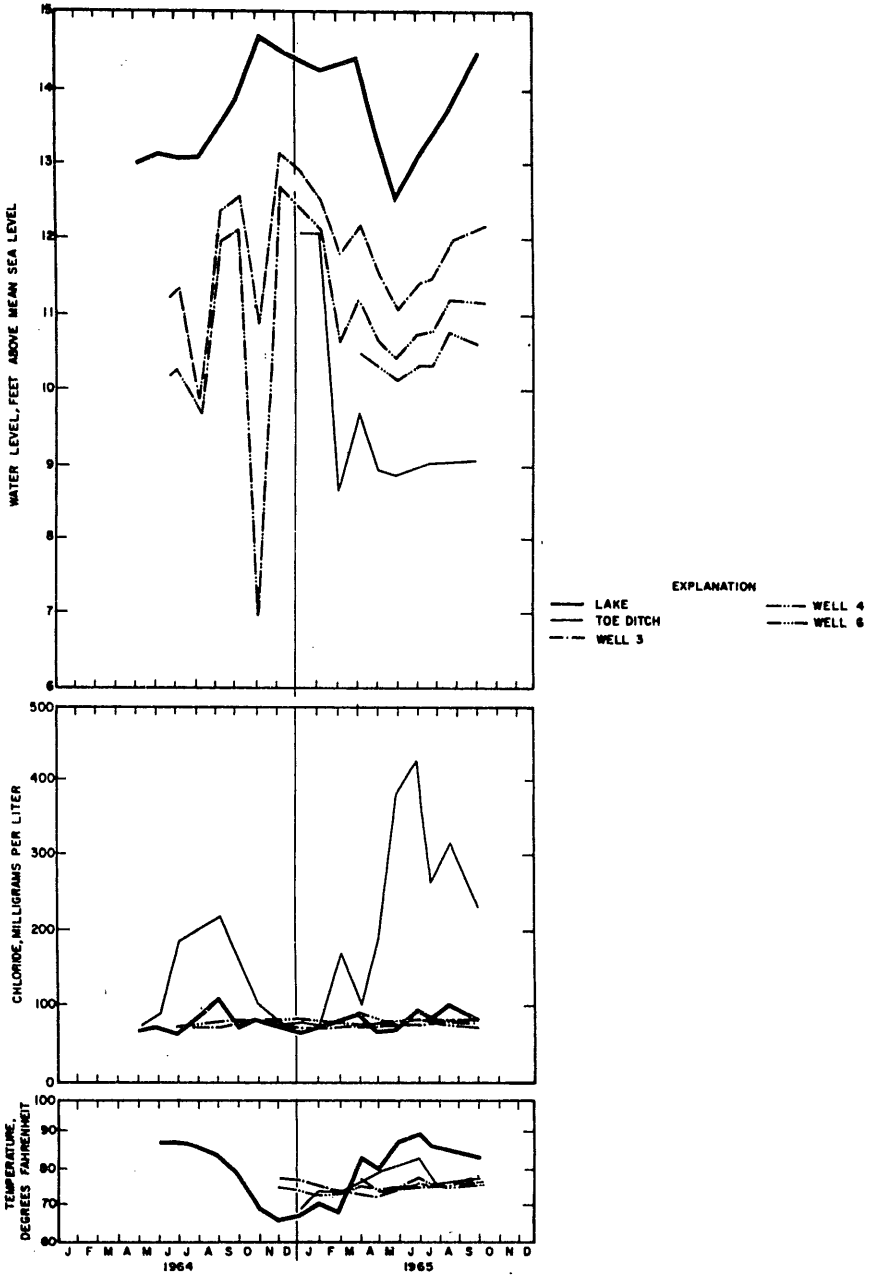

Figure 28. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-1 at site 3 with data for the lake and the toe ditch, 1964-65.

29. The water level in well 5 (taps bed C-1) south of the highway is directly affected by the drawdown in the nearby toe ditch. The drawdown in well 1 (near the lake in bed C-2), is caused indirectly by the drawdown in aquifer A-1.

A comparison of the chloride content in well 1 with the other chloride data in figure 29 suggests that the uniformly high chloride content in well 1 is an indication that seepage from the lake through the filtercake and confining beds is very slow. The time lag between the peak temperature in the lake and the peak temperature in well 1 also suggests that the rate of seepage through bed C-2 from the lake is slow.

A comparison of the chloride content in wells 4 and 5 (fig. 29) with the chloride content in wells 3, 4 and 6 (fig. 28) shows that the water in beds C-1 and C-2 contain slightly higher concentrations of chloride than bed A-1, therefore the high chloride content in the surface water (in canals and ditches) that is pumped from the agricultural area could be caused by the local flushing of brackish ground water from beds C-1 and C-2, or by flushing of residual brackish ground water from aquifer A-1 in an area considerably distant from the lake.

QUANTITATIVE STUDIES

Tests were performed at site 3 to determine the transmissivities of the beds which are the chief conveyors of seepage from the lake. A pumping test was conducted on well 4, which taps aquifer A-1. Well 4 was pumped for 62 minutes at a rate of 30 gpm and the water level fluctuations were measured in wells 1, 2, and 6, and in the pumped well (4). The data indicated that recharge from the Navigation Canal and the ditches south of the dike suppressed the drawdowns in the observation wells early in the test. However a few early data suggested that the T of aquifer A-1 is about 16,000 gpd/ft. No effects of pumping were observed in the nearby shallow wells suggesting that the permeabilities of confining beds C-1 and C-2 are low.

Slug tests conducted in the wells 1 through 7, suggested that the transmissivity of aquifer A-1 is about 18,000 gpd/ft., and the transmissivities of confining beds C-1 and C-2 are about 20 gpd/ft. and 200 gpd/ft respectively (table 4).

TABLE 4 – RESULTS OF SLUG TESTS TEST AT SITE 3.

Bed	Thickness (feet)	K_f (gpd/ft^2)	T (gpd/ft)
C-1	7	3	21
C-2	2.5	82	206
A-1	15	1,200	18,000

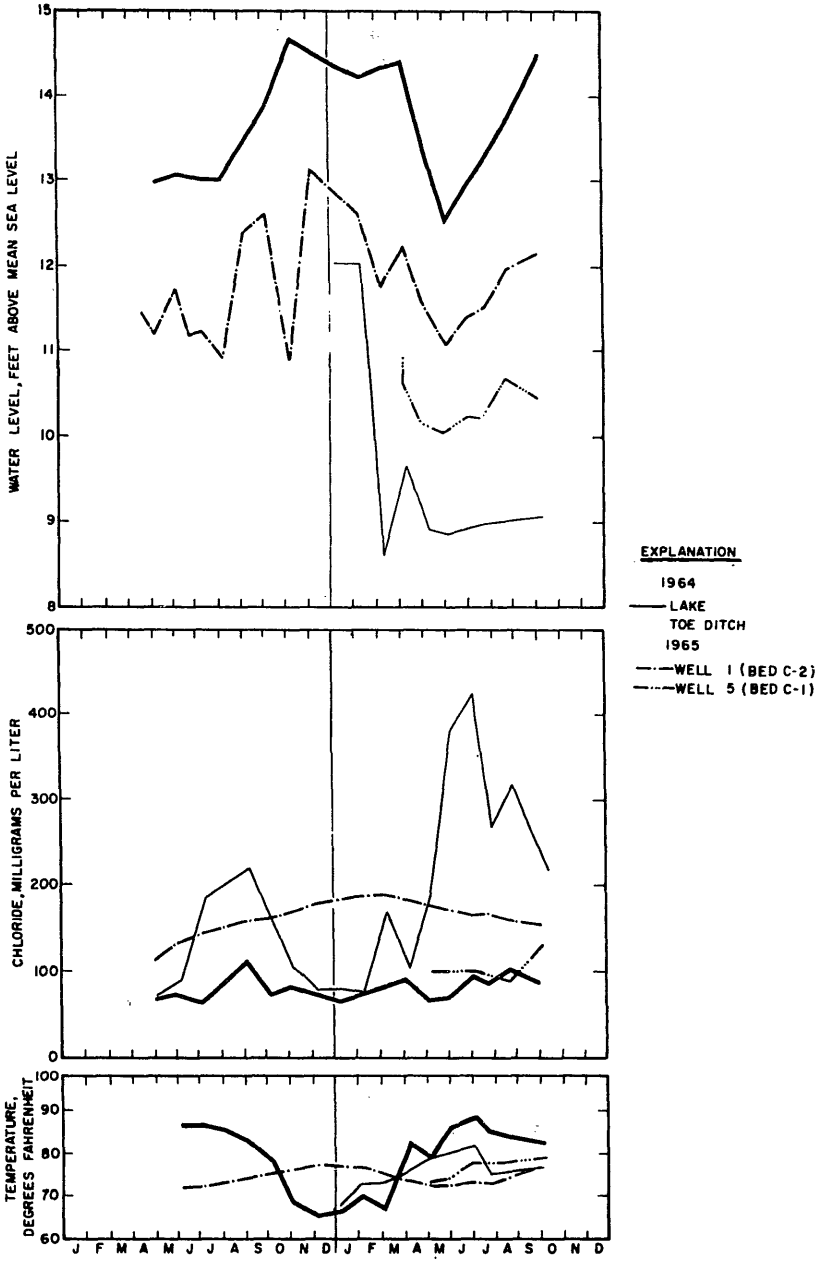

Figure 29. Graphs comparing water levels, chloride content, and water temperature in wells that tap confining beds C-1 and C-2 at site 3 with data for the lake and the toe ditch, 1964-65.

A seepage test was conducted on May 18, 1966 at site 3 in a 1,000-foot reach of the toe ditch which parallels the dike (see profile C in fig. 26). Pumping from the ditch was of sufficient duration that water levels approached steady state. About 0.2 cfs of seepage was measured in the 1,000-foot reach. The shape of hydraulic profile at site 3 during the seepage test indicates that the ditch was receiving seepage from both the lake and the agricultural area. The hydraulic gradients indicated that most of the seepage was from the lake. The transmissivity of aquifer A-1 was estimated using equation 9, where Q_c was the pickup in the 1,000-foot reach (0.2 cfs or 129,600 gpd), ΔS_c was an insignificant value, L was 1,000 ft, I_1 was the hydraulic gradient from the lake (0.0073), and I_a was the hydraulic gradient from the agricultural area (0.000154)

$$T = \frac{Q_c - \Delta S_c}{L\,(I_1 + I_a)} \quad \frac{129{,}600 \text{ gpd}}{1{,}000 \text{ ft } (.007454)}$$

$$= 17{,}500 \text{ gpd/ft.}$$

Thus results of the tests indicate that the transmissivity of aquifer A-1 is about 17,500 gpd/ft and that permeabilities of confining beds C-1 and C-2 are low.

SEEPAGE

Seepage from the lake at site 3 can be estimated best by using the transmissivity of the water-bearing strata that underly the dike and the average hydraulic gradients therein. On the other hand seepage from the lake can be related to the head across the dike if the head in the aquifer is directly related to the head across the dike. Seepage through a 1,000-foot long section of aquifer A-1 on May 18, 1966 was 0.2 cfs when the stage of the lake was 13.75 ft and the stage of the toe ditch was 7.44 ft. The transmissivity and drainage conditions were considered to be uniform along the 1,000-foot section of dike which was represented by the steady-state water levels at site 3. The seepage was expressed in terms of the seepage factor (S_e), which was determined by using equation 10, where Q_1 is 0.2 cfs, L is 0.189 mile, h_1 is 13.75 ft., and h_c is 7.44 ft.

$$S_e = \frac{Q_1}{L\,(h_1 - h_c)}$$

$$= \frac{0.2 \text{ cfs}}{0.189 \text{ mi } (13.75 \text{ ft} - 7.44 \text{ ft})}$$

$$= 0.168 \text{ cfs/mi/ft.}$$

Thus the seepage factor at site 3 is about 0.2 cfs per mile per foot of head between the water level in the lake and the water level in the toe ditch. The

seepage factor includes the head losses which might be attributed to the filtercake in the Navigation Canal; however, seepage from the lake will decrease as the filtercake, which was partly removed during construction activities in 1964, is redeposited.

Estimation of the increase in seepage that would result from raising the average stage of the lake from 14 feet to 16.5 feet requires a knowledge of the long-term relationships between the lake level and the water level in aquifer A-1 at the toe of the dike. Because those data are lacking, it must be assumed that some of the water-level data collected at site 3 during 1964 are representative of the long-term seepage conditions prior to changes in drainage and that some of the water-level data collected during 1965-66 are representative of the conditions which might be expected if a constant head drainage ditch, such as the ditch at site 3, were excavated into aquifer A-1 along the landside toe of the entire 8½-mile section of dike represented by site 3.

Prior to the excavation of the toe ditch at site 3 the average water level in aquifer A-1 at the foot of the dike was probably at a stage of about 12.5 feet; therefore, when the average lake stage was 14 feet, the average rate of seepage was about 0.3 cfs per mile. If no changes in drainage occurred and the average stage of the lake was raised to 16.5 feet, then the seepage would have increased from 0.3 to about 0.8 cfs per mile.

During 1965-66, the water level in the toe ditch at site 3 was controlled by pumping at a stage of about 9 feet; therefore, the average rate of seepage was about 1.0 cfs per mile when the average lake stage is 14 feet. If the average stage of the lake is raised to 16.5 feet then the seepage would increase from 1.0 to about 1.5 cfs per mile.

Due to the excavation of the toe ditch, the seepage at site 3 is not representative of the seepage along the assigned 8½-mile length of dike. The seepage along the 8½ miles of dike is considered to be related to the conditions at site 3 prior to excavation of the ditch, therefore, seepage from the lake along the 8 miles can be expected to increase from about 2.6 to 6.8 cfs as a result of raising the average lake stage from 14 to 16.5 feet. However, if a toe ditch similar to that at site 3 is excavated along the 8-miles of dike and the water level therein is controlled at a stage of 9 feet, then seepage from the lake will increase from 8.0 to 12.8 cfs if the average stage of the lake is raised from 14 to 16.5 feet.

SITE 4

DESCRIPTION

Site 4, as shown in figure 30, is in Palm Beach County on the southeastern shore of Lake Okeechobee about 3 miles northwest of Belle Glade. The site

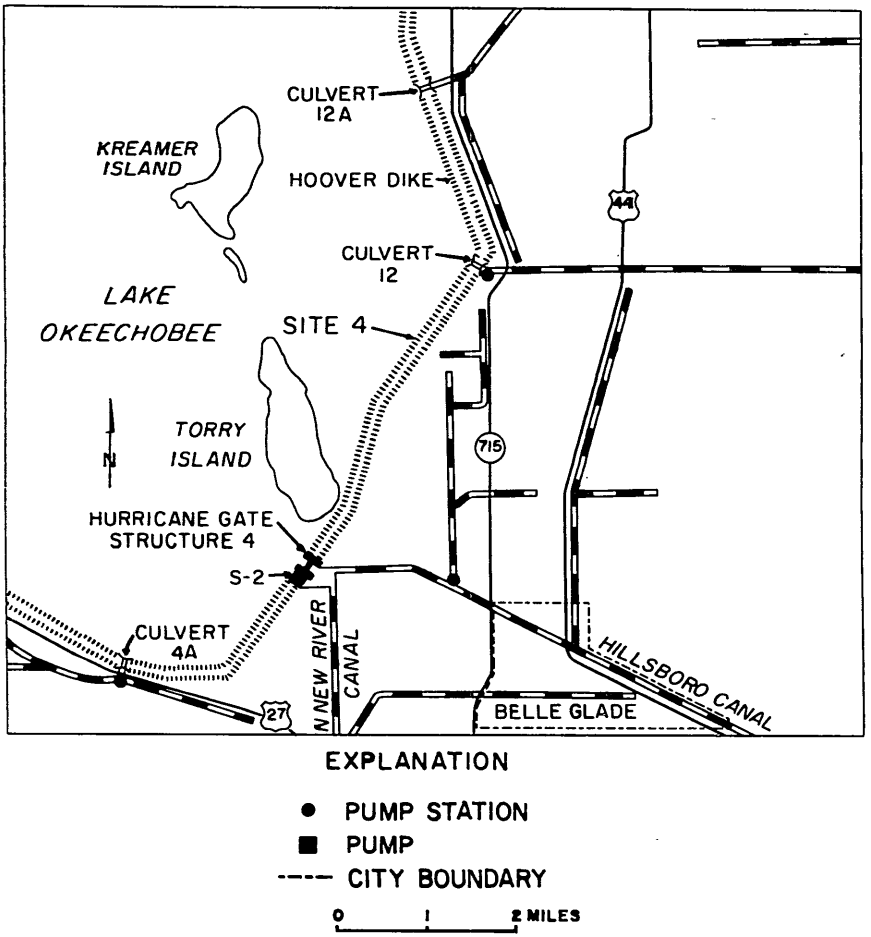

Figure 30. Map showing location of site 4 near Belle Glade.

consists of data-collection stations along a line about 1,400 feet long, as shown in figure 31, which was constructed normal to the Hoover Dike. The stations include 10 test wells, of which 6 were used to obtain data on ground-water levels, and two observation points (OP's) which were used to obtain water-level data in the lake and in the system of drainage canals in the nearby agricultural area. North of the dike is the Navigation Canal which was excavated in the thirties for borrow to construct the Hoover Dike. In 1963, borrow was taken from the west side of the Navigation Canal to raise the dike to its present height, as shown on the figure 31. South of the dike is a shallow ditch about 80 feet

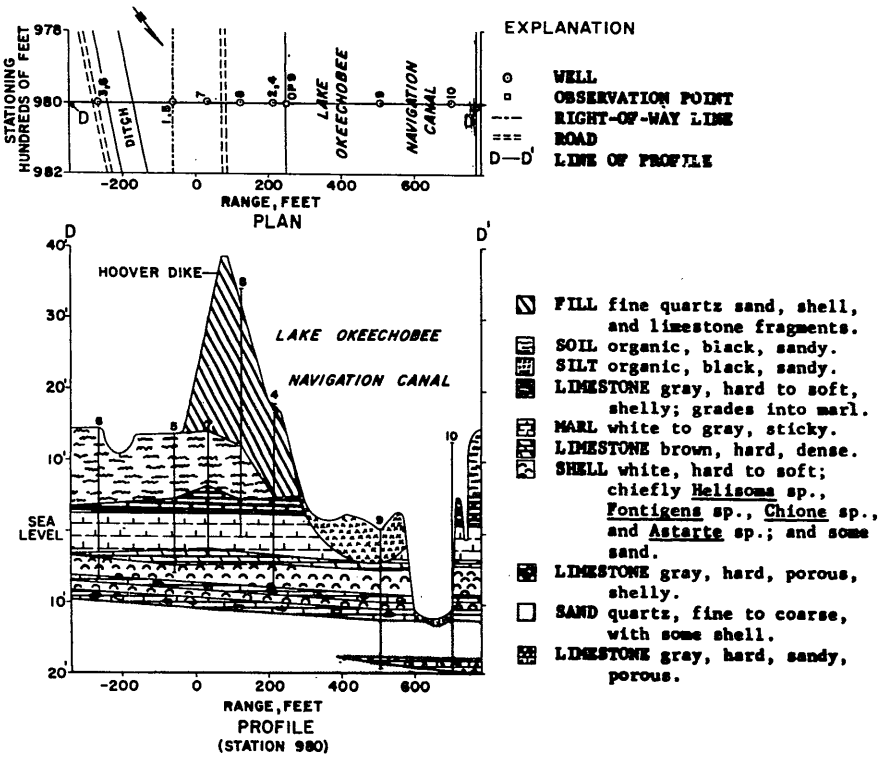

Figure 31. Plan and profile along line D-D′ at site 4.

wide, which parallels the toe of the dike. East of the ditch are fields which are drained by a system of north-south lateral ditches that are about 6 feet deep. The lateral ditches are spaced about 0.1 mile apart and they are connected to larger east-west canals. Water in the east-west canals can be pumped into a main north-south canal at State Road 715. Water levels in the agricultural area are regulated by the South Florida Conservancy Drainage District.

Natural land surface ranges from 13 to 14 feet above msl and is underlain by about 8 feet of organic soil (fig. 31). Beneath the soil are beds of shell, marl, limestone, and sand, which grade laterally and vertically into each other. Generally beds of limestone and shell comprise aquifers, and beds of organic soil, marl, clay and fine sand comprise confining beds. Seepage is probably greatest through permeable beds of limestone and shell that range between 2 and 6 feet above msl in the Fort Thompson Formation and through a permeable bed of limestone that ranges between 2 and 12 feet below msl in the Caloosahatchee Marl.

AQUIFERS AND CONFINING BEDS

Aquifers, confining beds, and the depths of observation wells along line D-D′ are shown on profile A in figure 32. The aquifers and confining beds are numbered consecutively with increasing depth from land surface and the numbers are peculiar only to site 4.

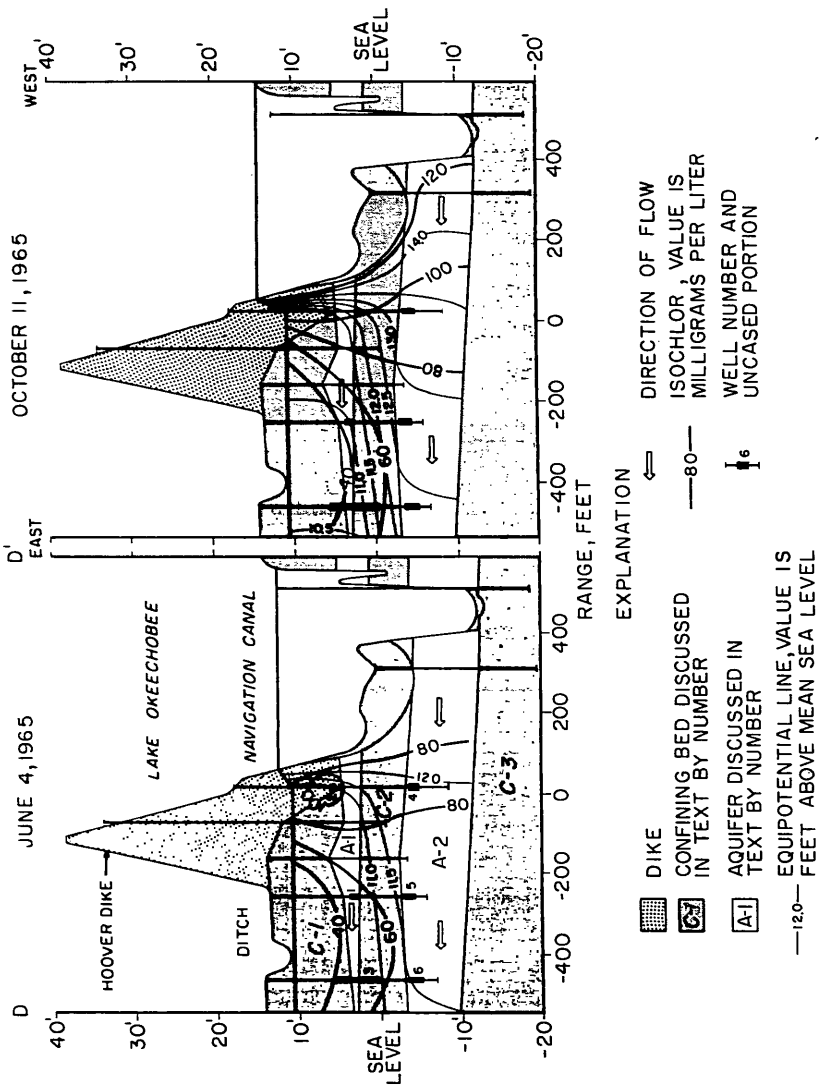

Figure 32. Selected hydraulic profiles along line D-D′ showing aquifers, confining beds and depths of observation wells at site 4.

Confining bed C-1 ranges from 8 to 10 feet thick and is composed of relatively impermeable, silty, organic soil. Bed C-1 retards the movement of water between the surface and the underlying beds, however its confining ability is locally ineffective where the bed is penetrated by canals and drainage ditches. Aquifer A-1 ranges from 0 to 4 feet thick and is composed of porous, permeable, gray limestone which grades laterally and vertically into clayey marl. The permeability of bed A-1 is locally high in solution zones. Confining bed C-2 ranges from 5 to 6 feet thick and is composed of shelly marl and limestone. Bed C-2 is relatively impermeable and confines water in the underlying aquifer. Aquifer A-2 ranges from 7 to 8 feet thick and is chiefly composed of porous limestone and shell. Confining bed C-3 is more than 6 feet thick and composed of fine to coarse sand with some shell and local beds of sandy limestone. The permeability of bed C-3 is assumed to be low because of the fine sand content.

Some seepage occurs through each bed but aquifer A-2 is the chief conveyor of seepage from the lake. Seepage is greatest through aquifer A-2 because it is highly permeable and it is exposed to direct infiltration from the lake in the new borrow on the west side of the Navigation Canal. Seepage through aquifer A-1 is retarded by the silt deposit, or filtercake, which lines the eastern wall of the Navigation Canal. Seepage through aquifer A-2 is expected to slowly decrease as the filtercake is redeposited on the walls of the new borrow.

WATER MOVEMENT AND FLUCTUATIONS

The principal direction of water movement at site 4 is eastward from the lake into the agricultural area. Short-termed reversals occur when the level of the lake is routinely lowered by the Corps of Engineers to create storage space prior to the annual rainy season. Hydraulic profiles A and B in figure 32 were constructed from water level data for June 4, 1965 and October 11, 1965, respectively, to show the direction of seepage and the distribution of equipotential lines and isochlors for low and high stages of the lake.

On June 4, 1965, a time of low water levels, the stage of the lake was 12.46 feet above msl and the stage of a ditch east of site 4 in the nearby drainage system in the agricultural area (shown in fig. 30) was about 10.4 feet. Water moved eastward from the lake through aquifers A-1 and A-2 toward the drainage system. The water levels in aquifer A-1 had been lowered by the drainage operations in the nearby fields however the water levels in aquifer A-2 had apparently been unaffected. The close spacing of the equipotential lines in beds C-1 and A-1 near the Navigation Canal indicates a relatively large loss in head occurred across the filtercake that lines the navigation Canal. Water movement in aquifer A-2 was chiefly eastward toward a distant point of discharge, probably the deep canals near State Road 715. The nearly horizontal equipotential lines in bed C-2 suggest that the bed confines the water in aquifer A-2 and that some water seeps upward from bed A-2 into bed A-1.

The 50 mg/1 chloride content in aquifer A-1 suggest that part of the water in the aquifer A-1 was diluted by local rainfall because the chloride content in the lake and in aquifer A-2 was between 70 and 80 mg/1. The nearly uniform chloride content in the lake and in aquifer A-2 indicates that the seepage from the lake occurs chiefly through aquifer A-2. About 200 mg/1 chloride content was found in the canal water at State Road 715, about ½ mile east of site 3, suggesting that most of the surface water in the agricultural area is derived from a source other than seepage from the lake.

On October 11, 1965, a time of high water levels, the stage of the lake was 14.45 feet and the stage of a ditch in the agricultural area near State Road 715 (shown in fig. 30) was about 8.8 feet. Water moved eastward from the lake through aquifers A-1 and A-2 toward the agricultural area. Water levels in aquifer A-1 had been lowered by the drainage operations in the nearby fields. However, the water levels in aquifer A-2 were relatively unaffected by the nearby surface drainage, a condition which indicates that most of the seepage through aquifer A-2 moved eastward beneath the nearby ditches and canals toward a more distant discharge point in the agricultural area. The chloride content of the canal water near State Road 715 was about 400 gm/1, which suggest that most of the surface drainage is related to a source other than the lake because the lake water contained 120 mg/1 chloride. Chloride content in the lake at site 4 is usually highest during wet periods when excess water is pumped from the agricultural area into the lake.

A graphical comparison of the fluctuations in the stage of the lake and the water level in well 1, which is located east of the dike and taps aquifer A-1, with local rainfall shows that the water level in well 1 is chiefly influenced by local rainfall, shown on figure 33. Water level peaks were caused by rain, and water level troughs were caused by local drainage operations. The relationship between drainage operations and the water-level fluctuations in well 1 indicates that the nearby drainage ditches tap aquifer A-1. Water levels in the nearby fields are probably controlled at a stage of 11 feet.

Water levels, chloride content and water temperature in wells that tap aquifers A-1 and A-2, respectively, are compared with data for the lake in figures 34 and 35. The lines are coded with dots and the line with the least number of dots represents the well nearest to the lake.

The water levels in the wells tapping aquifer A-1 fluctuated between 1 and 4 feet below the stage of the lake (fig. 34). The relatively small spread between the water levels in the wells shows that the hydraulic gradient in the aquifer beneath the dike was relatively low. Because of the low hydraulic gradient, the rate of seepage from the lake in aquifer A-1 is probably slow. The chloride content in well 2, located nearest the lake, is generally less than that of the lake.

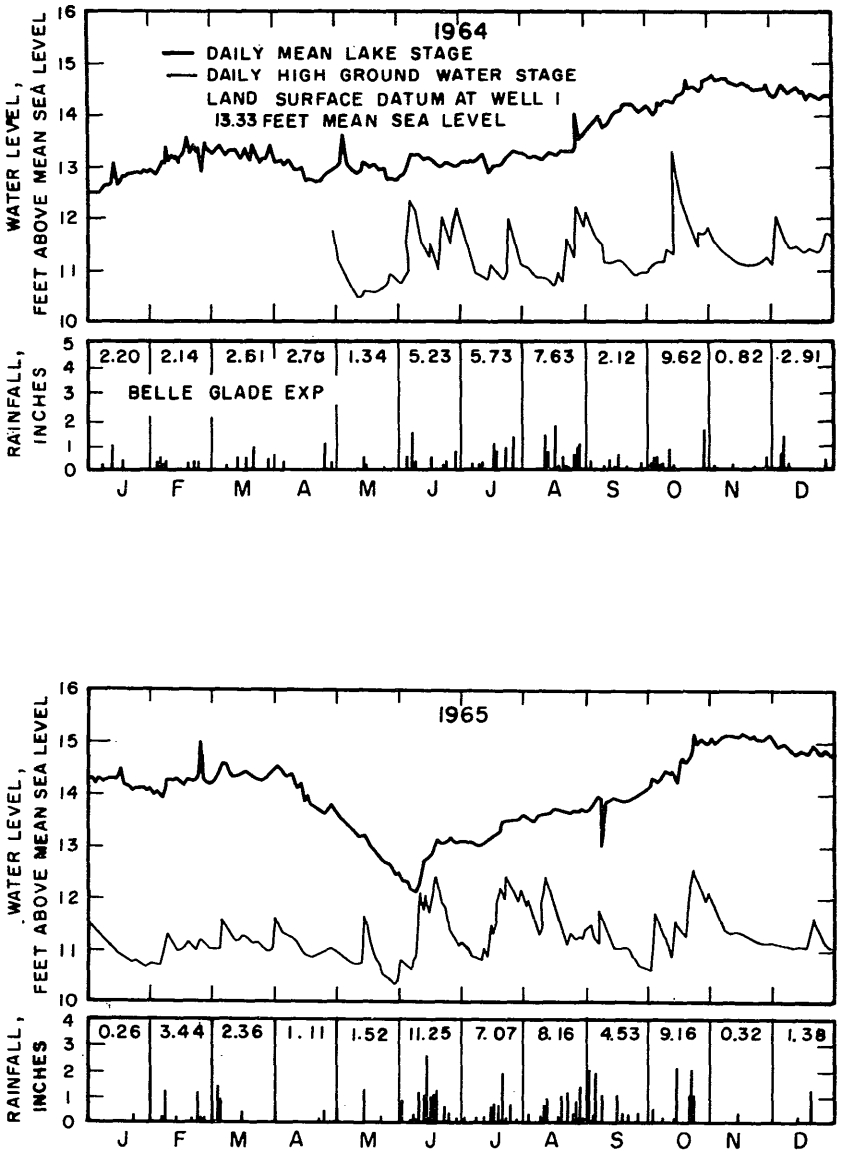

Figure 33. Graphs showing daily stages of Lake Okeechobee and ground-water levels in well 1 at site 4; and daily and monthly rainfall at Belle Glade; 1964-65.

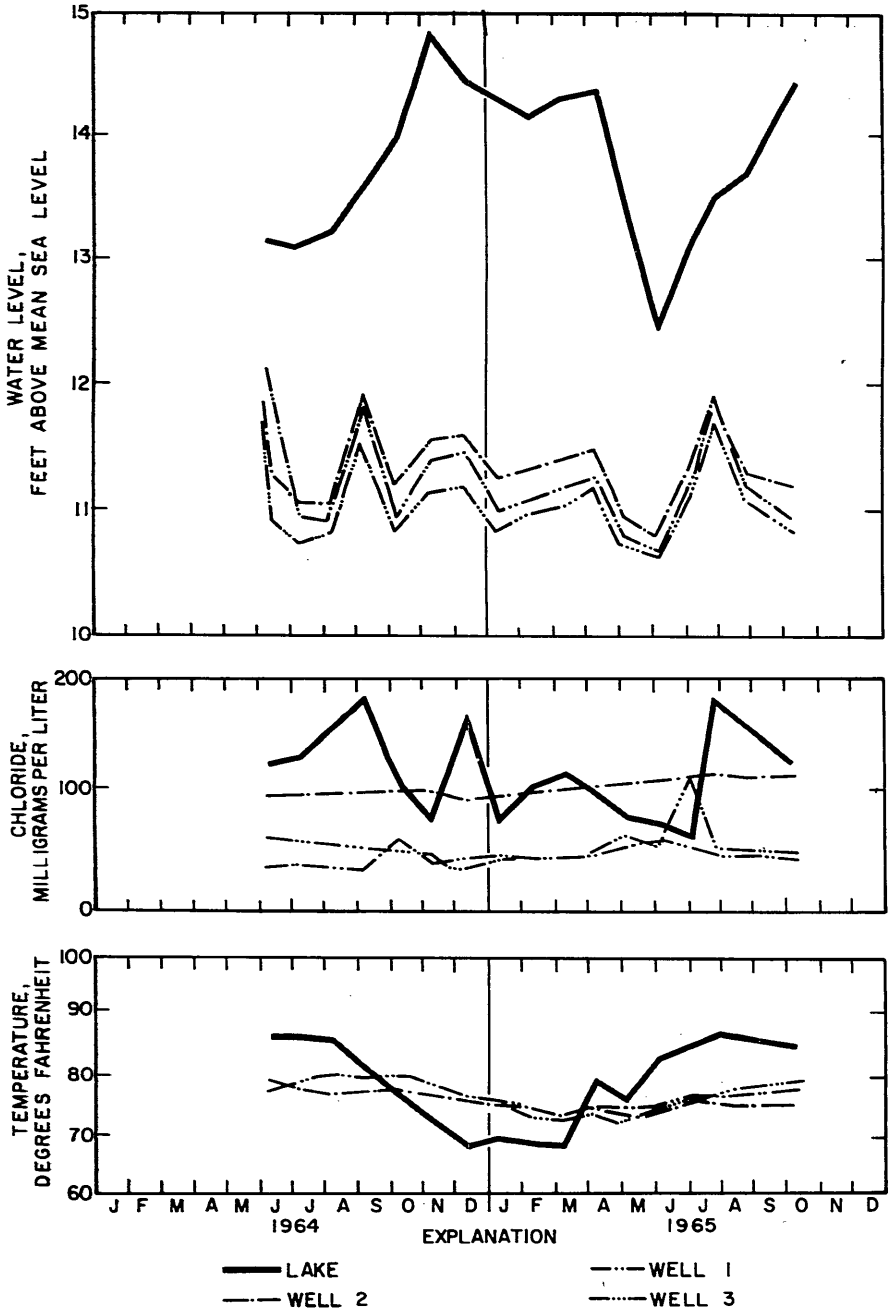

Figure 34. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-1 at site 4 with data for the lake, 1964-65.

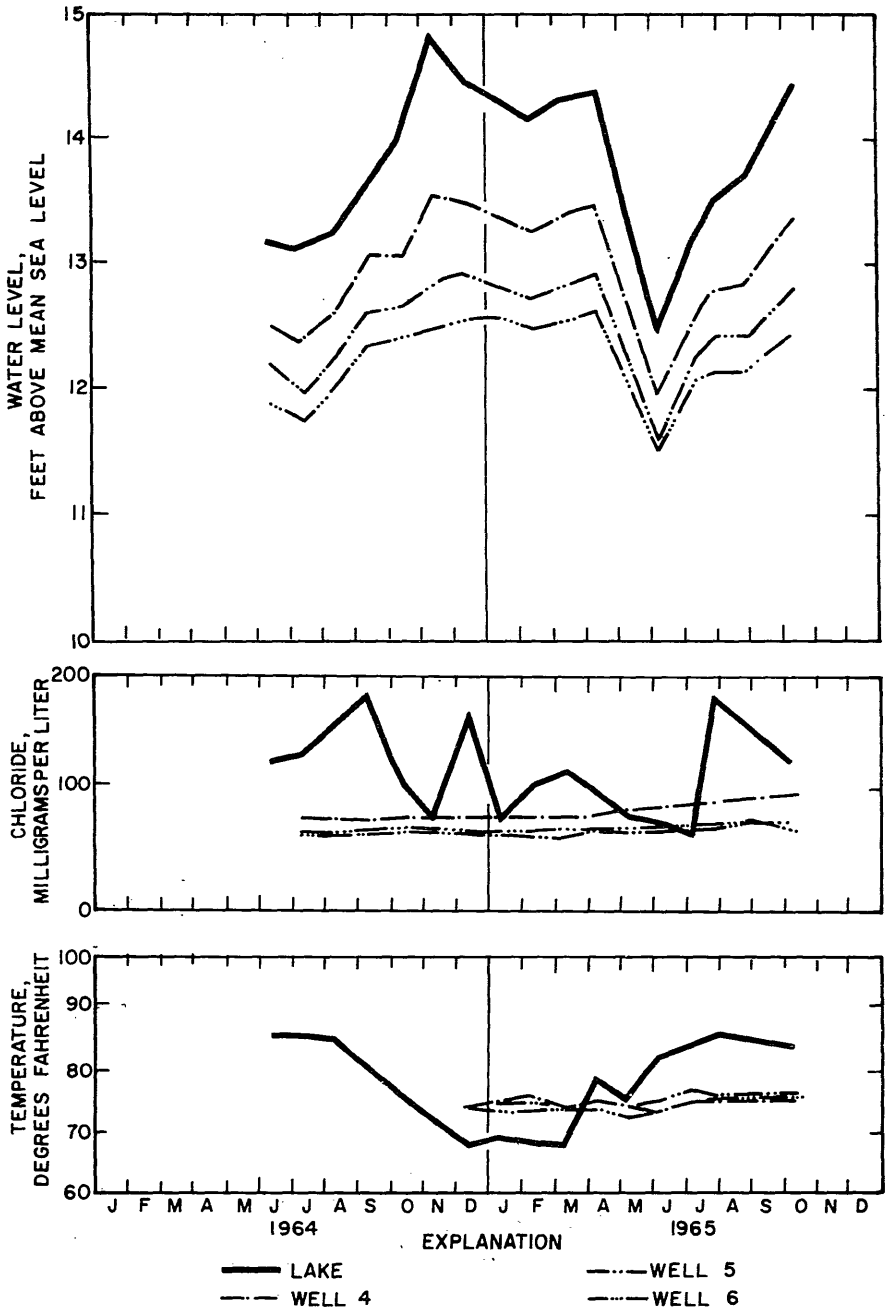

Figure 35. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-2 at site 4 with data for the lake, 1964-65.

The lower chloride content in wells 1 and 3, however, suggests that some low chloride source, such as local rainfall on the east side of the dike, accounts for a large part of the water in aquifer A-1 at this site. Fluctuations of water temperature in aquifer A-1 lag fluctuations of temperature in the lake, a condition which suggests that the rate of seepage from the lake is relatively slow, if the temperature changes in aquifer A-1 are due to seepage from the lake. Thus the data suggest that the drainage ditches in the nearby fields tap aquifer A-1, that the drawdown effects from pumping the ditches extends beneath the dike, and that seepage from the lake is retarded by the filtercake in the Navigation Canal.

The water levels in aquifer A-2 at site 4 are slightly lower than the water in the lake (fig. 35). Generally, the water level in well 4, located nearest the lake, fluctuated in concert with that of the lake, while the water levels in wells 5 and 6, located farthest from the lake, were only slightly affected by drainage operations in the agricultural area. During 1964-65, the chloride content and temperature in the wells tapping aquifer A-2 were nearly constant whereas the chloride content and temperature of the lake fluctuate seasonally. The temperature, chloride, and water-level data suggest that the seepage rate through aquifer A-2 is slow, and that the aquifer probably conveys a relatively small amount of seepage from the Navigation Canal in the lake to the drainage system in the agricultural area. The fact that water levels in aquifer A-2 were relatively unaffected by local drainage operations indicates that confining bed C-2 is relatively impermeable.

QUANTITATIVE STUDIES

Aquifer tests were conducted at site 4 to determine the transmissivity and/or the hydraulic conductivity of the water-bearing materials underlying the dike. A pumping test was conducted in well 5 which taps aquifer A-2. Well 5 was pumped for 95 minutes at a rate of 37 gpm while fluctuations of the water levels in the aquifer were measured in observation wells 4 and 6. The results of the test indicate that the transmissivity of aquifer A-2 is about 24,000 gpd/ft. Slug tests were performed in wells 1 through 6 to determine the hydraulic conductivities of the materials. The results of the tests were highly variable, indicating that K_f (the hydraulic conductivity) of aquifer A-1 could range from 100 to 4,000 gpd/ft and the K_f of aquifer A-2 could range from 1,000 to 2,000 gpd/ft^2. On the basis of the lithology and the slug tests, it was concluded that the transmissivity of aquifer A-1, (slightly more than a foot thick in places) is about 4,000 gpd/ft and the transmissivity of aquifer A-2 (about 8 feet thick) is about 16,000 gpd/ft (table 5).

TABLE 5. – RESULTS OF SLUG TESTS AT SITE 4.

Bed	Maximum Thickness (feet)	K_f (gpd/ft^2)	T (gpd/ft)
Dike Fill			
A-1	4	100 - 1,000	400 - 4,000
A-2	8	1,000 - 2,000	8,000 - 16,000

However, on the basis of the combined results of the tests, it was estimated that the transmissivity of aquifer A-1 is 4,000 gpd/ft and that the transmissivity of aquifer A-2 is 24,000 gpd/ft; and these values were used to compute seepage from the lake.

SEEPAGE

Seepage from the lake at site 4 can be estimated best by determining the flow through 25 feet of saturated material underlying the dike. The flow through the materials for a given period can be determined if the transmissivities of the aquifers within the materials and the hydraulic gradients are known. A comparison of the fluctuation of water levels in wells in the agricultural area with that of the lake shows that hydraulic connection exists, and comparison of water levels in wells and the lake at a given time establishes the gradient. Therefore the seepage through aquifers A-1 and A-2 was computed for June 6, 1965, a time of low water levels, and for October 11, 1965, a time of high water levels; and the seepages were related to the hydraulic gradient between the lake and the water level in well 1 in order to determine the seepage factor (S_e) in the same manner as shown in the previous sections pertaining to seepage at sites 1, 2, and 3. The results of the analysis are shown in table 6.

TABLE 6. RESULTS OF SEEPAGE ANALYSIS AT SITE 4.

Date	Q_{A-1} (cfs/mi)	Q_{A-2} (cfs/mi)	Q_{total} (Cfs/mi)	S_e (cfs/mi/ft)
6-4-65	0.01	0.24	0.25	0.12
10-11-65	0.03	0.41	0.44	0.13

The seepage factor at site 4 is about 0.1 cfs per mile per foot of head between the lake and well 1.

The geologic cross section prepared by the Corps of Engineers (1961, plate 17) indicates that there is considerable variation in the material underlying the 10-mile section of dike represented by site 4. Even so, the seepage factor at site 4 is estimated to be within the order of magnitude which would be expected for the type of material. The seepage factor includes the present retarding effect of the filtercake in the Navigation Canal. The seepage factor at site 4 will probably decrease in the future as the filtercake is slowly redeposited on the exposed portions of the aquifers in the bottom of the Navigation Canal.

Long-term water-level data in the nearby agricultural area are needed to determine the average seepage from the lake. These data are lacking. However water-level data for well 1 during 1964-65 (see fig. 33) suggest that the operations in the nearby drainage district control the water levels in the nearby fields at about a stage of 11 feet. On this basis, the average rate of seepage from the lake at site 4 would probably be about 0.3 cfs/mi when the average lake stage is 14 feet, and about 0.55 cfs/mi when the average lake stage is 16.5 feet. Therefore seepage from the lake along the 10-mile section of dike represented by site 4 should increase from 3 to 5.5 cfs if the average lake stage is raised from 14 to 16.5 feet.

SITE 5

DESCRIPTION

Site 5 is in Palm Beach County on the eastern shore of Lake Okeechobee about 1.2 miles north of Canal Point, as shown in figure 36. The site consists of data-collection stations along a line about 1,600 feet long which was constructed normal to the Hoover Dike. The stations include 9 test wells, of which 6 were used to obtain data on ground-water levels, and two observation points which were used to obtain water level data in the lake and in the landside toe ditch, shown in figure 37. West of the dike is the lake and the Navigation Canal which was excavated in 1964 for borrow to raise the Hoover Dike to its present height. The filled channel on the west side of the Navigation Canal was excavated for borrow to construct the dike in the early thirties and was backfilled with organic material in 1964. East of the dike is a shallow toe ditch which conveys runoff and seepage southward to the West Palm Beach Canal at Canal Point. East of the ditch is the Florida East Coast Railroad and a 200-foot wide sand ridge on which U. S. Highway 441 and most of the residences and businesses are located. About 0.6 mile east of U. S. Highway 441 is a drainage canal used for flood control by the Pelican Lake Drainage District (not shown on fig. 37).

Natural land surface ranges from 15 feet above msl at the landside toe of the dike to 19 feet at the top of the sand ridge. The area is underlain by 7 to 8 feet of organic soil, 3 to 4 feet of marl, 23 feet of shell and hard crystalline limestone, and at least 15 feet of fine sand (fig. 37). Generally, beds of limestone and shell are aquifers and beds of organic soil, marl, and fine sand are confining

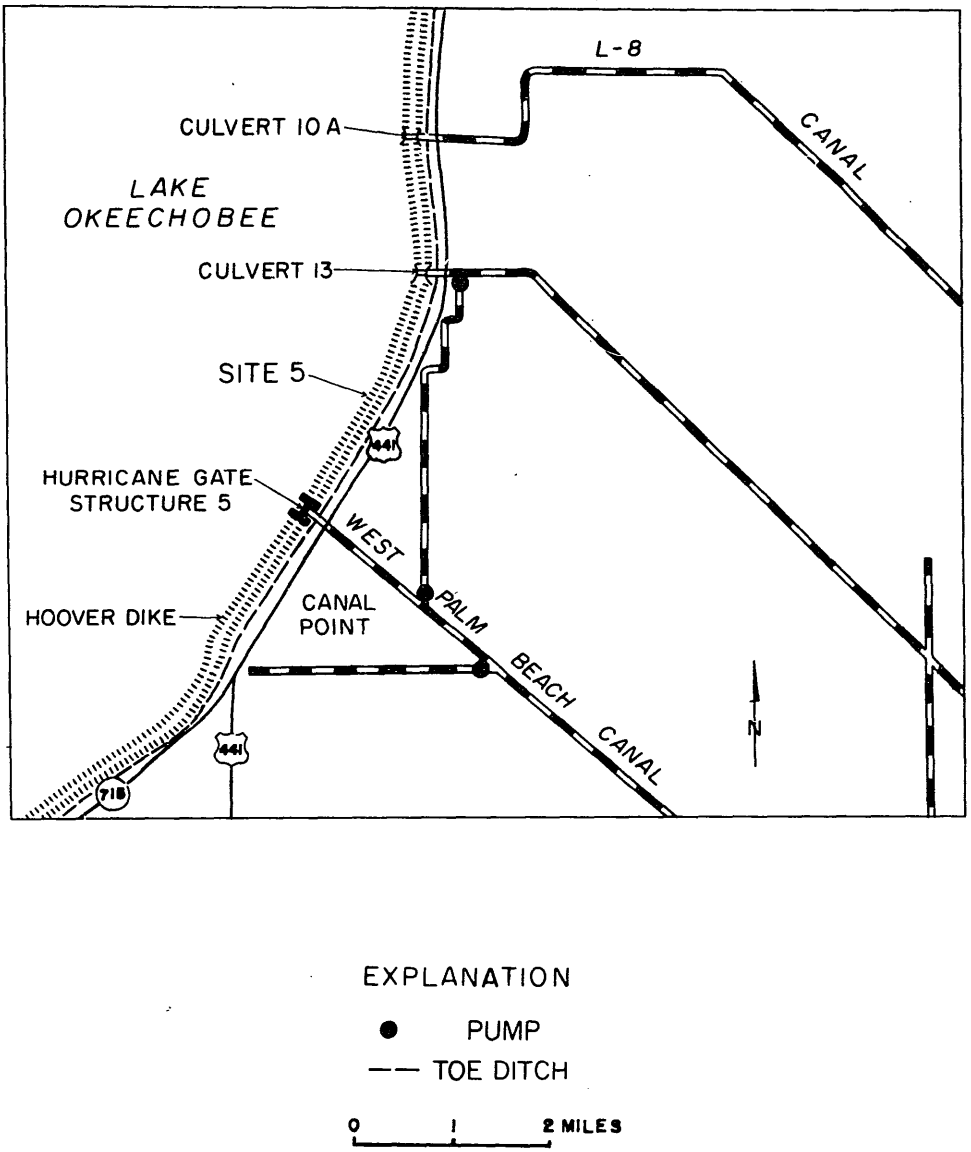

Figure 36. Map showing location of site 5 near Canal Point.

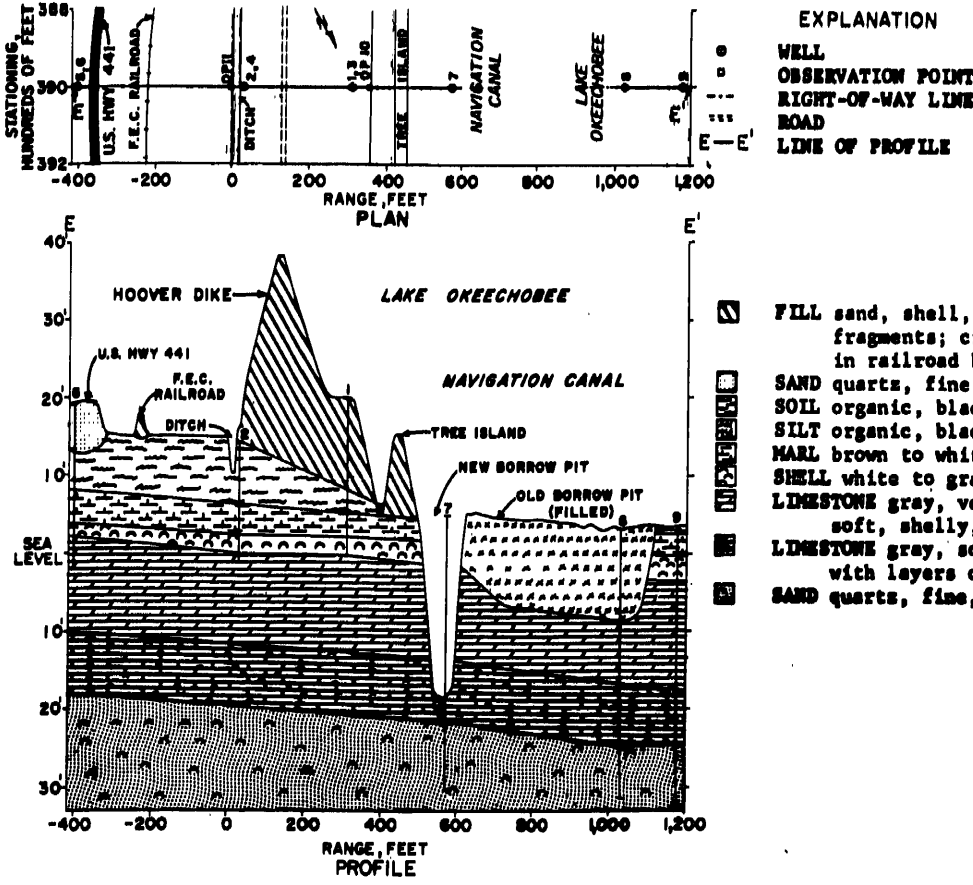

Figure 37. Plan and profile along line E-E' at site 5.

beds. The shelly limestone which underlies the dike between 12 and 20 feet below msl in the Caloosahatchee Marl is the most permeable unit.

AQUIFERS AND CONFINING BEDS

The aquifers, confining beds, and depths of observation wells along line E-E′ at site 5 are shown on profile A in figure 38. The aquifers and confining beds are numbered consecutively with increasing depth and the unit numbers are peculiar only to site 5.

Confining bed C-1 has a maximum thickness of 12 feet. The upper 8 feet is organic soil and the lower 4 feet is clayey shelly marl. The bed is about 9 feet thick beneath the sand ridge and about 3 feet thick beneath the dike. Bed C-1 is relatively impermeable and confines the water in the underlying aquifer. Aquifer A-1 has a maximum thickness of 22 feet. The upper 2 feet is permeable shell and soft permeable limestone which is underlain by a 12-foot bed of hard crystalline limestone that locally contains stringers of sand. The lower 8 feet is soft, porous, shelly limestone that locally contains stringers of sand.

Confining bed C-2 is at least 15 feet thick. It is chiefly composed of fine, quartz sand and it is relatively impermeable.

WATER MOVEMENT AND FLUCTUATIONS

The principal direction of water movement at site 5 is eastward from the lake toward the drainage canals in the agricultural area. Short term reversals occur however when the water levels in Lake Okeechobee are routinely lowered by the Corps of Engineers prior to the annual rainy season and water flows westward toward Lake Okeechobee. Hydraulic profiles A and B in figure 38 were constructed for June 4, 1965 and October 11, 1965 respectively, to show the direction of seepage, and the distribution of equipotential lines and isochlors for high and low stages of the lake.

On June 4, 1965, a time of low water levels, the stages of the lake and the water level in the toe ditch were about 12.4 feet. Flow through confining bed C-1 was chiefly westward from the sand ridge toward the toe ditch. However, seepage into the ditch was insignificant due to the low permeability of the confining bed. The widely spaced equipotential lines show that flow through aquifer A-1 was eastward from the lake toward the drainage canals in the agricultural area, and that the hydraulic gradient was low. The nearly horizontal equipotential lines beneath the sand ridge at U. S. Highway 441 indicate the loss in head across confining bed C-1. Flow through aquifer A-1 was eastward toward the drainage canals in the Pelican Lake Drainage District. Seepage was induced by pumping in the agricultural area at the time of the measurement.

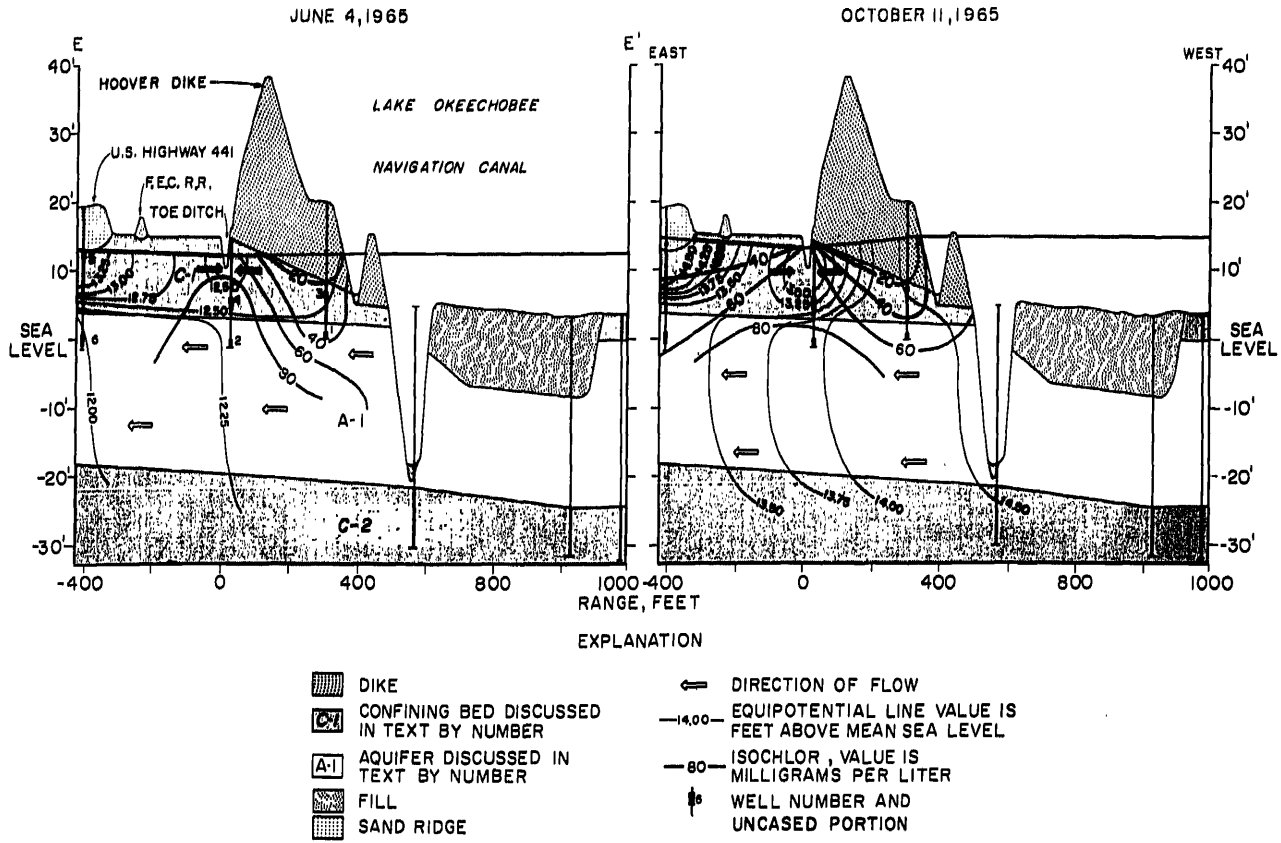

Figure 38. Selected hydraulic profiles along line E-E' showing aquifers, confining beds and depths of observation wells at site 5.

On October 11, 1965, at time of high water levels, the direction of flow through confining bed C-1 was eastward from the lake and westward from the ground-water mound beneath the sand ridge toward the tow ditch. However, no significant flow was observed in the toe ditch, which confirmed that bed C-1 is relatively impermeable.

Flow through aquifer A-1 was eastward from the lake toward the drainage system in the agricultural area. Comparison of the spacing of the equipotential lines in the profiles indicates that the rate of flow on October 11 was more than twice the rate during June 4; and the eastward shift of isochlors on October 11 also indicates that flow from the lake through aquifer A-1 had increased.

The daily stages of the lake and the water level in well 2, located at the toe of the dike and tapping aquifer A-1, are compared on figure 39. The water level in well 2 fluctuates primarily in response to changes in the level of the lake. Short-term fluctuations in the well were caused by seiche and wind tides in the lake and by drainage operations in the agricultural area east of the dike. Drawdown in the well by the drainage was greatest after heavy rains in mid October 1964, but daily drawdowns of a few hundredths of a foot were common. The data indicate that there is a linear relationship between the stage of the wells and the stage of the lake and that locally a good hydraulic connection occurs between the lake and aquifer A-1.

Water levels, chloride content, and water temperatures in confining bed C-1 and aquifer A-1 are compared with data for the lake in figures 40 and 41, respectively. The data on the graphs are coded so that the line with the least dots represents the well nearest the lake.

Water levels in well 3 located west of the dike in bed C-1 compare well with the stage of the lake while the water levels in wells 4 and 5 located east of the dike do not (fig. 40). The water level in well 4 (landside toe of dike) is about comparable to the water level in the toe ditch which drains southward into Palm Beach Canal. The water level in well 5 indicates that water levels beneath the sand ridge are often higher than the lake level.

Prior to the excavation of the toe ditch in August 1964, the area between the dike and the sand ridge was periodically inundated following periods of heavy rainfall. Many local residents believed that the flooding was caused by seepage from the lake. However, hydrologic data, and on site investigation of the flooded area have led this investigator to conclude that flooding was due chiefly to inadequate surface drainage and to seepage westward from the sand ridge and not due to seepage from the lake. For example, on July 8, 1964 the water level in the area between the toe of the dike and the railroad was 15.45 feet above msl (more than a foot above land surface) while the stage of the lake was only 13.2 feet. Obviously, the direction of seepage must have been toward the lake and not from the lake. Therefore the observed flooding at that time was caused by runoff that was trapped in the small basin between the railroad and the dike.

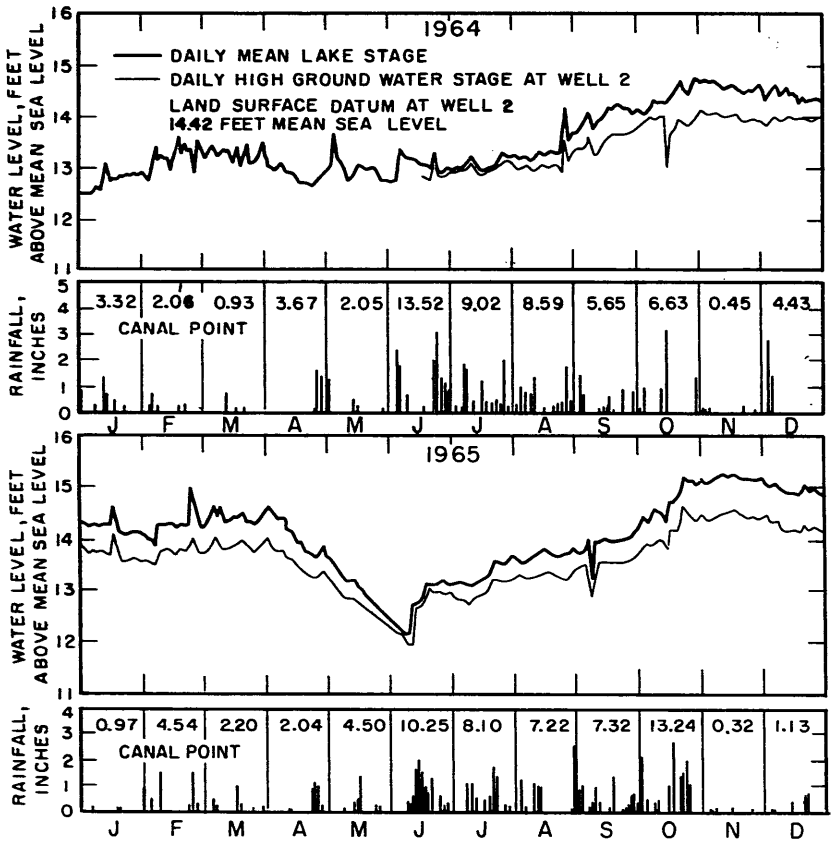

Figure 39. Graphs showing daily stages of Lake Okeechobee and ground-water levels in well 2 at site 5; and daily and monthly rainfall at Canal Point; 1964-65.

After the toe ditch was excavated the water level in well 4 declined and since then no flooding has been observed.

Water levels in observation wells 1, 2 and 6 that tap aquifer A-1 fluctuate in concert with the level of the lake, as shown by the hydrographs on figure 41. The water levels in the aquifer slope eastward away from the lake, thus the flow is eastward from the lake. Water levels in the wells were slightly affected by drainage operations in the agricultural area. Well 6, which is closest to the agricultural area, was affected most by pumping from the drainage canal located 0.7 mile east of the dike.

The chloride content in the lake at site 5 appears to be highest during the wet periods when water containing high chloride is pumped from the agricultural

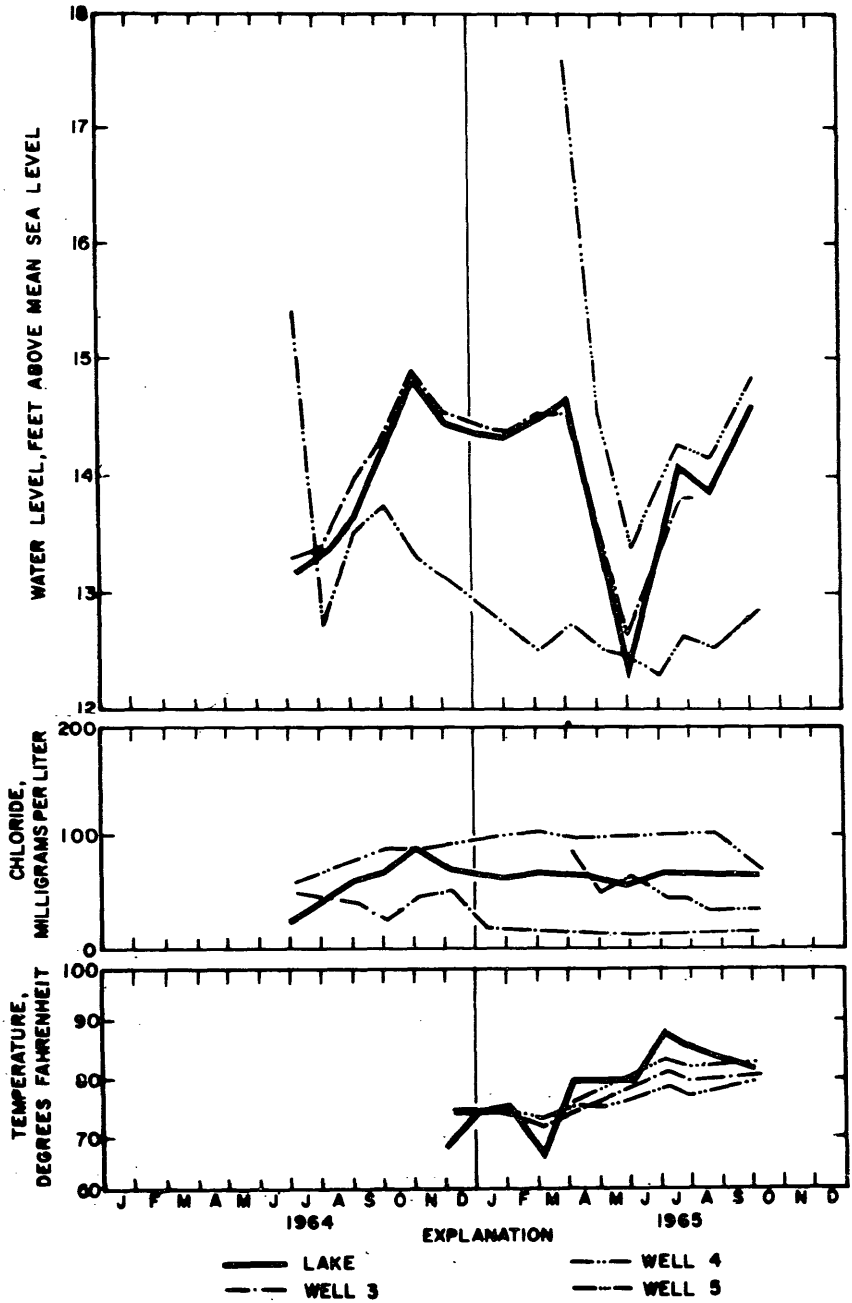

Figure 40. Graphs comparing water levels, chloride content, and water temperature in wells that tap confining bed C-1 at site 5 with the data for the lake, 1964-65.

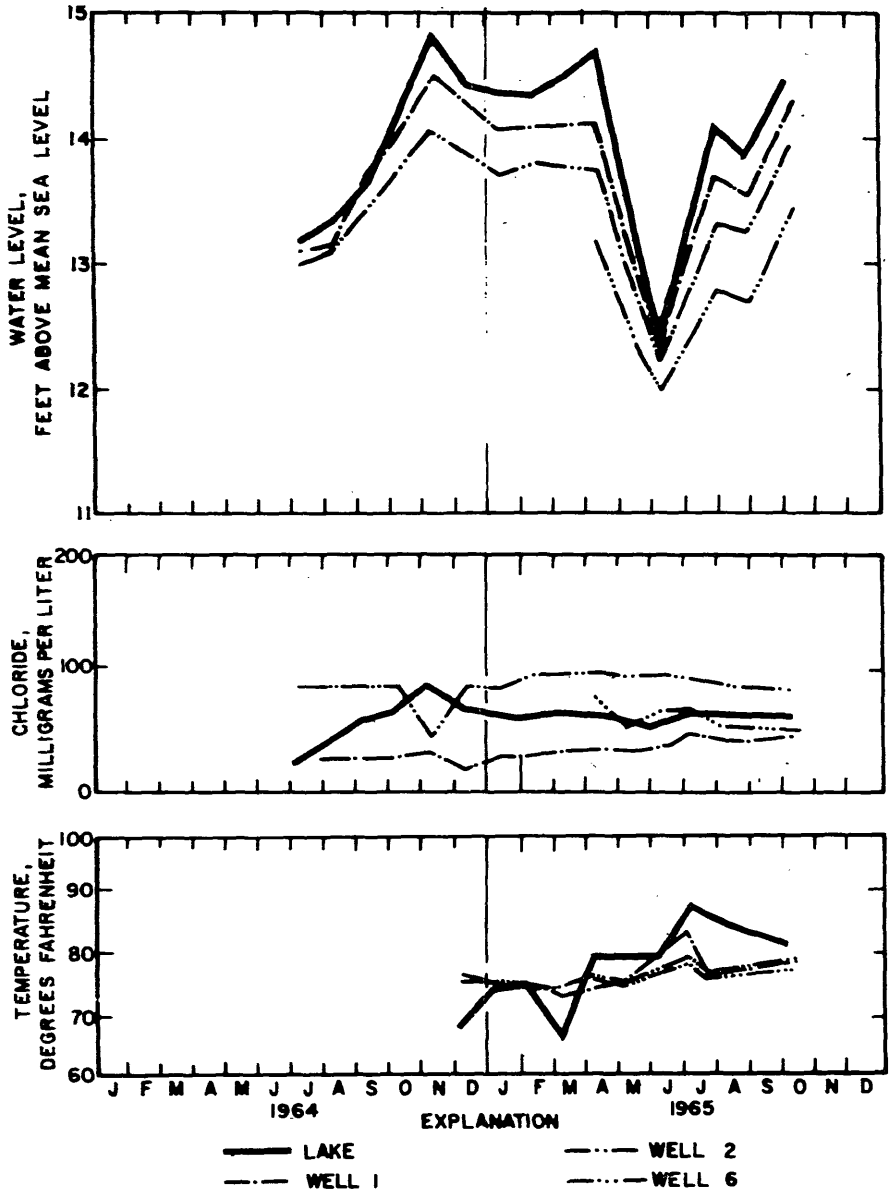

Figure 41. Graphs comparing water levels, chloride content, and water temperature in wells that tap aquifer A-1 at site 5 with data for the lake, 1964-65.

area into the lake. The chloride and temperature data appear to show no direct relation between water in the lake and wells. Perhaps the reason for the nonconformity of the data can be partly attributed to the lack of good circulation at the lake sampling point, which was located in the lagoon between the dike and the tree islands, and to recharge from the toe ditch and the sand ridge when water levels there were higher than water levels in aquifer A-1.

QUANTITATIVE STUDIES

Aquifer tests were conducted at site 5 to determine the transmissivity (T) and/or hydraulic conductivity of the water-bearing materials underlying the dike. Attempts were made to perform pumping tests at the site but the yields of the wells were insufficient to provide meaningful data. Slug tests were conducted in wells 1 through 4 with equally poor results because the wells were either partly filled with sand or lacked sufficient open hole in the limestone to allow the water to freely enter the well. But a few data indicate that hydraulic conductivity of the lower 4 feet of bed C-1 is about 4.6 gpd/ft^2, and that the hydraulic conductivity of the upper 14 feet of aquifer A-1 is about 70 gpd/ft^2 (table 7).

TABLE 7. – RESULTS OF SLUG TESTS AT SITE 5

Bed	Thickness (feet)	K (gpd/ft^2)	T (gpd/ft)
C-1[1]	4	4.6	18.4
A-1[2]	14	66.0	924.0

[1] Marl in lower part of C-1.

[2] Hard limestone and shell in upper part of A-1.

Water-level fluctuations in well 2, which were induced by wind-driven tides and seiche of the lake, were analyzed by a method suggested by Ferris (1962 p. 133); and the analysis indicated that the transmissivity of the upper 14 feet of aquifer A-1 is about 1,200 gpd/ft.

Geologic data from wells 7-9 indicate that the shell which comprises the lower 8 feet of aquifer A-1 at site 5 is equivalent to the permeable shell in aquifer A-2 at site 1. The transmissivity of the total water-bearing section at site 1 is about 72,000 gpd/ft, however, the transmissivity of the 18.5 feet of shell that comprises aquifer A-2 probably represents 63 percent of the total transmissivity (72,000 gpd/ft), or about 45,400 gpd/ft., based on the ratio of the T value for aquifer A-2 to the total T in table 2. Therefore the transmissivity of

the lower 8 feet of aquifer A-1 at site 5 would be 43 percent (8 ft/18.5 ft) of the T value for aquifer A-2 at site 1, or 19,500 gpd/ft. Thus the total transmissivity of the aquifer A-1 at site 5 would be the sum of the T values for the upper 14-foot section (1,200 gpd/ft) and the lower 8-foot section (19,500 gpd/ft), or 20,700 gpd/ft.

SEEPAGE

Seepage from the lake at site 5 can be estimated best by determining the steady-state flow for a given period through 33 feet of saturated material underlying the dike. As explained in the preceeding sections dealing with seepage at sites 1 through 3, the flow through the materials for a given period can be determined from the transmissivities and the prevailing hydraulic gradients.

Seepage was computed from water-level measurements made on January 14, June 4, and October 11, 1965. Seepage through confining bed C-1 (Q_{C-1}) was computed using the prevailing hydraulic gradient between wells 3 and 4 and a transmissivity of 50 gpd/ft. Seepage through aquifer A-1 (Q_{A-1}) was computed using the prevailing hydraulic gradient between wells 1 and 2 and a transmissivity of 20,700 gpd/ft. The seepage factor, S_e, was determined by relating the total seepage through beds A-1 and C-1 to the head between the lake and well 2 which taps aquifer A-1 and is located at the landward toe of the dike. The results of the analysis are shown in table 8.

TABLE 8. – RESULTS OF SEEPAGE ANALYSES AT SITE 5.

Date	H (ft)	Q_{C-1} (cfs/mi)	Q_{A-1} (cfs/mi)	Q_{total} (cfs/mi)	S_e (cfs/mi/ft)
1-14-65	0.66	0.002	0.246	0.248	0.38
6-4-65	.23	.0002	.0845	.0847	.37
10-11-65	.64	.003	.193	.196	.31

The average seepage factor at site 5 is about 0.4 cfs per mile per foot of head between the lake level and the water level in well 2. The seepage factor includes the present effects of the filtercake in the Navigation Canal, however, seepage will probably decrease in the future as the filtercake is slowly redeposited on the exposed portion of the aquifers in the bottom of the canal.

Long term water-level data in the agricultural area are needed to determine the average seepage from the lake. However, these data are lacking, therefore the relationship between the lake and well 2 was used to estimate the steady-state hydraulic gradient between the lake and the discharge point in the agricultural

area. Seepage can be estimated for selected stages of the lake by multiplying the head between the lake and the water level in well 2 by the seepage factor (0.4 cfs/mi/ft).

The relationship between the water levels of the lake and well 2 indicate that when the stage of the lake is 14 feet, the water level in well 2 is about 13.64 feet. Therefore the head across the dike in aquifer A-1 would be about 0.36 foot and the corresponding rate of seepage at site 5 would be 0.1 cfs/mile. If the average stage of the lake is raised to 16.5 feet, then the average stage of the water-level in well 2 would be about 15.6 feet and the average rate of seepage would be 0.4 cfs/mile.

Thus seepage beneath the 14-mile segment of dike represented by site 5 should increase from 1.4 cfs to 5.6 cfs if the average lake stage is raised from 14 feet to 16.5 feet.

SEEPAGE ALONG SOUTHERN SHORE OF LAKE OKEECHOBEE

Studies of seepage at five sites along the southern shore of Lake Okeechobee indicate that seepage factors ranged from 0.9 cfs/mi/ft at site 1 near Moore Haven to 0.1 cfs/mi/ft at site 4 near Belle Glade (table 9).

TABLE 9. – SUMMARY OF SEEPAGE BENEATH HOOVER DIKE ALONG THE SOUTHERN SHORE OF LAKE OKEECHOBEE

S_e seepage factor, cubic feet per second per mile per foot of head across the dike.

L length of dike assumed represented by each site, miles.

S_{14} seepage rate for average stage 14 feet, cfs per mile.

$S_{16.5}$ seepage rate for average stage 16.5 feet, cfs per mile.

T_{14} total seepage along L for stage 14 feet, cfs.

$T_{16.5}$ total seepage along L for stage 16.5 feet, cfs.

SITE	S_e	L	S_{14}	$S_{16.5}$	T_{14}	$T_{16.5}$
1	0.9	9.0	1.6	3.4	14.4	30.6
2	.2	8.5	.1	.15	.8	1.3
3	.2	8.5	.3	.8	2.6	6.8
4	.1	10.0	.3	.55	3.0	5.5
5	.4	14.0	.1	0.4	1.4	5.6
TOTALS		50.0			22.2	49.8

When the average stage of the lake is 14 feet, seepage beneath the Hoover Dike ranges from 1.6 cfs/mi at site 1 near Moore Haven to 0.1 cfs/mi at site 2 near Clewiston and at site 5 near Canal Point. Seepage is greatest at site 1 because deep borrows, located adjacent to both sides of the dike, penetrated permeable beds of shell, and hydraulic gradients there are steep.

Seepage is expected to increase as a result of raising the average lake stage from 14 to 16.5 feet. Seepage along the 50-mile shoreline between Moore Haven and Port Mayaca should increase from 22 to 50 cfs as a result of raising the average lake stage 2.5 feet. The 22 cfs seepage loss at stage 14 feet is equivalent to 0.43 in/yr loss from lake storage and the 50 cfs seepage loss at stage 16.5 feet is equivalent to 1.00 in/yr loss from the lake. The seepage rates determined during this study compare favorably with rates determined previously by the Corps of Engineers (1963). The seepage rates presented herein are only valid for the conditions which prevailed at each site. Changes in agricultural drainage could greatly increase the seepage if, for example, drainage ditches were deepened so that they penetrated confining beds, drainage ditches were dug closer to the dike, and water levels in nearby fields were lowered. However, seepage from the lake into the agricultural area can be controlled by the C&SFFCD if a system of toe ditches and canals were designed to intercept seepage from the lake through the chief aquifers underlying the dike. This seepage could then be returned to the lake by pumping. An authorized pumping station (S-4) to be constructed near site 1 will intercept seepage from the lake between Moore Haven and Clewiston by controlling the stages of the L-Dl canal.

SUMMARY

Studies were made of seepage from Lake Okeechobee beneath the Hoover Dike at five selected sites along the southern shore of Lake Okeechobee. The objectives of the studies were to describe the manner in which seepage was occurring, to determine the seepage rate at each site, and to estimate the increase in average seepage that would result if the average stage of the lake were raised from 14 to 16.5 feet above msl.

Studies at site 1 near Moore Haven indicate that seepage from the lake occurs chiefly through two contiguous aquifers that underlie the dike between 10 feet above msl and 20 feet below msl. The aquifers are composed of limestone and shell and function hydraulically as a unit. The total transmissivity of the aquifers is about 72,000 gpd/ft and the seepage factor is about 0.9 cfs per mile per foot of head between the lake level and the water level and the water level in the nearby L-D1 Canal. Seepage from the lake into the agricultural area depends upon the drainage operations in the agricultural area. During dry periods the stage of the L-D1 Canal is regulated at, or slightly above, the desired stage of the water table in the adjacent fields and the L-D1 canal intercepts most

of the seepage from the lake and conveys the water to the agricultural area. During wet periods the L-D1 Canal is ponded by controls, and water from the lake seeps southward through the L-D1 Canal into the nearby fields. If the average stage of the lake is raised from 14 to 16.5 feet then the average rate of seepage at site 1 would increase from 1.6 to 3.4 cfs/mi and the average seepage beneath the 8½-mile length of dike represented by site 1 would increase from 14.4 to 30.6 cfs.

Studies at site 2 near Clewiston indicate that seepage from the lake occurs generally through the upper 28 feet of strata. However, most seepage occurs through an 8-foot thick limestone aquifer which has a transmissivity of 3,000 gpd/ft. Beneath the limestone is a bed of fine sand that retards the movement of water from the lake into the agricultural area and into the underlying aquifers. The seepage factor is about 0.2 cfs/mi per foot of head between the lake level and the water level in the L-D2 Canal. If the average stage of the lake is raised from 14 to 16.5 feet then the average rate of seepage at site 2 would increase from 0.1 to 0.15 cfs/mi and the average seepage beneath the 8½-mile length of dike represented by site 2 would increase from 0.8 to 1.3 cfs.

Studies at site 3 near Lake Harbor indicate that most of the seepage from the lake occurs through a 17-foot thick aquifer composed of shell and porous limestone. The transmissivity of the aquifer is about 17,500 gpd/ft. The seepage factor is about 0.2 cfs/mile per foot of head between the lake level and the water level in the toe ditch. If the average stage of the lake is raised from 14 to 16.5 feet then the average rate of seepage would increase from 0.3 to 0.8 cfs/mi and the average seepage beneath the 8½-mile length of dike represented by site 3 would increase from 2.6 to 6.8 cfs.

Studies at site 4 near Belle Glade indicate that seepage from the lake occurs through two aquifers. The uppermost aquifer is 4 feet thick and is composed of porous limestone. The transmissivity of the aquifer is about 4,000 gpd/ft. The lowermost aquifer is 10 feet thick and is composed of porous limestone and shell. The transmissivity of this aquifer is about 24,000 gpd/ft. The seepage factor is about 0.1 cfs/mi per foot of head between the lake level and the water level in well 1, which taps the shallow aquifer and is located at the landside toe of the dike. If the average stage of the lake is raised from 14 to 16.5 feet then the average rate of seepage at site 4 would increase from 0.3 to 0.55 cfs/mile and the average seepage beneath the 10-mile length of dike represented by site 4 would increase from 3 to 5.5 cfs.

Studies made at site 5 near Canal Point indicate that most of the seepage occurs through an aquifer 22 feet thick composed of shell and hard porous limestone. The transmissivity of the aquifer at site 5 is estimated to be 20,700 gpd/ft on the basis of the transmissivity of similar material at site 1. The seepage factor is estimated to be 0.4 cfs/mi per foot of head between the lake level and the water level in well 2, which taps the aquifer and is located at the

landside toe of the dike. If the average stage of the lake is raised from 14 to 16.5 feet then the average rate of seepage would increase from 0.1 to 0.4 cfs/mi; and the average seepage beneath the 14-mile length of dike represented by site 5 should increase from 1.4 to 5.6 cfs.

If the average stage of the lake is raised from 14 to 16.5 feet, then the seepage beneath the total 50-mile length of dike represented by the five sites would increase from 22 to 50 cfs. Because of the large distances between sites, variations in values can be expected in the intervening areas. Therefore the results of these studies are only an indication of the seepage rates that might be expected around the southern shore of Lake Okeechobee. The studies indicate a need for additional data near South Bay and along the newly constructed dikes on the northern shore of Lake Okeechobee, and for a monitoring program which will be useful in determining the effects that deposition of filtercake in lakeside borrows and changes in drainage works will have on future seepage rates.

REFERENCES

Bredehoeft, J. D.
1967 (See Cooper, H. H.)

Cooke, C. W.
1944 (See Parker, G. G.)

Cooke, C. W.
1929 (and Mossom, Stuart) *Geology of Florida:* Florida Geol. Survey 20th Ann. Rept.

Cooke, C. W.
1939 *Scenery of Florida interpreted by a geologist:* Florida Geol. Survey Bull. 17.

Cooke, C. W.
1945 *Geology of Florida:* Florida Geol. Survey Bull. 29.

Cooper, H. H.
1967 (and Bredehoeft, J. D., and Papadopulos, I. S.) *Response of a finite-diameter well to an instantaneous charge of water:* Water Resources Research, v. 3, no. 1.

Dall, W. H.
1887 *Notes on the geology of Florida:* Am. Jour. Sci., 3rd Ser., v. 34.

Dall, W. H.
1893 *Geological results from the study of the Tertiary fauna of Florida:* Wagner Free Inst. Sci. Trans., v. 3, pt. 6.

Davis, J. H.
1943 *The natural features of southern Florida:* Florida Geol. Survey Bull. 25.

Dubar, J. R.
1958 *Stratigraphy and paleontology of the late Neogene strata of the Caloosahatchee River area of southern Florida:* Florida Geol. Survey Bull. 40.

Ferguson
1955 (See Parker, G. G.)

Ferris, J. G.
1962 (et al) *Theory of aquifer tests:* U. S. Geol. Survey Water Supply Paper 1536-E.

Greene, F. A.
1966 (and Pruit, M. M.) *Revised plan of reclamation, Diston Island Drainage District:* Gee & Jenson Consulting Engineers Inc., West Palm Beach, Florida.

Heilprin, Angelo
1887 *Explorations on the west coast of Florida and in the Okeechobee wilderness:* Wagner Free Inst. of Sci. Trans. v. 1.

Herr, Ben
1943 *Caloosahatchee River and Lake Okeechobee drainage areas, Florida:* Soil Sci. Soc. Florida Proc., v. 5-A.

Hull, J. E.
1969 (See Meyer, F. W.)

Johnson, Lamar
1951 (See Stephens, J. C.)

Jones, L. A.
1948 *Soils, geology and water control in the Everglades region:* Univ. Florida Agr. Expt. Sta. Bull. 442.

Kenner, W. E.
1961 *Stage characteristics of Florida lakes:* Florida Geol. Survey Inf. Circ. 31.

Klein, Howard
1954 (See Schroeder, M. C.)

Klein, Howard
1964 (and Schroeder, M. C. and Lichtler, W. F.) *Geology and groundwater resources of Glades and Hendry counties, Florida:* Florida Geol. Survey Rept. of Inv. 37.

Lichtler, W. F.
1960 *Geology and groundwater resources of Martin County, Florida:* Florida Geol. Survey Rept. of Inv. 23.

Lichtler, W. F.
1964 (See Klein, Howard)

Love, S. K.
1954 (See Schroeder, M. C.)

Love, S. K.
1955 (See Parker, G. G.)

Mansfield, W. C.
1931a *Pliocene fossils from limestone in southern Florida:* U. S. Geol. Survey Prof. Paper 170-D.

Mansfield, W. C.
1931b *Some Tertiary mollusks from southern Florida:* U. S. Nat. Mus. Proc., v. 79, art. 21.

Mansfield, W. C.
1939 *Notes on upper Tertiary and Pleistocene mollusks of peninsular Florida:* Florida Geol. Survey Bull. 18.

Matson, G. C.
1913 (and Sanford, Samuel) *Geology and groundwaters of Florida:* U. S. Geol. Survey Water-Supply Paper 319.

Meyer, F. W.
1969 (and Hull, J. E.) *Seepage tests in L-D1 Borrow Canal at Lake Okeechobee, Florida:* Florida Geol. Survey Inf. Circ. 59.

Milliken, D. L.
1954 (See Schroeder, M. C.)

Mossom, Stuart
1929 (See Cooke, C. W.)

Olsson, A. A.
1964 *Some Neogene Mollusca from Florida and the Carolinas:* Bull. of Am. Paleo. v. 47.

Papadopulos, I. S.
1967 (See Cooper, H. H.)

Parker, G. G.
1942 *Notes on the geology and ground water of the Everglades in southern Florida:* Soil Sci. Soc. Florida Proc., v. 4-A.

Parker, G. G.
1944 *Late Cenozoic geology of southern Florida, with a discussion of the ground water:* Florida Geol. Survey Bull. 27.

Parker, G. G.
1951 *Geologic and hydrologic factors in the perennial yield of the Biscayne aquifer, Miami area, Florida:* Am. Water Works Assoc. Jour.

Parker, G. G.
1955 (and Ferguson, G. E. and Love, S. K. and others) *Water resources in southeastern Florida:* U. S. Geol. Survey Water-Supply Paper 1255.

Perkins, R. D.
1968 *Late Cenozoic stratigraphy of southern Florida — A reappraisal, with additional notes on Sunoco-Felda and Sunniland oil fields:* Miami Geol. Soc. 2nd Ann. Field Trip Guide Book.

Pruit, M. M.
1966 (See Greene, F. A.)

Puri, Harbans
1964 (and Vernon, R. O.) *Summary of the geology of Florida and a guidebook to classic exposures:* Florida Geol. Survey Spec. Pub. 5.

Roland, L. Orlando
1969 *An application of geology to agriculture south of Lake Okeechobee:* Southeastern Section Geol. Soc. America, 18th, Columbia, South Carolina 1969, Abstracts with programs for 1969.

Sanford, Samuel
1913 (See Matson, G. C.)

Schroeder, M. C.
1954 (and Klein, Howard) *Geology of the western Everglades area, southern Florida:* U. S. Geol. Survey Circ. 314.

Schroeder, M. C.
1964 (See Klein, Howard)

Schroeder, M. C.
1954 (and Milliken, D. L. and Love, S. K.) *Water resources of Palm Beach County, Florida:* Florida Geol. Survey Rept. of Inv. 13.

Stephens, J. C.
1951 (and Johnson, Lamar) *Subsidence of organic soils in the Upper Everglades Region of Florida:* U. S. Dept. Agriculture, Soil Conserv. Service.

Stringfield, V. T.
1933 *Ground water in the Lake Okeechobee area:* Florida Geol. Survey Rept. of Inv. 2.

U. S. Corps of Engineers
1953 *Design Memorandum, Permeability investigations of well-pumping tests:* U. S. Corps of Engineers report on Central and Southern Florida Project, Part 1, Supp. 7.

U. S. Corps of Engineers
1961 *Detail Design Memorandum, Herbert Hoover Dike, Levees D-1 D-2 (part), and D-3 (Part):* U. S. Corps of Engineers report on Central and Southern Florida Project, Part 4, Supp. 14.

U. S. Corps of Engineers
1962 *Detail Design Memorandum, Herbert Hoover Dike, Levees D2 (part), D9, and D4:* U. S. Corps of Engineers report on Central and Southern Florida Project, Part 4, Supp. 18.

U. S. Corps of Engineers
1963 *General Design Memorandum, Nine-Mile Canal area:* U. S. Corps of Engineers report on Central and Southern Florida Project, Part 1, Supp. 39.

U. S. Geological Survey
1965 *Water resources data for Florida:* Water Resources Division, data report.

Vernon, R. O.
1964 (See Puri, Harbans)

Wallis, W. T.
1942 *The history of Everglades drainage and its present status:* Soil Sci. Soc. Florida Proc. v. 4-A.