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FLORIDA GEOLOGICAL SURVEY

REPORT OF INVESTIGATIONS NO. 24

# HYDROLOGIC CONDITIONS DADE COUNTY, FLORIDA

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STATE OF FLORIDA
STATE BOARD OF CONSERVATION

FLORIDA GEOLOGICAL SURVEY
Robert O. Vernon, Director

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REPORT OF INVESTIGATIONS NO. 24

PART I

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# HYDROLOGIC CONDITIONS IN THE VICINITY OF LEVEE 30, NORTHERN DADE COUNTY, FLORIDA

By
Howard Klein and C. B. Sherwood
United States Geological Survey

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Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

TALLAHASSEE, FLORIDA
1961

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## LETTER OF TRANSMITTAL

# *Florida Geological Survey*

*Tallahassee*

June 1, 1961

Honorable Farris Bryant, *Chairman*
Florida State Board of Conservation
Tallahassee, Florida

Dear Governor Bryant:

The Florida Geological Survey is publishing as Report of Investigations No. 24, Part I, a report on the hydrologic conditions in the vicinity of Levee 30, northern Dade County, which was prepared by Howard Klein and C. B. Sherwood of the U. S. Geological Survey. This report was prepared in cooperation with the Central and Southern Florida Flood Control District, and this department is publishing the report in its regular series of water resources papers.

The formations that underlie Levee 30 are a part of the very permeable sediments that underlie the southern tip of Florida. The opportunity to make this study has provided important data relative to the transmissibility of the sediments and will assist in design of control structures and in the development of the water resources of southern Florida.

Respectfully yours,

Robert O. Vernon, *Director*

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# HYDROLOGIC CONDITIONS IN THE VICINITY OF LEVEE 30, NORTHERN DADE COUNTY, FLORIDA

By
Howard Klein and C. B. Sherwood

## ABSTRACT

Thin layers of dense limestone of low permeability that occur near the top of the Biscayne aquifer in the vicinity of the north end of Levee 30 in Dade County, Florida are of hydrologic importance because they retard the downward infiltration of ponded water in Conservation Area No. 3. This retarding effect frequently results in high head differentials across the levee. Tests made in a small area adjacent to Levee 30 indicate that the coefficient of transmissibility of the aquifer is 3,600,000 gpd (gallons per day) per foot, and the coefficient of vertical permeability of the dense limestones is 13 gpd per square foot. If ground-water flow beneath the levee is laminar, the total inflow to the Levee 30 Canal from Conservation Area No. 3 will be about 350 mgd (million gallons per day), or 540 cfs (cubic feet per second), per mile length of levee when the head difference across the levee is 10 feet.

## INTRODUCTION

### GENERAL STATEMENT AND PURPOSE

One of the major responsibilities of the Central and Southern Florida Flood Control District is to minimize flood damage in urban and agricultural areas west of the coastal ridge in southeastern Florida. A second function is to protect areas of potential urban development. A large area of anticipated growth in Dade County (shown as Area B in fig. 1) is west of Miami and extends about 10 miles eastward from Levees 30 and 31.

The initial project of the Central and Southern Florida Flood Control District was the construction of an east-coast protective-levee system west of the Atlantic Coastal Ridge, extending from Lake Okeechobee southward into Dade County. Levees 33, 30, and 31 form the southern terminus of this levee system and are shown in figure 1. Its primary purpose was to alleviate flooding in urban and agricultural land, along and adjacent to the ridge, by retarding the overland eastward flow of floodwaters from the Everglades. When the flood-control system is completed, part of these excess floodwaters will be impounded in conservation areas west of the

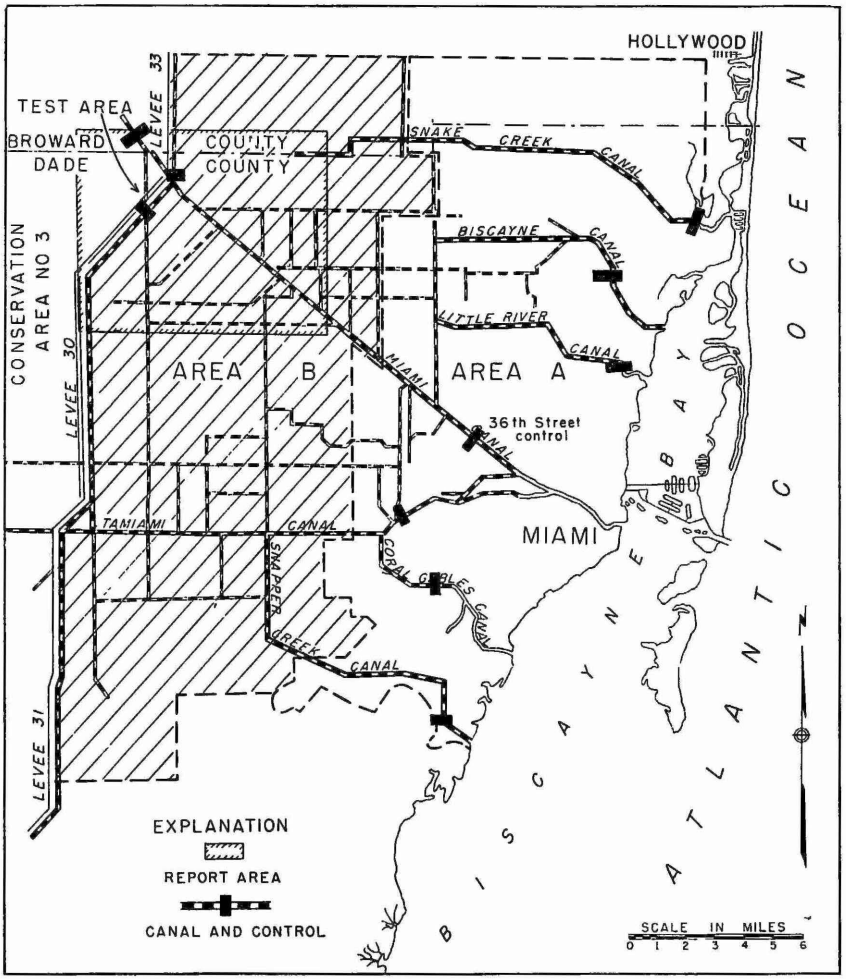



Figure 1. Map of northern Dade County showing the area of investigation.

levee. Regulated releases of water will be conveyed by canals from conservation areas to coastal areas to replenish ground-water reservoirs during periods of drought.

This report is one of a series prepared in cooperation with the Central and Southern Florida Flood Control District. The general purposes of these investigations are (1) to define the hydrology of certain areas within the Flood Control District, (2) to determine the effectiveness of existing flood-control and water-control measures, and (3) to furnish hydrologic data that will be used in the design and operation of proposed and existing structures and works.

The purpose of this investigation is to define the hydrologic characteristics of the water-bearing materials in the vicinity of Levee 30 in northern Dade County, in order to determine the feasibility of controlling water levels in Area B for maximum flood protection. Included is an analysis of the relation between the impounded water west of Levee 30 and the ground water in the area. From this relationship estimates of ground-water underflow along Levee 30 can be computed under existing conditions and under anticipated water-level conditions. Midway in the data-gathering stage of the investigation, major road construction altered the canal system in the immediate area and caused changes in water levels and discharge of canals. This resulted in curtailing of the field work; therefore the results of this investigation should be considered preliminary.

The work was done under the general supervision of P. E. LaMoreaux, chief, Ground Water Branch, Washington, D. C., and under the immediate supervision of M. I. Rorabaugh, district engineer, Tallahassee, Florida.

## PREVIOUS INVESTIGATIONS

A comprehensive report by Parker and others (1955) presented fairly complete information on the geology and hydrology of southeastern Florida, and Parker (1951) gave estimates of the availability and adequacy of the ground-water supplies of the Biscayne aquifer which underlies southeastern Florida. Schroeder and others (1958) summarized additional data on the Biscayne aquifer collected since 1950. Stallman (1956) made theoretical computations on the effect of drainage in the area west of Miami and gave estimates of the amount of seepage that might occur beneath Levee 30 under certain assumed conditions. A mimeographed report by the U. S. Army Corps of Engineers (1953) described the results of permeability tests along different levees within the Flood Control District.

## ACKNOWLEDGMENTS

The writers are indebted to personnel of the Surface Water Branch, U.S. Geological Survey, Miami, Florida, for making discharge measurements in the Levee 30 Canal and furnishing water-level information along the Miami Canal. Gratitude is expressed also to the Public Works Department of metropolitan Dade County for the record of water-level stages for several observation stations in the area. The office of the Central and Southern Florida Flood

Control District furnished complete information on the location, the construction details, and the layout of the Corps of Engineers test sites near Levee 30. The writers benefited from technical discussions with F. A. Kohout of the Miami office, and H. H. Cooper, Jr., and N. D. Hoy of the Tallahassee office, U. S. Geological Survey.

## DESCRIPTION OF AREA

The area described in this report comprises 60 square miles chiefly in northern Dade County, Florida (fig. 1). Figure 2, which is a large-scale map of the report area, delineates the test site within the area, locates certain water-level observation stations, and shows the drainage features. The western part of the area is traversed by Levees 30 and 33. These levees separate Conservation Area No. 3, which normally contains ponded water, from Area B which is swampy during much of the year. The altitude of the land surface is about 5 feet above msl (mean sea level).

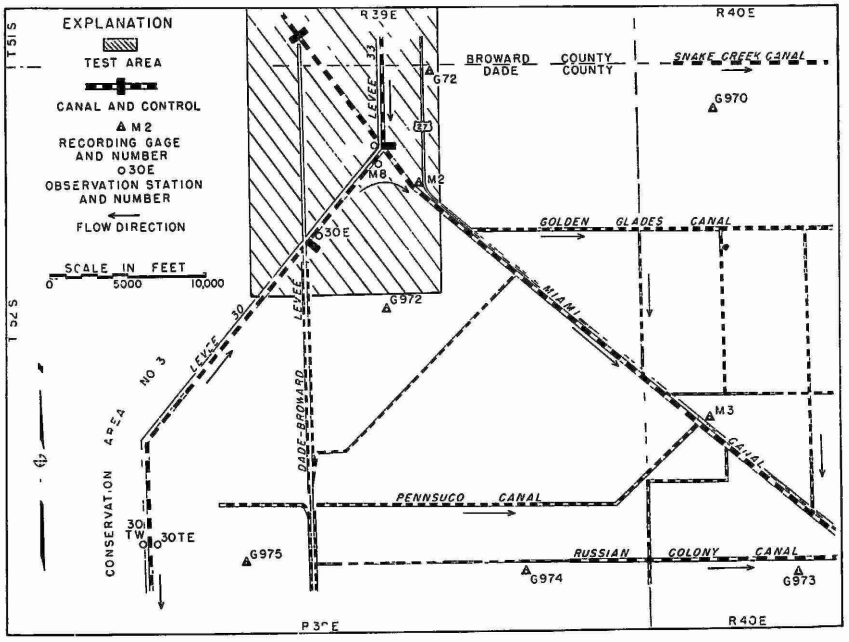



Figure 2. Map of area of investigation showing the location of the test area and the location of selected observation stations.

## GEOLOGY

The area of investigation is underlain to a depth of 55 feet by the Biscayne aquifer, a body of highly permeable limestone. The Biscayne aquifer is underlain by relatively impermeable silt, marl, and fine sand which retard downward seepage from the aquifer or upward seepage from deeper materials.

The cross section in figure 3 gives details of the near-surface geology near the north end of Levee 30 in Dade County, as determined from shallow test holes drilled at site A-A' (fig. 4). The area is blanketed by 3 to 5 feet of muck and marl that is underlain by a layer of solution-riddled Miami oolite, a part of the Biscayne aquifer, 1 to 2 feet thick. Figure 3 shows two thin layers of very hard, dense limestone at depths ranging from 0.5 foot above msl to 3.0 feet below msl. In contrast to the high permeability of the underlying limestones, these thin layers appear to be relatively impermeable; and the vertical flow of water through them is many times less than the horizontal flow of water through the deeper, more permeable rocks. By effectively retarding the downward infiltration of water, the thin layers act as a confining

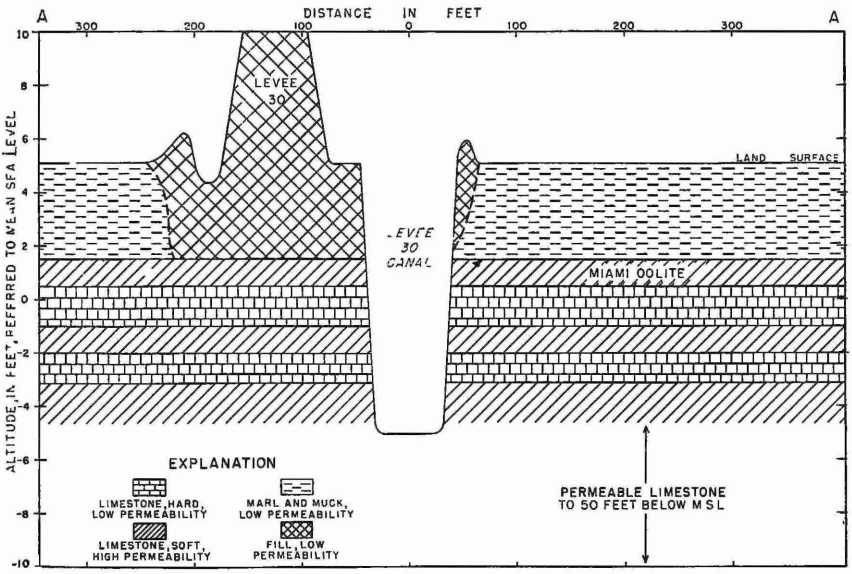



Figure 3. Cross section A-A' showing details of the near-surface geology near the north end of Levee 30.

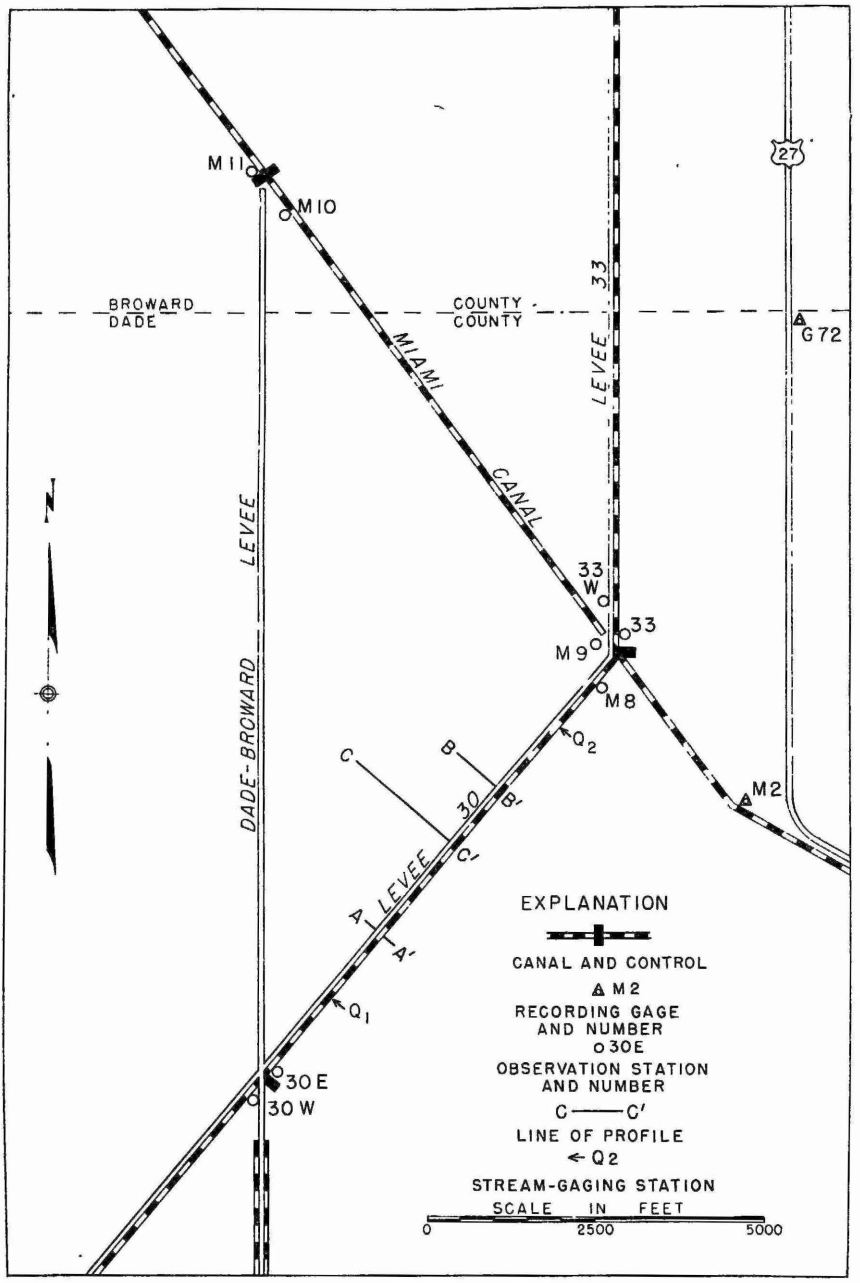



Figure 4. Map of test area showing locations of observation stations and test sites.

unit that separates the ponded water in Conservation Area No. 3 from the water contained in the permeable limestone.

Geologic information from test wells and shallow borings, and reported information obtained in connection with canal excavations, indicate that the hard layers of dense limestone occur throughout most of Area B and in southern Dade County, and that they occur at about the same altitude. Each of the wells (prefixed by letter G) shown in figure 2 penetrated the impermeable layers approximately at sea level. Similar layers were noted in wells near the southern terminus of Levee 31 (fig. 1), and in wells south of the Tamiami Canal and west of Levee 31. It is reasonable to assume that the relatively impermeable zones underlie much of Conservation Area No. 3 and that their confining characteristics are widespread. In places, the dense limestones probably contain openings through which rainfall can infiltrate rapidly; however, the overall continuity and the blanketing effect of these layers in general tend to retard infiltration. In the Miami area to the east, the Biscayne aquifer thickens and contains much sand. The thin, dense limestones either thin and disappear or they occur deeper in the aquifer near the coast.

## DRAINAGE FEATURES

During the past 10 years the improved canal system that provides gravity drainage to Biscayne Bay, as shown in figure 1, has effectively reduced flooding in Area A, the urbanized part of eastern Dade County. The system, as designed, can remove large quantities of excess runoff during rainy seasons and can lower ground-water levels in order to furnish storage in the aquifer to accommodate anticipated heavy recharge by rainfall. The controlled discharge of the canals has furnished good flood protection in Area A and at the same time has maintained adequate water levels in most coastal areas to retard the inland movement of salt water.

Area A must be at least partially drained before any depletion in storage can be effected in Area B; consequently, Area B normally remains inundated or swampy during long periods. Also, the eastward seepage beneath Levee 30 tends to maintain high water levels in the western part of Area B. Area B is drained chiefly by the Miami and Tamiami canals and to a lesser extent by the Snake Creek and Snapper Creek canals. Their capacities are not adequate to drain Area B by gravity during the rainy seasons.

Figure 2 shows the drainage features of the report area and indicates the normal directions of flow in the major canals. The

discharge of the Miami Canal is regulated by a control located at 36th Street, Miami, 6 miles inland from Biscayne Bay (fig. 1). The control normally is opened a few weeks before the rainy season and remains open throughout the rainy season to facilitate the discharge of excess water. During open periods the effect of tides extends upstream to a point beyond the Pennsuco Canal (fig. 2). After the rainy season the control is closed in order to conserve water for heavy municipal and irrigation use during the following dry months and to maintain high water levels along the coast as a protective measure against salt-water encroachment.

The main tributaries of the Miami Canal in northern Dade County are the Levee 30 and 33 canals, the Pennsuco Canal, and the Russian Colony Canal. Flow in some canals is controlled by use of earth dams or manually operated sluice gates as located in figure 2. The Levee 30 Canal is controlled at the Dade-Broward Levee and its flow to the Miami Canal is maintained by seepage to the northeast around the control and by ground-water inflow between the control and the Miami Canal. The control in the Levee 30 Canal usually remains closed. The flow in the reach of the Levee 30 Canal upstream from the control is so small that

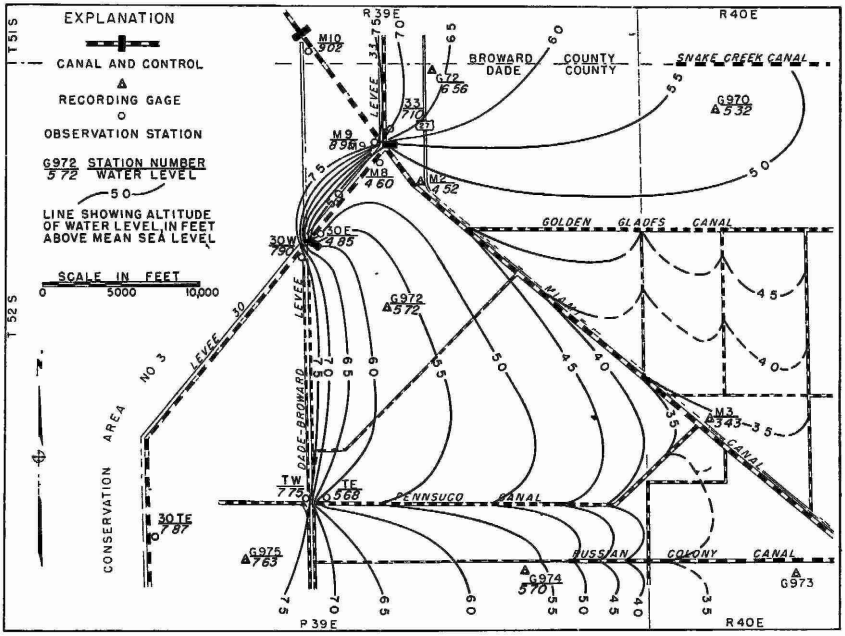



Figure 5. Contour map of the area investigated showing the altitude and configuration of the water level on January 21, 1960.

ordinarily it cannot be measured. Probably there is a very low water divide along the north-south reach of the canal from which there is a slight southward gradient toward the Tamiami Canal and northward gradient toward the Miami Canal.

The southward flow in the Levee 33 Canal is controlled at the Miami Canal. Operation of this control depends upon the ability to maintain water stages of 3.0 to 3.5 feet above msl at station M3, in the Miami Canal where it is joined by the Pennsuco Canal. When the stage is below this level, the control is opened and water is released into the Miami Canal to replenish supplies in the downstream reaches.

The southern part of the area is drained by the Pennsuco Canal, which extends westward to the Dade-Broward Levee, and by the Russian Colony Canal; however, effective drainage by the Russian Colony Canal extends only about 3½ miles west of its confluence with the Miami Canal. The westward extension of this canal is shallow and unimproved and therefore is effective only during flood periods. Partly effective drainage probably takes place along the shallow diagonal canal north of the Pennsuco Canal.

## HYDROLOGY

### WATER LEVELS AND MOVEMENT

Widespread fluctuations of water levels in Dade County are due to recharge by rainfall, to discharge into drainage canals and Biscayne Bay, and to evapotranspiration. Water levels in this part of northern Dade County are regulated also by the operation of the control in the Miami Canal at 36th Street, Miami, and by operation of controls in the Levee 30 and Levee 33 canals.

Figure 5 is a contour map of water levels in the area on January 21, 1960. The contours are based on water-level measurements obtained from observation points in canals that cut through the dense limestones and from observation wells. Water levels in the area were relatively high at that time and the control at 36th Street was open. The configuration shows that the drainage effect extended along the entire uncontrolled reach of the Miami Canal and its main tributaries and along the short reach of the Levee 30 Canal downstream from the Dade-Broward Levee. The pattern of the contours indicates the effectiveness of drainage by deep canals (Miami, Levee 30, and Pennsuco canals, and the lower reach of the Russian Colony Canal) and the lack of effective drainage by the shallow canals. High heads are maintained above the

control in the Levee 33 Canal and the control in the Levee 30 Canal; however, the close spacing of the contours at these controls indicates that there is considerable seepage through the aquifer around the controls.

It is important to compare the pattern of the contours east of the Dade-Broward Levee with that adjacent to Levee 30 between the Dade-Broward Levee and the Miami Canal. The distribution of the heads east of the Dade-Broward Levee indicates that the shallow diagonal canal and the Dade-Broward Levee borrow canals do not have an appreciable drainage effect. In contrast, the steep gradient on the northwest side of Levee 30 and the low gradient on the southeast side indicate that the Levee 30 Canal is intercepting nearly all the underflow along Levee 30.

High water levels prevailed throughout this part of northern Dade County during 1958-59 and the early part of 1960. On May 8, 1958, the 36th Street control was opened and drainage of the area proceeded until January 5, 1959, when the control was closed. The control again was opened on June 23, 1959, and remained opened throughout the first half of 1960. During the entire period the eastern part of Conservation Area No. 3 was inundated to depths ranging from 1 foot to more than 4 feet. The area between Levee 30 and the Dade-Broward Levee also was flooded during the period, but the depth of the water was less than that in Conservation Area No. 3. Flooding east of the Dade-Broward Levee probably was intermittent and corresponded with periods of heavy rainfall.

Figure 6 shows hydrographs of groups of observation stations in the area for 1959 and the early part of 1960. The locations of these stations are shown in figures 2 and 4. The hydrographs show the relation between canal stages and ponded-water stages in the area adjacent to the Levee 30 and 33 canals and the Miami Canal.

The hydrographs of stations 30TW and 30TE show the variation in head differential between the pool in Conservation Area No. 3 (30TW) and the stage in the Levee 30 Canal south of the Dade-Broward Levee. During dry periods, such as March-May 1959, the head differential across Levee 30 at this point was very small and a temporary reversal of gradient (east to west) occurred at the end of April and in early May. During the dry months, the eastward underflow of water from Conservation Area No. 3 probably was negligible as compared to that during periods of high water stages (July 1959-January 1960).

The persistent high head differential represented by the hydrographs of stations 30W and 30E show the effectiveness of the control in the Levee 30 Canal at the Dade-Broward Levee. This

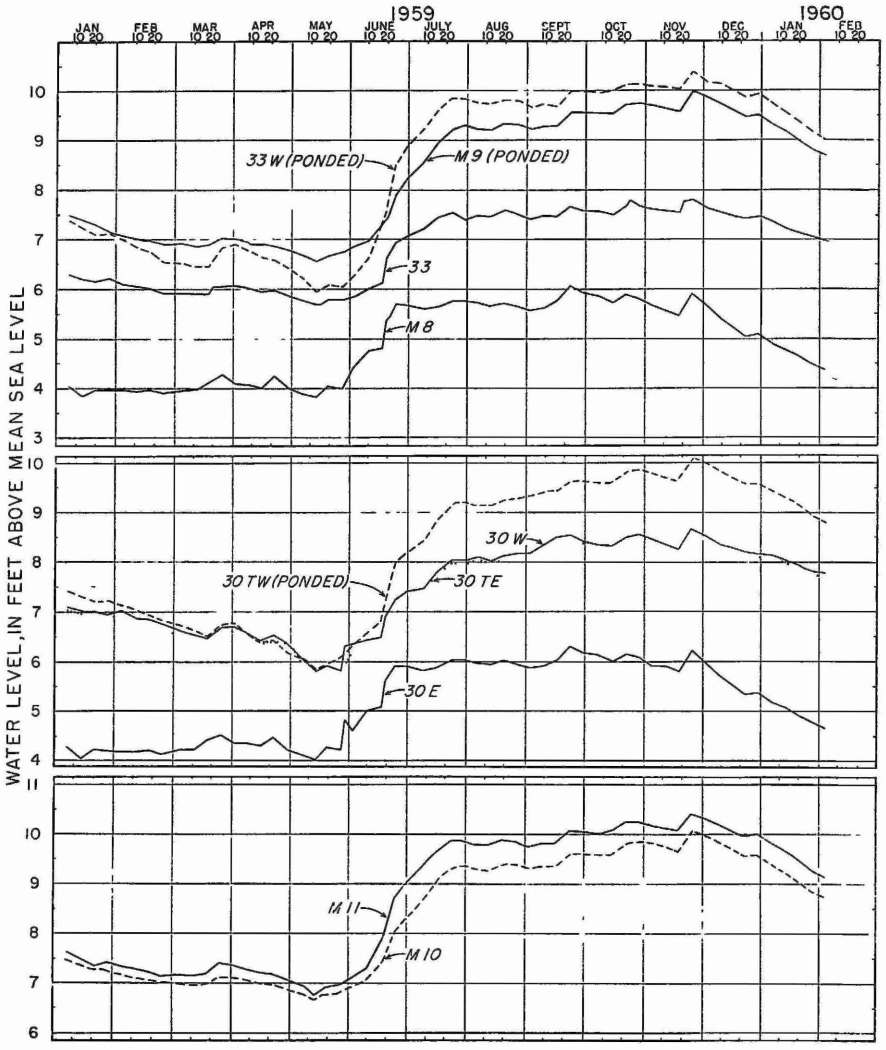



Figure 6. Hydrographs of groups of observation stations for 1959 and the early part of 1960.

differential in head suggests continuous leakage by underflow around the control which tends to maintain, in part, the flow in the lower reach of the Levee 30 Canal.

An outstanding feature of the hydrographs in figure 6 is the high head differential between stations M9 (ponded) and M8 (Levee 30 Canal); this differential ranged from 2.2 feet during a relatively dry period to more than 4.5 feet during high water

stages. Also shown in figure 6 are the heads maintained behind the control in the Levee 33 Canal (station 33) and the control in the Miami Canal at the Dade-Broward Levee (station M11). A comparison of the hydrographs of stations 30E and M8 shows the low gradient through the downstream reach of the Levee 30 Canal.

A continuous record of water-level fluctuations has been obtained from station G72 since 1940. A hydrograph of this station and the annual rainfall at the Miami Airport are shown in figure 7. The highest water level of record at station G72 was 9.4 feet above msl in October 1947, and the lowest of record was 1.1 feet above msl in June 1945. The hydrograph for the long period of record gives a comparison between water levels before the levee system and water-control practices were in effect (before 1952), and water levels after the water-control measures were in operation (1952-59). It can be seen that water levels during the drought period of 1955-56 did not decline as much as they did during the comparable drought periods of 1944-45 and 1950-52. Also, it is apparent that the unusually heavy rainfall of 1957-59 did not produce water levels as high as those during the wet years 1947-48. These facts demonstrate that the proper placement and operation of the existing controls in canals can decrease flood damage during rainy seasons and can maintain relatively high water levels during droughts.

## RELATION BETWEEN PONDED WATER AND GROUND WATER

Three test sites were established adjacent to the Levee 30 Canal downstream from the Dade-Broward Levee (fig. 4). The purpose

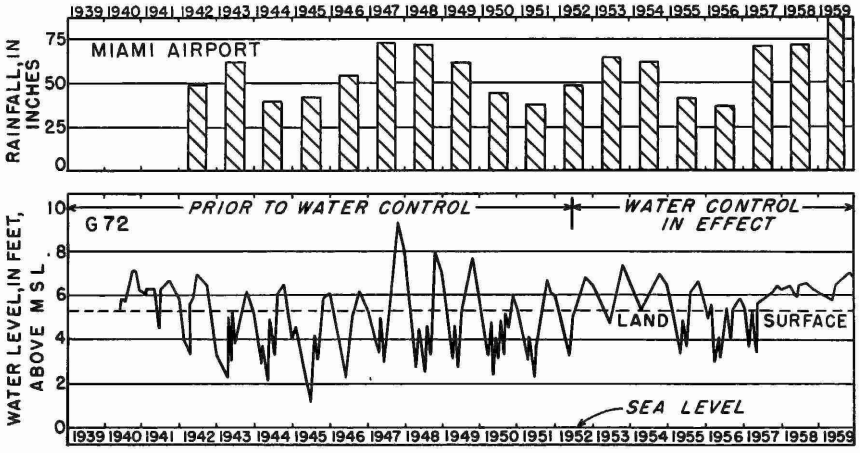



Figure 7. Hydrograph of station G72 for the period 1940-59 and the annual rainfall at the Miami Airport.

of studies at these sites was to determine the relation between the impounded water in Conservation Area No. 3 and ground water in the area. When this relationship is known, the amount of underflow occurring beneath Levee 30 can be calculated for the existing water-level conditions, and estimates of underflow can be made for various assumed water-level conditions.

Each of the test sites consists of a line or lines of test wells perpendicular to Levee 30; these sites are shown in the profile sections in figures 8, 9, and 10. The wells at site A-A′ (fig. 8) are the shallowest, but they penetrate the entire thickness of the dense limestones and terminate in the upper section of the highly permeable part of the aquifer. Site B-B′ (fig. 9) was drilled by the Corps of Engineers and consists of a line of nine wells extending northwestward from Levee 30 and one well on the berm between Levee 30 and the Levee 30 Canal. These wells range in depth from 17 to 40 feet.

The wells at site C-C′ (fig. 10) also were drilled by the Corps of Engineers and were used as observation wells during a pumping test to determine the permeability of the aquifer. The site consists of groups of multiple-depth wells extending northwestward into Conservation Area No. 3. Figure 10 shows the layout of the lines

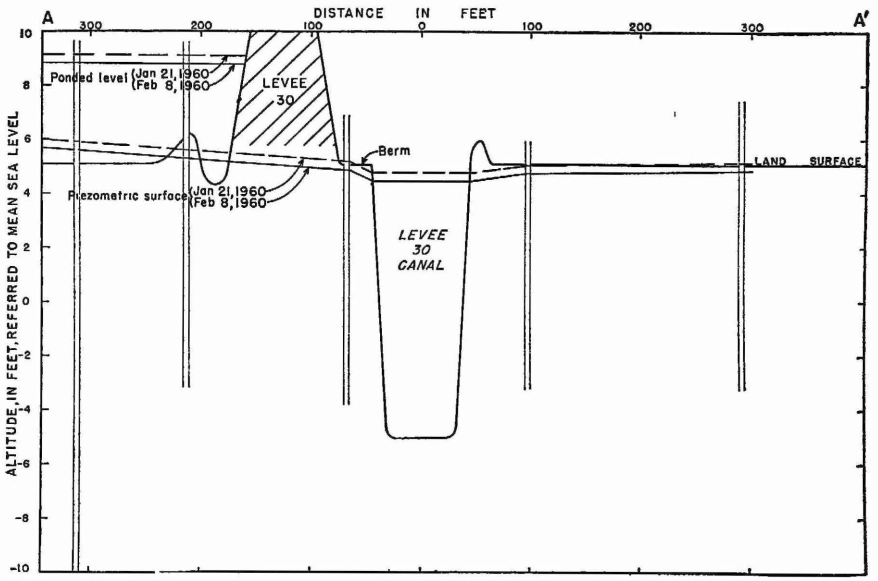



Figure 8. Profile showing the relation between the ponded water and the piezometric surface at site A-A′, January 21 and February 8, 1960.

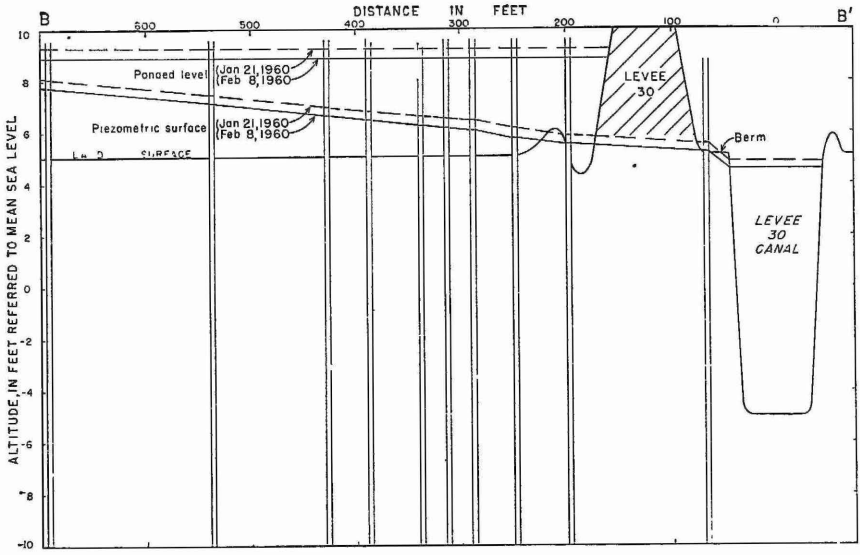



Figure 9. Profile showing the relation between the ponded water and the piezometric surface at site B-B', January 21 and February 8, 1960.

of wells with reference to Levee 30 and the Levee 30 Canal and indicates the altitude of the bottom of each well.

Water-level measurements were made at A-A' and B-B' on January 21 and February 8, 1960. Figures 8 and 9 show the water-level profiles at the two sites on the dates the measurements were made. At site A-A' (fig. 8) the gradient of the piezometric surface on the northwest side of the levee toward the Levee 30 Canal was 1.1 feet in 270 feet, or 0.0041 foot per foot. Within the 270-foot distance the head differential between the ponded water and the piezometric surface increased toward the levee and ranged from 3.1 feet at the end well of the profile to 3.6 feet at the levee. The gradient of the piezometric surface along the profile in figure 9 was 3.17 feet in 650 feet, or 0.049 foot per foot. The head differential between the ponded level and the piezometric surface ranged from 1.2 feet at the end well of the profile to 3.5 feet at the levee. The average gradient of the piezometric surface during the 3-week test period was 0.0045 foot per foot toward the Levee 30 Canal. The aquifer was being replenished by the downward leakage of ponded water, at a rate dependent upon the head differential, and no depletion of aquifer storage was occurring northwest of Levee 30.

Water-level measurements made during the drilling at site A-A'

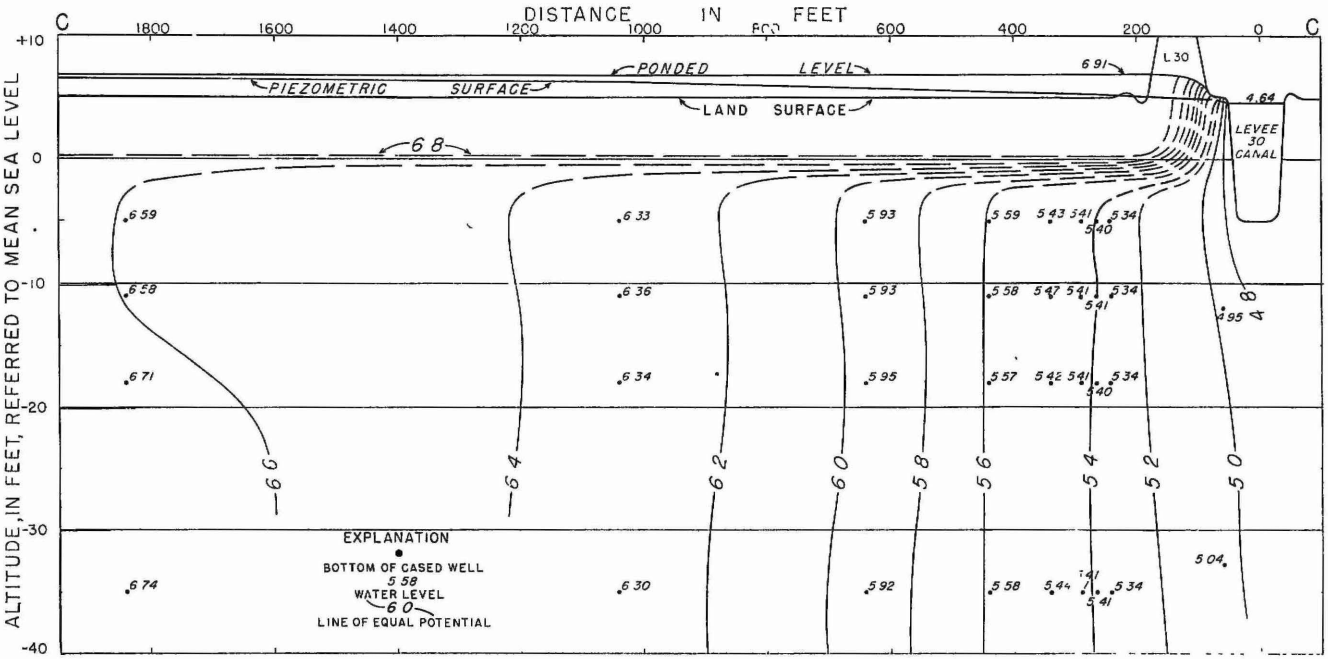



Figure 10. Profile along site C-C′ showing lines of equal potential, April 15, 1960.

showed that there was no head difference between the ponded level and the water level of wells bottomed in the Miami oolite. This indicates that the confining characteristics of the marl and muck blanket are of much less significance than those of the dense limestones.

No appreciable ponding occurred in the area immediately southeast of the Levee 30 Canal. Figure 8 shows also that the northwestward gradient of the piezometric surface on the southeast side toward the Levee 30 Canal was 0.40 foot in 250 feet, or 0.0016 foot per foot. Therefore, the quantity of inflow from the southeast was equivalent to approximately 40 percent of the inflow occurring from the northwest at the A-A′ site during the period January 21-February 8, 1960. The profile in figure 8 indicates a slight depletion of ground-water storage immediately southeast of the Levee 30 Canal. It is important to recognize that the contribution of water from the area southeast of the Levee 30 Canal to the canal was diminishing as shown on the contour map (fig. 5) by the decrease in ground-water gradient along the lower reach of the canal. It is estimated that the average gradient of the piezometric surface on the southeast side along the uncontrolled reach of the canal was 0.0010 foot per foot. Therefore, the total inflow to the Levee 30 Canal from the southeast was equivalent to approximately 20 to 25 percent of the total from the northwest.

### UNDERFLOW ALONG LEVEE 30

During periods when the control in the Levee 30 Canal is closed, discharge along the downstream reach of the Levee 30 Canal represents a composite of the following: (1) leakage by underflow around the control, (2) ground-water inflow from the thick permeable section of the aquifer, and (3) seepage of ponded water through the levee fill and through the thin layer of permeable Miami oolite that occurs between the fill and the dense limestone layers. At high water stages, such as those which prevailed from July through November 1959, the water level of the downstream reach of the canal was above the canal bank and sheet flow occurred toward the Miami Canal. Most of the discharge of the Levee 30 Canal was maintained by ground-water inflow from the northwest.

By January 21, 1960, water stages had lowered and discharge measurements were made at points 1 mile apart in the Levee 30 Canal ($Q_1$ and $Q_2$ in fig. 4), downstream from the control. Following is a tabulation of the discharge and water-level data obtained during the January 21 test:

A. Discharge measurements in Levee 30 Canal

| | | |
|---|---|---|
| At $Q_1$ | 76 cfs | (49 mgd) |
| At $Q_2$ | 252 cfs | (163 mgd) |
| $Q_2—Q_1$ | 176 cfs | (114 mgd) |
| Estimated seepage (visible) through the levee fill, across the berm to the canal ($Q_s$) | 10 cfs | (7 mgd) |
| Net pickup by ground-water inflow ($Q_g$) $Q_g=Q_2—Q_1—Q_s$ | 166 cfs | (107 mgd) |

B. Gradients (I) of piezometric surface toward Levee 30 Canal (fig. 8, 9).

| | |
|---|---|
| Northwest of canal | |
| A-A′ site | 0.0041 foot per foot |
| B-B′ site | .0049 foot per foot |
| Southeast of canal | |
| A-A′ site | .0016 foot per foot |
| Estimated average for area southeast of canal | .0010 foot per foot |

By Darcy's law the rate of flow of a fluid through a porous medium is directly proportional to the hydraulic gradient and can be written as follows (Wenzel, 1942, p. 3-7):

$$Q=PIA$$

where Q is the discharge rate, P is the coefficient of permeability of the material being tested, I is the hydraulic gradient, and A is the area of the cross section through which the fluid moves. If it is assumed that the permeable section of the aquifer beneath the dense limestone layers is isotropic and that underflow through this section is laminar, then the quantity of ground water discharging into the Levee 30 Canal is directly proportional to the gradient of the piezometric surface; therefore, about 80 percent of $Q_g$ or 86 mgd, represents underflow from the northwest along the 1-mile reach of the canal. (See tabulation above.)

In order to make computations that involve the entire thickness of an aquifer as a unit, Darcy's law may be written:

$$Q=TIL$$

in which Q is the quantity of water, in gpd (gallons per day), T is the coefficient of transmissibility, in gallons per day, for each vertical strip of the aquifer 1 foot wide; I is the hydraulic gradient,

in feet per foot; and L is the length of section, in feet, through which the quantity (Q) flows. By substituting in the above equation the hydrologic data obtained during the January 21 test, a determination of the coefficient of transmissibility of the aquifer can be made as follows:

$$Q = TIL$$

$$T \text{ (gpd per foot)} = \frac{Q \text{ (gpd)}}{I \text{ (foot per foot)} \times L \text{ (feet)}}$$

$$T = \frac{86{,}000{,}000}{0.0045 \times 5{,}280}$$

$$T = 3{,}600{,}000 \text{ gpd per foot, or } 5.6 \text{ square feet per second}$$

This computed coefficient of transmissibility compares very closely with the value of 5.76 square feet per second determined by the Corps of Engineers for the highly permeable part of the aquifer adjacent to Levee 30 (U.S. Army Corps of Engineers, 1953, p. D-6).

Dry weather prevailed during the spring of 1960, and by the middle of April the water stage in Conservation Area No. 3 had declined so that the multiple-depth wells along site C-C′ were accessible. On April 19, 1960, water-level measurements were made in all wells in this test site. The profile in figure 10 shows the relation between the pool in Conservation Area No. 3 and the piezometric surface on that day and shows also, by equipotential lines, the approximate head distribution in the aquifer along the profile. The gradient of the piezometric surface within 1,000 feet of the Levee 30 Canal was 0.0017 foot per foot, but for the remaining 800 feet of the section the gradient decreased to 0.0011 foot per foot. The head differential between the ponded water and the piezometric surface ranged from 0.32 foot at the northwestern end of the profile to 1.57 feet near the toe of the levee.

The equipotential lines, shown in figure 10, indicate that flow through the highly permeable part of the aquifer (depths more than 5.0 feet below msl) toward the Levee 30 Canal is virtually horizontal, except for the section adjacent to and beneath the canal where the flow direction has an upward component. The distribution and pattern of the lines suggest that about 75 percent of the loss in head occurs within 1,000 feet of the levee. The horizontality and the close spacing of the lines at depths between 0.5 foot above and 3.0 feet below msl indicate a large vertical head loss caused by

vertical flow through the dense limestone of low permeability at that interval (fig. 3). The flow through the shallow materials immediately beneath the levee is virtually horizontal and probably occurs chiefly through a thin layer of the permeable Miami oolite beneath the fill.

Detailed information on head distribution through a part of the aquifer, as shown in figure 10, makes it possible to estimate the amount of surface water that was seeping downward through the confining layers to the thick permeable part of the aquifer. The amount of ground water moving toward the canal in 1 day, across a section of the aquifer 1 mile long at a distance of 800 feet from the edge of the canal, may be computed as follows:

$$Q=TIL$$

$$Q=3{,}600{,}000 \times \frac{0.4 \text{ foot}}{400 \text{ feet}} \times 5{,}280 \text{ feet}$$

$Q=19$ mgd per mile, or 29 cfs per mile

A similar computation for a distance 400 feet from the canal is as follows:

$$Q=3{,}600{,}000 \times \frac{0.59 \text{ foot}}{400 \text{ feet}} \times 5{,}280 \text{ feet}$$

$Q=28$ mgd per mile, or 43 cfs per mile.

The 9-mgd difference in flow represents approximately the amount of surface water picked up by leakage through the confining beds to the permeable flow section within the rectangular area 1 mile long between 400 and 800 feet from the levee.

Inasmuch as the approximate amount of downward infiltration in a given area has been determined, a computation of the coefficient of vertical permeability of the confining layers can be made. The coefficient of permeability is defined as the rate of flow through a cross section of 1 square foot, under a gradient of 1 foot per foot. The computation of the coefficient of vertical permeability of the dense limestone is as follows:

| | |
|---|---|
| Rectangular area used in computation | 5,280 feet x 400 feet, or 2.1 million square feet |
| Downward leakage | 9 mgd, or 4.3 gpd per square foot |

Altitude of piezometric surface 600 feet from levee ..... 5.93 feet above msl

Altitude of ponded level ..... 6.91 feet above msl

Head differential 600 feet from levee (assumed average for area 400 to 800 feet from levee) ..... 0.98 foot

Thickness of confining layers ..... 3.0 feet

Gradient across confining layers ..... 0.33 foot per foot

$$P = \frac{Q}{IA}$$

$$P = \frac{4.3 \text{ gpd}}{0.33 \text{ foot per foot} \times 1 \text{ square foot}}$$

$P =$ 13 gpd square foot, or $2.0 \times 10^{-5}$ foot per second

A proposed method of flood control in Area B is to reduce ground-water storage by means of a network of canals and a series of large pumping stations. The pumps would be placed at selected locations along Levees 30 and 31 and would pump water from the interconnected canal system of Area B westward into Conservation Area No. 3. Initially, it was proposed that the water stage in Area B be maintained at mean sea level in order to give maximum protection during all major storms. It is probable that water levels along the levee side of Area B will be lowered temporarily below mean sea level in order to provide adequate gradients toward the pumping stations.

Reducing the water stage in Area B would result in gradients across Levee 30 that would greatly exceed those shown in the profiles of figure 9. There might be times when the head differential between the pool in Conservation Area No. 3 and the stage in the Levee 30 Canal would be as much as 10 feet. It is extremely important, therefore, to determine the amount of water that would move from Conservation Area No. 3 to the adjacent canals in order that adequate pumping stations be provided.

To make a determination of the anticipated underseepage it is necessary to determine the relation between the head across the levee and the head differential at the toe of the levee at different water stages. Figure 11 is a graph showing this relationship; and the plotted points are based on the water-level profiles of figures

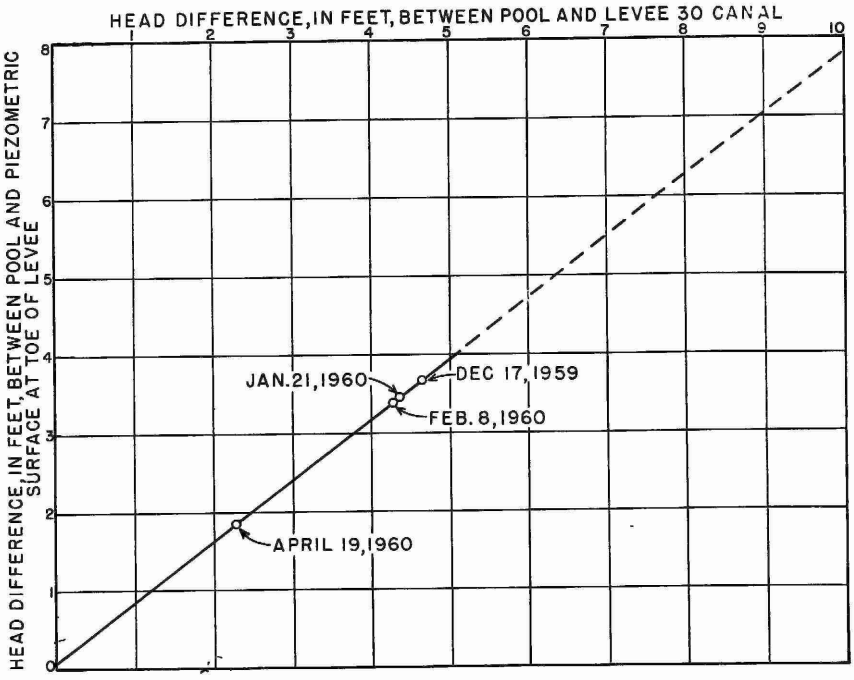



Figure 11. Graph showing the relation between the head difference across Levee 30 and the head difference between the pool and the piezometric surface at the toe of the levee.

9 and 10 and on a series of measurements made on December 17, 1959. The projection of the graph indicates that, if a 10-foot head were held across the levee, the head difference between the pool and the piezometric surface at the toe of the levee would be 7.8 feet; thus the gradient of the piezometric surface across the 150-foot width of the levee would be 2.2 feet.

Following is a computation of the amount of underflow that would be intercepted along a 1-mile reach of the canal ($Q_1$ to $Q_2$ in fig. 4) when the head differential across the levee was 10 feet:

$$Q=TIL$$

$$Q=3{,}600{,}000 \text{ gpd per foot} \times \frac{2.2 \text{ feet}}{150 \text{ feet}} \times 5{,}280 \text{ feet}$$

$$Q=279 \text{ mgd per mile, or } 432 \text{ cfs per mile}$$

In order to determine the total quantity of water that would be intercepted by the Levee 30 Canal along the 1-mile reach,

consideration must be given to the seepage that would occur through the levee materials and through the thin permeable layer of Miami oolite that underlies the levee fill. This approximate determination is shown by the following tabulation:

| | |
|---|---|
| Composite estimate of coefficient of permeability of levee fill and Miami oolite | 20,000 gpd per square foot |
| Length of flow section | 5,280 feet |
| Thickness of flow section (10-foot head differential) | 10 feet |

$Q = PIA$

$$Q = 20{,}000 \text{ gpd per square foot} \times \frac{10 \text{ feet}}{150 \text{ feet}} \times 5{,}280 \text{ feet} \times 10 \text{ feet}$$

$Q = 70$ mgd per mile, or 108 cfs per mile

The estimated coefficient of permeability used in the above computation probably is high and compares with a well sorted gravel that contains only small quantities of fine material (Wenzel, 1942, p. 13). However, the estimate was made in consideration of the probable high permeability of the layer of Miami oolite through which much of the direct seepage may occur.

The total quantity of water that would be intercepted along the 1-mile reach of Levee 30 Canal when the head difference across the levee was 10 feet is computed to be 349 mgd, or 540 cfs. These results were obtained by assuming that water movement beneath Levee 30 occurs by laminar flow. If there is turbulence through the large openings in the aquifer beneath the levee, the underflow would be less. For laminar flow the underflow to the canal would be directly proportional to the head difference across the levee, and for turbulent flow the underflow would be directly proportional to the square root of the head difference; in the transitional zone underflow would vary exponentially between the first and one-half powers of the head difference.

## CONCLUSIONS

Water-level measurements and geologic data obtained from test wells indicate that the upper part of the Biscayne aquifer in the vicinity of Levee 30 in northern Dade County contains dense layers of limestone of relatively low permeability that retard downward

infiltration to the thick permeable parts of the aquifer. The coefficient of transmissibility of 3,600,000 gpd per foot, or 5.6 square feet per second, as determined from water-level profiles taken normal to Levee 30 and from discharge measurements made in the Levee 30 Canal, compares closely with the coefficient determined by the Corps of Engineers by pumping-test methods. The computed coefficient of permeability of 13 gpd per square foot, or $2.0 \times 10^{-5}$ foot per second, for the thin dense layers indicates that these layers form a fairly effective confining unit which separates the ponded water in Conservation Area No. 3 from the ground water. Geologic information obtained from the surrounding areas suggests that the thin, dense limestones probably are widespread, and therefore that the blanketing effect occurs throughout a large area.

Conservation Area No. 3 generally is flooded for several months of each year, the result being high head differentials across Levee 30. When the plan for the development of Area B is in effect, there may be times when the differential of head across the levee will be as much as 10 feet. When this condition occurs, it is estimated that the inflow to the Levee 30 Canal from Conservation Area No. 3 will be about 350 mgd per mile, or 540 cfs per mile. This estimate was made by computing separately (1) the underflow through the main permeable section at the aquifer and (2) the seepage through the levee fill and the thin layer of permeable limestone that immediately underlies the levee fill.

When the road construction is completed in the area it would be desirable to obtain additional data to define more accurately the relation between head difference across the levee and discharge in the Levee 30 Canal.

The coefficient of transmissibility of the aquifer, the coefficient of vertical permeability of the confining layers, and the estimated rates of inflow from Conservation Area No. 3, as determined from this study, may be valid only for the north end of Levee 30. It is probable that hydrologic conditions vary along the entire length of Levee 30, and therefore similar studies will be required for the southern reaches in order to determine total leakage along the levee system.

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STATE OF FLORIDA
STATE BOARD OF CONSERVATION
DIVISION OF GEOLOGY

FLORIDA GEOLOGICAL SURVEY
Robert O. Vernon, Director

REPORT OF INVESTIGATIONS NO. 24

PART II

# HYDROLOGIC STUDIES IN THE SNAPPER CREEK CANAL AREA, DADE COUNTY, FLORIDA

By
C. B. SHERWOOD and S. D. LEACH
U. S. GEOLOGICAL SURVEY

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

TALLAHASSEE
1962

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## LETTER OF TRANSMITTAL




# *Florida Geological Survey*

*Tallahassee*

December 15, 1961

Honorable Farris Bryant, *Chairman*
Florida State Board of Conservation
Tallahassee, Florida

Dear Governor Bryant:

I am pleased to forward the second of three papers to be published as Report of Investigations No. 24, Part II, entitled "Hydrologic Studies in the Snapper Creek Canal Area, Dade County, Florida."

These studies are contributing greatly to the basic data which leads to a more complete understanding of the hydrology of the area.

Respectfully yours,
Robert O. Vernon, *Director*

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# HYDROLOGIC STUDIES IN THE SNAPPER CREEK CANAL AREA, DADE COUNTY, FLORIDA

By

C. B. SHERWOOD and S. D. LEACH

## ABSTRACT

The Snapper Creek Canal drains the southernmost part of the Greater Miami area and a part of the lower Everglades in Dade County, Florida. The canal and a control structure near Biscayne Bay are part of a water-control system designed to provide maximum drainage during flood periods and to maintain water levels high enough to retard salt-water encroachment during dry periods.

The area is underlain by highly permeable limestone and sand of the Biscayne aquifer. Because of the high permeability, there is excellent hydraulic interconnection between the canal and the aquifer, and inflow to or losses from the canal occur rapidly in response to changes in canal levels. When the control structure is closed, canal levels along the lower reach are generally higher than ground-water levels and appreciable losses from the canal occur by underflow toward the bay. Except under very low water conditions, these losses are balanced by ground-water inflow from the western part of the coastal ridge. When extreme drought conditions prevail, it is estimated that about 50 cfs (cubic feet per second) will be needed in the canal to balance the losses that will occur if a water level of 2.75 feet above msl (mean sea level) is maintained in the canal at the control structure. During prolonged droughts a large part of the water withdrawn by the nearby city of Miami well fields will be derived from infiltration from the canal. This loss could amount to more than twice as much as the natural losses from the system.

## INTRODUCTION

The development of the Greater Miami area has required the construction of an extensive system of water-control facilities to reduce flooding and to prevent further sea-water encroachment into the aquifer. The continued rapid growth of the population in the area has indicated an urgent need for a comprehensive plan

to extend the existing water-control system to include a large lowland area of anticipated urbanization west of the city, hereafter referred to as Area B. Figure 1 shows Area B and the existing major water-control facilities in the Miami area. Major development in Area B is not now practicable because of perennially high ground-water levels and frequent flooding. However, any major water-control plan for the area must be designed not only to prevent flooding within the area but also to maintain the existing carefully

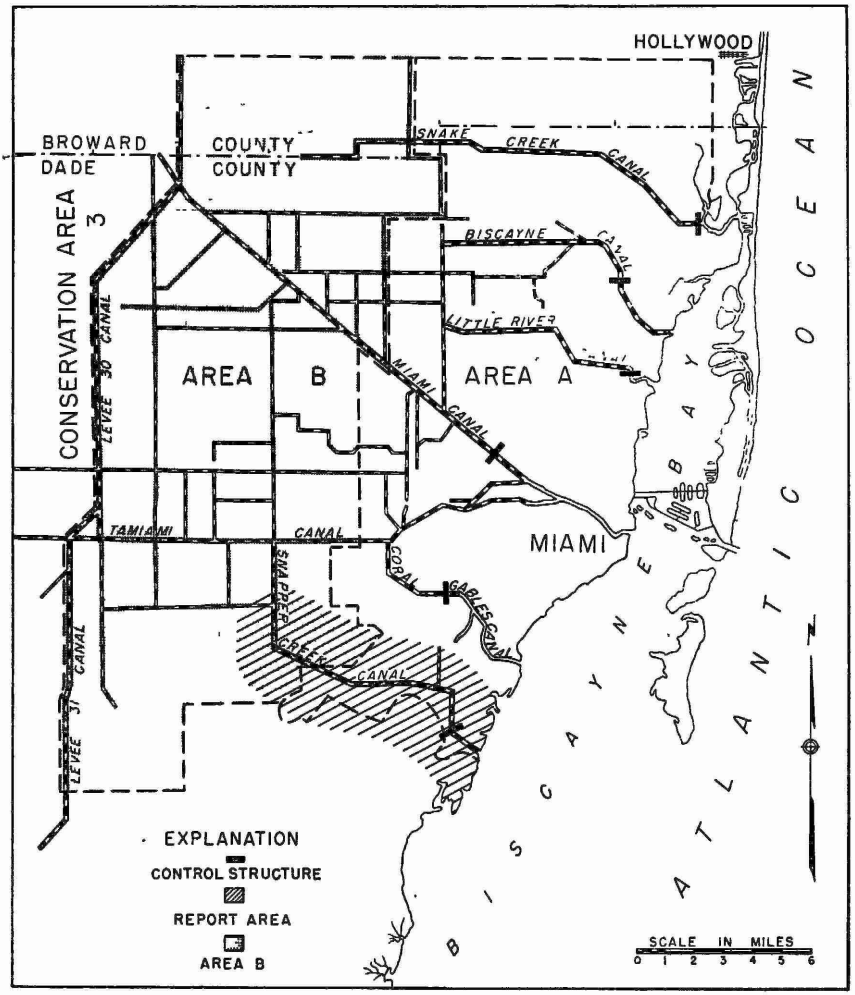



Figure 1. The Greater Miami area showing selected hydrologic features, drainage area boundaries, and the area investigated.

controlled ground-water conditions in the Miami area and to provide for maximum future water use.

The hydrologic study of the Snapper Creek Canal area is one of a series of canal area studies undertaken by the U. S. Geological Survey, in cooperation with the Central and Southern Florida Flood Control District, for the purpose of furnishing hydrologic data that will be useful in formulating an overall water-control plan.

The investigation was made in 1959-60 under the general supervision of P. E. LaMoreaux, chief, Ground Water Branch, and E. L. Hendricks, chief, Surface Water Branch, U. S. Geological Survey. It was under the immediate supervision of Howard Klein, geologist in charge, Ground Water Branch, and J. H. Hartwell, engineer in charge, Surface Water Branch, Miami, Florida.

## PURPOSE AND SCOPE

The main purpose of the series of investigations of the hydrology of the canal systems in eastern Dade County is to determine the following:

(1) The discharge rates at selected points in the drainage canals.
(2) The discharge from ground-water storage to the canal systems.
(3) The effect of water control in Area B on salt-water encroachment in coastal areas.

The specific purpose of this study was to obtain a detailed description of the hydrologic environment in the Snapper Creek Canal area and to provide quantitative definition for the following hydrologic factors:

1. Coefficients of transmissibility and storage of the aquifer.
2. Relation between ground-water movement and canal flow in different reaches of the canal.
3. The quantity of water needed to maintain a given head in the canal for the control of salt-water encroachment.

The feasibility of this type methodology for studies of other canal areas in Dade County may be determined by a review of the problems experienced in this study.

## ACKNOWLEDGMENT

Appreciation is expressed for the wholehearted cooperation of the personnel of the Dade County Public Works Department during this study.

## PREVIOUS INVESTIGATIONS

A brief paper by Parker (1951) discusses the geologic and hydrologic factors in the perennial yield of the Biscayne aquifer in southeastern Florida and a later report by Parker and others (1955) presents a comprehensive account of the geology and water resources of southeastern Florida. Schroeder and others (1958) summarize the hydrology and geology of the Biscayne aquifer and evaluate the perennial yield of the aquifer from data obtained since 1950. Stallman (1956) gives the results of electrical analog studies of the hydrology of intercanal areas of Dade County.

## AREA OF INVESTIGATION

The investigation was made in an area about 4 miles wide along the reach of the Snapper Creek Canal, which extends about 10 miles inland from Biscayne Bay to the approximate boundary between the coastal ridge and the lower Everglades (fig. 1). This 40 square mile area is the southernmost part of the highly urbanized Greater Miami area.

## CLIMATE

The climate in the Miami area is subtropical. Rainfall averages approximately 60 inches per year, about 75 percent of which occurs during June through October; this 5-month period includes both the normal rainy season and the hurricane season. The average annual temperature is approximately 75°F.

## TOPOGRAPHY AND DRAINAGE

The generally flat topography of the Snapper Creek area is broken by several natural drainageways or transverse glades that cut through the coastal ridge and by isolated limestone ridges upon the coastal ridge. The configuration of the coastal ridge and the natural drainageways is shown in figure 2. Throughout most of its extent the Snapper Creek Canal follows a natural drainageway, and in recent years its channel was widened and deepened.

The altitude of the land surface ranges from 5 to 7 feet above msl in the eastern edge of the Everglades and along the transverse glades, and from 9 to 21 feet above msl on the coastal ridge.

Drainage from the area is through the Snapper Creek Canal, which flows generally eastward to Biscayne Bay. Canal flow is maintained chiefly by ground-water inflow, but during periods of

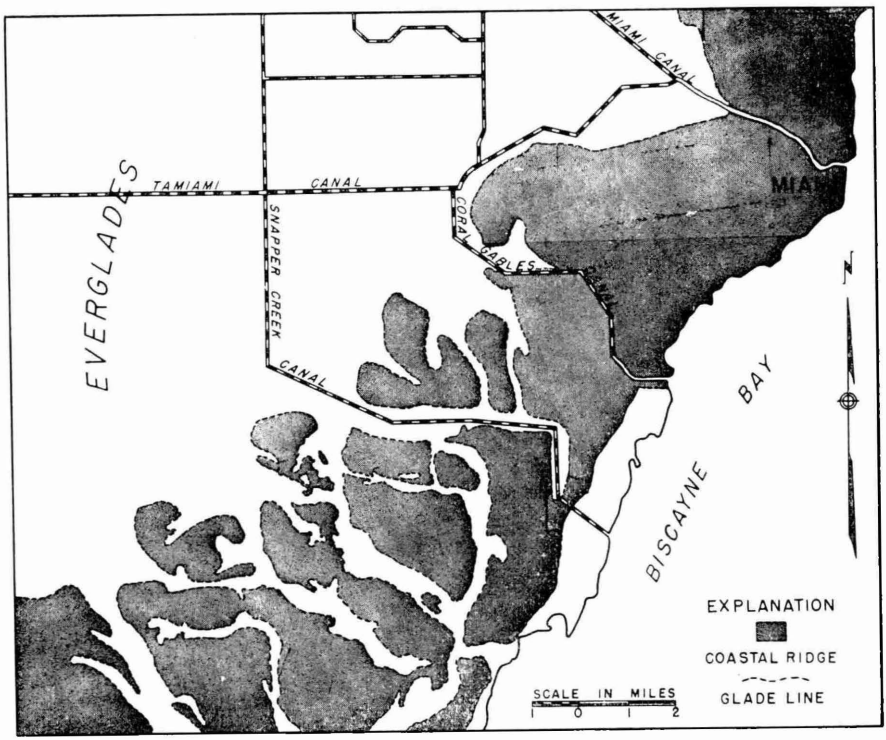



Figure 2. The Greater Miami area showing the configuration of the natural drainageways and the coastal ridge.

heavy rainfall the canal receives considerable runoff directly from the natural drainage channels and from the eastern part of the Everglades.

As shown in figure 1, the Snapper Creek Canal connects with the Tamiami Canal and several secondary drainage canals in Area B; thus, it not only acts as the primary drainage channel for the southernmost part of Greater Miami, but also carries a large part of the drainage from Area B. The Snapper Creek Canal intercepts a secondary drainage canal, Ludlum Drain, at a point about 2 miles inland from Biscayne Bay (fig. 3). Ludlum Drain follows the southern part of a natural drainageway that extends northward toward the Coral Gables Canal.

The flow in the Snapper Creek Canal is regulated by the operation of a control structure (submerged sluice gate) about 1¼ miles upstream from Biscayne Bay. This control is regulated so that water can be discharged to Biscayne Bay to reduce flooding in low

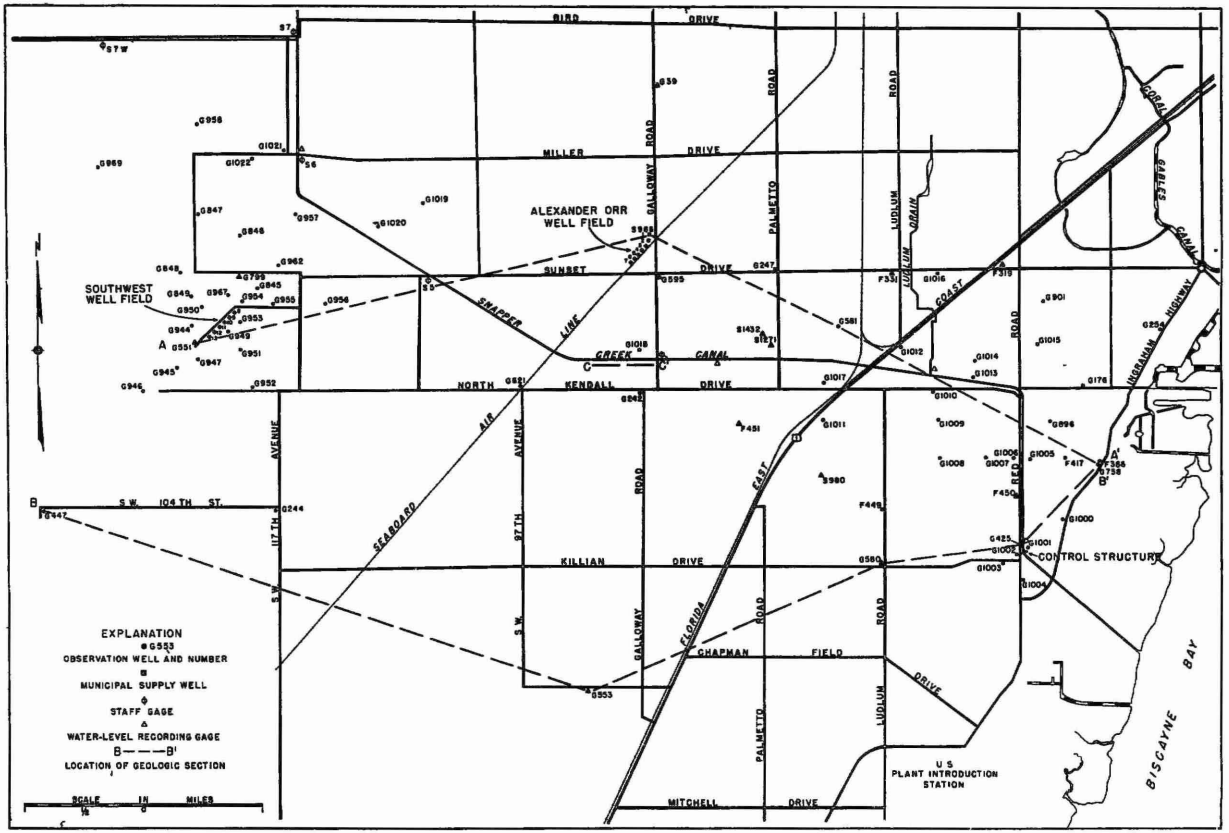



Figure 3. The Snapper Creek Canal area showing the location of wells and geologic sections.

areas during periods of heavy rainfall. Before the rainy season ground-water levels in the aquifer are lowered in order to provide additional ground-water storage and thus lower flood peaks. The maximum discharge recorded, since the canal was recently improved, was 2,010 cfs at the control after the hurricane of September 9-10, 1960. During dry periods the control is closed to maintain water levels high enough to retard salt-water encroachment into the aquifer and to prevent direct movement of salt water up the canal channel.

## GEOLOGY

The Snapper Creek Canal area is underlain by the Biscayne aquifer, composed of highly permeable limestone, sandstone, and sand. Within the area the aquifer ranges in thickness from about 85 feet in the western part, to about 120 feet at the coast. Farther west, along the western edge of Area B, the aquifer is about 50 feet thick. The surface materials of the area are permeable limestone and sand, but the natural drainageways are bottomed by several feet of marl or silt of relatively low permeability. Figures 4 and 5 show geologic sections of the area from west to east. The locations of the sections and test wells are shown in figure 3.

A section of the materials penetrated by a line of test borings along the canal from Galloway Road to a point 3,000 feet west is shown in figure 6. The section indicates that a large percentage of the shallow materials is composed of sand and marl, which is of considerably lower permeability than the limestone. The section also indicates some nonuniformity in the shallow materials. The unconsolidated shallow materials persist chiefly within the natural canal drainageway.

The Biscayne aquifer is the source of water for the Southwest and Alexander Orr well fields of the city of Miami (fig. 3). Supply wells in these fields tap highly permeable limestones in the lower part of the aquifer. Pumping facilities in the Southwest well field presently can withdraw 40 mgd (million gallons per day), but additions now being made will increase the total capacity to about 80 mgd. The Alexander Orr well field is designed to withdraw about 50 mgd. Both well fields probably receive recharge from the Snapper Creek Canal during periods of low ground-water levels.

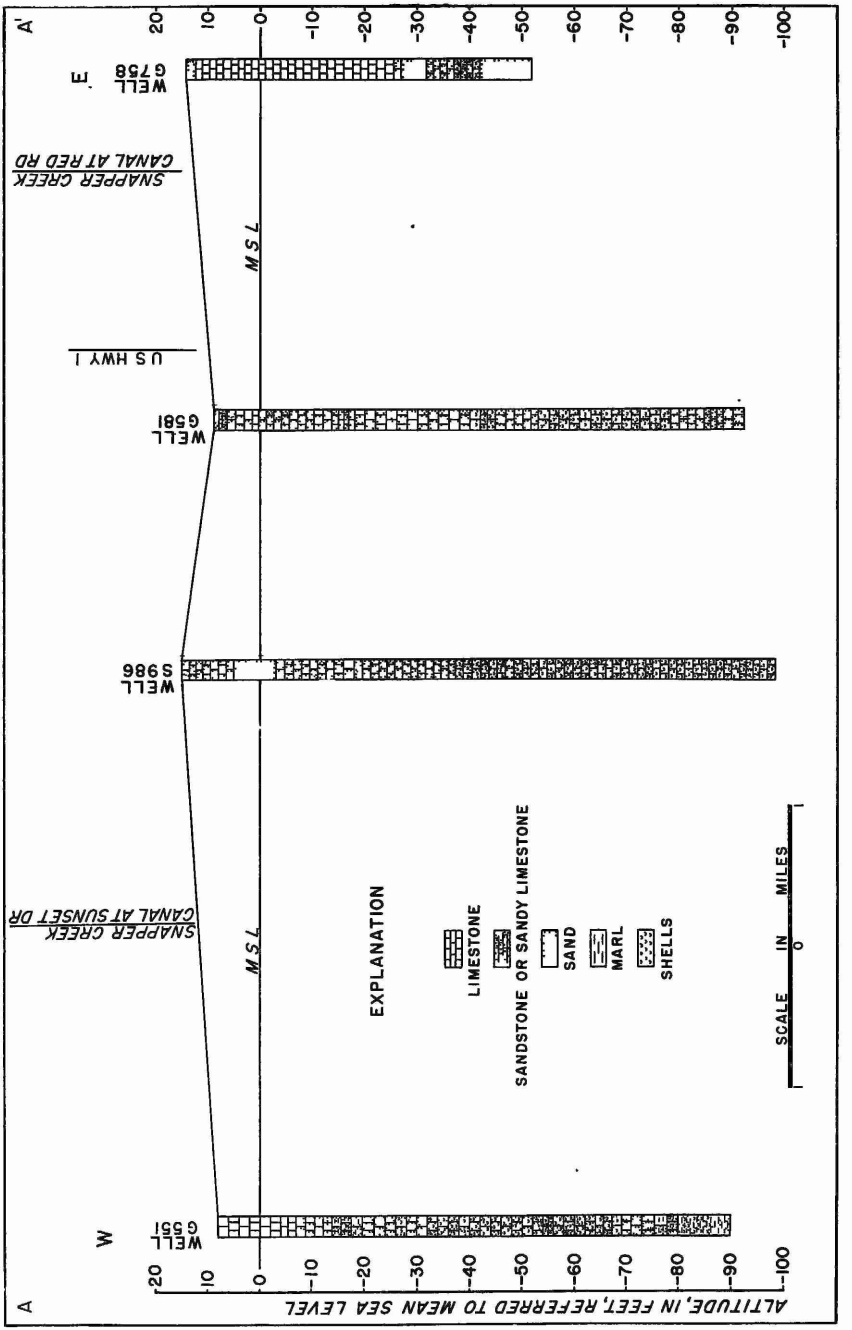



Figure 4. Geologic section along line A-A'.

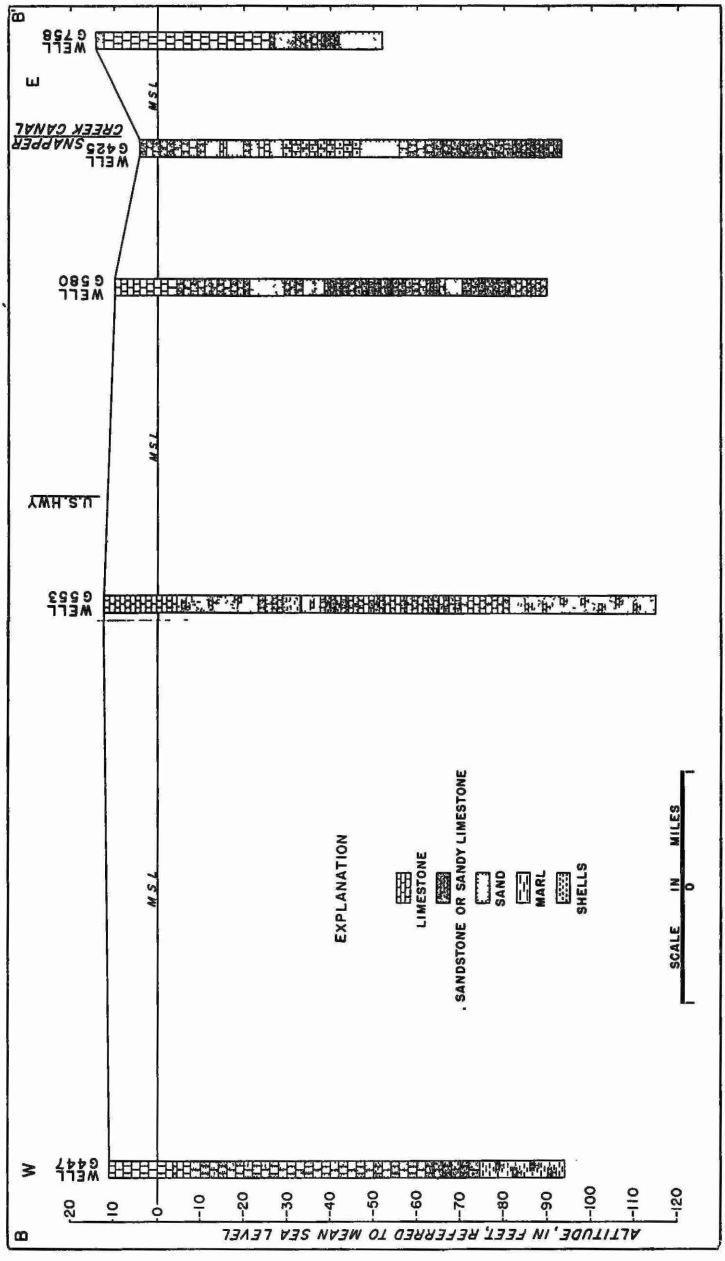



Figure 5. Geologic section along line B-B'.

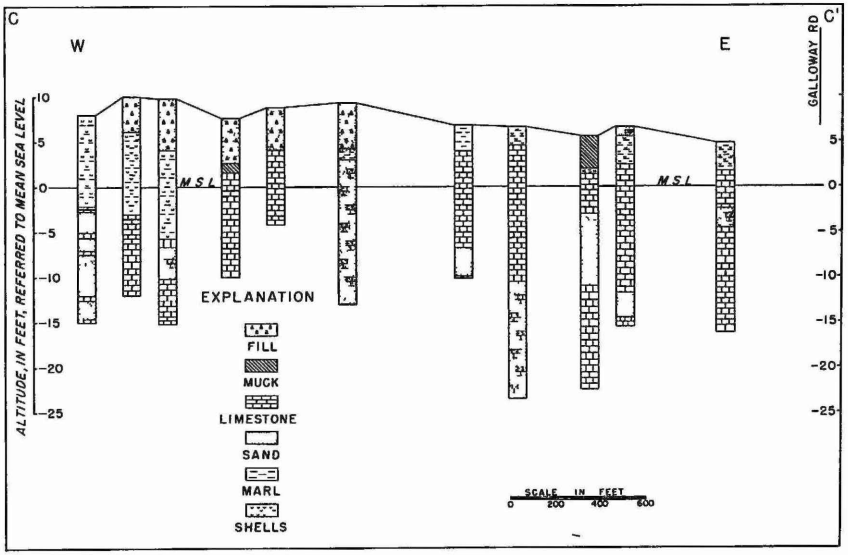



Figure 6. Geologic section along line C-C'.

## METHOD OF INVESTIGATION

Hydrologic tests in the Snapper Creek Canal area were made by observing the effects of varying the amount of canal discharge through the control structure. The control was opened and closed at different times during June and July 1959 to cause abrupt changes in area-wide surface-water and ground-water conditions. Observations were made of the changes in water levels and flow that resulted from changes in canal discharge at the control structure. Data collected during previous investigations and the continuing observational program were integrated with the test data.

### COLLECTION OF DATA

The continuous observation program in the area includes 37 observation wells, 7 wells equipped with recording gages, and recording stations in the canal at Miller Drive and at the control structure (fig. 3). The installation at the control structure includes a recording deflection meter from which a continuous record of the canal flow can be obtained. Records from these installations provide data throughout the drainage area. In addition, 23 shallow

observation wells were drilled for the purpose of obtaining water-level measurements, and water-level recording gages were installed on six privately owned wells and in the canal at Ludlum Drain and half a mile east of Galloway Road. All observation points were referred to mean sea level datum by spirit level. The locations of all measurement sites are shown in figure 3. Figure 7 shows hydrographs of water levels at selected wells and canal stations, discharge at the control structure, and rainfall at the U. S. Plant Introduction Station during part of 1959. The Plant Introduction Station is about 1½ miles south of the control structure (fig. 3).

The amount that the control gates could be manipulated during the period of the tests was greatly influenced by the high-water stages during May through July 1959 that resulted from extremely heavy rainfall (fig. 7). The control structure remained partly or wholly open throughout most of the spring and early summer to reduce flooding in low areas. It was necessary, therefore, that any closing of the control gates be for only short periods during the tests. Under existing conditions the control normally would remain open, in order to lower ground-water levels in preparation for the rains of September and October.

During the period June 24-30 the methods and facilities were tested to determine the magnitude of the fluctuations of stage and discharge to be expected, and the general adequacy of the observational network. Figure 8 shows the fluctuation of the water surface at different points along the canal and in selected wells near the canal during the period June 24-July 2. Also shown is discharge at the control structure during the period. The changes in discharge at two additional stations on the canal during the tide cycle and at the time of closing and opening the control are given in the following tabulation:

| Red Road | | Palmetto Road | |
|---|---|---|---|
| Time | Discharge (cfs) | Time | Discharge (cfs) |
| | June 25 | | |
| 8:20 a.m. | 1,000 | 8:35 a.m. | 891 |
| 10:30 a.m. | 806 | 10:30 a.m. | 803 |
| 1:00 p.m. | 666 | 1:00 p.m. | 771 |
| | June 29 | | |
| 11:50 a.m. | 828 | 11:45 a.m. | 734 |
| 2:10 p.m. | 587 | 2:10 p.m. | 666 |
| 4:50 p.m. | 508 | 4:50 p.m. | 560 |
| | June 30 | | |
| | | 5:20 p.m. | 328 |

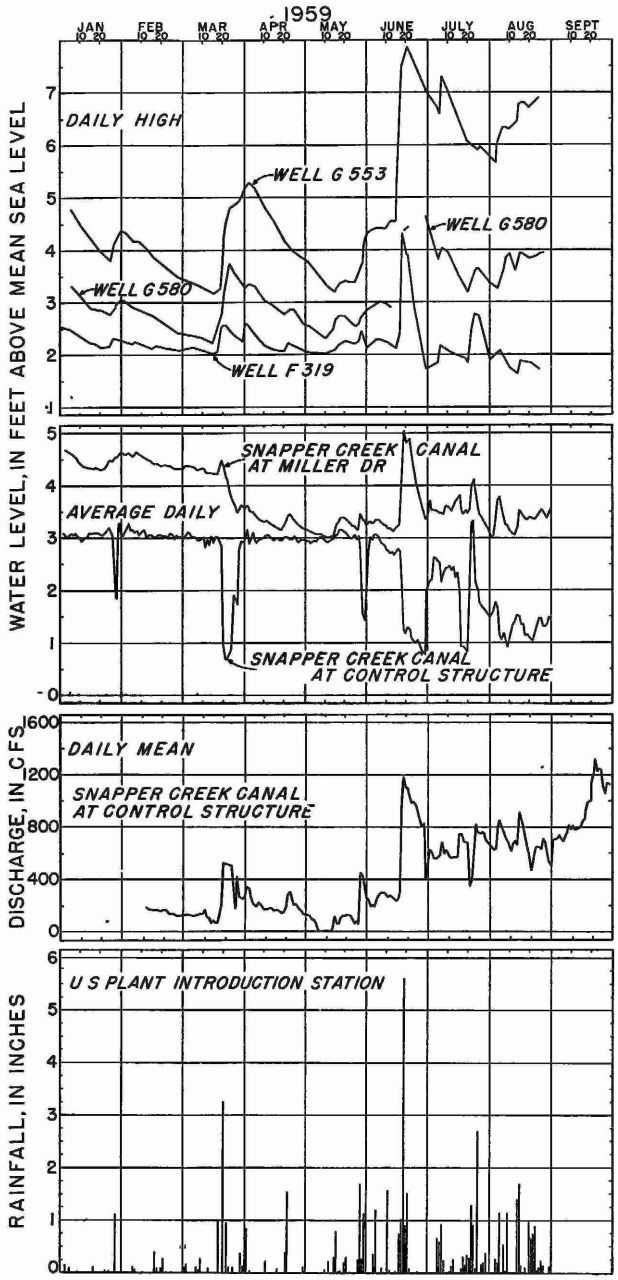



Figure 7. Hydrographs of selected wells and canal stations, discharge at the control structure, and rainfall in the Snapper Creek area during part of 1959.

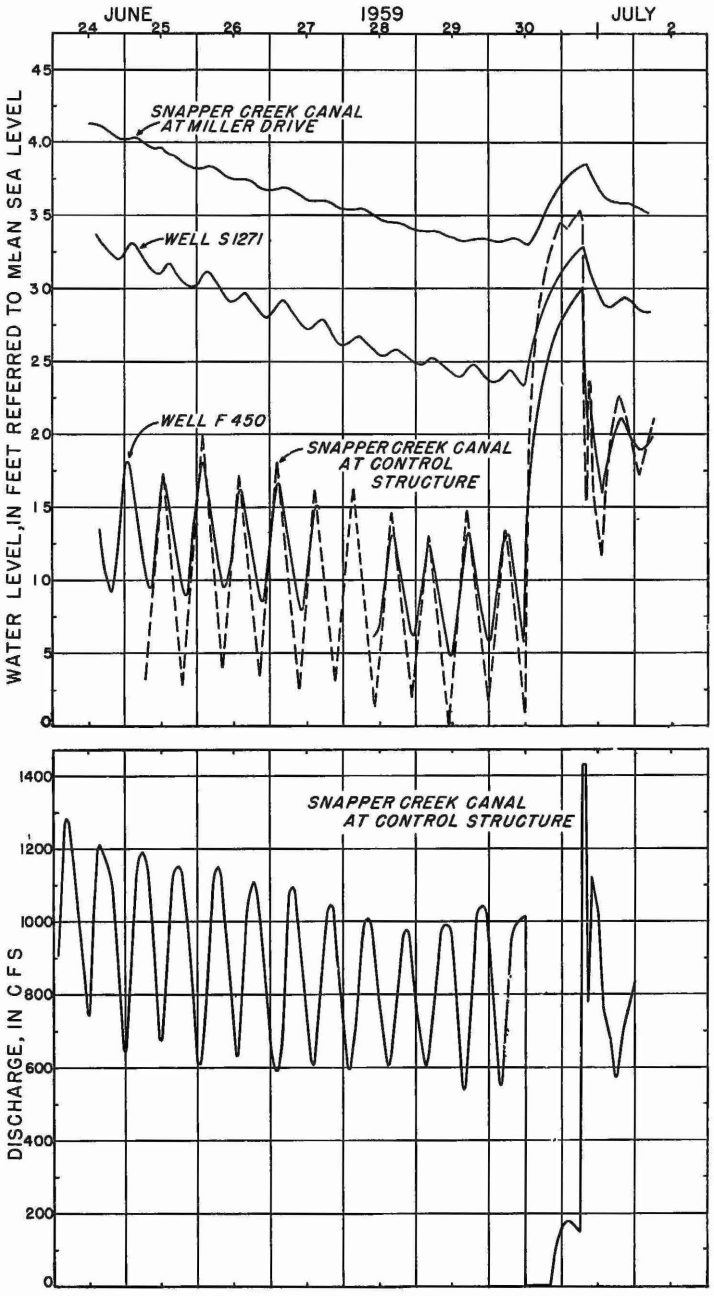



Figure 8. Hydrographs of ground-water levels and canal stage at selected stations and discharge at the control structure June 24-July 2, 1959.

About 10 hours after closing the gates a partial opening was made to prevent flooding in low areas along the canal. At 7:15 a.m., July 1, the gates were fully opened.

A more intensive test was conducted during the latter part of July. Fluctuations of water levels and canal discharge at selected points during the test period are shown in figure 9, and canal stage and discharge data collected at the times of opening and closing the control are shown on an expanded scale in figure 10.

For several days prior to July 21 the control gates were open and ground water was discharging from storage. The hydrographs in figure 9 indicate that during the period July 17-20 the rate of recession of the water table in areas near the canal was very slow. On July 21 the canal discharge was measured at Red Road, Palmetto Road, and Galloway Road, along with the discharge recorded at the control structure, and water-level measurements were made in the network of observation wells. These measurements furnish a picture of the canal system when flow and stage are relatively steady.

At 10:30 a.m. on July 21 the control gates were closed, and discharge and stage measurements were continued until 6:30 p.m. The effect on the system is shown in the hydrographs (fig. 9, 10) by the rise of water levels in the area and the sharp reduction of discharge at different points in the canal. After 7½ hours (6:00 p.m.) the gates were adjusted in an effort to hold a high constant head at the dam for as long a period as possible and at the same time to prevent flooding along the banks of the lower reaches of the canal.

On the morning of July 24, stage and discharge measurements were made immediately before the control gates were opened and were continued for 5 hours after the gates were opened.

## ANALYSIS OF DATA

### CHANGES IN STORAGE AND FLOW

An important part of the investigation of the Snapper Creek Canal area flow system is the relation between the stage and discharge of the canal and the change in ground-water storage in the aquifer. Fluctuations of stage and discharge within the flow system depend chiefly upon (1) the quantity of rainfall recharging the system, (2) the quantity of inflow from the Everglades by canals and by underflow, and (3) operation of the control.

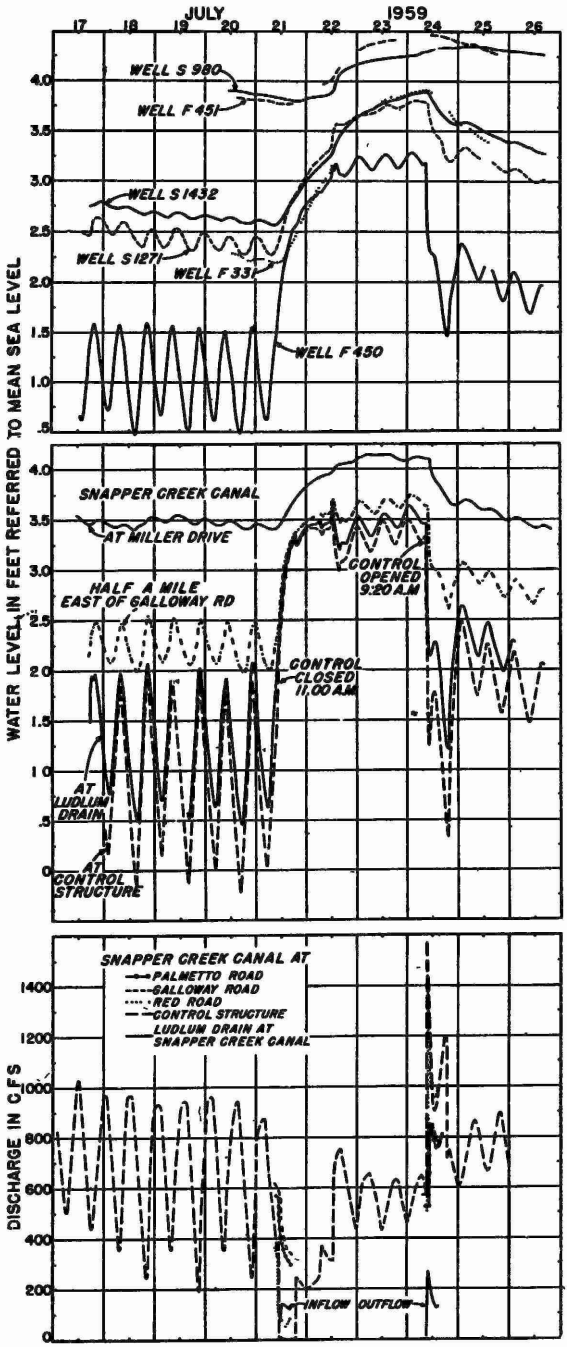



Figure 9. Hydrographs of ground-water levels and canal stage and discharge at selected stations July 17-26, 1959.

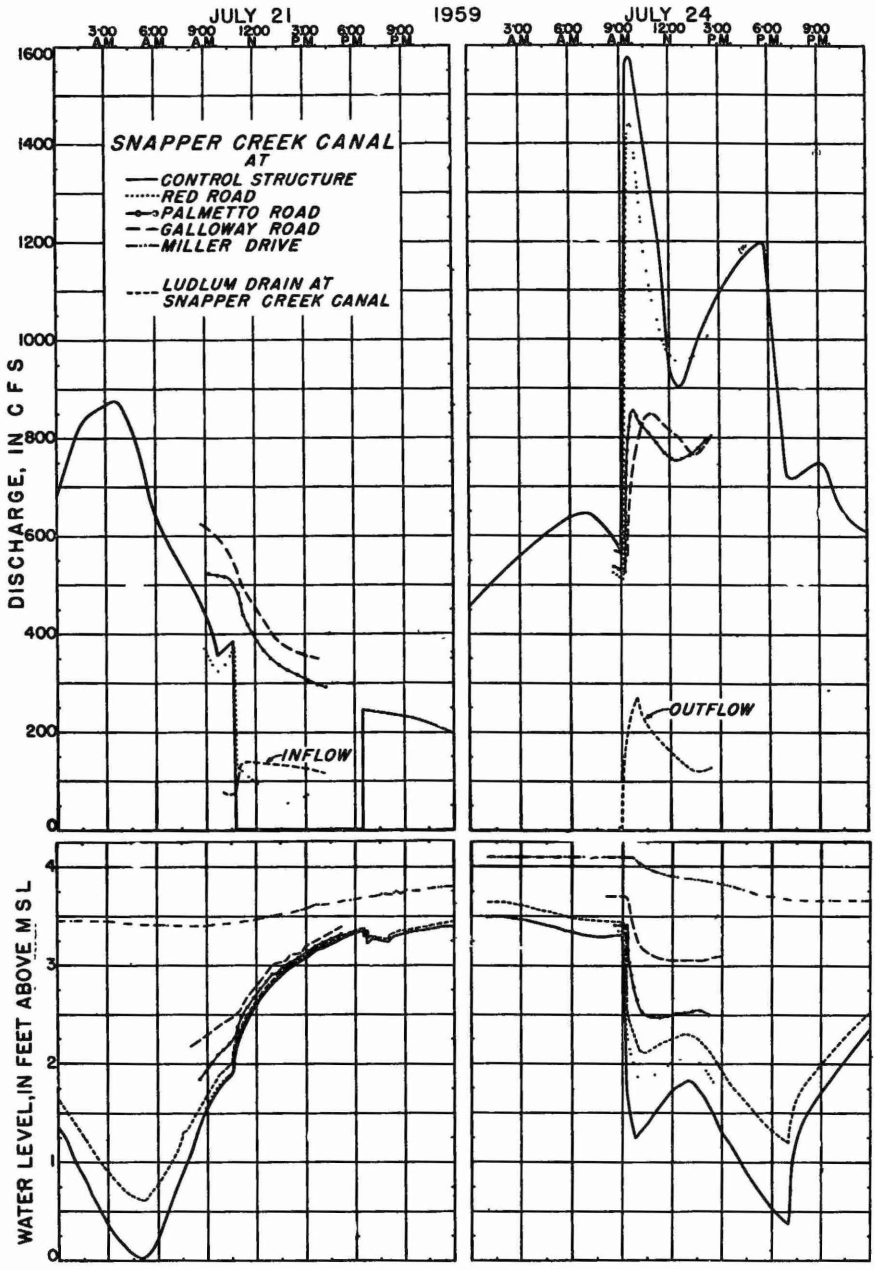



Figure 10. Hydrographs of canal stage and discharge at selected stations July 21 and 24, 1959.

Figure 7 shows fluctuations of the water levels and rainfall for much of 1959, and includes also a graph of the daily mean discharge of the Snapper Creek Canal at the control structure. Each heavy rainfall caused a corresponding rise of the water table and canal stage, except in the lower reaches of the canal where levels were generally lowered by the opening of the control gates. When the heavy rains of March 18-22 and June 17-21 occurred, the control gates were opened; this caused a rapid decline of canal stage at the dam and a large increase in discharge. These periods can be noted readily in figure 7. The effectiveness of drainage by the canal is shown by the rapid decline of peak ground-water levels after these rains.

The quantity of inflow from the Everglades areas varies with the ground-water gradient toward the coast. During flood periods this gradient is initially slight because of high water levels underlying the coastal ridge, but as coastal ground-water levels decline, large quantities of water enter the canal system and the aquifer from the west. As a result, the control gates must be kept open for long periods.

When the control is open a large part of the system is affected by tides. The magnitude of the effect decreases upstream and depends upon the magnitude of the gate opening and the rate of discharge. Maximum discharge from the canal occurs 1 to 2 hours before low tide, and minimum discharge occurs at high tide. Figure 11, from Parker and others (1955, fig. 127), is an idealized sketch showing progressive changes of slope of the water surface, directions of flow, and storage in a tidal canal. Tidal changes in Snapper Creek during the test periods were similar to those shown in figure 11 except that the seaward flow in the canal was sufficient to prevent reverse flow at high tide. A comparison of the tidal fluctuations in the canal east of Galloway Road and in wells F451, S1271, and S1432 in figure 9 shows the lag in time and decrease in magnitude of the fluctuations with increased distance from the canal. The tidal fluctuation in the canal was about 1 foot, while in wells F451, 2,900 feet south of the canal, S1432, 1,100 feet north of the canal, and S1271, 600 feet north of the canal, the fluctuation was about 0.0, 0.10, and 0.25 foot, respectively.

The changes caused by opening or closing the control gates during the tests correspond generally with the changes caused by a falling or rising tide, except in rate and magnitude. The extent of the changes within the flow system depends chiefly on the length of time the control gates remain open or closed, and the antecedent hydrologic conditions. The hydrographs in figure 9 indicate that a

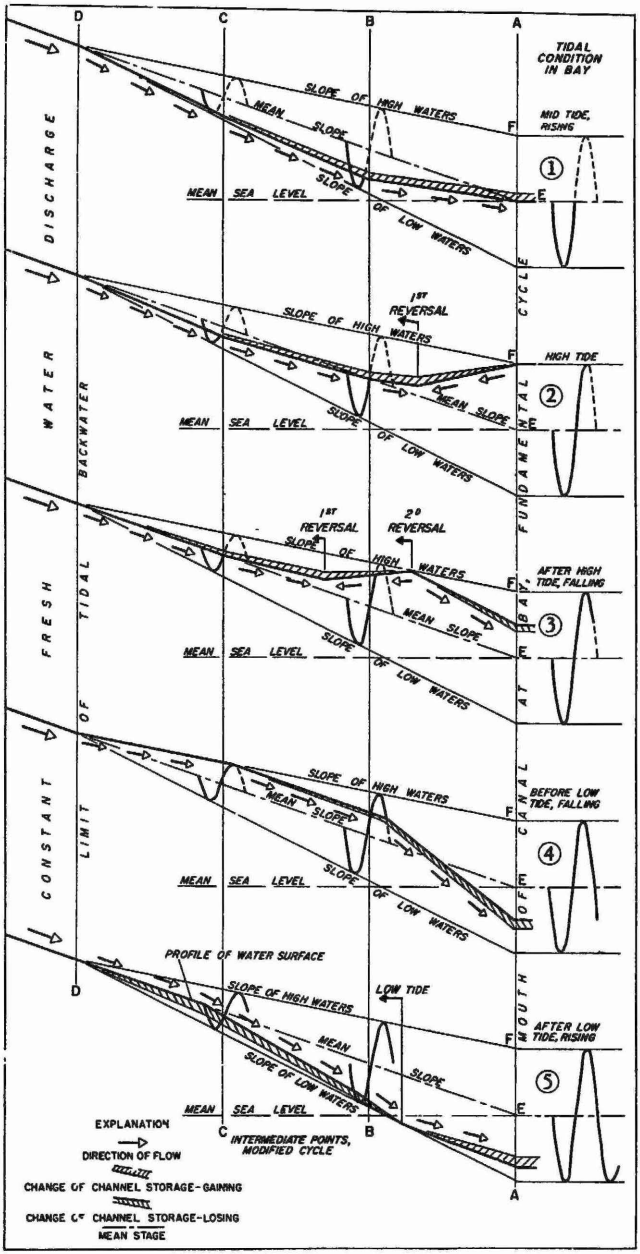



Figure 11. Idealized sketch showing progressive changes of slope, directions of flow, and storage in a tidal canal (Parker and others, 1955, fig. 127).

period of several days is required for water levels throughout the area to adjust to a given control setting.

The test of July 17-24 presents fairly complete data on fluctuations of water levels and discharge within the flow system. This test was complicated by heavy rainfall that began July 22 and caused a sharp rise in water levels, necessitating a slight opening of the control gates. The control change is indicated by the increase in discharge at the control and the stabilizing of canal stage in the hydrographs (fig. 9). A comparison of the hydrographs suggests that ground water moved away from the canal in the area near wells S1271 and S1432 during the period after the closing of the control. The slight opening of the control on July 22 caused a reversal of this gradient and ground water began to flow toward the canal. The changes in the flow system caused by the closing and opening of the control on July 21 and 24, respectively, are shown in detail by the hydrographs in figure 10, the flow patterns and canal profiles in figure 12, and the water-level contours in figures 13 and 14. Figure 12 shows canal profiles and the flow regime of the canal at selected times before and after the closing and opening of the control. Figures 13 and 14 show water-level contours under relatively stable conditions before the closing and opening of the control.

As seen in detail on figure 10, the closing of the control gates at high tide on July 21 extended the flow pattern established previously by the rising tide. A comparison of the discharges measured immediately before the closing (fig. 10, 12) shows that water was entering the aquifer from the canal in all reaches east of Galloway Road except the section along Red Road. In the Red Road section, ground water was flowing into the canal because of the steep gradient of the water table in the area west of the canal (fig. 13). The sharp rise in canal level after the closing of the control caused recharge to the aquifer in all coastal reaches. The flattening of the stage and discharge curves about 5 hours after the closing reflects the increase in channel and bank storage and the decrease of seaward gradient in the canal. The computed rates of increase in channel storage 5 hours after the closing of the control, shown in figure 12, indicate that most of the canal discharge was entering the aquifer. At this time more than half the flow passing Galloway Road was entering the aquifer in the Red Road reach of Snapper Creek Canal and Ludlum Drain. In this area the canals run in a north-south direction and the groundwater gradient is steep toward the sea.

The discharges measured in the canal immediately before the

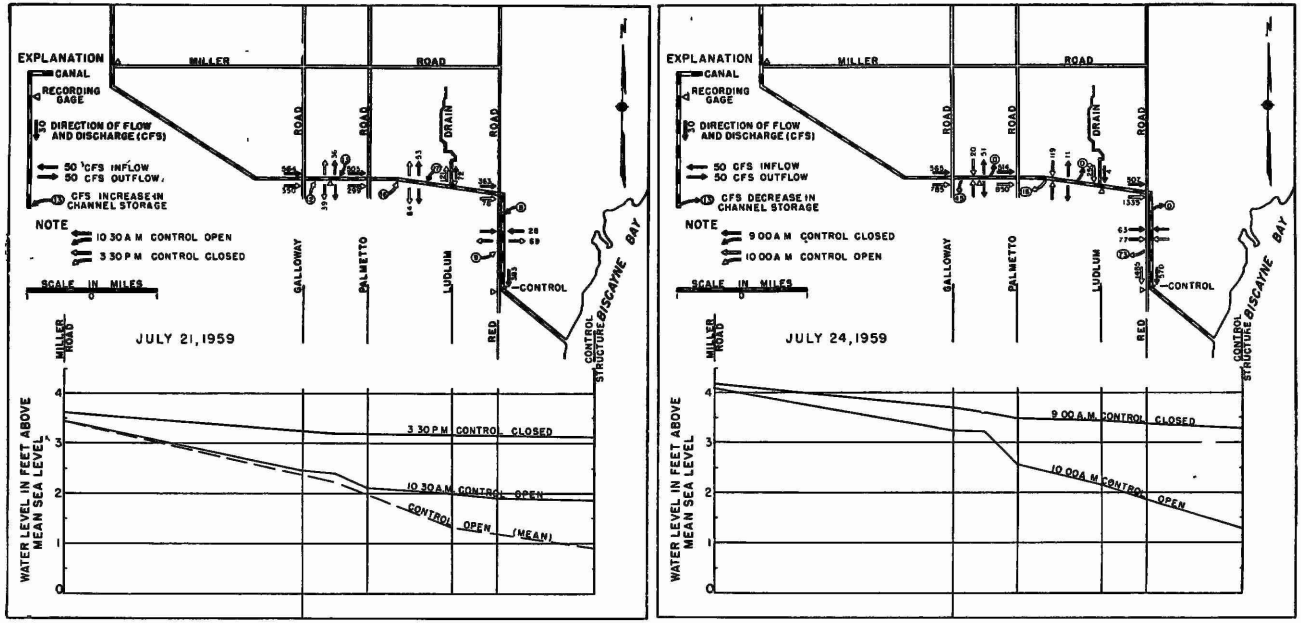



Figure 12. The flow regime and water-level profiles in Snapper Creek Canal at selected times on July 21 and 24, 1959.

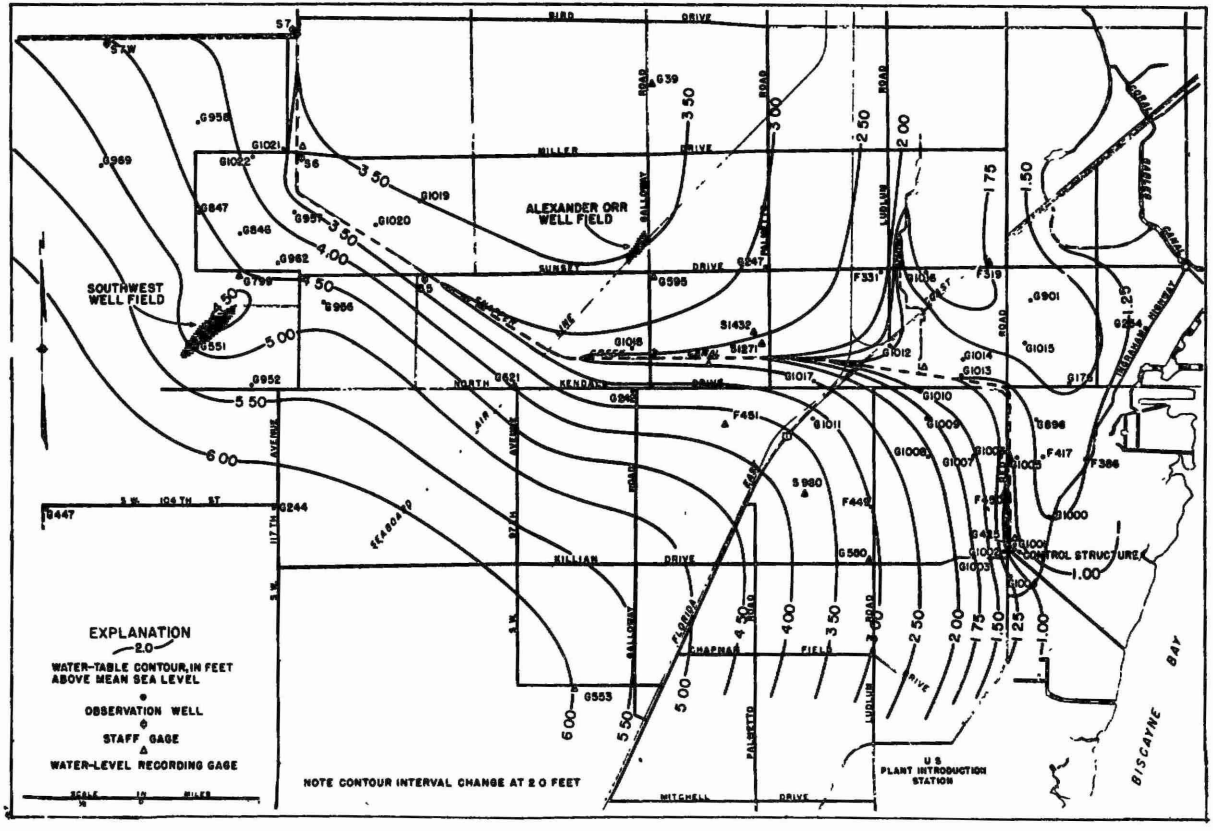



Figure 13. Contour map showing water levels in the Snapper Creek area July 21, 1959.

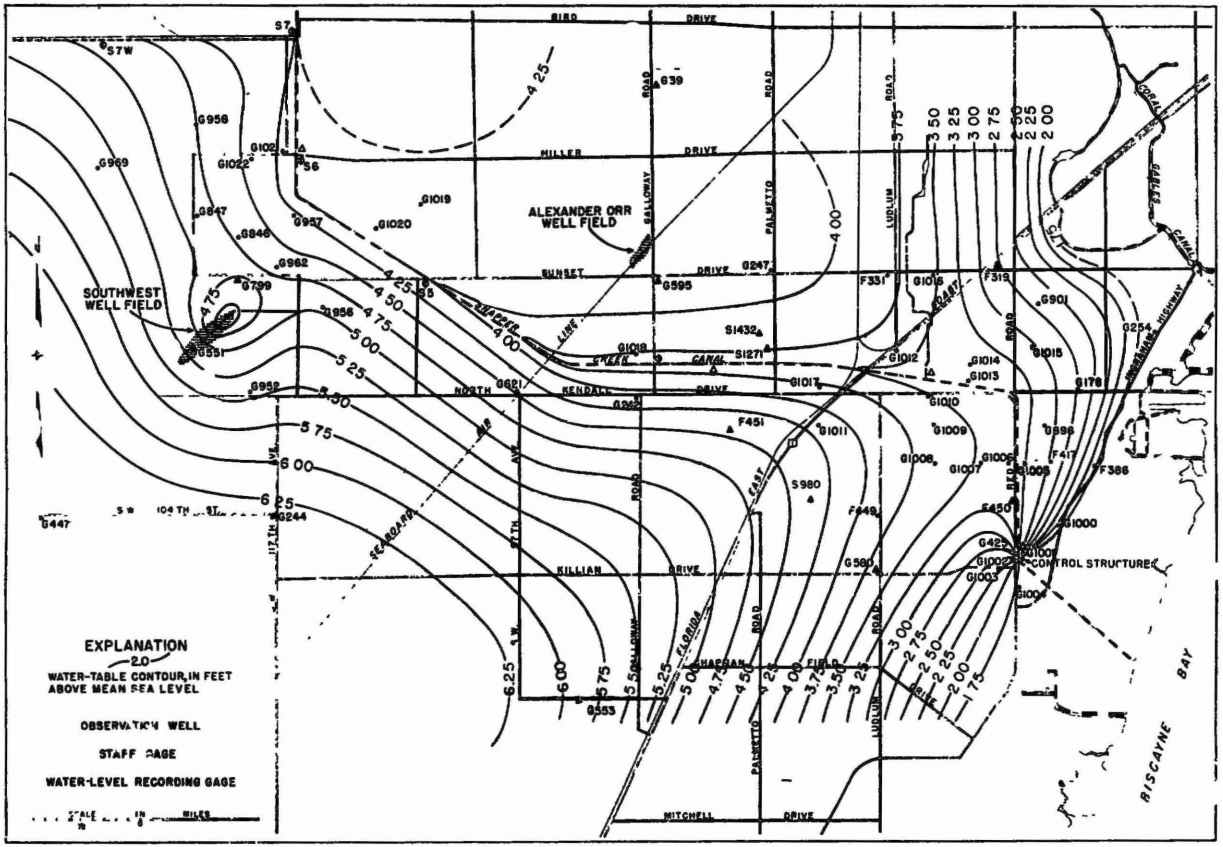



Figure 14. Contour map showing water levels in the Snapper Creek area July 24, 1959.

full opening of the control on July 24 (9:00 a.m.) were relatively high in spite of the small (50 square feet) opening at the control structure. As seen in figure 9, the mean discharge at the control was only slightly less than the mean discharge shown when the control was completely open. Measurements made before the full opening (fig. 12) show that the discharge at Galloway Road was about the same as that measured at the control. These discharge measurements and the gradients shown by the contours in figure 14 indicate that the inflow to the canal within the coastal ridge area was considerably greater than the losses to the bay. The rate at which the discharge at the control structure reached 1,575 cfs, after the opening of the control gates, suggests that most of this initial flow was from channel storage in Snapper Creek Canal and Ludlum Drain. The much smaller increase in flow at Palmetto Road shows the effect exerted on the system by the inflow from Ludlum Drain.

The sharp reversals in stage and discharge rates about an hour after the opening of the control on July 24 reflect the damming effect of the incoming tide. This tidal action also caused a reversal in the direction of ground-water flow adjacent to the canal in most reaches. The sharp change in slope in the canal profiles at Palmetto Road during periods of high flow (fig. 12) is caused by a constriction in the canal at that point. This change in the cross-sectional area of the canal may have affected the accuracy of the discharge measurements at this station.

The changes in the water table shown by the contours in figures 13 and 14 indicate the increase in storage in the aquifer during the period the control structure was closed. The hydrographs for this period indicate that an appreciable part of the increase in storage in inland areas was caused by the rain on July 22; however, in the coastal areas the effects of the rainfall were largely overcome by drainage to the canal. The large changes shown by the contours indicate the effectiveness of the control structure in lowering or raising water levels. The system is especially effective near the coast where Snapper Creek Canal and Ludlum Drain extend in a north-south direction.

## AQUIFER COEFFICIENTS

The principal hydraulic properties of an aquifer are its capacity to transmit and store water. These properties may be expressed as the coefficients of transmissibility (T) and storage (S). The coefficient of transmissibility is defined as the amount of water

in gpd (gallons per day), at the prevailing temperature, transmitted through a 1-foot strip of saturated thickness of the aquifer under a hydraulic gradient of 1 foot per foot. The coefficient of storage is defined as the unit volume of water released from or taken into storage per unit surface area of aquifer per unit change in the component of head normal to that surface.

When water is pumped from a well in the Biscayne aquifer, the unwatering of the adjacent materials causes the water table to slope toward the well, thus forming a cone of depression. The slope or hydraulic gradient of the cone causes ground water to move from the surrounding areas to the well. The movement of water through the aquifer follows a law developed experimentally by Darcy, which may be modified for use with the tranmissibility coefficient and written as:

$$Q = TIW$$

where Q = the average pumpage from a well field, in gpd
T = the transmissibility of the aquifer, in gpd per foot
W = the circumference of a cylinder through the aquifer at a given radius from the center of pumping, in feet
I = the average slope of the cone of depression around this cylinder, in feet per foot.

Approximate values for the coefficient of transmissibility of the aquifer were computed from the ground-water gradients caused by pumping in the Alexander Orr and Southwest well fields. Using gradients shown in the contour maps of April 22, 1958, and May 12, 1960 (fig. 15) for the two fields and the corresponding average pumping rate for each well field, the computations indicate a coefficient of transmissibility of 8.6 mgd per foot in the vicinity of the Southwest field and 5.5 mgd per foot in the vicinity of the Orr field.

The coefficient of storage of a water-table aquifer approximates the specific yield, which may be expressed as the ratio of the volume of water that the saturated material will yield by gravity to the volume of the material. A calculation was made of the approximate storage coefficient of the aquifer in the area adjacent to the canal between Palmetto and Galloway roads by measuring the quantity of water required to replenish a section of the aquifer, as shown in the profiles in figure 16, during the 5 hours after the closing of the control gates on July 21. The difference between the discharge measured at Galloway Road and that at Palmetto Road during the period, minus the change in channel storage, indicates that approximately 650,000 cubic feet of water were introduced to the 1-mile

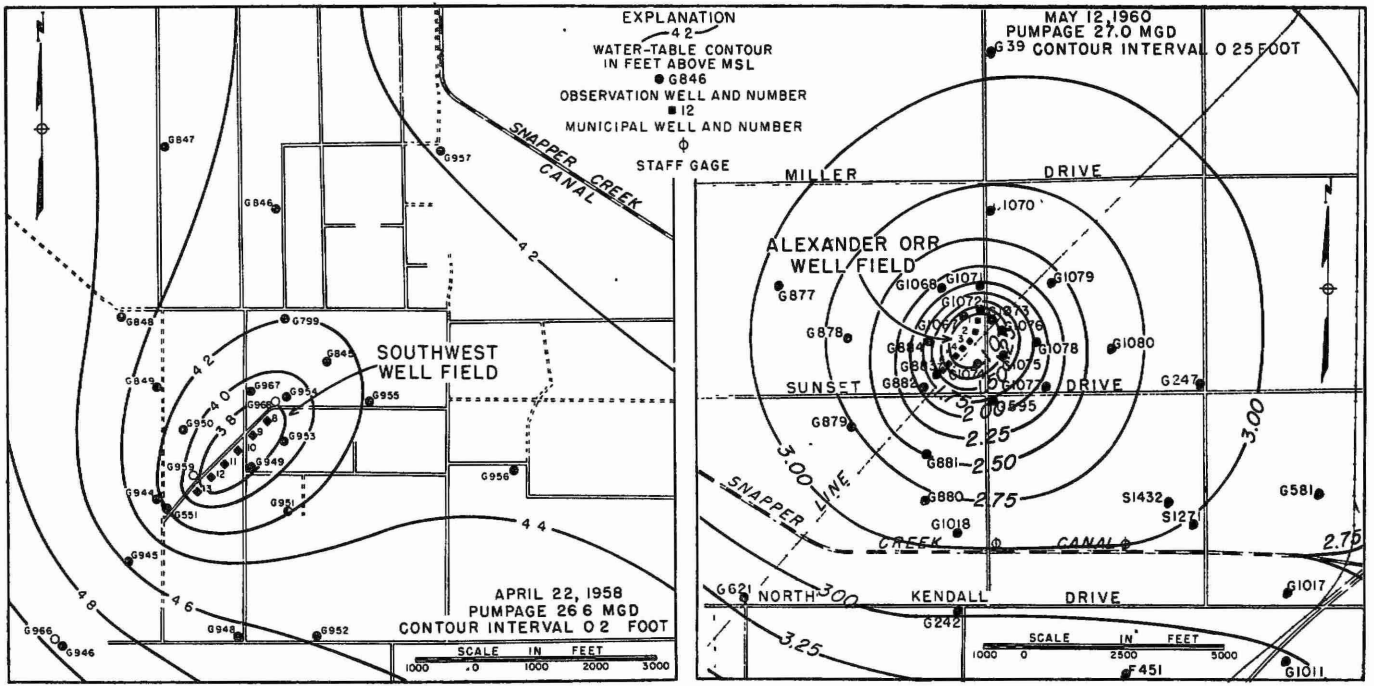



Figure 15. Contour map showing water levels in the Southwest and Alexander Orr well fields on April 22, 1958 and May 12, 1960, respectively.

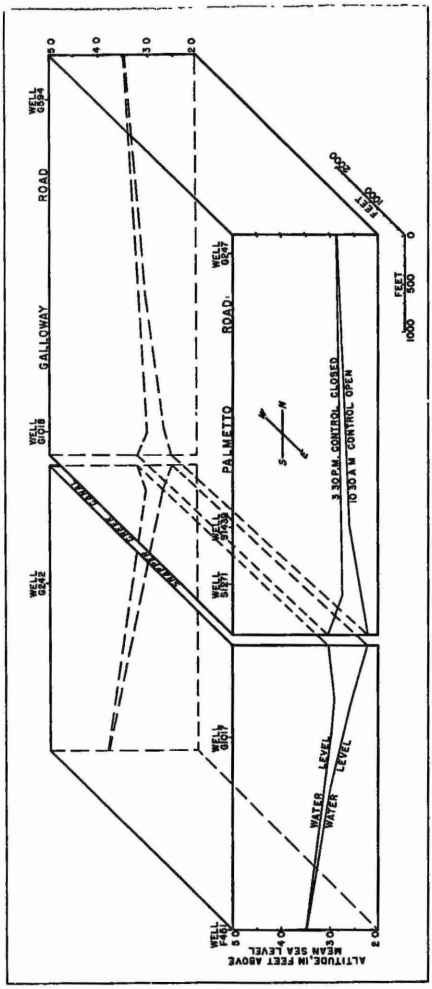



Figure 16. Diagram showing water-level profiles along Palmetto Road and Galloway Road on July 21, 1959.

section of the aquifer from the canal. In addition to this, computations using the transmissibility coefficient obtained for the vicinity of the Alexander Orr well field and ground-water gradients shown in the profiles and the contour map (fig. 13) indicate that about 420,000 cubic feet of ground water flowing toward the canal entered the test area.

The product of the average rise of the water table (between the low and high water profiles in figure 16) and the area within the test site indicates that the volume of material filled during this period was approximately 9,700,000 cubic feet. Thus, the storage coefficient is about 0.11. This coefficient is in the proper order of magnitude for an aquifer under water-table conditions but is lower than the average storage coefficient of 0.20 as determined from pumping tests in the Miami area. The storage coefficient in the vicinity of the canal probably is lower than in most of the Miami area because of the presence of shallow marls throughout most of the transverse glade (fig. 2) along the test section.

## GROUND-WATER MOVEMENT AND CANAL FLOW

Of primary importance in the study of the canal area are the accretions to and withdrawals from ground-water storage and the corresponding changes in canal stage and discharge under different hydrologic conditions. Under controlled drainage conditions ground-water flow is toward the canal and canal flow increases toward the bay. Any reduction of canal flow caused by the operation of the control structure raises canal stages and reduces or reverses the ground-water gradients in areas adjacent to the canal.

If a given head is maintained at the control, the contours in figure 14 indicate that the losses from the canal would occur chiefly around the control structure, and eastward from the canal and from Ludlum Drain. The magnitude of these losses is proportional to the gradient between the canal system and the bay, but the thickness of the seaward flow section near the canal system and the bay and around the control structure is greatly reduced by the salt-water wedge extending inland in the lower part of the aquifer. If it is assumed that the base of the fresh-water flow section is near the depth of the 5,000 ppm (parts per million) isochlor (Kohout, 1960), salinity data in the Snapper Creek Canal area indicate that the flow section underlying the edge of the coastal ridge is only about 35 feet thick.

The only complete streamflow and water-level data available for a period of low-water conditions are shown in figures 17 and

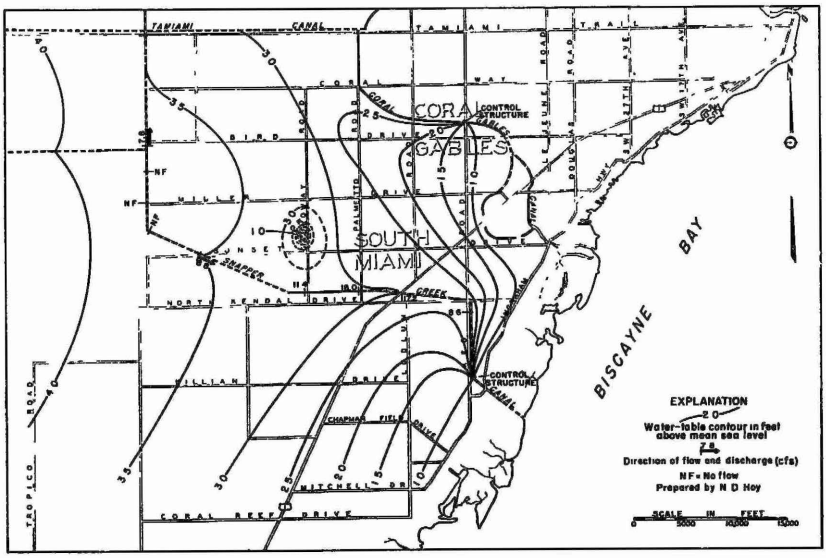



Figure 17. Contour map showing water levels in the Snapper Creek area and flow at selected points in the canal on March 21, 1951.

18, prepared during 1951 by Nevin D. Hoy of the U. S. Geological Survey. Figure 17 shows the discharge measured at different points in the canal and the water-table contours on March 21, 1951. A sheet-steel dam, in use at that time, was closed during January 1-September 1, 1951, except for a partial opening April 10-13, and only 0.06 inch of rain had occurred in the 30 days that preceded the measurements. These data show the same general pattern of canal discharge and ground-water inflow as that indicated by the high-stage discharge measurements and contour map of July 24, 1959. Most of the water lost from the eastern reaches of the canal came from the aquifer in the western part of the coastal ridge.

It is apparent that under both high and low ground-water conditions the flow in the canal was being maintained by ground-water inflow from the western part of the coastal ridge. This inflow was sufficient to balance losses along the lower reaches of the canal. The point in the flow system where losses by outflow from the canal exceed the quantity of ground-water inflow to the canal moves upstream as water levels in the area decline.

No flow was observed in the canal near Miller Drive at the time of the 1951 measurements. Downstream from Miller Drive the flow increased to 18 cfs at Palmetto Road, then decreased to zero

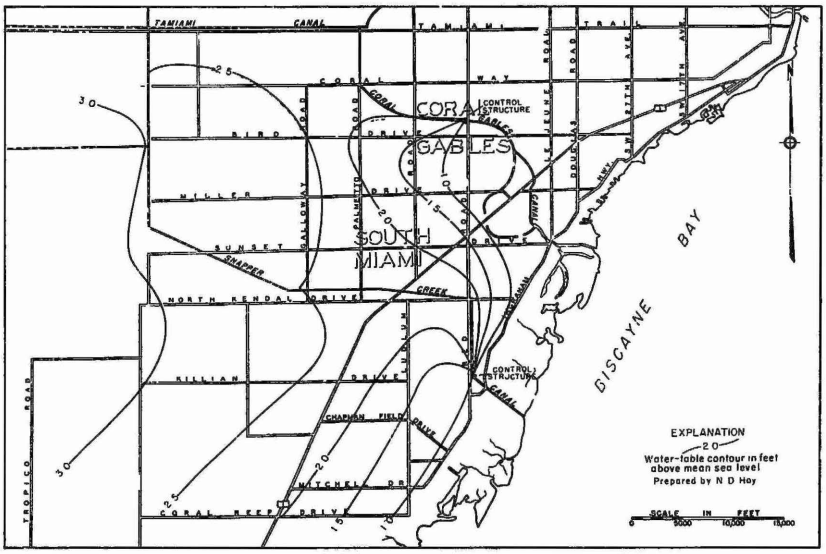



Figure 18. Contour map showing water levels in the Snapper Creek area on June 12, 1951.

at the control structure. Ludlum Drain was not in existence in 1951, but by superimposing this drainageway on the contour map of figure 17 and estimating the change in eastward losses through the area from the ground-water gradients and the transmissibility of the aquifer, the total losses from the flow system east of Palmetto Road under these hypothetical conditions can be calculated. Substituting a coefficient of transmissibility of 5 mgd per foot, the average ground-water gradient in area (fig. 17), and the length of Ludlum Drain in the formula $Q = TIW$, the eastward loss on March 21, 1951 was computed to be about 15 cfs. On the assumption that the water level in Ludlum Drain would have been equal to that at its junction with Snapper Creek Canal (2.9 feet above msl), it is estimated that eastward losses from Ludlum Drain would have been about 25 cfs, thus the increase in losses due to the presence of Ludlum Drain would have been about 10 cfs and the total loss from the canal system downstream from Palmetto Road would have been about 28 cfs. If the same canal levels were maintained under prolonged drought conditions, the losses east of Palmetto Road would remain about the same, but additional losses would occur from the western reaches when ground-water levels declined to a level lower than that maintained in the canal.

An estimate of maximum losses was made by superimposing the canal levees of March 21, 1951 (2.75 feet above msl at the control structure, 3.71 feet above msl near Miller Road), on the low stage water-table contour map of June 12, 1951 (fig. 18), which shows near record low ground-water levels for controlled conditions. If the canal levels were maintained constant, the losses from the canal system east of Palmetto Road would be about equal to the 28 cfs estimated at the time of the March 21 measurements but the contours in figure 18 indicate that additional losses would have occurred from the canal west of Palmetto Road. On the basis of average ground-water gradients estimated from the assumed canal levels and the low stage water-table contour map, the computed losses from the canal between Palmetto Road and the bend near Miller Road were about 25 cfs. Thus the total losses from the canal system would have been about 53 cfs.

During low-water periods large additional losses from the canal may be caused by pumping in the large municipal well fields. It is possible that more than 50 percent of the water withdrawn from the Orr well field (49 mgd) and the Southwest well field (80 mgd) may be derived from the canal. This loss would increase with any increase in well field pumpage and could be more than twice the magnitude of all other losses from the canal system.

## SUMMARY

The Snapper Creek Canal drains the southernmost part of the Greater Miami area and also a large part of the lower Everglades west of the city. Flow in the canal is maintained chiefly by inflow of ground water, but considerable surface runoff is introduced from low areas on the coastal ridge and from the Everglades during periods of heavy rainfall. Canal discharge is regulated by a control structure near Biscayne Bay, in order to provide maximum flood protection during periods of heavy rainfall and to maintain water levels high enough to retard salt-water encroachment during dry periods. The maximum discharge of record, 2,010 cfs, was recorded at the control structure during the hurricane of September 9-10, 1960.

The area is underlain by permeable limestone, sandstone, and sand of the Biscayne aquifer, which extend from the surface to a depth of about 85 feet in the western part of the ridge and to about 120 feet at the coast. Geologic sections show that the deeper subsurface materials are relatively uniform throughout the area. In several places the shallow limestone of the coastal ridge is cut by

natural drainageways which are bottomed by a few feet of marl or silt of relatively low permeability. The coefficient of transmissibility of the aquifer ranged from about 8.6 mgd per foot at the Southwest well field of the city of Miami to about 5.5 mgd per foot at the Alexander Orr well field. The average coefficient of storage of the aquifer as determined by pumping tests in the Miami area was about 0.2. The storage coefficient computed for the Snapper Creek Canal area was about 0.1.

Water-level data indicate that by manipulation of the control structure, ground-water levels can be effectively raised or lowered throughout the drainage area, especially adjacent to the north-south reach of the canal near the coast. However, during severe floods high-water levels in lower reaches of the system temporarily reduce the effectiveness of the canal in lowering ground-water levels within the ridge area.

Discharge data indicate that when the control gates are open, ground water flows toward the canal and canal flow increases toward the bay. When the control gates are closed canal levels near the coast are generally higher than ground-water levels and appreciable losses from the canal occur. Under all but the lowest ground-water levels, however, these losses are balanced by ground-water inflow in the western part of the coastal ridge.

By using water-level and discharge information collected during 1951 as an index of low-water conditions, it was calculated that about 53 cfs would have to be brought into the system to maintain a 2.75-foot stage at the control structure during severe drought. In addition to this, a large part of the water withdrawn from the Orr and Southwest well fields would probably be derived from the canal. This loss could amount to more than 50 percent of the current capacity of the well fields (129 mgd) and would increase with future enlargement of the fields.

Because of the changes in the canal system since 1951, it is important that further hydrologic data be obtained throughout the Snapper Creek flow system during forthcoming low-water periods. Analysis of these data will provide more accurate determinations of the quantity of water needed to maintain the desired water levels in the Snapper Creek Canal.

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STATE OF FLORIDA
STATE BOARD OF CONSERVATION
DIVISION OF GEOLOGY

FLORIDA GEOLOGICAL SURVEY

Robert O. Vernon, *Director*

REPORT OF INVESTIGATIONS NO. 24

PART III

# HYDROLOGIC STUDIES IN THE SNAKE CREEK CANAL AREA, DADE COUNTY, FLORIDA

BY

C. B. SHERWOOD AND S. D. LEACH

U. S. GEOLOGICAL SURVEY

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

Tallahassee

1963

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## LETTER OF TRANSMITTAL

# *Florida Geological Survey*

*Tallahassee*

February 18, 1963

Dear Governor Bryant:

The Division of Geology is publishing as Part III of Report of Investigations No. 24, a report entitled, "Hydrologic Studies in the Snake Creek Canal Area, Dade County, Florida," prepared by C. B. Sherwood and S. D. Leach of the U. S. Geological Survey. The study was made as a part of the cooperative program of water studies between the Division of Geology and the Central and Southern Florida Flood Control District.

This is a part of a series of short papers recording the hydrology and geology of several areas in the District. An attempt has been made to relate the characteristics of the water resources existing before the construction of control structures in the District to the attitude of those resources after the control structures have been made operative.

These studies will be helpful to the District in managing the water resources, controlling the loss of water and in further design planning.

Robert O. Vernon, *Director*
and *State Geologist*

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# HYDROLOGIC STUDIES IN THE SNAKE CREEK CANAL AREA, DADE COUNTY, FLORIDA

By
S. D. Leach and C. B. Sherwood

## ABSTRACT

Snake Creek Canal was constructed primarily to drain parts of northern Dade County and southern Broward County, Florida. During dry periods, however, it conveys water from the Everglades seaward to replenish coastal sections of the Biscayne aquifer. A salinity-control structure at the mouth of the canal prevents the upstream movement of salt water and helps to maintain upstream water levels high enough to prevent salt-water encroachment into the aquifer. These hydraulic effects are made possible because of the high permeability of the aquifer and the excellent interconnection between the canal and the aquifer.

Hydrologic tests made March 25-26, 1961, on the flow system indicate that an inflow of 36 cfs (cubic feet per second) from Area B was required in the canal to maintain a water level of 2.7 feet above msl (mean sea level) at the control structure. This water is used to recharge the aquifer in the coastal ridge.

Future well fields of Metropolitan Dade County will withdraw as much as 200 mgd (million gallons per day) from the Biscayne aquifer in the western part of the Snake Creek Canal area. These large quantities of water will be derived chiefly by infiltration from the canal system and will greatly increase the amount of water needed to maintain desired levels near the coast. During drought periods this quantity could amount to more than four times the natural losses from the system.

## INTRODUCTION

This study is one of a series of hydrologic studies of canal area made in cooperation with the Central and Southern Florida Flood Control District to provide data for use in formulating an overall water-control plan for southeastern Florida. The rapid growth of population in the Greater Miami area has indicated a need to extend the existing water-control system to include a large swampy area of anticipated urbanization, designated as Area B, west of the

city (fig. 1). However, an urbanization plan for Area B must also be designed to prevent flooding within the area, and to maintain careful water control in the coastal area to prevent flooding and salt-water encroachment.

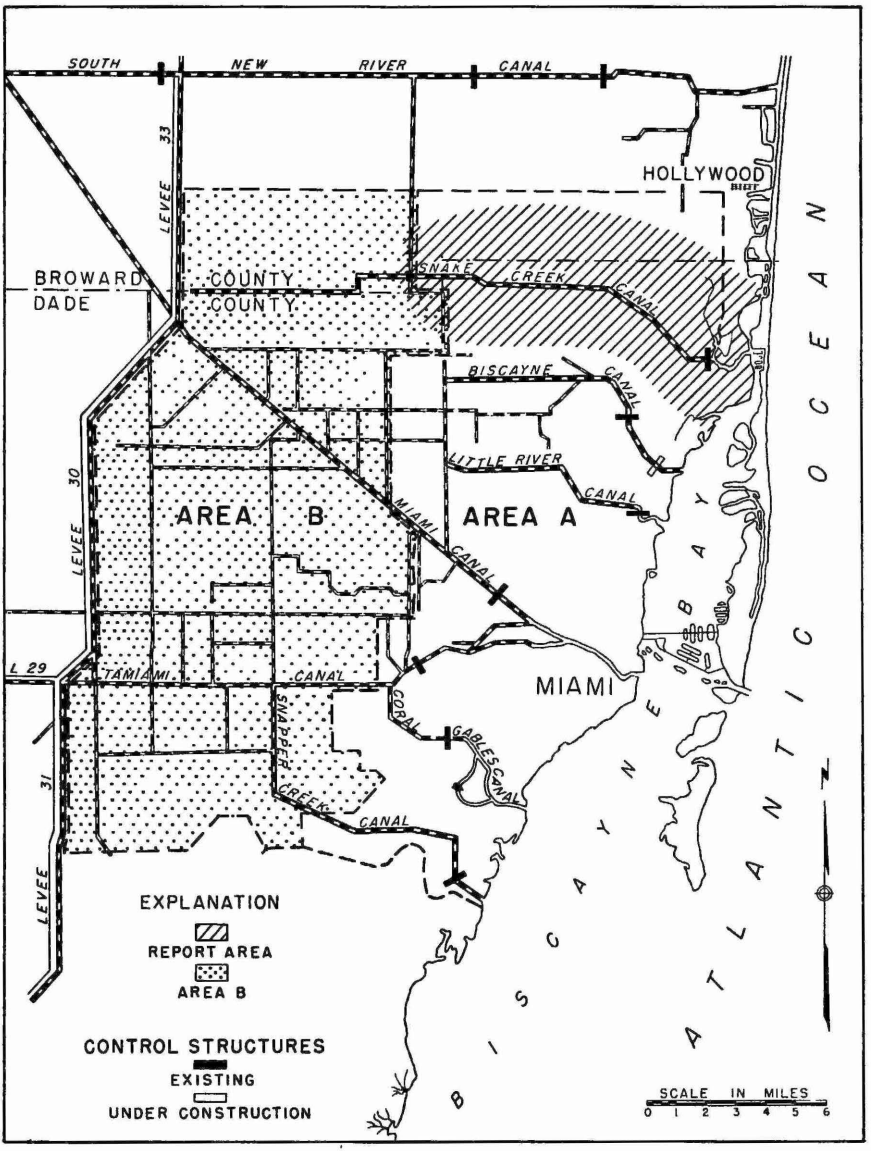



Fig. 1. Greater Miami area showing major hydrologic features and the area investigated.

The purpose of this study was to obtain a detailed description of the hydrologic environment in the Snake Creek Canal area and to provide quantitative definition of the following hydrologic factors:

1. The quantity of water needed to maintain a given head near the coast, for the control of salt-water encroachment.
2. The discharge rates at selected points in the canal system under various controlled conditions.
3. Relation between ground-water movement and canal flow in different canal reaches.

The investigation was made in 1961 by personnel of the Water Resources Division of the U. S. Geological Survey under the general supervision of A. O. Patterson, district engineer, Surface Water Branch, Ocala, and M. I. Rorabaugh, district engineer, Ground Water Branch, Tallahassee. It was under the immediate supervision of J. H. Hartwell, engineer-in-charge, Surface Water Branch, Miami, and Howard Klein, geologist-in-charge, Ground Water Branch, Miami.

## ACKNOWLEDGMENTS

The writers are indebted to the Central and Southern Florida Flood Control District, for furnishing complete information on their installations in the study area, and for operating control structure 29 during the test. Appreciation is expressed to the Dade County Public Works Department for information on the water-control system in the area, and the City of North Miami Beach for providing the equipment for aquifer tests and records of pumpage from their municipal well field.

## PREVIOUS INVESTIGATIONS

A brief paper by Parker (1951) discusses the geologic and hydrologic factors in the perennial yield of the Biscayne aquifer in southeastern Florida, and a later report by Parker and others (1955) presents a comprehensive account of the geology and water resources of southeastern Florida. Schroeder and others (1958) summarize the hydrology and geology of the Biscayne aquifer and evaluate the perennial yield of the aquifer from data obtained since 1950. Stallman (1956) gives the results of electrical analog studies of the hydrology of intercanal areas of Dade County. Klein and Sherwood (1961) describe hydrologic conditions in the vicinity of Levee 30, which is southwest of the Snake Creek Canal area.

## AREA OF INVESTIGATION

The Snake Creek Canal area is in the northernmost part of the Greater Miami area, Dade County, Florida. The area investigated extends about 2½ miles north and 2½ miles south of Snake Creek Canal from Biscayne Bay to the eastern edge of Area B (fig. 1), a distance of about 11 miles. Supplemental water-level data were collected in the northern part of Area B.

## CLIMATE

The climate in the Miami area is subtropical. Rainfall averages approximately 60 inches per year, about 75 percent of which occurs during the period May through October. This wet period includes both the normal rainy season and the hurricane season. The average annual temperature is approximately 75°F.

## TOPOGRAPHY AND DRAINAGE

The dominant topographic features of the area are the coastal ridge and the natural drainageways or transverse glades which cut through the coastal ridge from the Everglades. The configuration of the ridge and the drainageways is shown in figure 2. The land surface ranges from 5 to 7 feet above msl at the eastern edge of the Everglades and along the transverse glades, and from 9 to 20 feet above msl on the coastal ridge.

Snake Creek Canal, the main drainage features of the area, flows eastward from Levee 33 to Biscayne Bay (fig. 1). The canal is the primary drainage channel for a large part of Area B, as well as for the northern part of the Miami area. Several secondary canals in the western part of Area A drain to Snake Creek Canal. South New River Canal in Broward County and Snake Creek Canal are connected by a north-south canal along the eastern edge of Area B (fig. 1).

Flow in the canal system is maintained chiefly by ground-water discharge. During periods of heavy rainfall, considerable surface drainage is collected from low areas on the coastal ridge and from Area B. The flow in Snake Creek Canal is regulated by the operation of a control structure (fig. 3), about 1¼ miles upstream from Biscayne Bay. Submerged sluice gates in the structure are manipulated to provide maximum discharge for flood protection during periods of heavy rainfall and to prevent salt-water encroachment into the aquifer and into the upper reaches of the canal during dry periods.

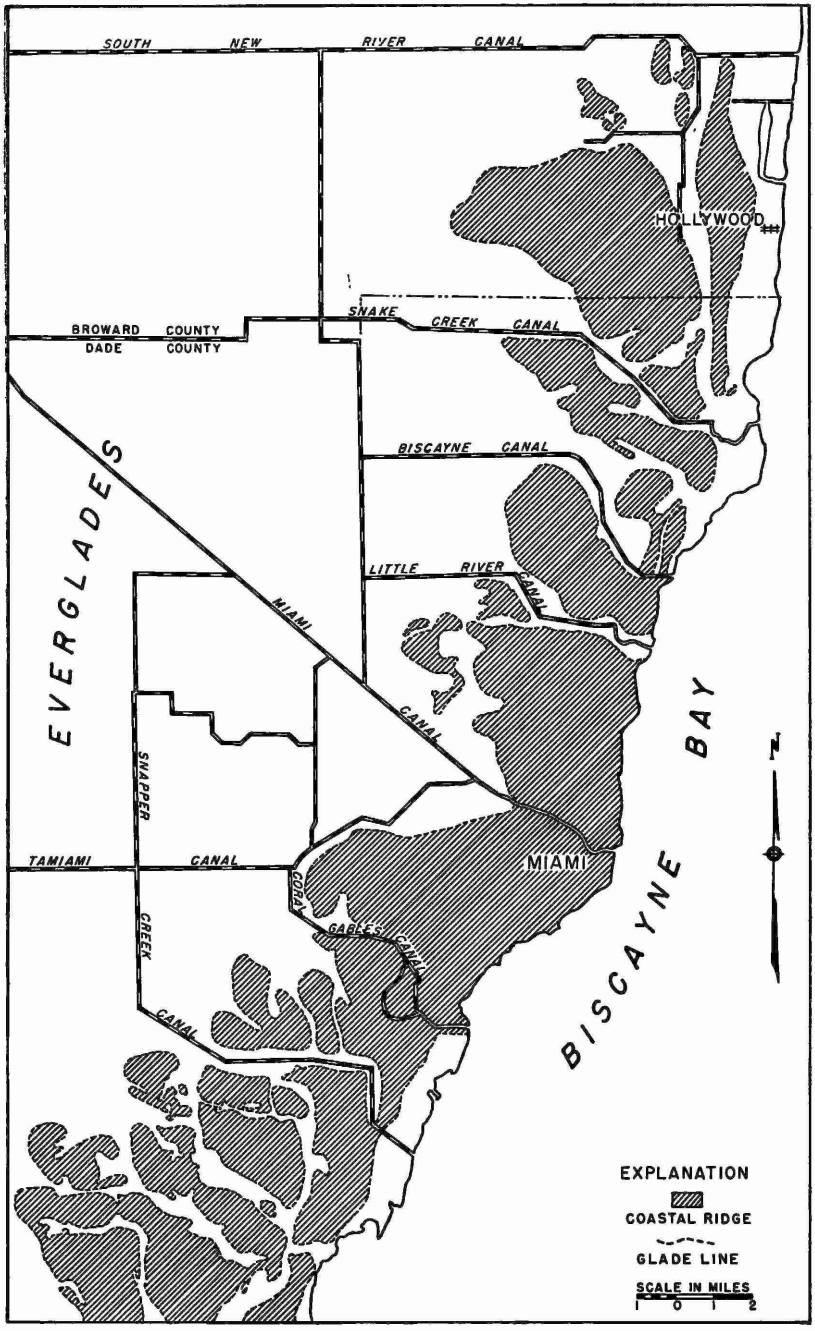



Fig. 2. Greater Miami area showing the configuration of the natural drainage-ways and the coastal ridge.

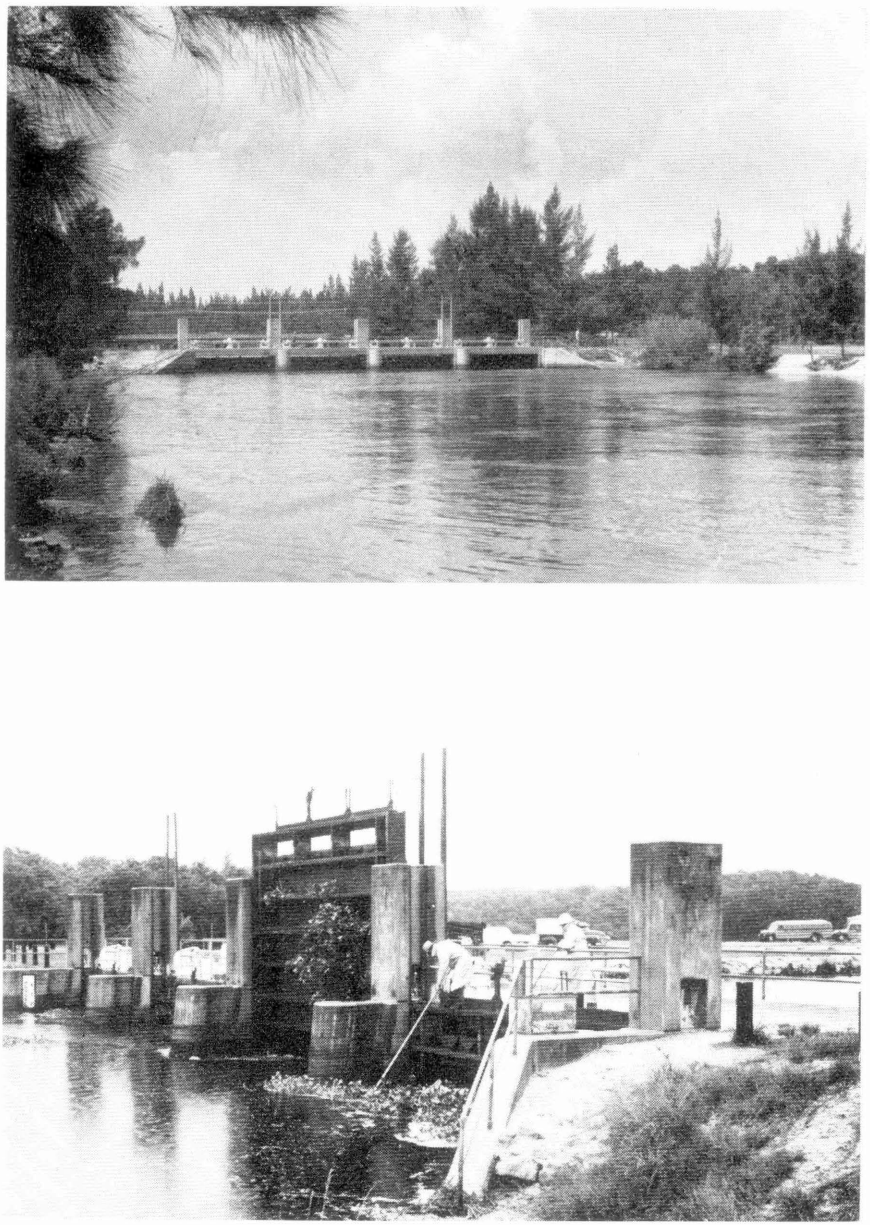


Fig. 3. Photographs of salinity-control structure near mouth of Snake Creek Canal.

### GEOLOGY

The area crossed by the Snake Creek Canal is underlain by the permeable limestone, sandstone, and sand of the Biscayne aquifer. The aquifer underlies the land surface to a depth of about 200 feet near the coast and to about 55 feet at the western end of the Snake Creek Canal. The aquifer is predominantly limestone at the coastline and in Area B, but it varies sharply between limestone and sand throughout most of the coastal ridge. The changes in the shallow, subsurface materials are shown in the geologic section in figure 4. The section also indicates that low areas along the natural drainageways are covered by several feet of muck or organic material. The nature of the deeper materials within the aquifer is shown in the west-east geologic section, along Snake Creek Canal, figure 5. In general, the most permeable zones occur in the lower part of the aquifer.

Supply wells in the Sunny Isles and Norwood well fields, operated by the City of North Miami Beach (fig. 14), tap highly permeable limestones at depths ranging from 60 to 120 feet below the land surface. Individual wells in these well fields yield as much as 2,000 gpm (gallons per minute) with a water-level drawdown of approximately 6 feet. Combined pumpage from the two well fields during 1960 ranged from 5.4 to 14.6 mgd.

## METHOD OF INVESTIGATION

Hydrologic tests of the Snake Creek Canal area flow system were made during the period March 25 to April 1, 1960. The control was closed March 25-26 and the water level was held in equilibrium at a high stage of 2.7 feet. Measurements were made during this condition at several points along the canal to determine the flow required to maintain the head existing at the control structure. The structure was opened on March 27 and then closed on March 30 to induce abrupt changes in area-wide water-level conditions. On March 31, the control was opened for 4½ hours to flush out salt water that was trapped upstream from the control structure during the test.

Observations and analyses were made of the changes in water levels and flow that resulted from the operation of the control structure. Data collected during previous investigations and during a continuing observational program were used to supplement the test data.

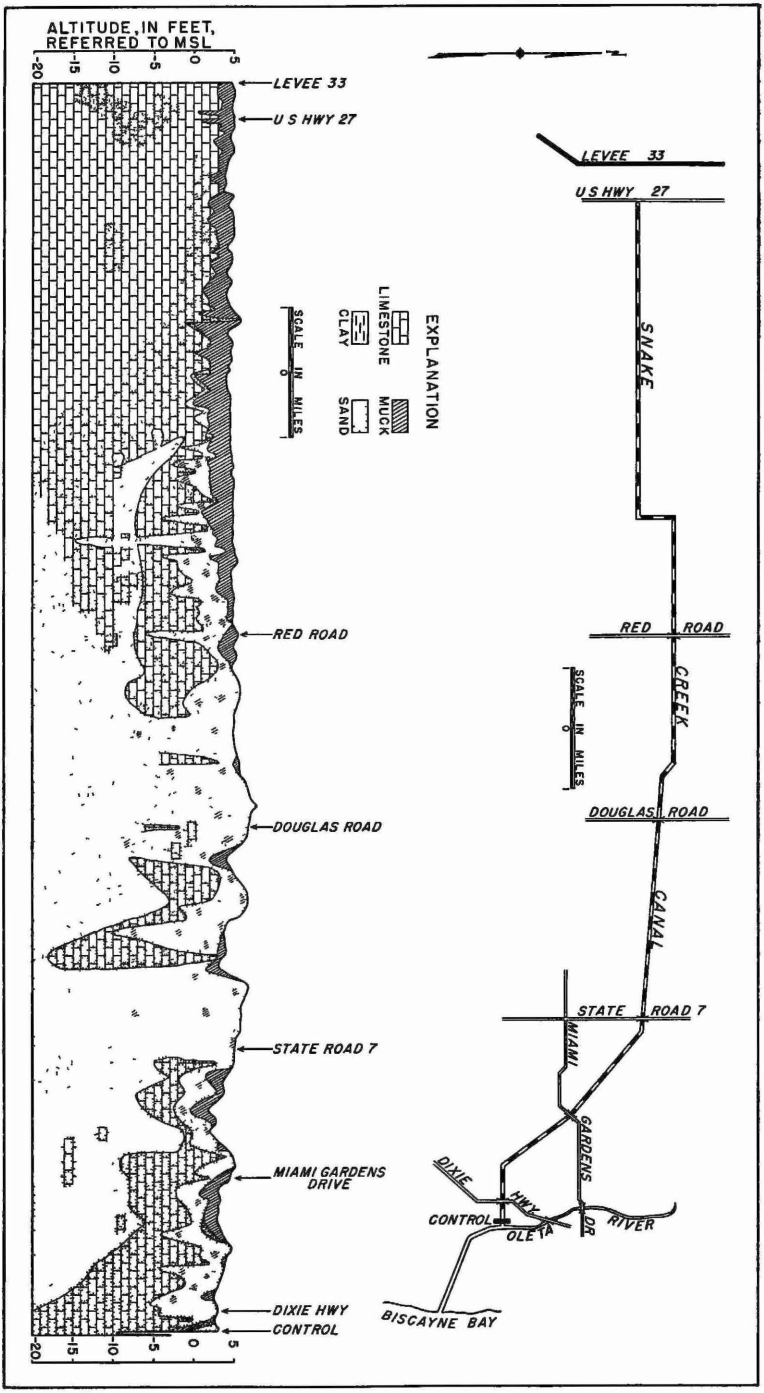



Fig. 4. Geologic section along Snake Creek Canal. (Adapted from U. S. Corps of Engineers 1954, pl. 94)

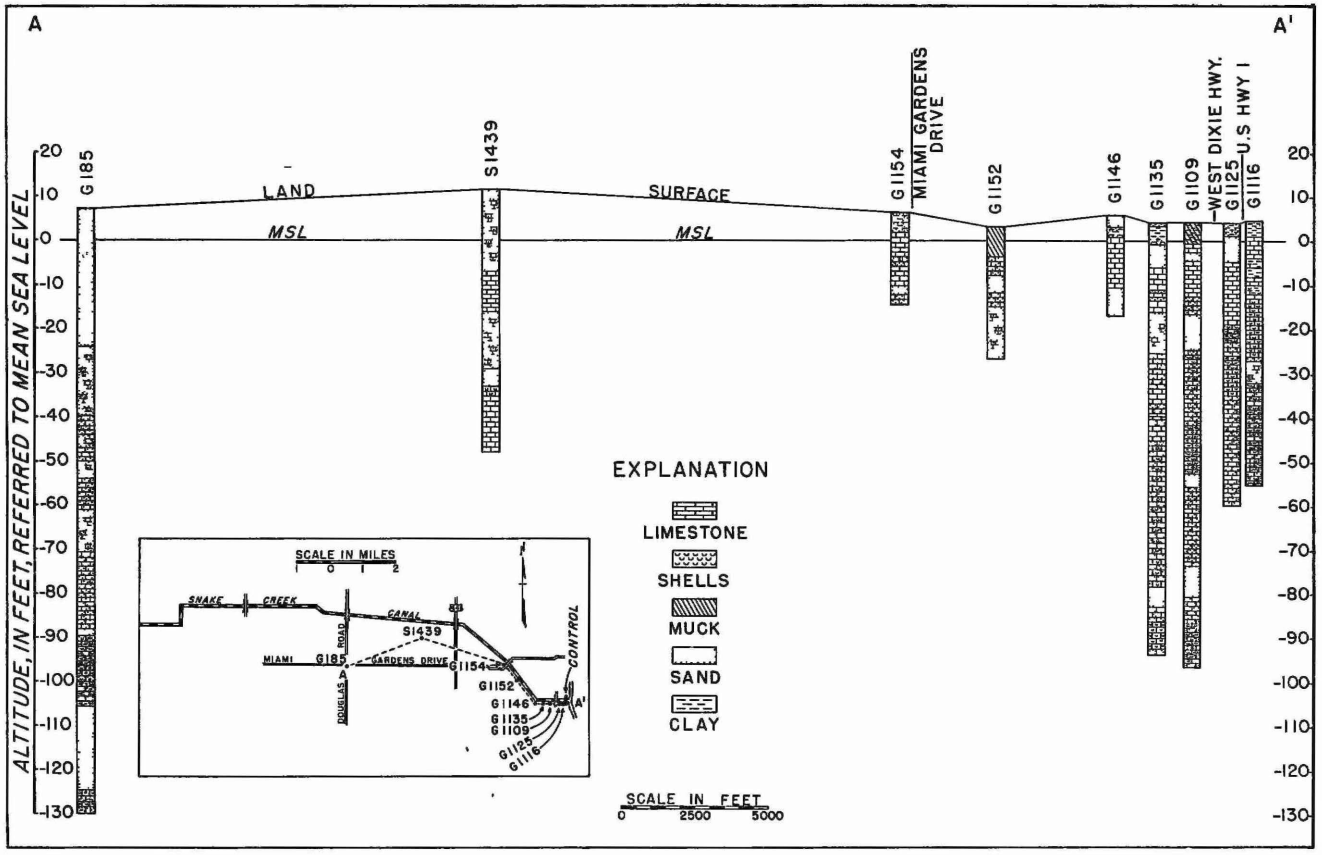



Fig. 5. Geologic section along line A-A′ near Snake Creek Canal.

Discharges at selected points in the canal were computed during the test periods from stage-area and deflection-mean velocity relationships. Current-meter measurements were made by conventional methods and, from these measurements, the cross-sectional area and the mean velocity of the canal were determined under various conditions. Continuous stage records were obtained from water-stage recorders, and continuous records of an index of velocity were obtained from deflection meters installed at midchannel. A deflection meter consists of an underwater vane attached to a vertical shaft that is free to rotate. The amount of angular rotation caused by the force of the flowing water is recorded in deflection units on a chart.

Discharge was thus computed from the basic formula $Q = AV$, in which Q is the discharge, in cubic feet per second

A is the cross-section area of the canal, in square feet, from the stage-area relationship

V is the mean velocity of flow, in feet per second, from the deflection-mean velocity relationship.

## COLLECTION OF DATA

The continuing water-records program in the area includes 22 observation wells, a water-level recording station in Snake Creek Canal at Red Road, and a water-level and discharge measuring station in the canal at West Dixie Highway (fig. 14). Six of the observation wells are equipped with water-level recording gages. Records from these data-collection stations provided considerable background data on the fluctuation of water levels throughout the drainage area.

For use during the test period, 28 additional shallow observation wells were drilled. Water-level recorders were installed on three of these wells and on seven privately owned wells. Two portable deflection meters and four water-level recorders were installed in the canal, and a water-level recorder was installed near the mouth of the Oleta River. All observation points were referred to mean sea level datum by spirit level. The locations of all data-collection sites are shown in figure 14.

Water-level fluctuations in six selected wells and at two canal stations, discharge of the canal near the control structure, and rainfall measured at Douglas Road are shown for the period July 1960 to April 1961 in figure 6. The effects of control operations during the test period; March 25 to April 1, 1961 are shown by sharp fluctuations of discharge and water levels.

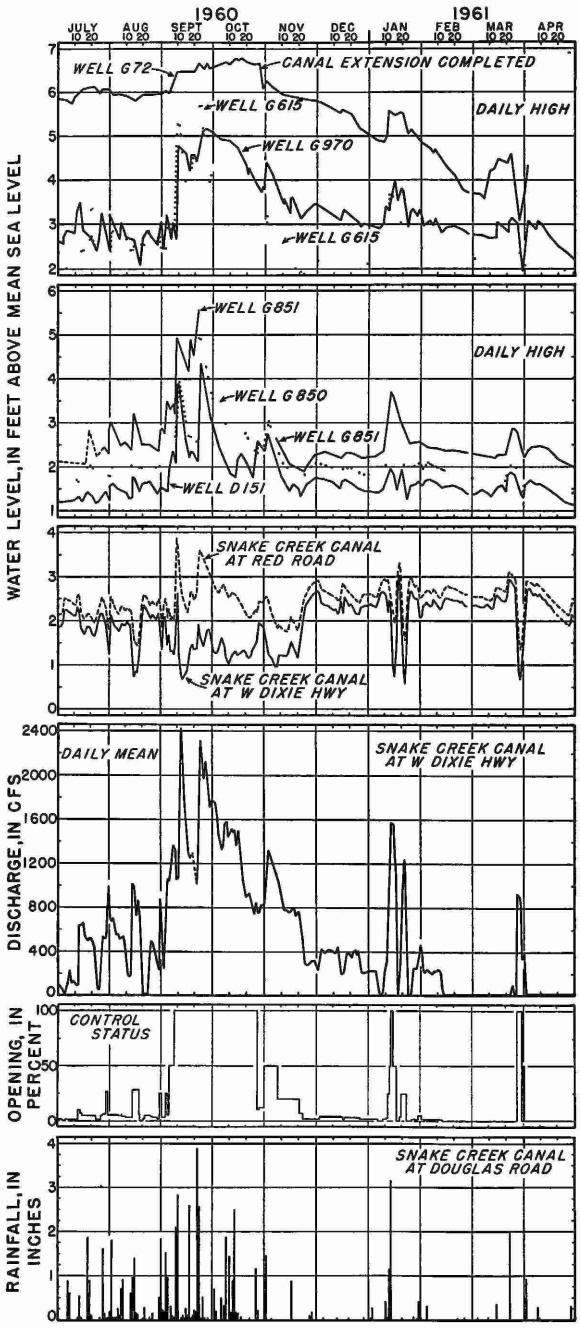



Fig. 6. Graphs of water levels at six selected wells and two canal stations, discharge near the control structure, control opening, and rainfall in the Snake Creek area for the period July 1960 to April 1961.

On March 25 and 26, observations were made throughout the test area to determine the magnitude and direction of flow required to maintain a constant water level of 2.7 feet above msl at the control structure. Stage and discharge of Snake Creek Canal at selected stations during this period are shown in figure 7.

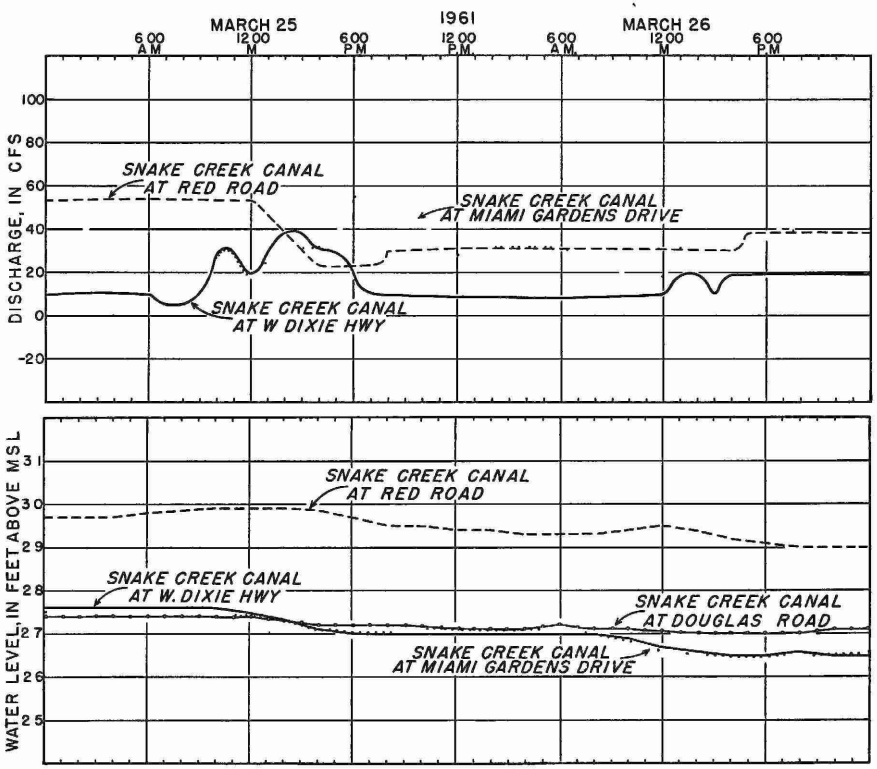



Fig. 7. Stage and discharge of Snake Creek Canal at selected stations on March 25-26, 1961, when the control was closed.

After the four bays of the control structure were opened at 10:15 a.m. on March 27, water-level fluctuations were measured in the observation wells, and continuous records of stage and streamflow were collected in Snake Creek Canal at West Dixie Highway, at Miami Gardens Drive, and at Red Road. The discharges measured on March 28 at the three stations along the canal during a tide cycle and near the time of opening (10:15 a.m. March 27) and closing (9:00 a.m. March 30) the control dam are shown in the following tabulation:

| Red Road | | Douglas Road | | Miami Gardens Drive | |
|---|---|---|---|---|---|
| | | March 27 | | | |
| Time | Discharge (cfs) | Time | Discharge (cfs) | Time | Discharge (cfs) |
| 12:10 p.m. | 639 | 11:00 a.m. | 637 | | |
| 2:40 p.m. | 706 | 12:10 p.m. | 1,010 | 12:20 p.m. | 2,310 |
| | | 1:35 p.m. | 1,010 | | |
| | | 2:55 p.m. | 960 | | |
| | | March 28 | | | |
| 9:50 a.m. | 333 | 8:05 a.m. | 240 | 8:40 a.m. | 189 |
| 12:05 p.m. | 496 | 10:30 a.m. | 516 | 10:35 a.m. | 1,130 |
| 1:45 p.m. | 550 | 1:30 p.m. | 780 | 11:40 a.m | 1,340 |
| 3:50 p.m. | 613 | 4:35 p.m. | 734 | 1:40 p.m. | 1,550 |
| | | March 30 | | | |
| 9:25 a.m. | 154 | | | 7:50 a.m. | —421 |
| 11:25 a.m. | 244 | | | (— indicated flow upstream) | |

Fluctuations of stage and discharge at four canal stations during the test period are shown in figures 8 and 9. Fluctuation of levels in selected wells and canal stations during the period March 25 and April 4 are shown in figure 10.

Starting near low tide at 1:30 p.m. on March 31, a 4½-hour flushing operation was conducted to remove the salt water that was trapped in the canal upstream from the salinity-control structure. This flushing operation was scheduled as part of the test because its effects are similar to those caused by normal operating procedures for removing debris from the canal. The abrupt changes in water level and discharge caused by this operation are shown in figure 9. The additional rise in water level and discharge during the morning of April 1 was caused by heavy rainfall in Area B.

## ANALYSIS OF DATA

### CHANGE IN STORAGE AND FLOW

Changes in storage and flow within the system depend chiefly upon: (1) the quantity of rainfall recharging the system, (2) the quantity of inflow from the Everglades by canals and by underflow, (3) operation of the control structure, and (4) tidal backwater in the canal.

The correlation of these factors is shown by the hydrographs in figure 6. Each heavy rainfall caused a corresponding rise of the water table and the canal stage, except in the lower reaches of the canal where levels generally are regulated by the control

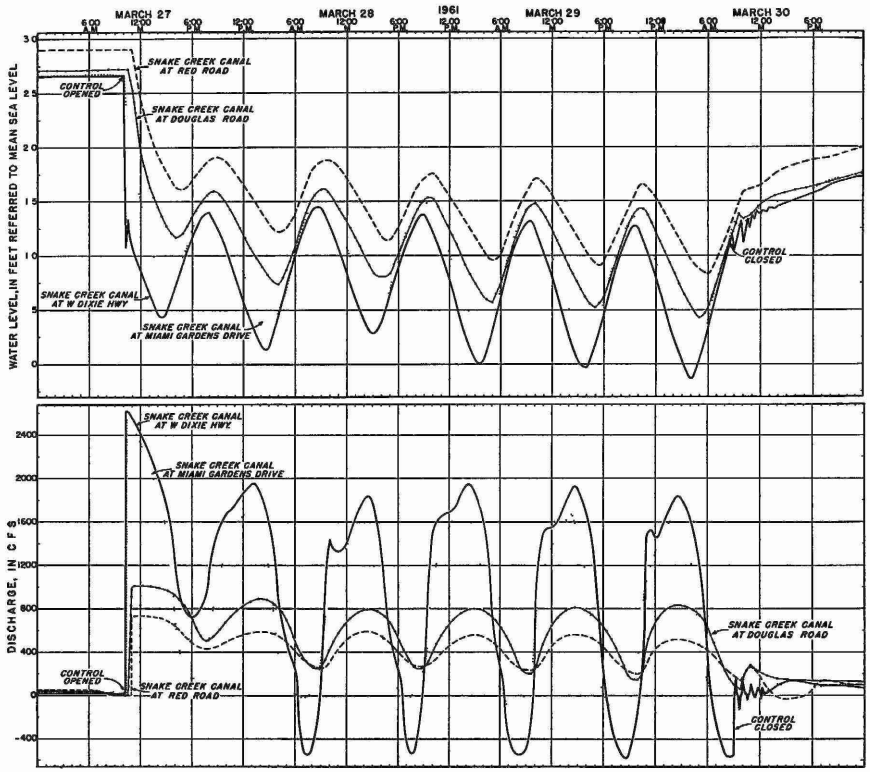



Fig. 8. Hydrographs of stage and discharge at selected canal stations during test March 27-30, 1961.

structure. During long periods of heavy rainfall, ground-water levels rise to 4 or 5 feet above msl in areas near the coast (wells G850 and D151). Water levels in areas near the coast decline rapidly as the rainfall decreases, but in upgradient areas the release of water from storage is slower (wells G72 and G970).

The quantity of ground-water inflow from the Everglades areas varies with the gradient toward the coast. During flood periods, the hydraulic gradient across Area B and the coastal ridge is initially slight because of high water levels underlying the ridge. However, as coastal ground-water levels decline, after the control is opened, large quantities of water from the west drain into the canal system and the aquifer. The control structure is kept open for long periods to discharge this excess water. The extension of Snake Creek Canal to the western edge of Area B, during October

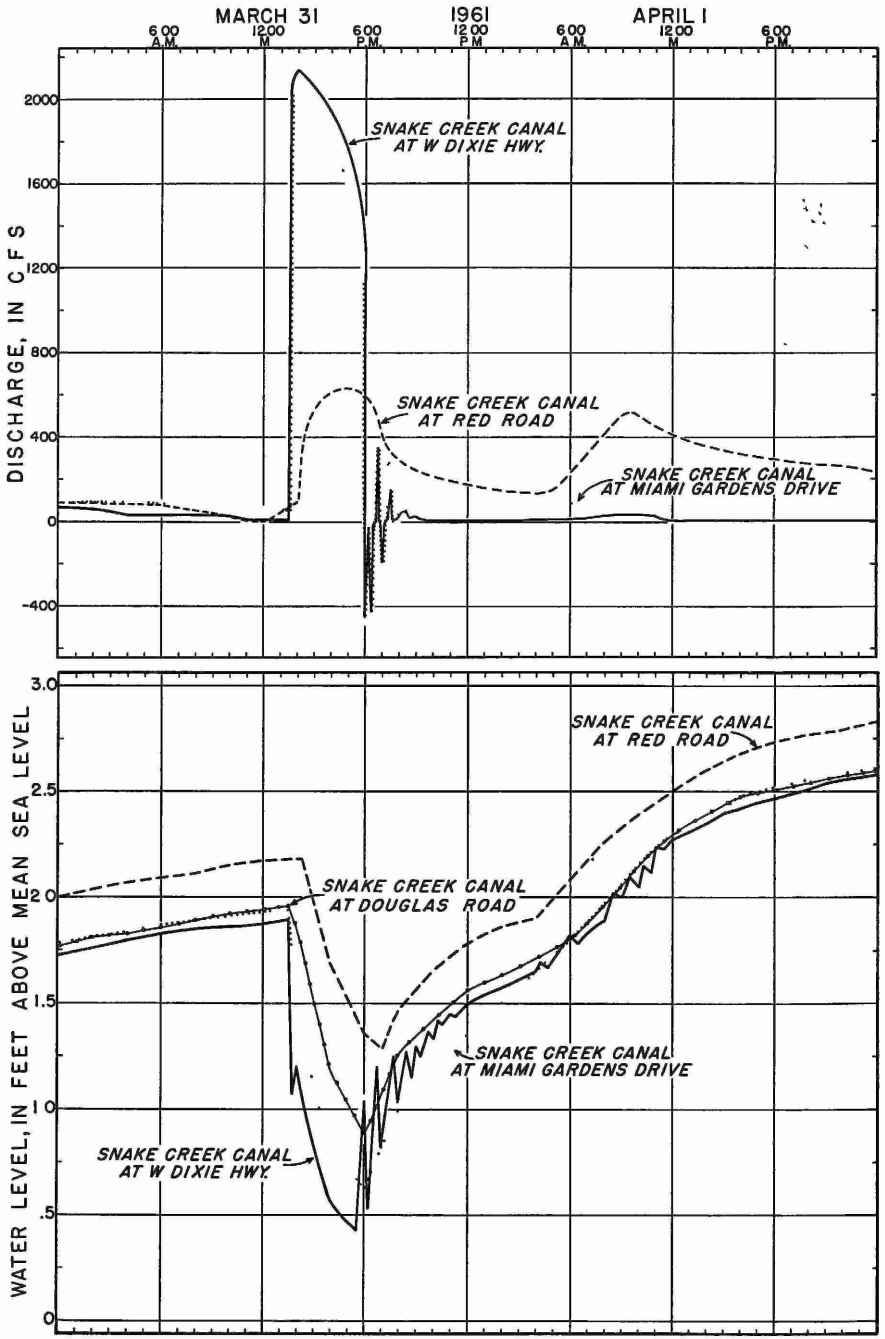



Fig. 9. Hydrographs of stage and discharge at selected canal stations during flushing operation March 31 to April 1, 1961.

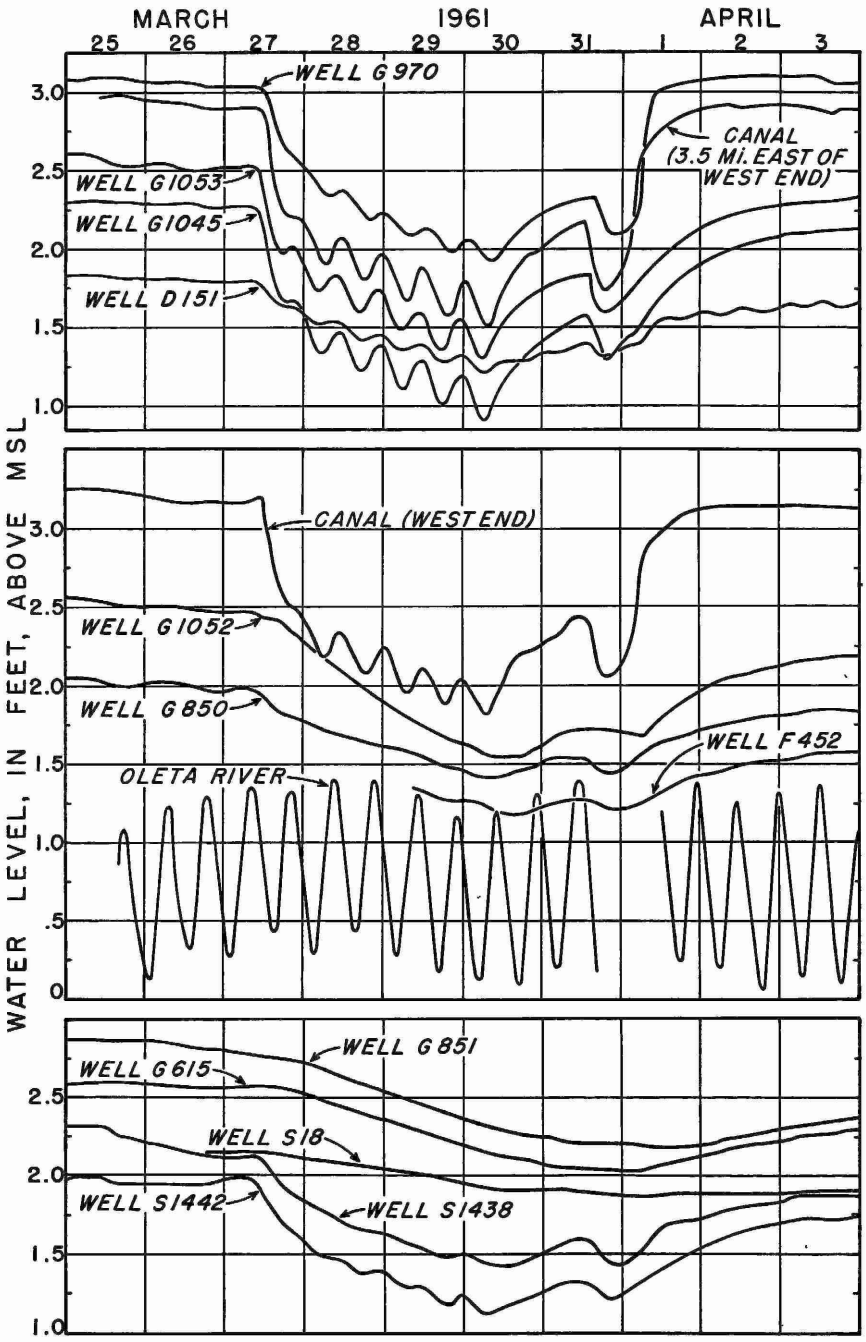



Fig. 10 Hydrographs of selected wells and canal stations March 25 to April 3, 1961.

1960, had a marked effect on water levels in that area as shown by wells G72 and G970 in figure 6. The water level in well G72 near the western end of the canal declined sharply when the canal was completed on October 28, 1960, and by the end of February 1961, had declined to less than 4.0 feet above msl. The gradient between well G72 and the control structure at this time was less than 1.5 feet in 17 miles, or 0.09 foot per mile. As the canal has been extended, higher flood discharges through the control structure will probably occur; however, the duration of high discharge should be shorter because of the more rapid drainage of Area B.

When the control structure is open, a large part of the system is affected by tides. The magnitude of the effect decreases upstream and depends upon the amount of the gate openings and the rate of discharge. Tidal fluctuations of 0.3 of a foot were observed at the western end of the canal during the test; however, when the control was open during flood periods prior to the test very little fluctuation occurred in the canal west of Red Road. Maximum discharge from the canal occurs 1 to 2 hours before low tide, and minimum discharge occurs at high tide (fig. 8). Figure 11, from Parker and others (1955, fig. 127), shows progressive changes of slope of the water surface, direction of flow, and changes in storage in a tidal canal.

The changes in flow and stage caused by opening or closing the control structure during the test correspond generally with the changes caused by a falling or rising tide, except for rate and magnitude. The extent of area affected within the flow system depends chiefly on the length of time the control structure remains open or closed, and the antecedent hydrologic conditions. The hydrographs in figure 10 indicate that a period of several days is required for water levels throughout the area to adjust fully when the control is open or closed. The hydrographs also show the effects of the difference in permeability between the sandy materials in the coastal ridge and the limestones underlying Area B. The water level in well G970, half a mile south of the canal and 15 miles inland, responds more readily to changes in canal stage than the water level in wells G1052 and S1442 which are closer to the canal within the coastal ridge.

The hydrographs in figure 7 show the canal discharges on March 25-26 when an average water level of 2.7 feet above msl was maintained at the closed control structure. A strong easterly wind was the chief factor contributing to variation of discharges. The

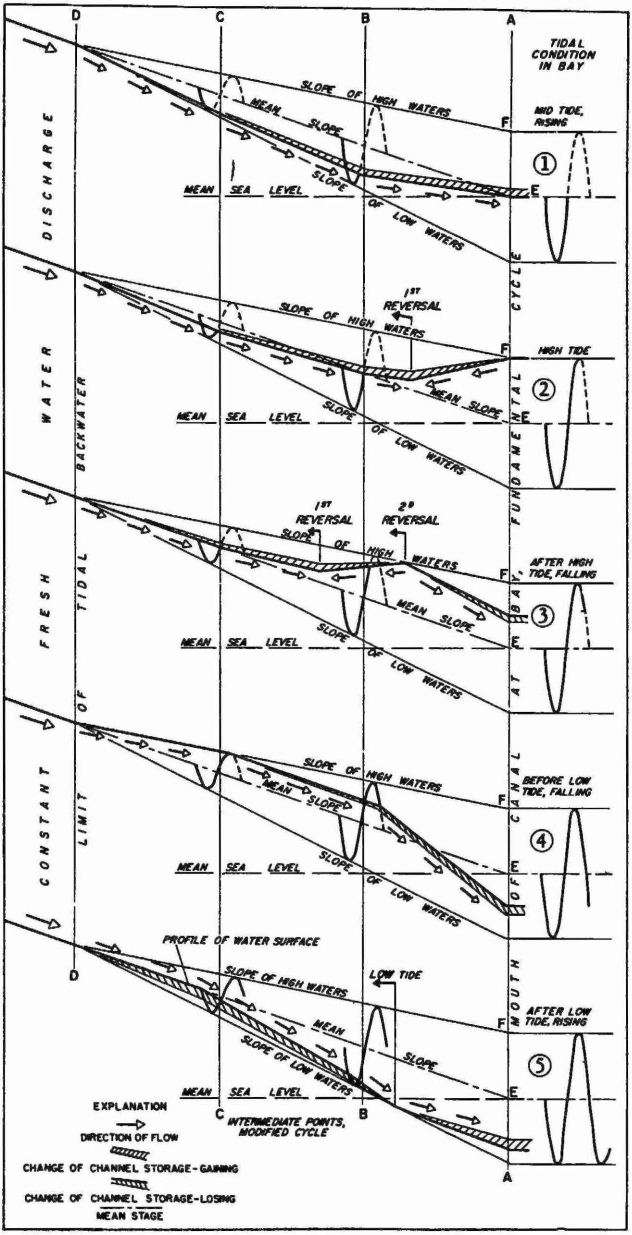



Fig. 11. Diagram of tidal backwater in a canal and progressive changes of slope, direction of flow, and changes in storage of a tidal canal (Parker and others, 1955, figure 127).

mean discharges at Red Road, Miami Gardens Drive, and West Dixie Highway for this period are shown schematically in figure 12. These discharges were 36, 32, and 16 cfs, respectively. The discharge of 36 cfs at Red Road represents the inflow required from Area B on March 25-26 to maintain the water level at 2.7 feet at the control. The measurements indicate that seepage from the canal to the aquifer increases rapidly in the reach between Miami Gardens Drive and the control structure.

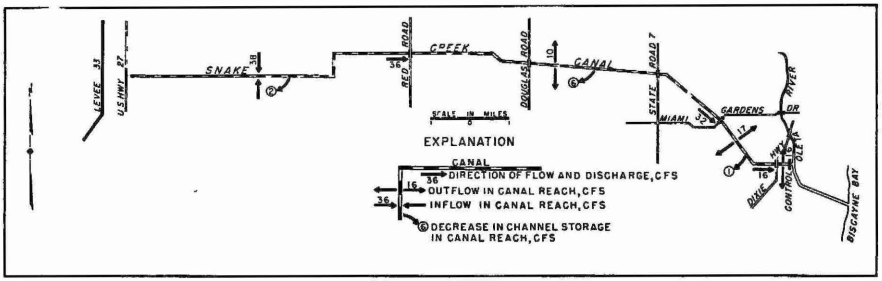



Fig. 12. Map of Snake Creek Canal showing mean flow regime, March 25-26. 1961.

The hydrographs in figure 8 give a comprehensive picture of the fluctuations of water levels and discharges in the flow system during the test period of March 27-30 when all four gates of the control structure were open. The gates were opened at 10:15 a.m. on March 27, at low tide, to induce the maximum possible change in water level and flow throughout the test area. The control structure was left open, as long as it was feasible to do so, to establish relatively stable drainage conditions within the flow system. The length of the period was limited by the rapid intrusion of salt water up the canal. The discharge at West Dixie Highway during each tide cycle on March 27-30, is shown in figure 8. The anomaly in the discharge graph at West Dixie Highway immediately preceding a tidal peak discharge, is probably related to the upstream movement of the salt-water wedge in the lower reach of the canal. The effect of this wedge on discharge is strikingly shown in figure 13 by the velocity profiles in a vertical section at midchannel of the canal.

The sharp oscillations in flow and water level (fig. 8, 9) were caused by the abrupt closing of the control.

The configuration of the water table on March 27 under relatively unchanging conditions before the opening of the control

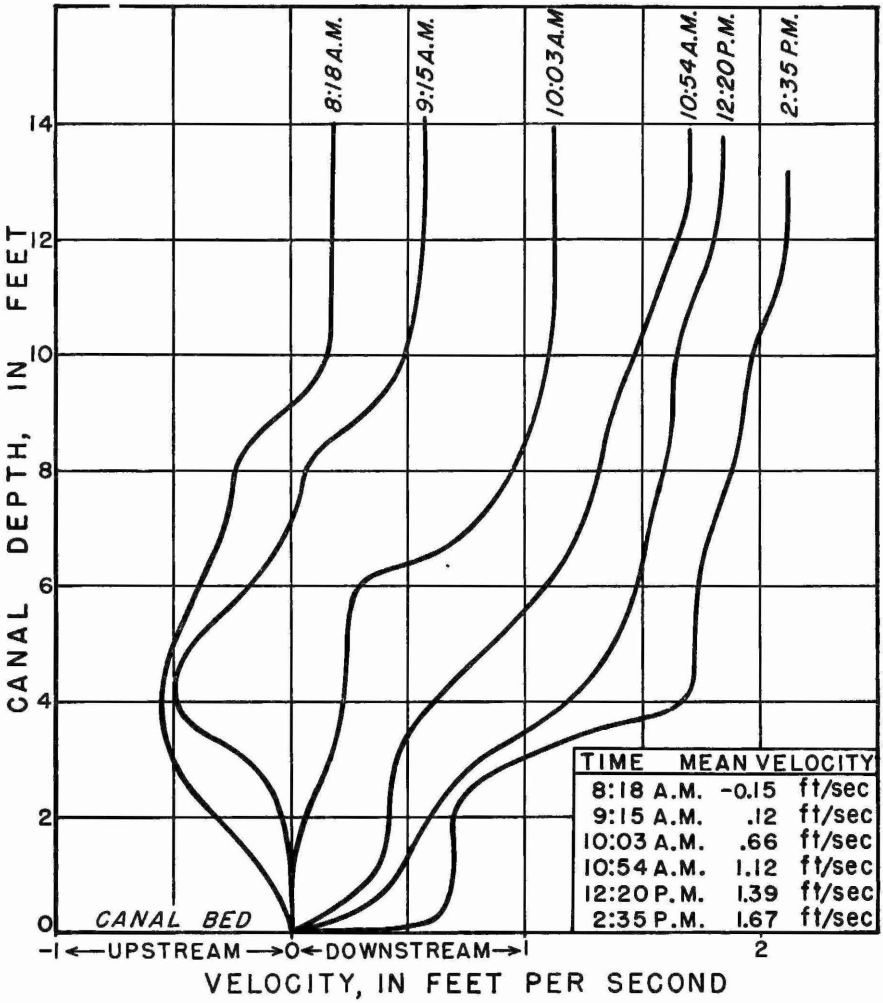



Fig. 13. Vertical velocity profiles in midchannel for Snake Creek Canal at West Dixie Highway on March 29, 1961.

structure, is shown by the contour map in figure 14. The ground-water gradients (fig. 14) and the canal discharges (fig. 12) on March 25-26, when the control structure was closed, indicate that water was entering the aquifer from the canal in all reaches east of Red Road. A comparison of the hydrographs of well G970 and the adjacent canal station in figure 10, shows the ground-water gradient in Area B to be toward the canal at this time. When the control structure is closed, the ground-water gradients are steepest and the seepage from the canal is greatest near the coast and

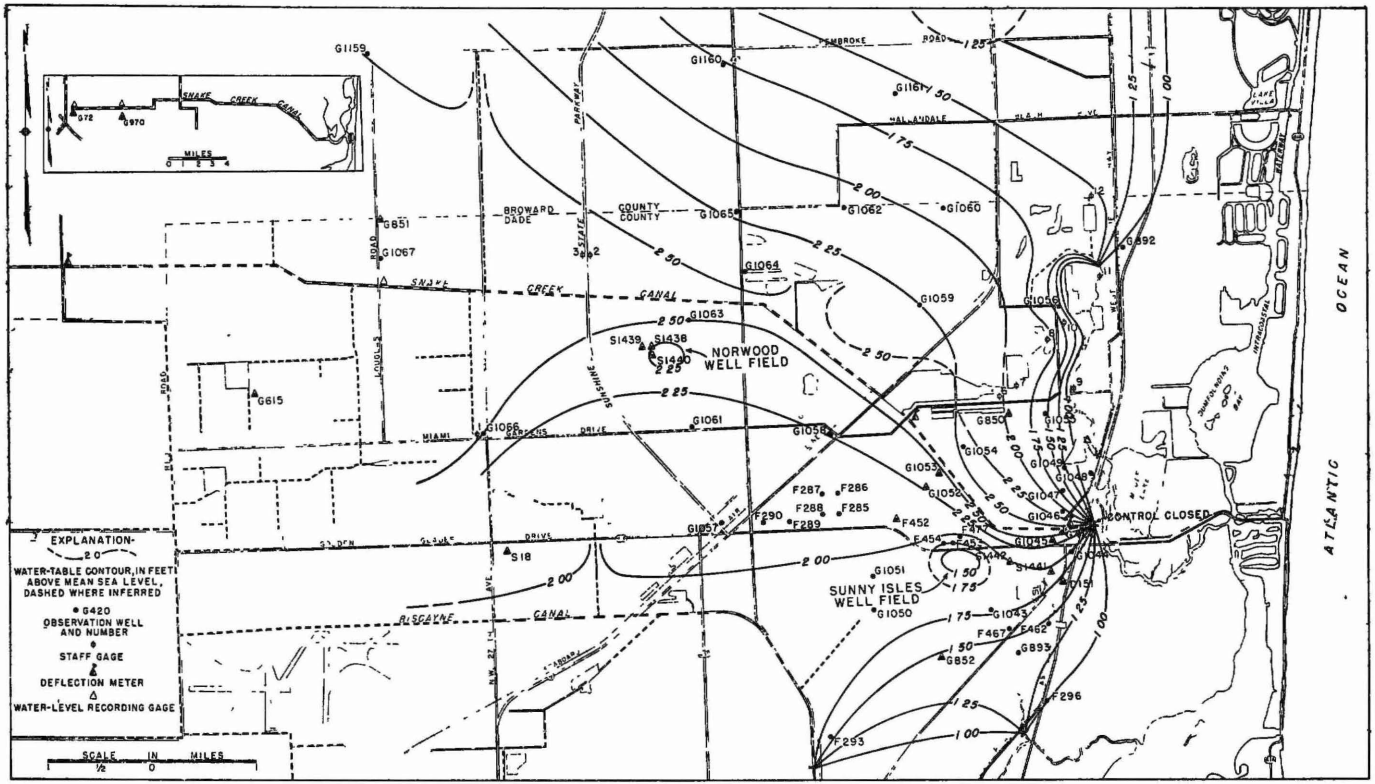



Fig. 14. Snake Creek Canal area showing contours on the water table, March 27, 1961.

through the area of limestone quarries between the canal and the Oleta River. In these areas the shallow materials are highly permeable.

As shown in figure 14 ground-water gradients south of the Snake Creek Canal are reduced by the effects of the controlled reach of the Biscayne Canal except in the area near the coast; north of the Snake Creek Canal the water table slopes northeastward toward the coast and toward the uncontrolled reach of South New River Canal in Broward County (fig. 1).

The secondary canals which connect Snake Creek Canal to the major canals of the regional water-control system (fig. 1) are highly constricted in many places and convey very little water, except during flood periods. Thus, it is evident that most of the water that enters the canal during extended dry periods is derived from ground-water storage in the western part of the coastal ridge (fig. 2) and in Area B.

The average flows and water levels which occurred when the control structure was open are shown in figure 15. The magnitude and direction of flow at any time can be obtained from the hydrographs in figure 8. The maximum and minimum discharges and water levels in the canal during this period are shown in figure 16.

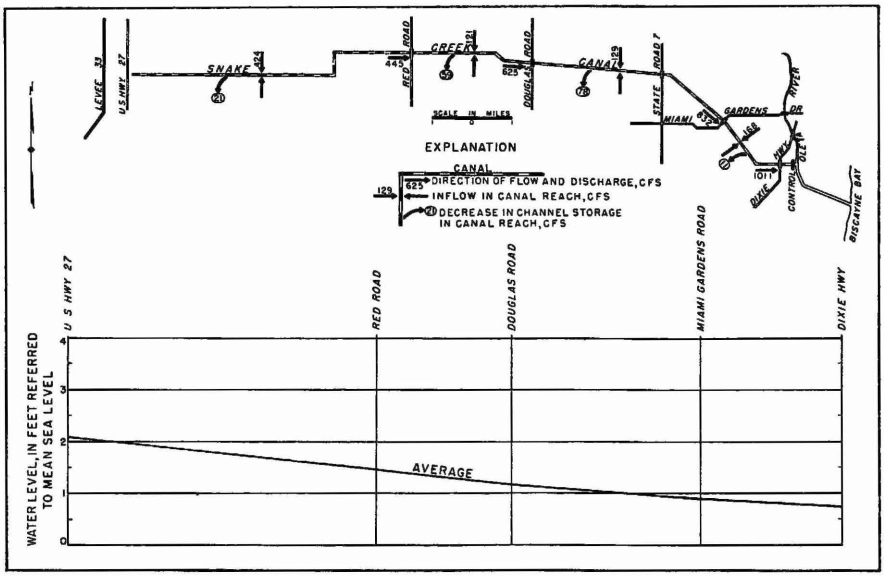



Fig. 15. Snake Creek Canal showing average flow regime and water-level profiles during March 27-30, 1961.

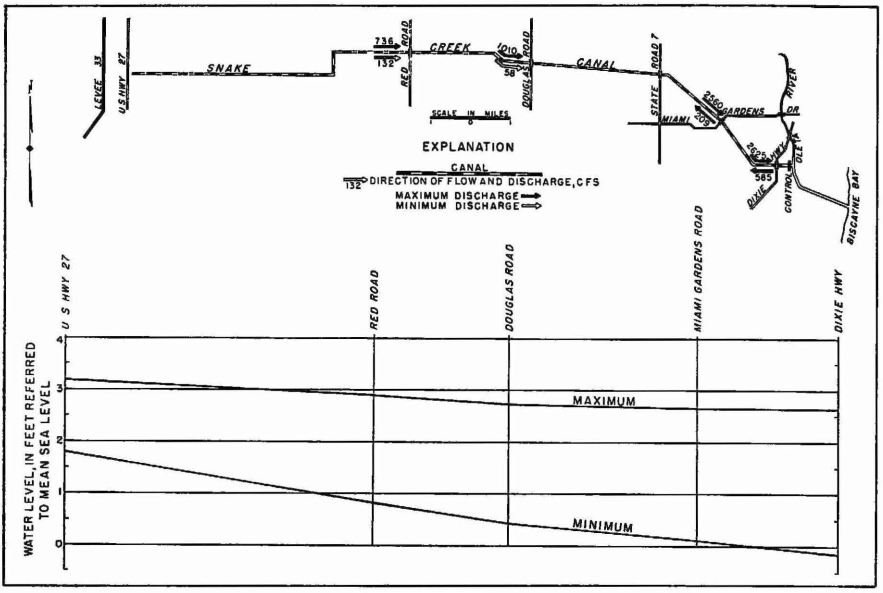



Fig. 16. Snake Creek Canal showing maximum and minimum discharge regimes and water-level profile during March 27-30, 1961.

Changes in storage in the canal occur as the water level changes. The quantitative amounts of these storage changes have been computed from the water-surface area and change in stage during the test period. The surface area changes very little with changes in stage because the side slope of these canals and rock pits are steep. The tabulation below includes the area of Snake Creek Canal and the connecting secondary canals and rock pits.

| Canal reach | Surface area, (square feet) |
|---|---|
| Control structure to West Dixie Highway | 171,000 |
| West Dixie Highway to Miami Gardens Drive | 1,280,000 |
| Miami Gardens Drive to Douglas Road | 9,872,000 |
| Douglas Road to Red Road | 8,238,000 |
| Red Road to U. S. Highway 27 | 3,485,000 |

The rate of change in canal storage was computed by the formula $Q_s = \frac{Ad}{t}$, where $Q_s$ is the discharge from storage, in cfs, A is the water-surface area in square feet, d is the average decline in water level, in feet, (static level at opening of control to mean tide level at closing), and t is the time in seconds of the period under consideration. The computations for the average discharge

from storage in the canal reach between the gaging stations for the period March 27-30 are, as follows:

West Dixie Highway to Miami Gardens Drive:

$$Q_s = \frac{Ad}{t} = \frac{1{,}280{,}000 \times 2.17}{254{,}700} = 11 \text{ cfs}$$

Miami Gardens Drive to Douglas Road:

$$Q_s = \frac{9{,}872{,}000 \times 2.00}{254{,}700} = 78 \text{ cfs}$$

Douglas Road to Red Road:

$$Q_s = \frac{8{,}238{,}000 \times 1.82}{254{,}700} = 59 \text{ cfs}$$

Red Road to U.S. Highway 27:

$$Q_s = \frac{3{,}485{,}000 \times 1.52}{254{,}700} = 21 \text{ cfs}$$

The mean discharges for the test period March 27-30 at West Dixie Highway, Miami Gardens Drive, Douglas Road, and Red Road were 1,011, 832,625, and 445 CFS, respectively, as shown in figure 15. The discharge at Red Road, 445 cfs, was the average inflow from the Everglades and Area B.

The average ground-water inflow along reaches between the canal discharge stations was computed by the following formula: $Q_g = Q_1 - Q_2 - Q_s$, where $Q_g$ is the inflow from the aquifer, in cfs, $Q_1$ is the discharge at the downstream station, in cfs, $Q_2$ is the discharge at the upstream station, in cfs, and $Q_s$ is the discharge from (decrease in) the canal storage, in cfs, from a foregoing paragraph. The computations of the mean ground-water inflow in the canal reach between the gaging stations are shown in figure 15 and are as follows:

West Dixie Highway to Miami Gardens Drive:
$Q_g = Q_1 - Q_2 - Q_s = 1{,}011 - 832 - 11 = 168$ cfs
Miami Gardens Drive to Douglas Road:
$Q_g = Q_1 - Q_2 - Q_s = 832 - 625 - 78 = 129$ cfs
Douglas Road to Red Road:
$Q_g = Q_1 - Q_2 - Q_s = 625 - 445 - 59 = 121$ cfs
Red Road to U.S. Highway 27
$Q_g = Q_1 - Q_2 - Q_s = 445 - 0 - 21 = 424$ cfs

The configuration of the water table on March 29 before the closing of the control is shown in figure 17.

The sharp decline of the water level in the canal after the opening of the control caused ground-water inflow to the canal in all

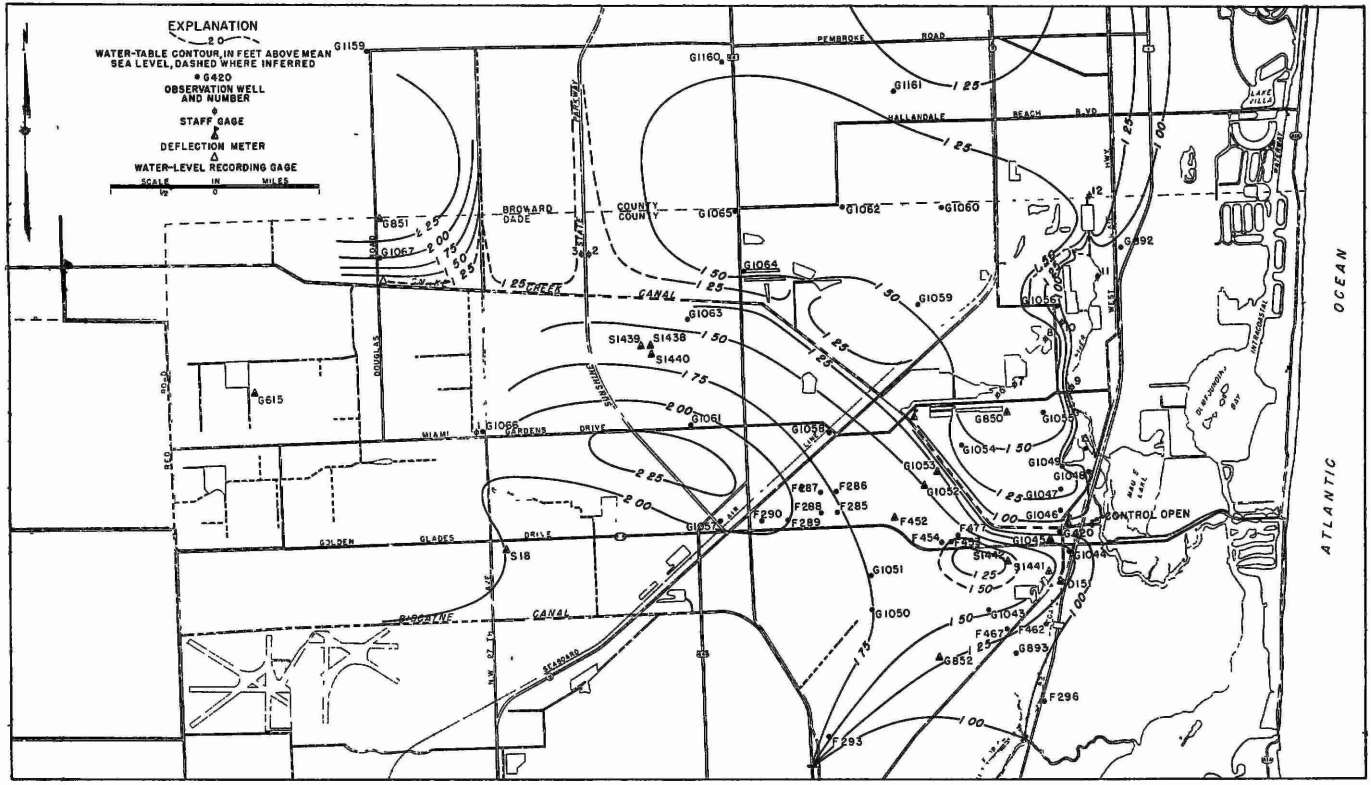



Fig. 17. Snake Creek area showing contours on the water table, March 29, 1961.

reaches (fig. 10, 17). The hydrographs in figure 8 indicate that the discharge at each gaging station in the canal declined very slowly during the test period. This was because of the sustained inflow of ground water. However, if the control structure were left open for an extended period, ground-water storage would be depleted, and the discharge in the canal would decline steadily.

## AQUIFER COEFFICIENTS

The principal hydraulic properties of an aquifer may be expressed as coefficients of transmissibility (T) and storage (S). The coefficient of transmissibility is defined as the amount of water, in gallons per day, at the prevailing temperature, transmitted through a 1-foot strip of saturated thickness of the aquifer under a hydraulic gradient of 1 foot per foot. The coefficient of storage is defined as the unit volume of water released from, or taken into, storage per unit surface area of aquifer per unit change in the component of head normal to that surface.

Two short aquifer tests were conducted to define the aquifer coefficients in the vicinity of the Norwood and Sunny Isles well fields of the City of North Miami Beach. In addition, the approximate coefficient of transmissibility in several areas along the canal was computed by a method involving the cyclic fluctuation of ground-water levels caused by tides in the canal.

The two aquifer tests were made by pumping selected municipal supply wells in the well fields (fig. 14) and observing the drawdown of water levels in nonpumping supply wells and in observation wells. The supply wells are developed in beds of highly permeable limestone that are overlain by 60 to 100 feet of less permeable sandy limestone and sand. The layout of the wells in the Sunny Isles well field and the drawdown of water level in selected wells during various pumping conditions are shown in figure 18.

The drawdown data collected during the aquifer tests were adjusted to correct for fluctuations caused by factors other than pumping—chiefly, a steady rise in regional water levels caused by operation of the salinity control— and were analyzed by use of a family of leaky aquifer-type curves developed by H. H. Cooper, Jr., U. S. Geological Survey, from a method outlined by Hantush (1956). This method provides a means to compute the values of the coefficients of transmissibility and storage of the producing zones, and the coefficient of leakage of the less permeable beds that overlie the producing zone. The coefficient of leakage may be

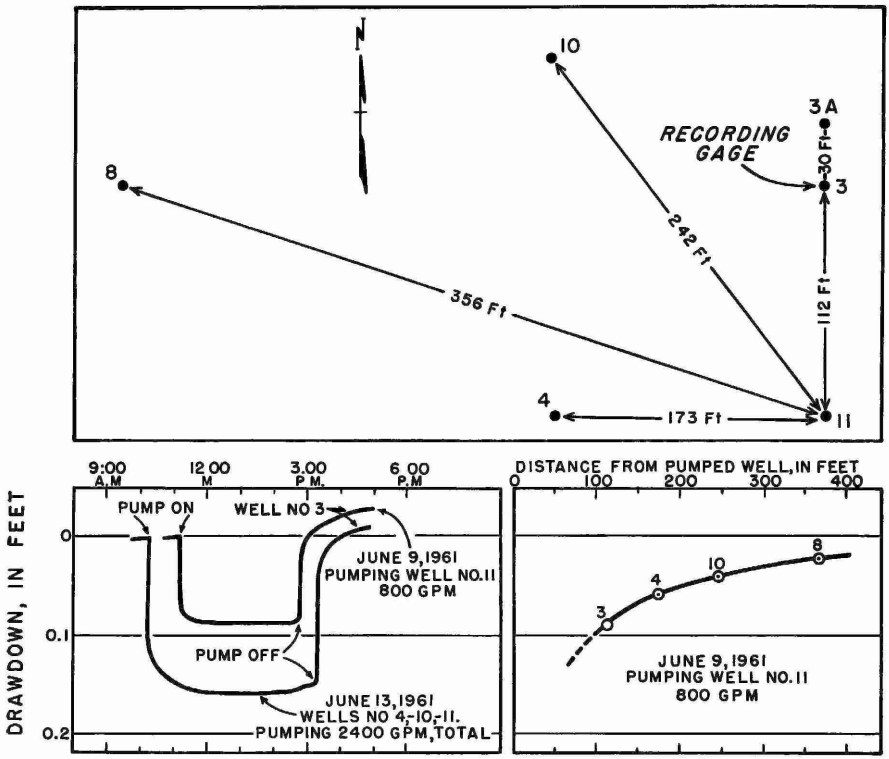



Fig. 18. Sketch showing selected wells in the Sunny Isles well field and graphs showing drawdown in water levels under various pumping conditions.

defined as the quantity of flow that crosses a unit area of the interface between the main aquifer and its semiconfining bed if the difference in head between the main aquifer and the beds supplying the leakage is unity. Although the characteristics of the aquifer do not ideally match the theoretical conditions assumed in this method of analysis, the determined coefficients provide valuable indications of the capacities of the aquifer.

The computed coefficient of transmissibility and storage for the well field areas ranged from 2.0 to 2.5 mgd per foot and 0.1 to 0.2, respectively, and the coefficient of leakage ranged from 20 to 30 gpd (gallons per day) per square foot per foot of head differential. The magnitude of the leakage coefficient indicates that the drawdown caused by long-term pumping would be reflected at the water table and that infiltration would occur readily from surface water sources such as the Snake Creek Canal.

The configuration of the water table between the Sunny Isles well field and the canal in figure 14 indicates that water was flowing from the canal toward the well field at that time. During extended periods of drought and heavy pumping, a large part of the water withdrawn from this well field would be derived from the canal and, as a result, the drawdown in the well-field area would be minimized. Thus, the possibility of maintaining the well field, which is near the coast and close to the salt front in the aquifer, is largely dependent upon the effectiveness of the water-control system to maintain the canal level high enough to prevent further intrusion of salt water. The proximity of the salt front in the aquifer is indicated by the chloride content of more than 8,000 ppm (parts per million) in water samples collected at a depth of 57 feet below the land surface in well D151 (fig. 14).

The tidal data collected from wells near the canal were analyzed by a method which relates the time lag and stage efficiency of the tidal fluctuations in the aquifer and the canal to the value of T/S for the aquifer (Ferris 1951). An approximate value for T was computed using values for S determined by the pumping test methods and by examination of well-log data. The equation relating the transmissibility of the aquifer to the ratio of the range of ground-water level fluctuation to the range of the tidal fluctuation in the canal can be simplified if the range ratio is plotted on a logarithmic scale against the distance from the suboutcrop to the observation well on an arithmetic scale. Then the equation may be written as follows:

$$T = \frac{4.4\ x^2\ S}{t_0}$$

T = coefficient of transmissibility, in gallons per day per foot
S = coefficient of storage (dimensionless)
$t_0$ = period of the stage fluctuation, in days
x = distance with the observation well to the surface-water contact with the aquifer (suboutcrop), in feet
x = change in x over one log cycle

The equation relating the time lag between the occurrence of a given tidal peak or trough in a well and the corresponding state in the canal to the value of T/S for the aquifer can be written

$$T = \frac{0.6x^2t_0S}{t_1^2}$$ Where $t_1$ is the lag in time, in days.

Tidal data from selected wells, and computations using both methods are shown in figure 19. In both cases the effective distance to the offshore outcrop is assumed to be half the canal width (60 feet). The error introduced by this assumption would be small

because the width of the canal is small in comparison to the distance to the observation wells. In theory, however, the intercept of the line established by the plotted data with the line of zero time lag, or 100 percent stage efficiency, would indicate the distance from the shoreline to the outcrop.

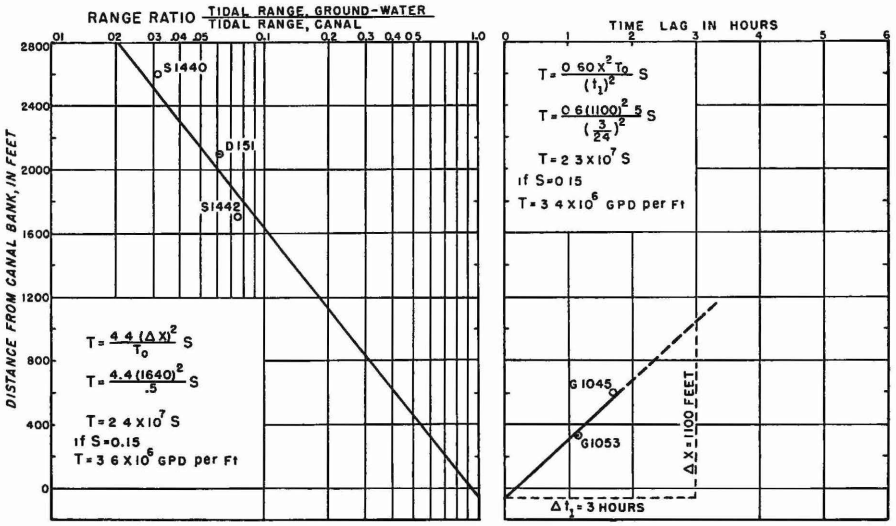



Fig. 19. Graphs showing relation between tidal fluctuations in Snake Creek Canal and selected wells.

Coefficients of transmissibility computed by these methods (fig. 19) were about 3.5 mgd per foot within the coastal ridge. This value is appreciably higher than those computed from aquifer test data (2.0 to 2.5 mgd per foot) and probably not as reliable, but provides a useful indication of the capacity of the aquifer, if no other data were available. Computations based on tidal data from well G970 in Area B, for example, indicate a coefficient of transmissibility of more than 5.0 mgd per foot. This value seems high for an area where the aquifer is only 75 feet thick (Schroeder, 1958), but it is supported by both the known occurrence of highly permeable materials in that area and by studies of underflow along Levee 30 in the western edge of Area B where Klein and Sherwood (1961) indicate a coefficient of transmissibility of 3.6 mgd per foot where the aquifer is only 55 feet thick.

The high permeability of the aquifer and excellent interconnection between the canal and the aquifer in Area B indicate that this reach of the Snake Creek Canal system would be a highly

desirable area for the location of large future well fields. Withdrawals as high as 200 mgd are proposed from well fields of Metropolitan Dade County in the western part of the Snake Creek area by the year 2000. During dry periods these well fields will be largely dependent on recharge by induced infiltration from a network of secondary canals connected to Snake Creek Canal.

## SUMMARY

The Snake Creek Canal drains the northern part of the Greater Miami area and is the main drainage canal for the northern part of Area B. Flow in the canal is maintained chiefly by the inflow of ground water, but considerable surface runoff is introduced from low areas on the coastal ridge and from Area B during flood periods. Canal discharge is regulated by a control structure near Biscayne Bay to provide maximum flood protection and to main maintain water levels high enough to retard salt-water encroachment during dry periods.

The area crossed by the Snake Creek Canal is underlain by the highly permeable Biscayne aquifer, which extends from the surface to a depth of 200 feet at the coast and about 55 feet at the western end of the canal. Natural drainageways that connect Area B with Biscayne Bay are bottomed by several feet of material of relatively low permeability.

Ground-water levels can be effectively raised or lowered throughout the drainage area by manipulation of the control structure. When the control structure is open, ground water flows toward the canal and the canal flow increases toward the bay. When the control structure is closed canal levels near the coast are generally higher than ground-water levels and appreciable ground-water recharge from the canal occurs.

Information collected during a test on March 25-26, 1961, indicated that an inflow of 36 cfs from Area B was required to maintain a water level of 2.7 feet above msl near the coast when the control structure was closed. Ground-water gradients and canal discharges indicate the canal was recharging the aquifer throughout the system east of Red Road under these conditions. The secondary canals which connect Snake Creek Canal to other major canals of the regional water-control system are constructed in many places and convey very little water except during flood periods. Thus, most of the water entering the canal during extended dry periods is derived from ground-water storage in the western part of the coastal ridge and in Area B. When the control

structure was open, approximately 45 percent of the flow through the control structure was contributed by Area B.

Ground-water hydraulic studies conducted by aquifer test methods and by tidal fluctuation methods indicate coefficients of transmissibility ranging from about 2.5 mgd per foot within the coastal ridge to more than 5.0 mgd per foot in Area B. The difference in transmissibility is caused by the presence of greater quantities of sand in the thick section of the aquifer underlying the coastal ridge, whereas, in Area B the aquifer is composed entirely of solution-riddled limestone.

Because of the excellent interconnection between the canal and the permeable aquifer in Area B, future well fields withdrawing as much as 200 mgd are planned by Metropolitan Dade County in the western part of the Snake Creek Canal area. These proposed fields would be important because withdrawals would be largely derived from Snake Creek Canal during dry periods and they would greatly exceed the present losses from the canal. The continuing changes in water control and withdrawals for water supply will alter the flow within the system and greatly increase the quantity of water required to maintain the desired levels in Snake Creek Canal. This study was limited in scope to the conditions existing at this time. However, the data presented will provide a basis for the analysis of the effects of major changes in the flow system and of the quantity of water needed in the future.

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STATE OF FLORIDA
STATE BOARD OF CONSERVATION
DIVISION OF GEOLOGY

FLORIDA GEOLOGICAL SURVEY

Robert O. Vernon, *Director*

REPORT OF INVESTIGATIONS NO. 24
PART IV

# SALT-WATER MOVEMENT CAUSED BY CONTROL-DAM OPERATION IN THE SNAKE CREEK CANAL, MIAMI, FLORIDA

By
F. A. Kohout and S. D. Leach
U. S. Geological Survey

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

Tallahassee
1964

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## LETTER OF TRANSMITTAL




# *Florida Geological Survey*

*Tallahassee*

October 10, 1963

Honorable Farris Bryant, *Chairman*
Florida State Board of Conservation
Tallahassee, Florida

Dear Governor Bryant:

The Florida Geological Survey has published four short papers as Parts 1, 2, 3, and 4 of Report of Investigations No. 24. This publication, Part 4, is the last of these brief papers and discusses the "Salt-Water Movement Caused by Control-Dam Operation in the Snake Creek Canal, Miami, Florida." The report was prepared by F. A. Kohout and S. D. Leach, hydrologists for the United States Geological Survey.

The principles of the relationships of fresh and salt water in the Biscayne aquifer and the movement of the salt-water, fresh-water contact along the canals and in the aquifer, with use, with development of the control stations in the Central and Southern Florida Flood Control District, and in response to cyclic changes in the weather, are of great importance in understanding similar occurrences. These four reports present interesting details of these relationships.

Respectfully yours,

Robert O. Vernon
*Director and State Geologist*

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# SALT-WATER MOVEMENT CAUSED BY CONTROL-DAM OPERATION IN THE SNAKE CREEK CANAL, MIAMI, FLORIDA

By
F. A. Kohout and S. D. Leach

## ABSTRACT

Movement of salt water in the Biscayne aquifer and the Snake Creek Canal was investigated to establish criteria for operation of the salinity-control dam in the canal. All four gates of the dam were opened for 3 days during a special test in March 1961. Although salt water oscillated landward and seaward a distance of 2 miles from the control in response to tide, the salinity of the ground water near the canal did not change greatly during this time. Salt water trapped in the canal by closing the dam at high tide moved landward as a density current at a rate of about 900 feet per hour and began to flow into a connected deep rock pit. A flushing operation removed salt water from the canal but the salt water in the rock pit remained. During subsequent months, wind and tide action caused upward dispersion of salt into the uppermost water of the rock pit, and the trapped salt water was gradually removed by seaward discharge through the canal.

Some of the salt water trapped in the canal moved into the aquifer. This salty water was traced by sampling fully cased wells of different depths and distances from the canal. Some of the salty water was retrieved by drainage from the aquifer when the gates were partially opened 2 months after entrapment. Because of its relatively great density some of the salt water moved downward in the aquifer and was not retrieved.

The data show the negative effects of trapping salt water, and also that the control can be closed gradually without trapping salt water. If the total opening of the control is distributed uniformly among the four partially closed gates, the increased velocity of the fresh water as it flows under the submerged sluice gates, will impede upstream movement of salt water at the bottom of the control. Calculations indicate that salt water probably will not move upstream in the canal if a head of 0.3 foot is maintained between upstream and downstream sides of the control at the time of minimum head differential, about 2 hours before high tide.

## INTRODUCTION

This report gives detailed attention to the movement of salt water in and adjacent to the Snake Creek Canal in the northern part of the Miami area, Florida (fig. 1). The movement results primarily from operations of a salinity-control dam located near the mouth of the canal.

From 1909 to 1930, canals were constructed westward from the coast through the Miami area into the Everglades to drain low-lying land for urban and agricultural use. The uncontrolled canals caused overdrainage. The water table was lowered nearly to sea level in some areas and this caused salt water to encroach into the Biscayne aquifer by two processes (Parker, 1951, p. 826):

(1) Where the water table was lowered greatly, salt water moved horizontally landward from the ocean through the highly permeable solution-riddled limestone of the Biscayne aquifer to replace the drained fresh water.

(2) Salt water moved directly inland in the canals where, because of its greater density, it tended to leak downward and laterally to contaminate the underlying fresh ground water.

Although the end result of these separate processes is the same, they attack the fresh-water resources from different directions and occur at different rates. The general aim of this report is to establish the conditions under which each process provides the greater danger of salt-water contamination.

## HISTORY

In 1945, salinity-control dams were installed in most of the canals of the Miami area as barriers against further encroachment of salt water. These were emergency dams constructed by driving sheet-steel piles into the limestone. The dams were opened and closed by removing some or all of the piles during the rainy season and replacing them during the dry season. This was an inefficient procedure which frequently resulted in the dams being left open much longer than necessary.

In recent years, the emergency dams have been replaced by permanent concrete structures with submerged sluice-gate openings. The control structure S-29 (Snake Creek Canal) is representative of some of the more recent structures. Each of the four gates, figure 2, is connected through a gear box to rollers which are driven by the rear-wheel drive of an anchored automobile. In the most recently contructed controls, in the Little River and

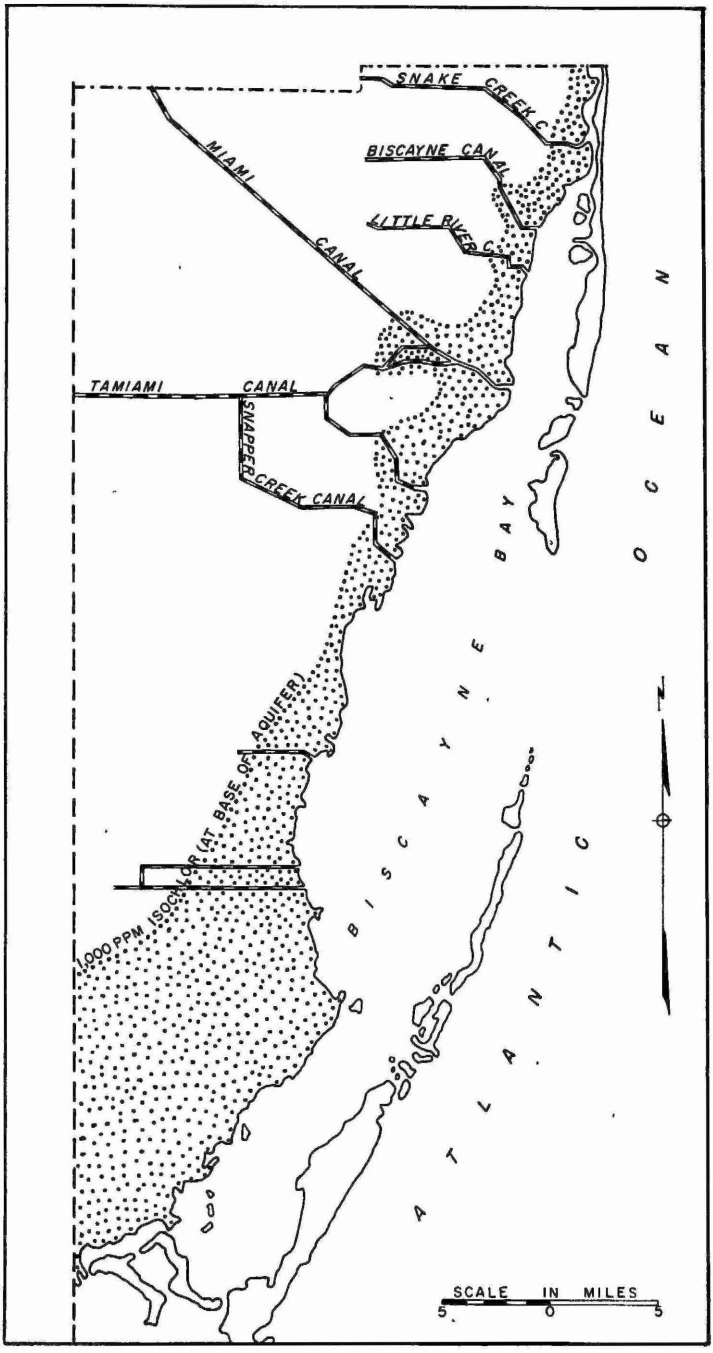



Figure 1. Miami area, Florida, showing the approximate landward extent of salt water at the base of the Biscayne aquifer in 1961.

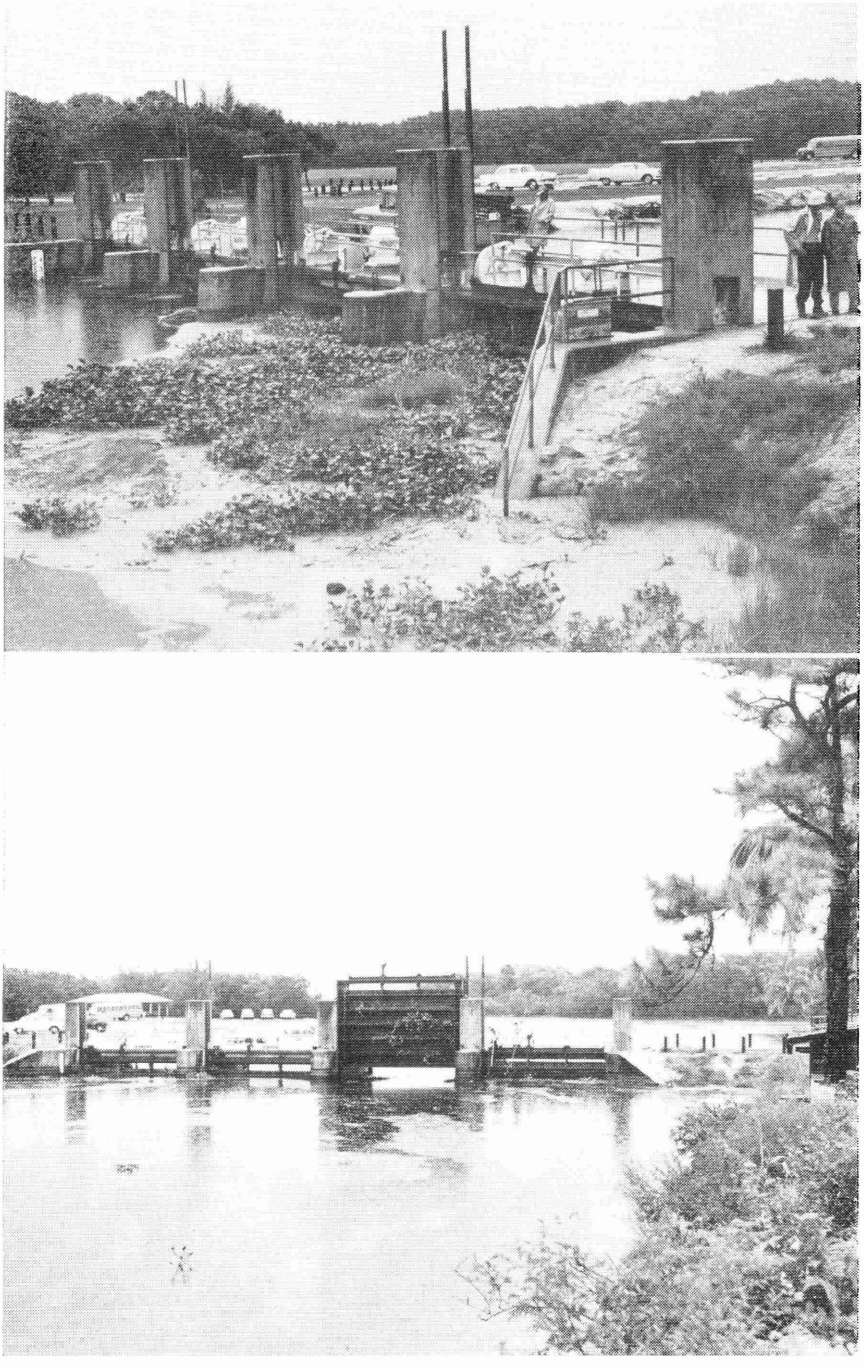


Figure 2. Photographs of the salinity-control dam (S-29) in the Snake Creek Canal: (a) with right-handgate opened 1 foot; (b) with one gate fully open.

Biscayne Canals, electric motors raise and lower the gates automatically by sensing the water levels upstream and downstream from the control dam. These automatically operated dams permit delicate control of water levels. However, the relation of salt-water movement to head differential needs further study before fresh-water resources can be effectively entrusted to automatic head-activated devices. As will be shown later, the relations of head and salt-water movement are very complicated and transient, and much more study and experience should be accumulated before true automatic control is attempted.

## PURPOSE OF INVESTIGATION

Frequently, after heavy rainfall, headwater areas of the Snake Creek Canal remain flooded at the same time that fresh-water discharge at the control dam is not sufficient, with fully open gates, to keep the canal flushed of salt water. Under these circumstances salt water moves upstream in the lower reaches of the canal and contaminates the fresh ground water.

Questions had arisen as to the magnitude of this encroachment, the extent to which the encroachment might be tolerated during gate openings, and the feasibility of flushing the salt water out later when the gates were closed after flooding subsided. Accordingly, goals of the investigation were to establish the time-rate of movement of the salt water for various circumstances of dam operation and, if possible, to develop principles that might have practical application not only in the operation of the salinity-control dam in the Snake Creek Canal but also in other canals of the area.

The investigation was made in cooperation with the Central and Southern Florida Flood Control District (C&SFFCD). Most of the data were collected between October 1960 and January 1962. The investigation was under the general supervision of M. I. Rorabaugh and, subsequently, C. S. Conover, Tallahassee, A. O. Patterson and K. A. Mac Kichan, Ocala, district engineers respectively of the Ground Water, Surface Water and Quality of Water Branches, U.S. Geological Survey. The investigation was under the immediate supervision of Howard Klein, geologist-in-charge, Ground Water Branch, and J. H. Hartwell, engineer-in-charge, Surface Water Branch, Miami.

## LOCATION AND EXTENT OF AREA

The Snake Creek Canal extends about 18 miles inland to the vicinity of Levee 33, on the east side of Conservation Area 3 (Inset map, fig. 3). Under the plans of the C&SFFCD (the operating agency) and the U. S. Corps of Engineers (the constructing agency), Conservation Area 3 will impound water pumped westward from urbanized areas during the rainy season. During the dry season, water stored in the conservation area will be delivered coastward to maintain water levels, thus preventing salt-water encroachment and providing replenishment water for municipal and private well systems.

This report covers the seaward reach of the Snake Creek Canal (Canal C-9) extending about 15,000 feet westward from the salinity-control dam (structure S-29). The width of the area extends 200 feet on either side of the centerline of the canal, but

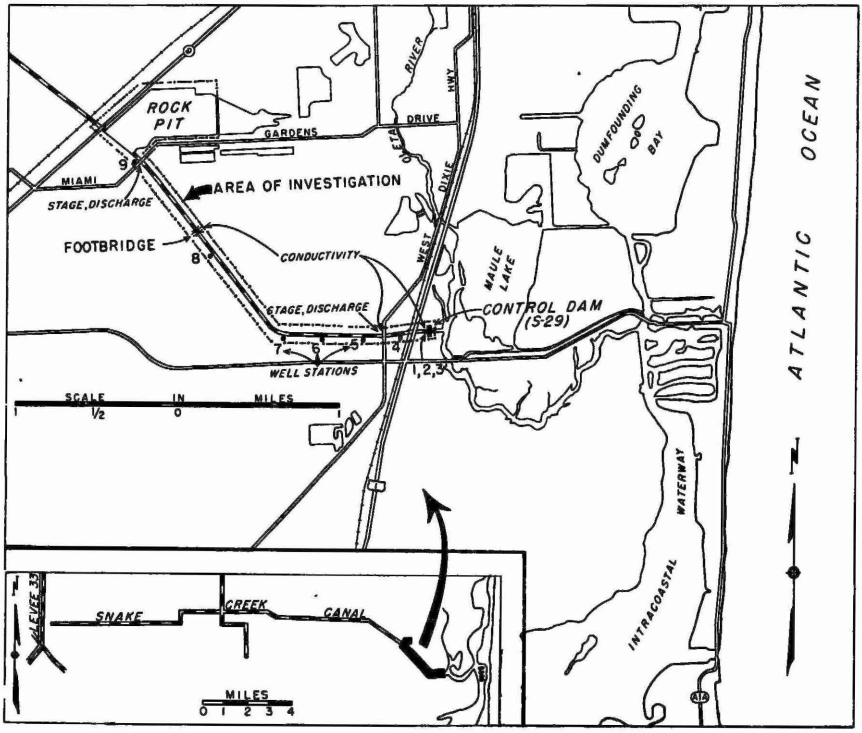



Figure 3. Northern part of the Miami area showing observation points along Snake Creek Canal.

as one side should be the mirror image of the other, work was confined to the south bank of the canal. The canal widens into a lake whose dimensions are about 3,500 by 1,700 feet at the western end of the area of investigation, between State Highway 9 and Miami Gardens Drive (fig. 3). The lake, formed by removal of rock for concrete aggregate and other building materials, has a maximum depth of 40 feet below msl (mean sea level) and was included in the investigation because of its important influence on salt-water contamination.

## CLIMATE

The climate of the Miami area is subtropical. The average temperature for January is about 68°F and for July about 82°F. Rainfall averages about 60 inches per year, three-quarters of which falls in the May to November rainy season.

In relation to this investigation, 1960 was unusually wet with rainfall of about 75 inches, 25 inches falling in September when hurricane Donna and tropical storm Florence passed nearby. The year of 1961 was unusually dry; the rainfall amounted to about 42 inches.

## PREVIOUS INVESTIGATIONS

Some phases of the present study coincided with, and were contemporaneous with, a study of the general hydrology of the Snake Creek Canal area by Leach and Sherwood (1963). Where data and graphs were applicable to the present report, they were used freely without acknowledgment.

Reports by Parker (1951), Parker, Ferguson, and Love (1955), and Kohout (1961) give much background information on the influence of drainage canals on salt-water encroachment in the Miami area. Many other reports cover the hydrology of the area and may be found in the "List of Publications" of the Florida Geological Survey in Tallahassee.

## PERSONNEL AND ACKNOWLEDGMENTS

Thanks are extended to the Dade County Office of Water Control, especially to John Wilhelm, for furnishing rainfall and gate-opening data. Robert L. Taylor of the C&SFFCD aided by making available the facilities and personnel of his organization during the special test period of March 1961.

Electrical-conductivity measurements of water in the canal during the test period of March 1961 were made under the direction of R. N. Cherry of the U. S. Geological Survey, Ocala. Other Geological Survey personnel who contributed materially were B. F. Joyner of Ocala and C. B. Sherwood of Miami.

## GEOLOGY AND DRAINAGE

The Biscayne aquifer of the Miami area is a highly permeable water-table aquifer consisting of solution-riddled limestone and calcareous sandstone with fairly frequent layers of unconsolidated sand. The generalized lithologic characteristics in wells drilled during the investigation are shown in figure 4.

Except for the peat and muck deposits at the surface, the sediments were deposited during the Pleistocene glacial epoch. Accumulation of snow and ice during glacial advances in the northern latitudes removed water from the oceans and lowered sea level. Alternately, melting of the glaciers returned water to the oceans and caused sea level to rise. The alternation of limestone and sandstone beds in figure 4 relates to these fluctuations of sea level—estimated by Cooke (1939, p. 34) to have ranged from about 270 feet above to 300 feet below present sea level.

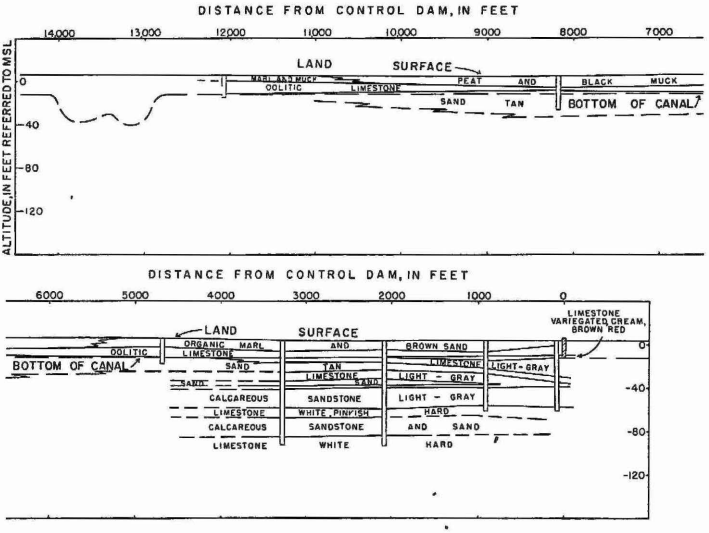



Figure 4. Section along the south bank of the Snake Creek Canal showing generalized lithologic characteristics of the Biscayne aquifer.

The peat and muck deposits were formed by the accumulation of partially decayed vegetation in swamps after the last glacial recession, about 8,000 years ago.

The Snake Creek Canal traverses a natural overflow channel from the Everglades. These numerous overflow channels are wide, topographically low areas (4 to 8 feet above sea level) that cut through relatively high land (8 to 15 feet) near the coast; they are called transverse or finger glades because of the manner in which they cut through the coastal ridge.

Prior to construction of drainage canals (fig. 1), the water level in the Everglades was high enough to cause discharge through the finger glades by poorly channelized sheet flow. In the deeper pockets, aquatic plants grew lushly and, after dying, settled to the bottoms of sloughs. In these locations, the organic material was protected from oxidation and accumulated to form the peat and black muck deposits.

In the higher parts of the finger glades, where water levels were below ground surface during the dry season, rapid oxidation prevented heavy accumulation of organic material. In these areas, the remnant plant materials were mixed with particles of limestone and sand, eroded from the adjacent higher limestone hills, to form a deposit called marl (fig. 4).

Since construction of drainage canals, the finger glades are flooded only during extremely heavy rainfall, and the rich organic soils are cultivated to provide table vegetables for northern markets in the winter season. With continuing improvements in the canal system and improved efficiency of water control, the agricultural activities are gradually giving way to urbanization.

## METHODS OF INVESTIGATION

The investigation followed two main courses: (1) Long-term observation of the position and rate of movement of salt water under the past method of operating the control dam (S-29). The dam has been operated on an arbitrary water-level basis with no consideration being given to the movement or the position of salt water; (2) detailed inventory of the position and movement of salt water under special short-term test conditions. The short-term test served as an index of typical conditions for analysis of the long-term data. These phases required continuous inventory of changes, both in the canal and in the aquifer.

The long-term study of salt-water occurrence in the canal was made primarily from fluctuations of chloride content as determined by three electrical-conductivity recorders located at S-29, at West Dixie Highway, and at the footbridge (fig. 3). The electrodes of these recorders were positioned about 1.5 feet above the bottom of the canal, and the landward movement of salt water was sensed by a sharp rise in the electrical conductance of the water. During and after the short-term test of March 27-31, 1961, the position of salt water in the canal was determined by traversing the canal water vertically with the cell of a portable conductivity instrument. The measurements were made from a boat that moved to specific stations along the canal.

The long-term study of salt-water occurrence in the aquifer was made from fluctuations of chloride content in samples of ground water from nine stations of wells drilled along the south bank of the canal (fig. 3). The general scheme was to drill individual wells to different depths at distances of about 5 and 60 feet from the canal. Thus, a typical station might consist of wells 10, 20, 50, and 100 feet deep near the canal and wells 10 and 20 feet deep at a distance of 60 feet from the canal. Although drilling operations did not always fulfill the preferred condition of paired wells terminating at the same altitude, the rectangular coordinate positioning of the wells relative to the canal was virtually fulfilled. Each well was cased so that the water which it yielded was representative of that particular point in the aquifer. Details of the position and depth of each well terminus relative to the canal are shown in the map and section views of figures 16 to 20.

An attempt has been made to simplify the illustrations as much as possible, but as this three-dimensional problem can be shown only in two dimensions, much must be left to the imagination of the reader to keep himself oriented in three-dimensional space. Herein lies the understanding of the physical parameters being discussed.

## LONG-TERM POSITION OF SALT WATER IN THE CANAL

The long-term position of salt water in the canal can be inferred by comparing figures 5 and 6. Figure 5 shows the peak daily chloride content, as indicated by the conductivity recorders at S-29, at West Dixie Highway, and at the footbridge. Also shown are the water level in the canal at West Dixie, the gate opening at S-29, and rainfall at the Opalocka gage. The maximum vertical opening

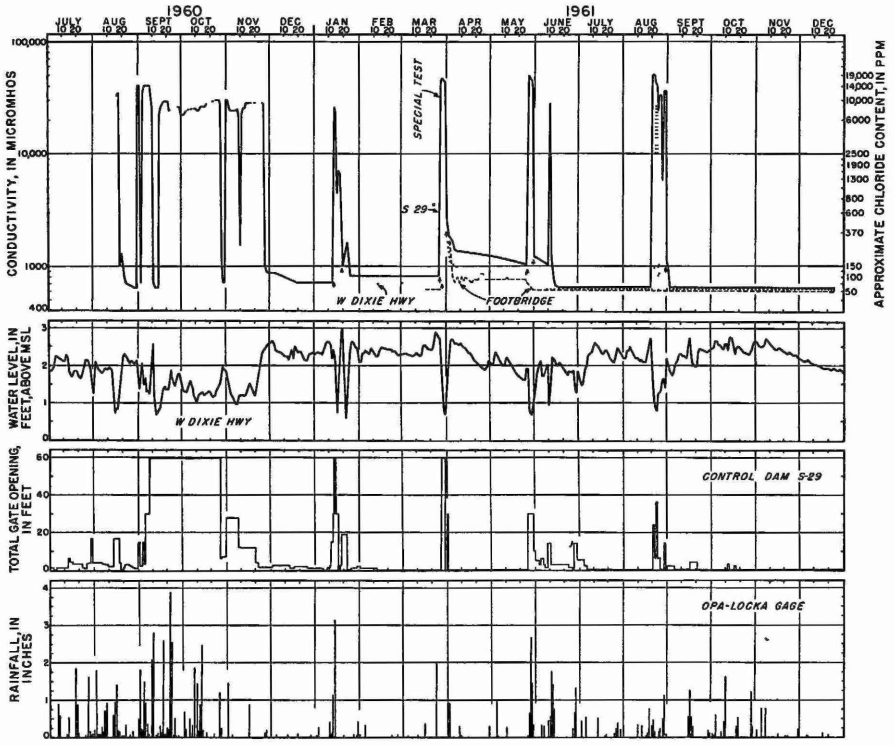



Figure 5. Graphs comparing rainfall, gate opening, and fluctuations of water level and chloride content along the Snake Creek Canal, 1960-61.

of each of the four gates is 15 feet (fig. 2); therefore, if all gates are fully open, the total gate opening is 60 feet. As the gates of S-29 are of equal width, the amount of gate opening in figure 5 represents the discharge area.

All gates were fully open from early September to late October 1960, after the heavy rains accompanying hurricane Donna and tropical storm Florence produced widespread flooding (fig. 5). Only during the period September 10 to 14, 1960, was the discharge from the canal great enough to keep the canal completely flushed of salt water (chloride-content graph at S-29, fig. 5). At all other times full opening of the dam permitted salt water to move upstream on a rising tide. During the special short-term test of March 27-31, 1961 (fig. 5), salt water invaded the canal inland as far as the footbridge. The time scale for this period is expanded in figure 6 to show the detailed relations of intrusion, water-level fluctuation, and discharge. Salt water intrudes on the rising tide, first appearing at S-29, then at West Dixie Highway 2 to 3 hours

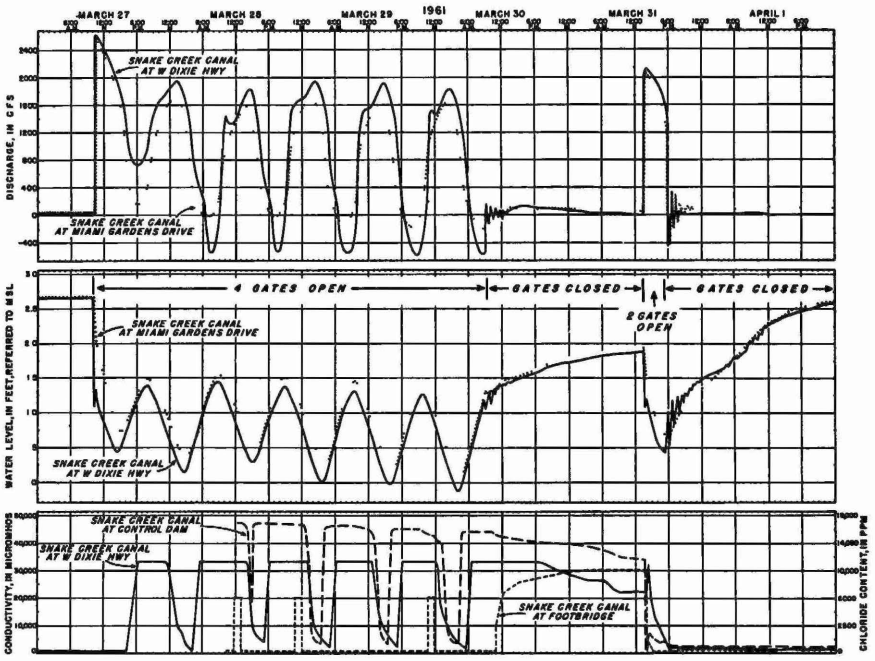



Figure 6. Graphs comparing fluctuations of discharge, water level, and chloride content in Snake Creek Canal during the special test of March 27-31, 1961.

later, and finally at the footbridge during the subsequent falling tide, about 8 hours after first appearing at S-29. Complicated relations are involved in this time lag and they will be discussed later, but it should be noted that the length of time of salt-water stay decreases landward and that the maximum concentration also decreases landward. For example, salt water did not reach the footbridge at all on March 29, just before noon (fig. 6). In light of the movement of salt water shown in figure 6, the long-term position of salt water in the canal can be inferred from figure 5 by comparing the relative fluctuations of conductivity at the three recording stations.

## IN THE AQUIFER

The interface between fresh water and salt water in the Biscayne aquifer is not sharp; a zone of diffusion is invariably present. The chloride content in the zone of diffusion ranges from about 16 ppm (parts per million), the concentration of fresh water in Miami, to about 19,000 ppm, the concentration of sea water. The concentration of chloride ion is commonly used to represent the

distribution of salt water, and isochlor lines are drawn through points of equal chloride content as determined by analyses of water from wells.

Cross sections of the zone of diffusion along the south bank of the Snake Creek Canal are shown in figure 7. The black dots represent the termini of individual fully cased wells located about 5 feet from the canal; the open circles represent the termini of wells located about 60 feet from the canal. In intercanal areas the the isochlor lines turn sharply downward at the inland extremity of the salt water, and the zone of diffusion takes the shape of a blunt-nosed wedge of salty water (Kohout, 1961, fig. 3, 4). Along the Snake Creek Canal (and presumably other canals) the blunted shape, although still present, tends to be modified by large changes in gradient and head near the canal.

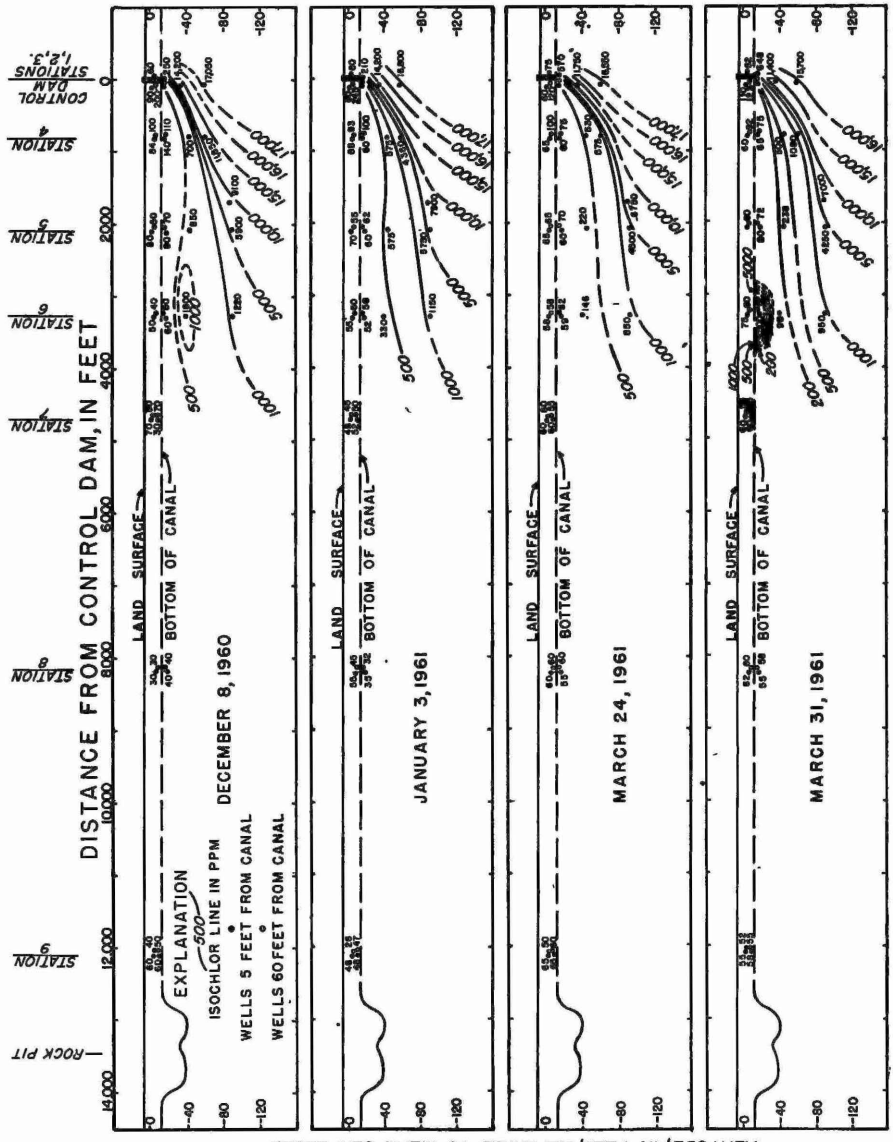
When the dam is open, the lowest level of the water table coincides with the water level in the canal, and ground water flows laterally toward the canal from either side. Also, at such times, ground water beneath the canal tends to flow upward through the canal bottom as it follows the part of least resistance to the ocean.

When the control gates are closed, the water level in the canal becomes the highest level of the water table because water flows quickly downstream from inland points of higher head. Under this condition the exchange of water between the canal and the aquifer is reversed, and water, whether it be fresh or salty, moves laterally and vertically from the canal to the aquifer.

In figure 7, the general processes of salt-water encroachment in the Biscayne aquifer are recognizable:

(1) The deep salt water, below and seaward of the 1,000-ppm isochlor, moves landward from the ocean in an essentially horizontal direction. This type of encroachment is relatively slow and insidious. It results from heads that are too low to prevent intrusion, and can be stabilized or corrected only by raising the heads.

(2) The lenses of salt water that appear near the bottom of the canal and then drift progressively downward with time originate as a result of inland movement of salt water directly in the canal. This type of encroachment occurs very rapidly and is the consequence of inadequate knowledge of the position of salt water in the canal during control-dam operations.


DISTANCE FROM CONTROL DAM, IN FEET
ALTITUDE, IN FEET, REFERRED TO MEAN SEA LEVEL
CONTROL DAM STATIONS 1,2,3
STATION 4
STATION 5
STATION 6
STATION 7
STATION 8
STATION 9
ROCK PIT
LAND SURFACE
BOTTOM OF CANAL
EXPLANATION
ISOCHLOR LINE IN PPM
WELLS 5 FEET FROM CANAL
WELLS 60 FEET FROM CANAL
DECEMBER 8, 1960
JANUARY 3, 1961
MARCH 24, 1961
MARCH 31, 1961

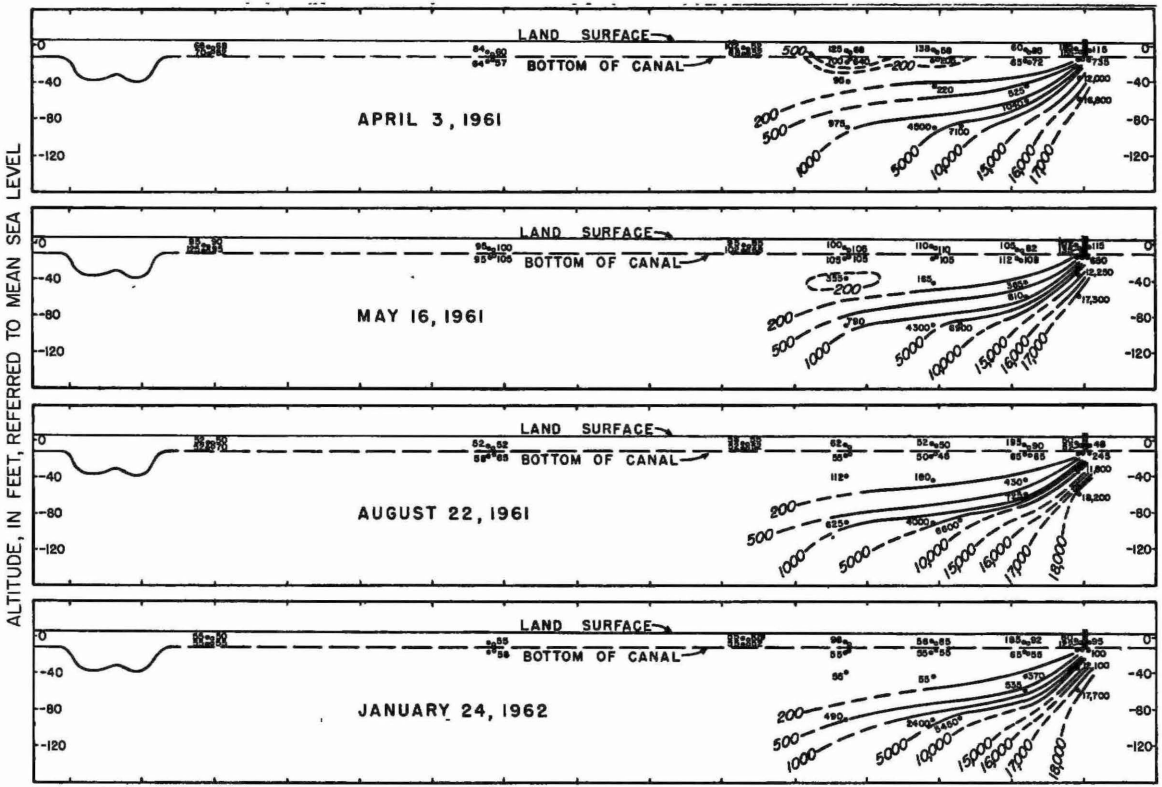



Figure 7. Sections along the south bank of the Snake Creek Canal showing the zone of diffusion in the Biscayne aquifer, 1960-62.

Although the isochlor pattern in figure 7 appears to remain practically stable from December 1960 to January 1962, careful comparison of data shows that significant changes occurred at certain wells. The chloride content in the deepest well at station 4 decreased from 11,850 to 535 ppm, indicating seaward expulsion of salt water from the aquifer. During the same time, the chloride content in the deepest well at station 6 decreased from 1,220 to 490 ppm.

The reason for the expulsion of salt water may be understood by following the events shown in figure 5. From early September to late October 1960 the control dam was fully open, because of flood conditions. During this time the heads in the aquifer in the vicinity of the canal were below normal and salt water moved horizontally landward and mounded beneath the canal. The chloride content in well G 420A (the only long-term data covering the period, fig. 18) increased from 6,800 ppm in June 1960 to 9,200 ppm on October 19, 1960. The year 1960, then, was essentially a year of encroachment.

The year 1961 was abnormally dry, and even during the normally rainy months of September and October the dam remained practically closed. The infrequent opening of the control dam caused heads to remain sufficiently high so that expulsion of salt water from the aquifer occurred throughout 1961 (fig. 7). The fluctuation graphs in figures 16 to 20 confirm the seaward movement of salt water; chloride contents in most of the wells decreased generally during 1961.

It is indeed a contradictory situation that the greatest inland movement of salt water took place in a wet year and the greatest expulsion of salt water took place during a dry year. Nevertheless, this fact indicates that the means are available for very effective control of the movement of salt water in the Biscayne aquifer.

## SHORT-TERM POSITION OF SALT WATER

While it is generally not feasible to observe continuously the complete distribution of salt water, short-term tests, keyed to recording instruments, provide much information with which to interpret the long-term data.

A short-term test was performed March 27-31, 1961. The control gates were completely closed for 6 weeks prior to the test, and conditions were almost stable despite rainfall of 2 inches that occurred 3 days before the test (fig. 5).

The sequence of control-dam operations is shown in the water level graph of figure 6. All four gates were opened fully at 10:00 a.m., March 27, just after high tide. The canal was in natural tidal oscillation until 9:15 a.m., March 30, when S-29 was completely closed just before high tide. The intention was to trap salt water in the canal, as might happen during normal control operations, and then trace its movement both in the canal and in the aquifer. The trapped salt water moved inland in the canal much more rapidly than expected, and at 1:30 p.m. on March 31, at high tide, two gates were opened for a flushing operation which continued until low tide, at about 5:45 p.m. The dam was then closed and remained so until May 26, 1961.

## SALT-WATER MOVEMENT IN THE CANAL

The tidal movement of salt water in a canal is rapid and transient. In figures 8-9 and 12-15 this movement is depicted by a time-lapse sequence of canal sections showing the approximate position of isochlor lines along the longitudinal axis of the canal.

### NATURAL TIDAL OSCILLATION

The movements of salt water under unimpeded tidal oscillation on March 29 are shown in figures 8A and 8B; figure 8A shows the inland extension on the rising tide, and figure 8B shows the seaward movement on the falling tide.

The stage of the tide cycle represented by each isochlor section is shown by an arrow on the water-level fluctuation graph (inset). The measured velocity profile for the middle vertical in the canal at West Dixie Highway is shown at the lower right side of each section. The discharge is divided into landward and seaward components as shown by the figures near the darkened arrows.

Comparison of sections 1, 2, and 3 (fig. 8A) indicates that the inland advance of salt water was slow during the early part of the rising tide. Significant landward advance of salt water did not take place until all flow became negative (landward) in section 3. This indicates that seaward-flowing water in the upper part of the canal removes the landward-flowing salt water in the bottom of the canal by a combined dispersion and interface erosion process.

Maximum inland velocity occurred at 7:37 a.m., about 1½ hours before high tide, section 4; the unshaded discharge arrows and dashed velocity curve show this condition. The solid velocity curve at 8:44 a.m., which corresponds in time with the isochlor

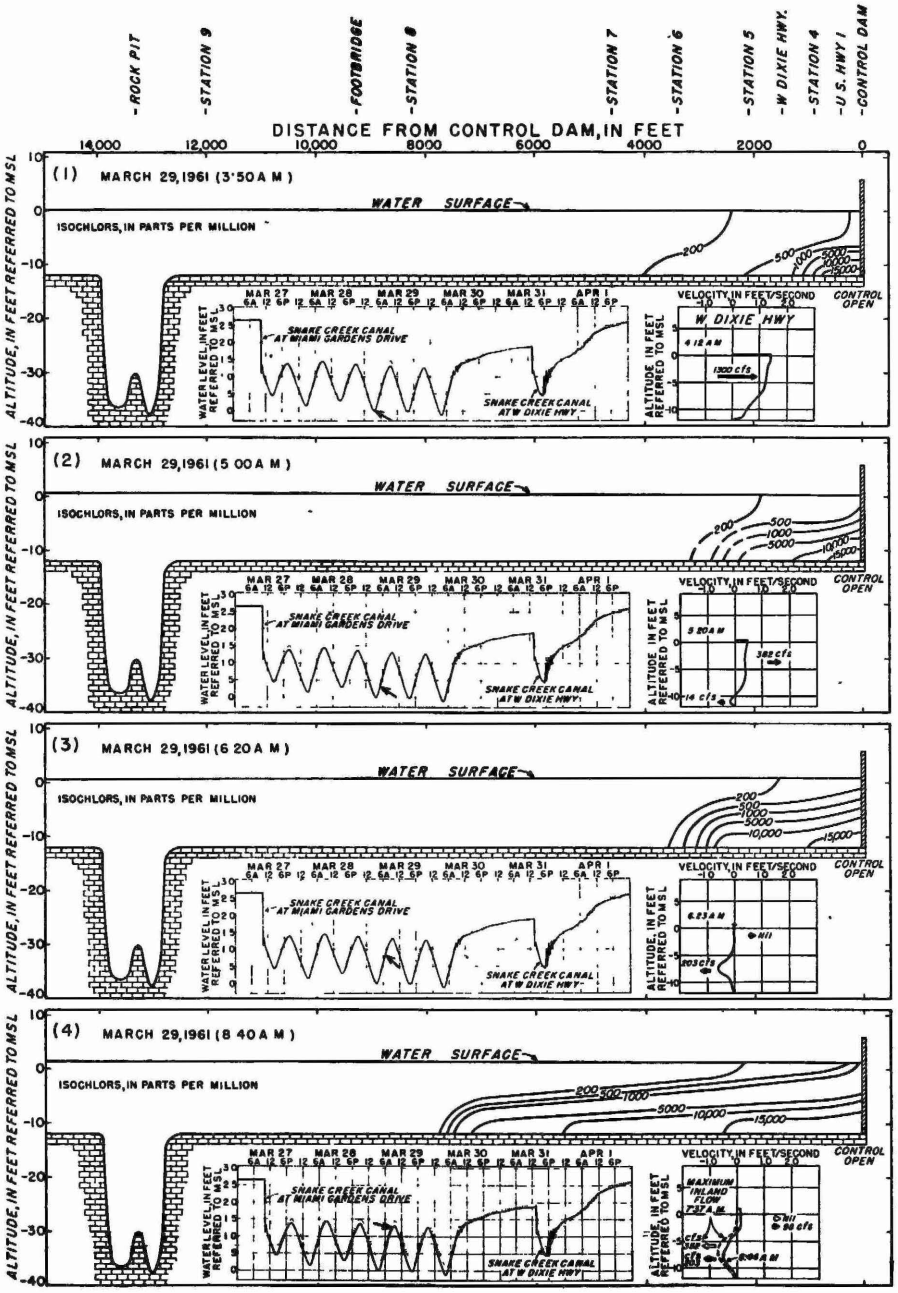



Figure 8A. Sections 1, 2, 3, and 4 through the Snake Creek Canal showing movement of salt water during the rising tide, March 29, 1961.

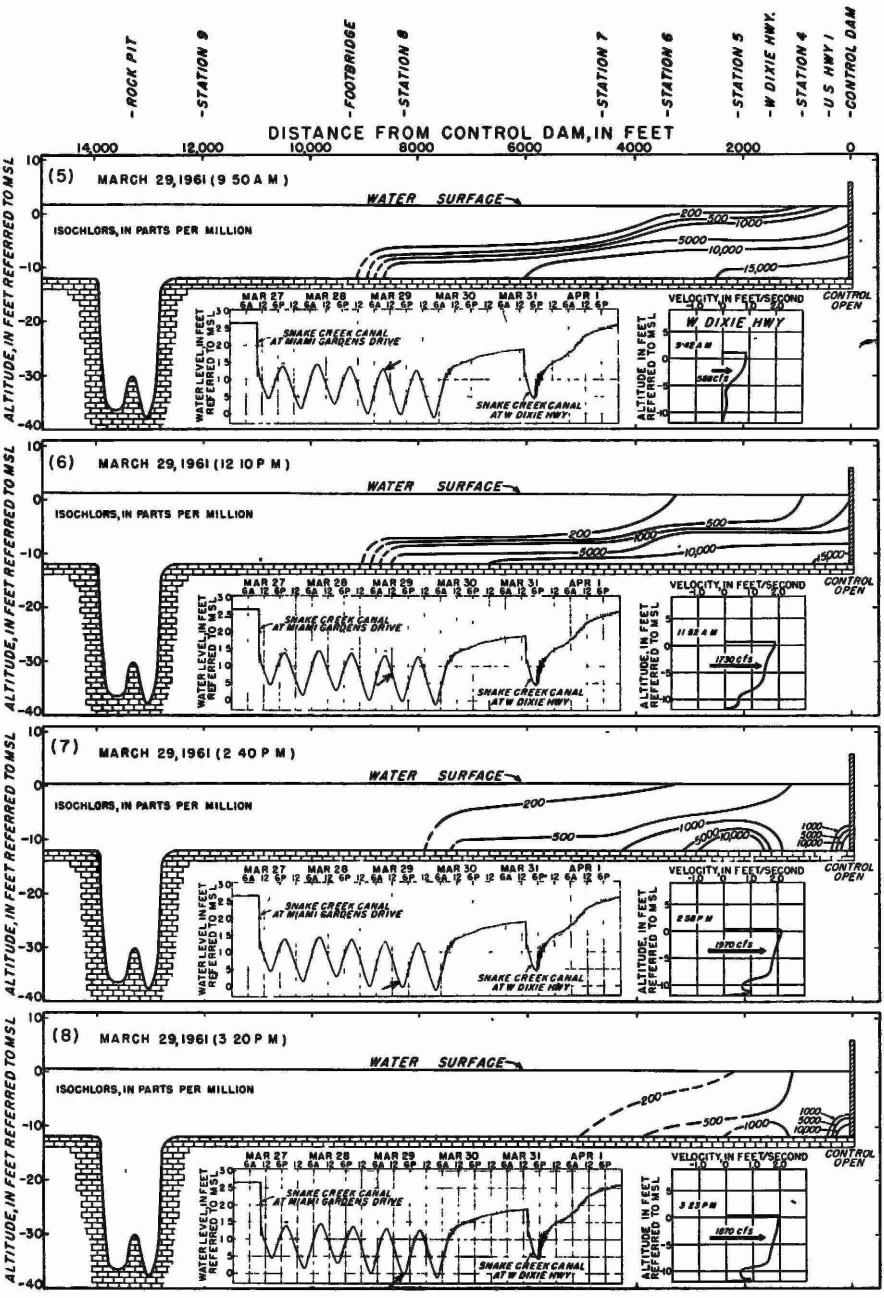



Figure 8B. Sections 5, 6, 7, and 8 through the Snake Creek Canal showing movement of salt water during the falling tide, March 29, 1961.

section, indicates that relatively fresh water near the surface began to flow seaward at least 1 hour before high tide. The high-salinity water at the inland toe of the wedge, however, continued to move landward until well after high tide. This time lag in landward movement of salt water was shown previously in the chloride-fluctuation graph of figure 6, where salt water did not appear at the footbridge until about 2 hours after high tide.

These out-of-phase flow characteristics in the upper and lower parts of the canal result from the density contrast between fresh water and salt water. At, and for some time after, high tide the fresh-water head at inland points is too small to counterbalance landward movement of salt water and the inland toe of the wedge moves landward as a density current. As the tide begins to fall more rapidly after high tide, the landward hydraulic gradient associated with the density current is overcome by seaward hydraulic gradient from falling ocean level. The salt water at the bottom of the canal, then, reverses direction and flows seaward.

The salinity distribution in the canal reflects the out-of-phase flow pattern. The upper part of the canal is rapidly freshened by large positive (seaward) velocities in the fresh water as the tide falls (fig. 8B), section 6. However, even after the reversal of landward movement of salt water, seaward velocities in the salt water near the bottom of the canal are small compared to those of the overlying fresh water (velocity curves, sections 7, 8). This velocity differential causes a lens or slug of salt water to lag behind in that part of the canal westward from West Dixie Highway. Apparently, downward-directed velocity components (possibly related to turbulence near bridge pilings) develop in the fresh water near the outlet. Salt water in this part of the canal is eroded and flushed seaward before all the salt water that moved landward during the rising tide can retrace its path to the outlet. The phenomena occurred repeatedly when the control dam was fully open. This indicates that the control should not be operated exclusively on the basis of water-level measurements, for slugs of salt water could be inadvertently trapped. The position of salt water should be determined directly by conductivity measurements at the bottom of the canal.

## TRAPPING SALT WATER

This section will show the dangers of inadvertently trapping salt water in a canal by shutting the gate on it. On March 30 at 9:15 a.m., just before high tide, all four gates of S-29 were closed.

The salinity distribution just prior to the time of closing is shown in figure 9, section 9.

A stable density stratification exists when fresh water overlies salt water with the isochlor lines horizontal. Sloping isochlor lines in stagnant water may be generally interpreted as an indication of hydraulic instability related to a nonstable density stratification. After the gates were closed, the water (for purposes of this discussion) may be considered to have been virtually stagnant, though

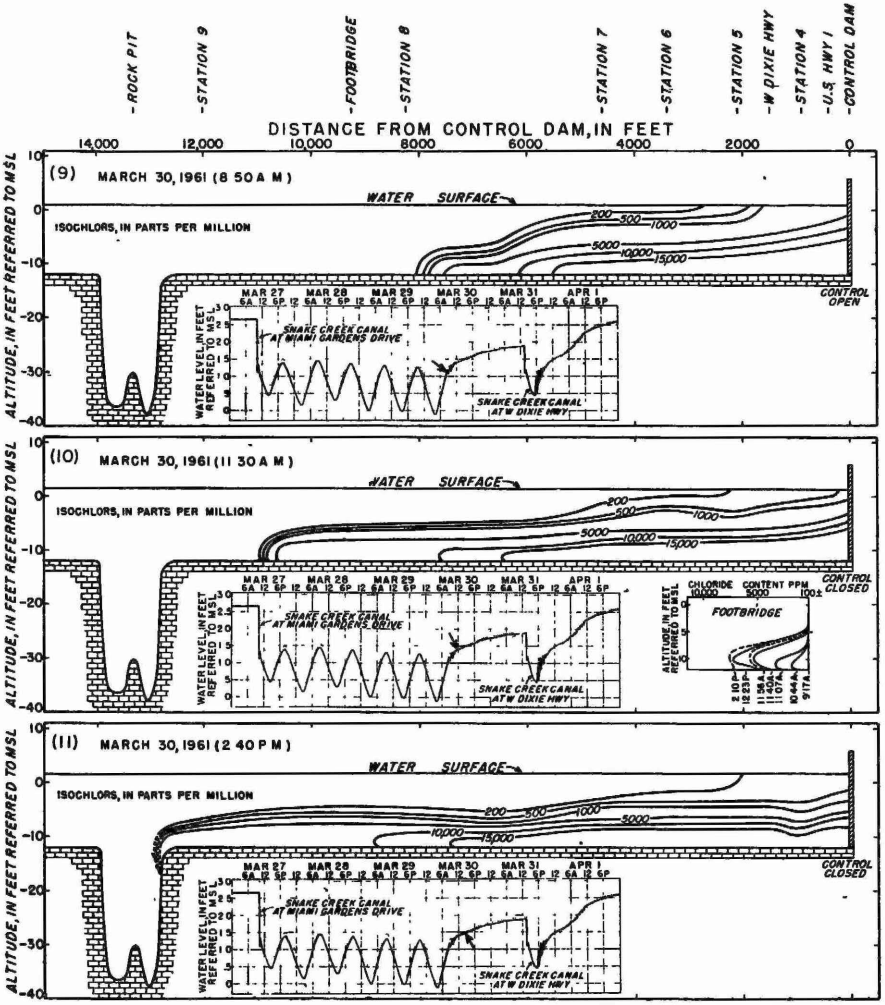



Figure 9. Sections 9, 10, and 11 through the Snake Creek Canal showing movement of salt water after closing of the control dam at high tide, March 30; 1961.

some net inflow of fresh water entered the canal as the stage rose; the sloping isochlor lines in section 9, then, indicate instability.

As expected, a density current developed when the gates were closed and salt water in the seaward reach of the canal moved landward. To maintain continuity between the individual water masses, fresh water from inland points moved seaward through the upper part of the canal to replace the salt water which moved landward through the lower part.

These movements were traced primarily by making vertical conductivity traverses of the canal water from the boat. Also, vertical conductivity traverses were made continuously at the footbridge and a series of these profiles is shown at the lower right side of section 10. The leading nose of the salt-water wedge passed the footbridge at 10:44 a.m., it was about 5 feet thick and had a maximum chloride content of about 1,500 ppm.

By tracking the intruding nose of the salt-water wedge for a period of time it was determined that the rate of landward movement was about 15 feet per minute, or about 900 feet per hour. The serene water surface completely belied the rapid encroachment taking place at the bottom of the canal.

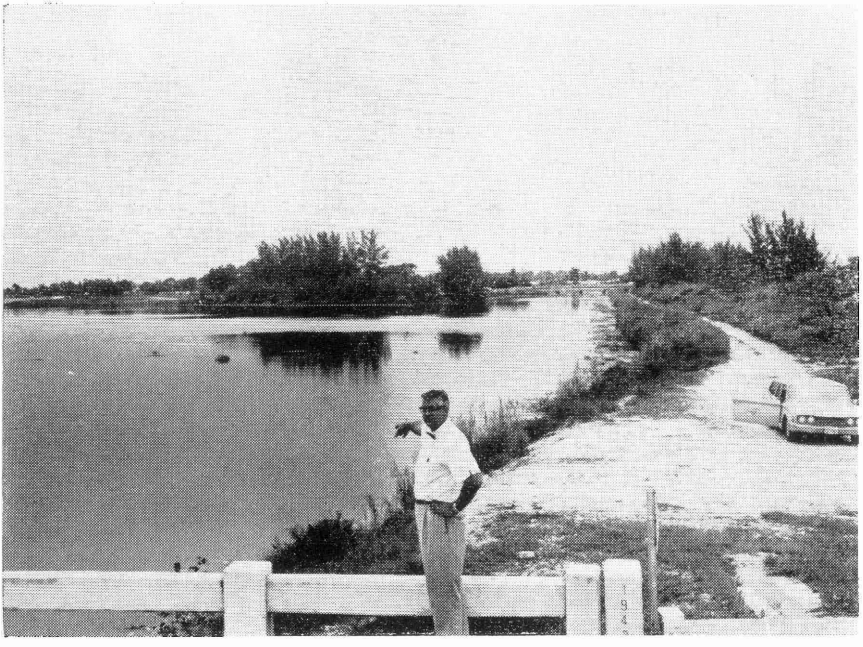


Figure 10. Photograph of rock pit (at left) looking in the downstream direction of the Snake Creek Canal (at right).

The salt water moved nearly 1 mile in the 4¼ hours between 9:15 a.m., the time of closing the gates, and 1:30 p.m. Careful inspection of the discharge graph at Miami Gardens Drive (fig. 6) shows a gentle increase in discharge at about 1:30 p.m. This increase was sensed by a small velocity vane positioned in the fresh water above the intruding salt-water wedge, and reflects the change in velocity in the seaward flow section as the wedge passed Miami Gardens Drive.

At about 2:00 p.m. salt water began to flow into the rock pit, in a manner similar to water passing over a waterfall (fig. 3, 9, 10, 11).

By late afternoon the hydrologic significance of the rock pit became clear. The rock pit was a hydraulic sink in which the salt water would temporarily collect. The salt water would resume its upstream movement only after it filled the rock pit above the level of the bottom of the canal.

Thorough investigation of the rock pit began the following morning, March 31. As shown by figure 12, section 12, a considerable quantity of salt water had flowed into the pit. The chloride content in the rock pit was low compared to that of water in the canal because, as the salt water flowed downward into the

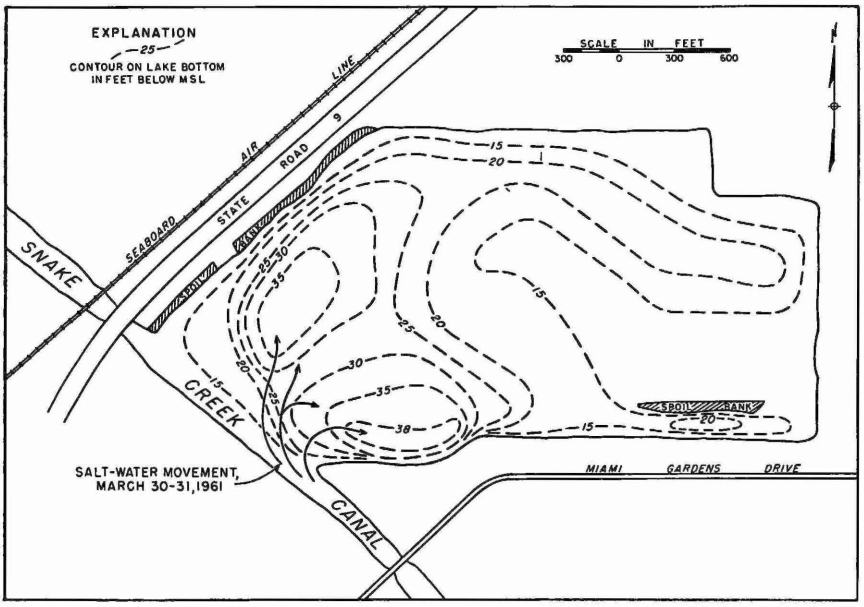



Figure 11. Rock pit showing approximate bottom topography.

lake, heavy mixing and dispersion of salt reduced the maximum concentration to less than 2,000 ppm chloride, though water with a concentration of 5,000 ppm was observed flowing into the pit.

Soundings, made in conjunction with numerous samplings and conductivity traverses during subsequent months, were used to develop a rough contour map of the bottom of the rock pit (fig. 11). Two deep holes nearly 40 feet below sea level are separated by a ridge having an altitude of about 25 feet below msl. In these holes most of the salt water samples were collected at depths greater than 20 feet below msl. The profile of the pit bottom in the canal sections (fig. 8, 9, 12-15) is generalized and represents no particular section line.

## FLUSHING OF SALT WATER FROM THE CANAL

Once having entered deep holes such as those in the rock pit, the heavy salt water cannot easily be retrieved and flushed. As most of the salt water remaining in the canal would eventually flow into the rock pit, the canal was flushed on March 31, the day after closing of the control gates. At high tide, at 1:30 p.m., two gates of S-29 were opened fully. The distribution of salt water before flushing is shown in figure 12, section 12, and the progress of flushing is shown in sections 13 and 14.

The principle of flushing is based on the tidal fluctuation of the ocean. In Miami, the range of fluctuation from high tide to low tide amounts to about 2 feet. Assuming that the water level upstream from the control dam is at least as high as the level of the ocean at high tide, the dam can be opened at high tide or shortly thereafter. The falling tide level continually creates a head differential between inland parts of the canal and the ocean; thus, for a period of about 6 hours, from high tide to low tide, a steep seaward hydraulic gradient produces a high rate of discharge from the canal. The discharge reaches a maximum slightly before low tide (fig. 6). Referring to the velocity curve in figure 8B, section 7, the seaward velocity of the fresh water just below low tide can be estimated at about 2 fps (feet per second) while that of the salt water can be estimated at about 0.7 fps. At this velocity, the salt water will move seaward at a rate of at least half a mile per hour. During the 6 hours of falling tide, flushing of 2 to 3 miles of the downstream reach of a canal is feasible. Turbulence disperses large quantities of salt water upward into the high-velocity fresh water and the flushing is probably more effective than the calculation indicates.

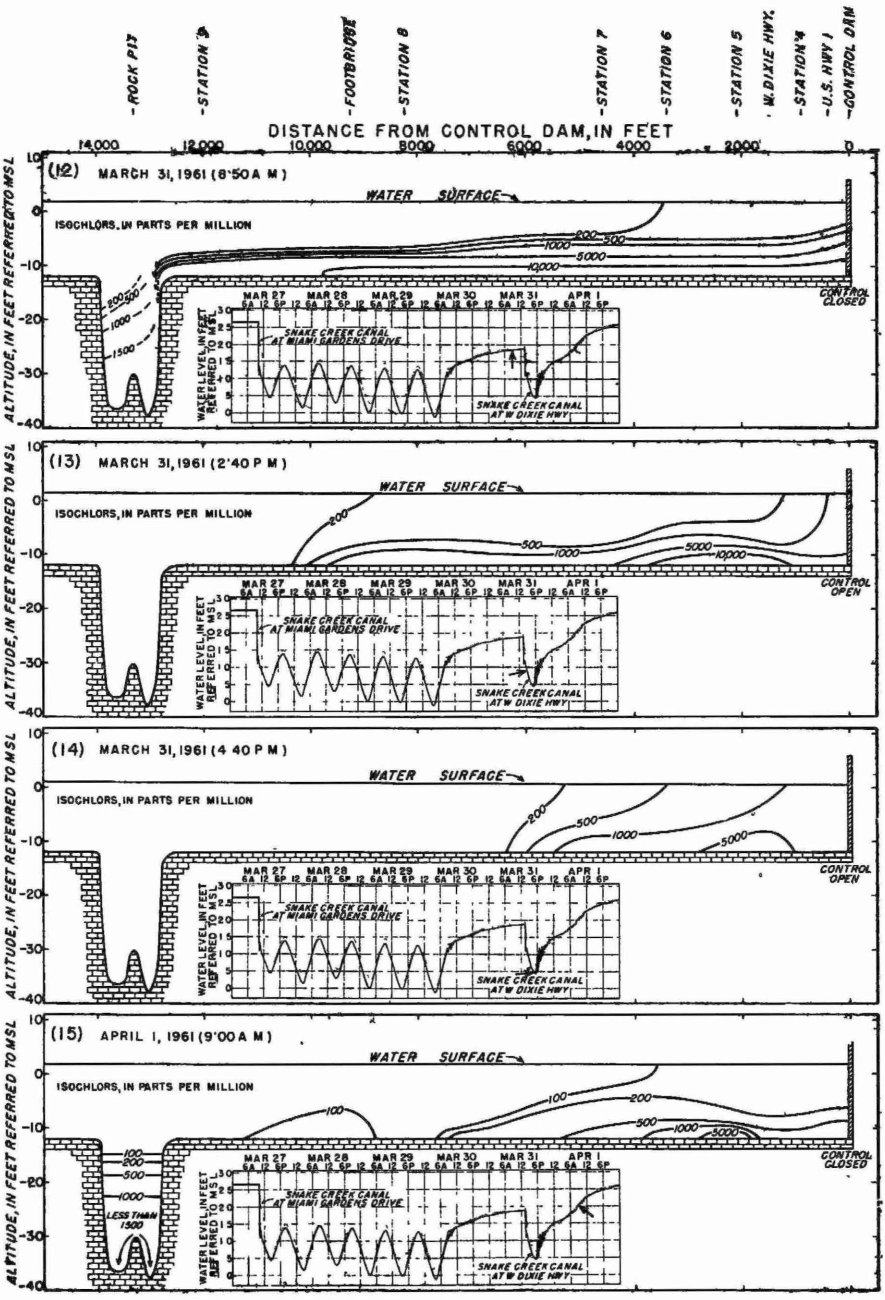



Figure 12. Sections 12, 13, 14, and 15 through the Snake Creek Canal showing movement of salt water during and after flushing, March 31 to April 1, 1961.

During the dry spring of 1962, high easterly winds on March 8 and 9 coincided with high average tides and the wind-driven waters of Biscayne Bay overtopped many control dams in the Miami area at high tide. Salt water invaded the canals at a time when dams throughout the area were held completely closed to maintain heads and to conserve fresh water. In spite of the entrapment of salt water in the canals there was reluctance to flush the canals, as it was felt that the consequent loss of fresh water could not be tolerated.

The series of isochlor sections for unimpeded tidal oscillation (fig. 8A, 8B) show that it is not necessary to have a high freshwater head behind the dam in order to perform a flushing operation. The principle of flushing depends almost entirely upon the falling stage in the ocean itself. The primary requisites are: (1) the canal should be long enough to tap a reservoir of fresh water at inland points, and (2) the control dam should be of a type that permits rapid operation so that opening and closing can be accomplished readily at opportune moments.

Flushing of salt water from a canal entails some loss of fresh water. However, wasting a small portion of the vast reservoir of fresh ground water tapped by a canal is preferable to allowing a small volume of salt water to move inland considerable distances where it may contaminate much larger volumes of fresh water.

### ULTIMATE LOSS AND FLUSHING OF THE REMAINING TRAPPED SALT WATER

In the 4½-hour flushing operation of March 31 not all salt water was removed. As shown by figure 12, section 15, a lens of salt water remained in the downstream reach of the Snake Creek Canal. Also, most of the relatively heavy salt water in the rock pit remained. These separated masses of salty water were traced until July 1961 (fig. 13-15).

The downstream lens in the canal tended to spread toward the rock pit, but a large part of the salt water in the lens disappeared between April 1 and 3 (compare sec. 15, 16). The disappearance coincided with an increase of chloride content in observation wells adjacent to the canal and will be considered in a later section.

The salt water in the rock pit appeared to remain practically stable from April 1 to 18 (sec. 15-19). The primary change during this period was a dispersion-caused widening of the contact between the 1,000- and 200-ppm isochlors.

Between April 18 and May 3, the isochlor positions changed significantly in the rock pit and also in the canal (compare sec. 19,

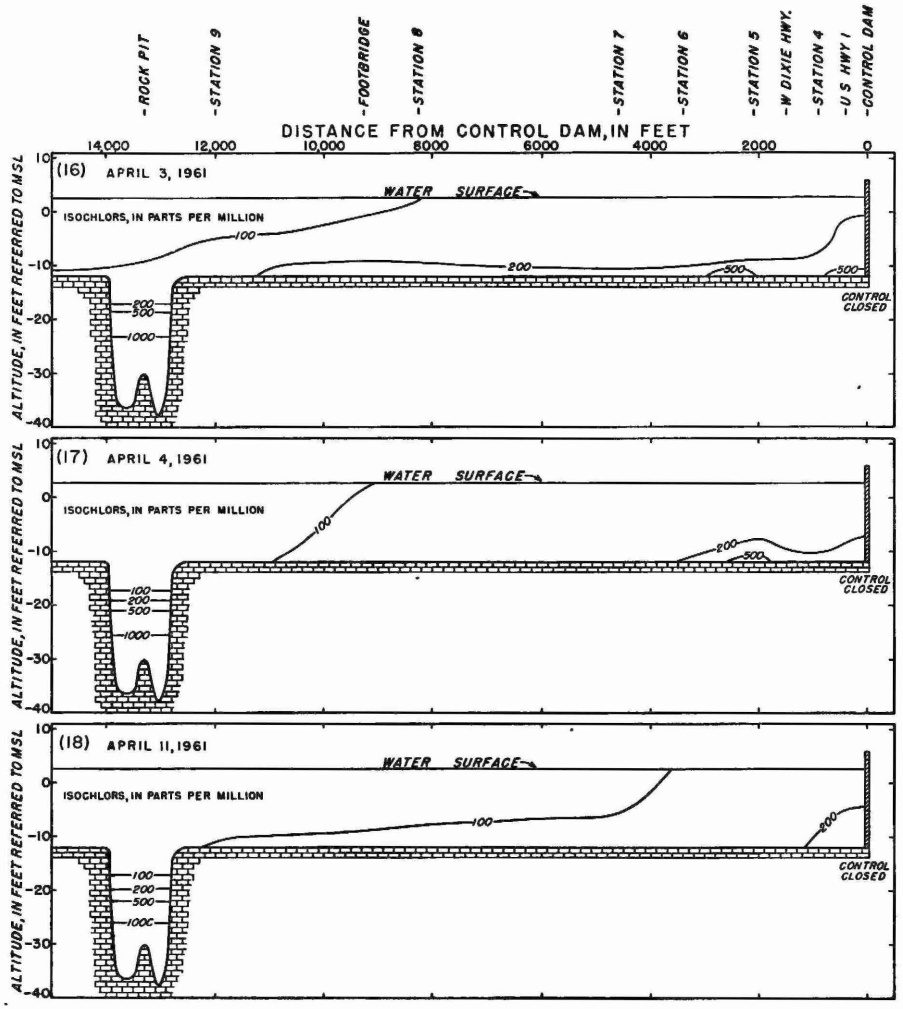



Figure 13. Sections 16, 17, and 18 through the Snake Creek Canal showing changes in isochlor positions, April 3-11, 1961.

20). An increase in chloride content was sensed by the conductivity recorder at the footbridge between April 22 and 26 (fig. 5) and, therefore, this was probably the period when the distribution of chloride content in the rock pit changed.

In the bar graph in figure 14, lower part of section 19, the wind movement exceeds 100 miles per day for 3 consecutive days, April 21-23; this period nearly coincides with the period of increase in chloride content at the footbridge. Apparently, the 3 days of strong wind mixed the water in the upper part of the rock pit. The

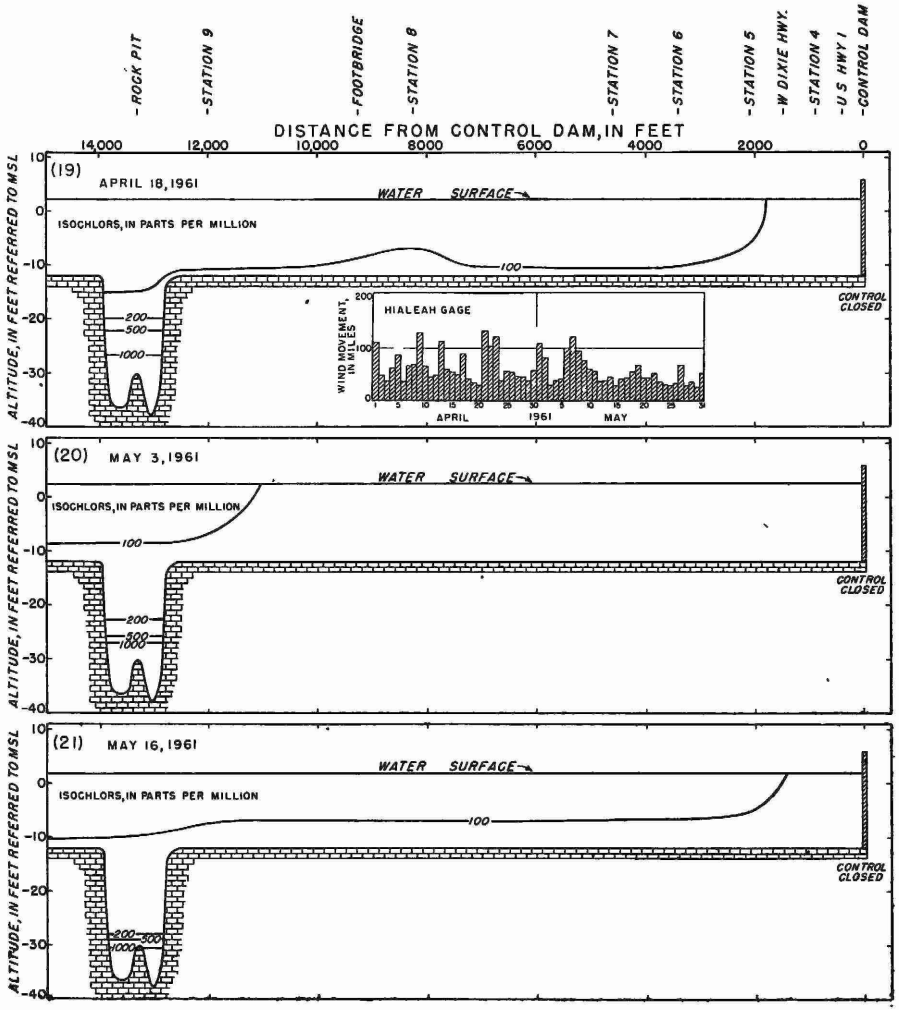



Figure 14. Sections 19, 20, and 21 through the Snake Creek Canal showing changes in isochlor positions, April 18 to May 16, 1961.

downward movement of isochlors in section 20 represents dispersion and upward movement of salt ions into the uppermost water of the rock pit. Small hydraulic gradients, associated with the wind and with ground-water discharge in the downstream reach of the canal, then carried the salty water downstream where it was sensed by the conductivity recorder at the footbridge.

Wave height on a given lake depends on the length of time the wind blows as well as on the wind speed. Therefore, the 3 consecutive days of high wind, April 21-23, were far more effective in

stirring the waters of the rock pit than were the single days of similar wind speed in early April. The downward movement of isochlors between May 3 and 16 (sec. 20-21) undoubtedly relates to the relatively high sustained winds of May 6 to 9. It is significant that wind and waves serve as agents for removal of trapped salt water.

On May 26, after heavy rainfall, the dam was opened (fig. 5). The resulting tidal oscillation and discharge produced small currents in the bottom of the rock pit. This agitation reduced the chloride content and density more in the eastern hole (fig. 11), by upward dispersion, and the salt was gradually flushed toward the partly open control dam. Although residual traces of the original contamination remained, the partial gate openings that started March 26 were effective in reducing salinity even at the very bottom of the rock pit (fig. 15). The decrease in chloride content at the footbridge (fig. 5) at the same time indicates that the tidal impulse of the ocean can be utilized to remove salt water that has become trapped in deep pits or lakes along the course of a canal.

## SALT-WATER MOVEMENT IN THE AQUIFER

The short-term movements of salt water in the aquifer are closely influenced by happenings in the canal. Fluctuations of chloride content in wells along the south bank of the canal during 1960 and 1961 are shown in figures 16-20. During the special test of March 27-31, water samples were collected as often as four times daily and these are plotted on an expanded time scale.

### NATURAL TIDAL OSCILLATION

Under unimpeded tidal oscillation, water moves from the aquifer into the canal on a falling tide and from the canal into the aquifer on a rising tide. This to-and-fro motion prevailed when the gates were open March 27 to 30 and is indicated by the two-headed arrow in the March 30 section of the sequence of insets in figure 19. During this period the chloride content in the shallow wells fluctuated only slightly at stations 1 to 5 (fig. 16-18), and practically none at the more landward stations (fig. 19-20). Although high-salinity water oscillated landward beyond station 8 in the canal (fig. 8), salt water did not appear in wells located as little as 5 feet from the canal. This is not surprising. The net flow of fresh ground water in the upper part of the aquifer is toward the canal. Any small amount of salt water that penetrates the aquifer

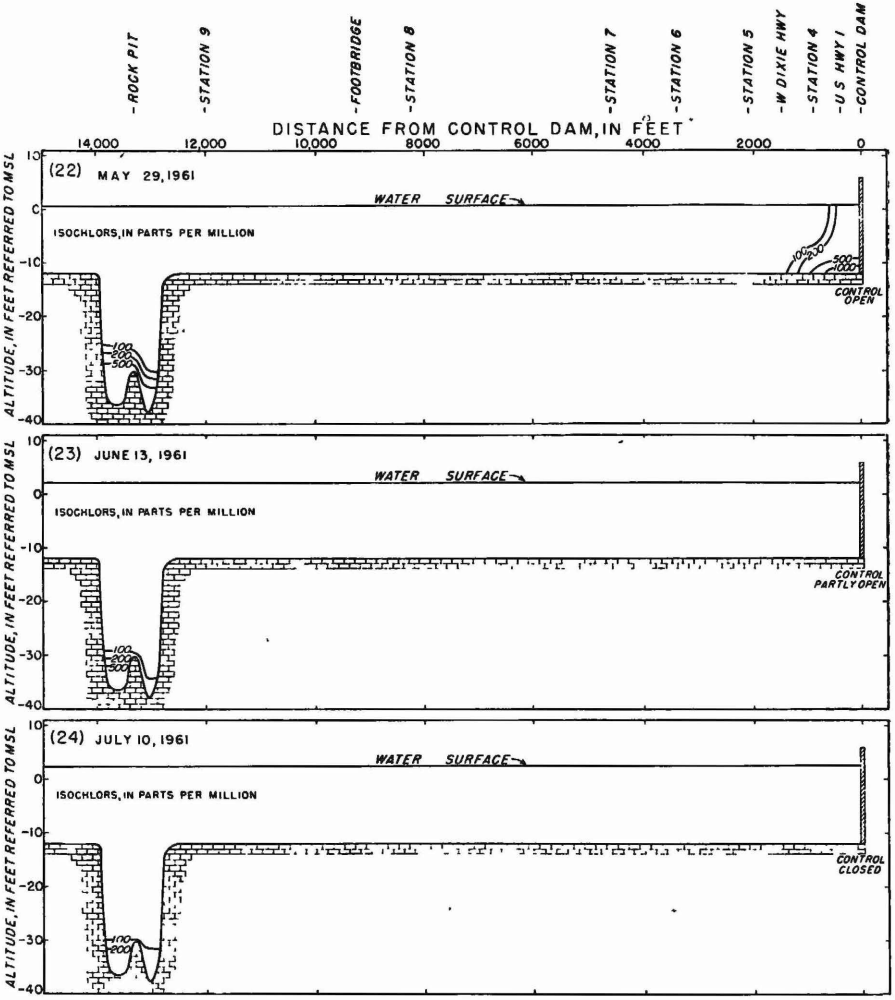



Figure 15. Sections 22, 23, and 24 through the Snake Creek Canal showing changes in isochlor positions May 29 to July 10, 1961.

on a rising tide is flushed back to the canal on the subsequent falling tide. Thus, the average flow of fresh ground water toward the canal opposes and greatly minimizes movement of salt water from the canal to the aquifer during unimpeded tidal oscillation.

A different situation exists in the deep part of the aquifer. The average head in the aquifer is lowered when the gates are open. This causes salt water, deep in the aquifer, to move landward. The movement is slow but relentless. An example is the increase in chloride content from 6,800 to 9,200 ppm in well G 420A between

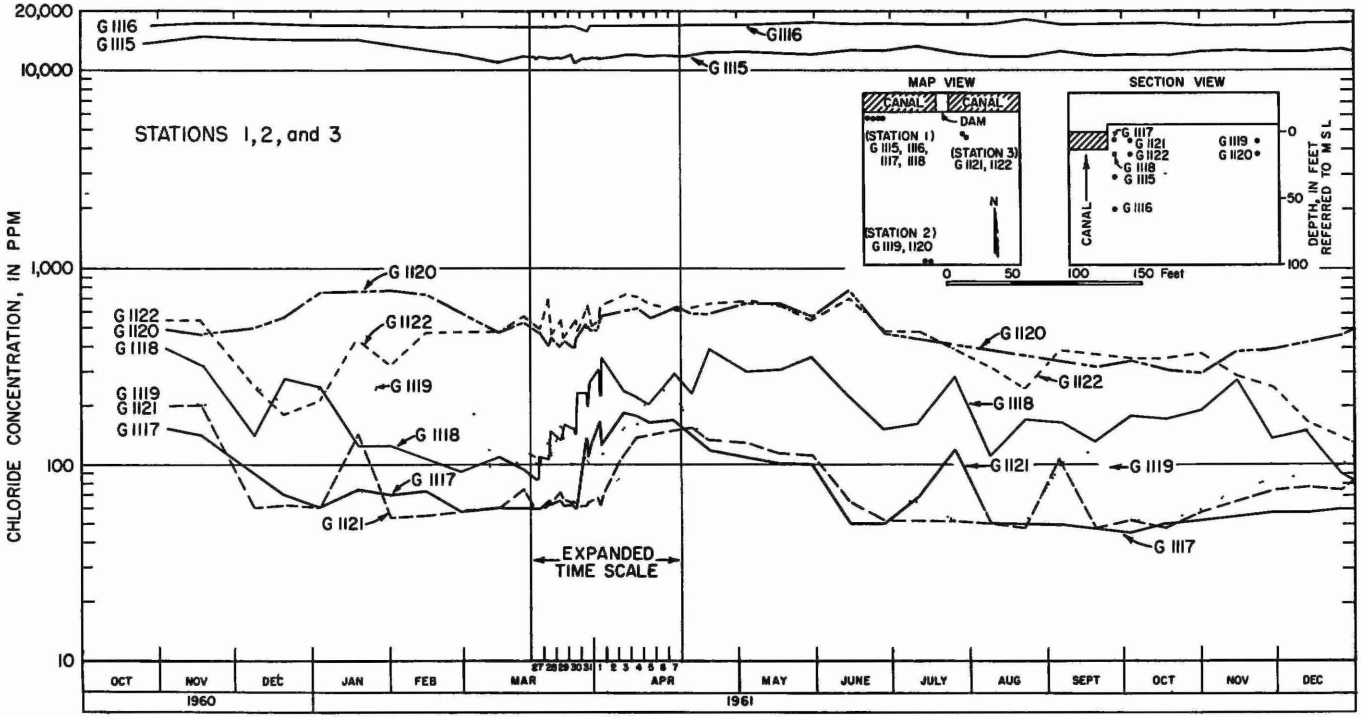



Figure 16. Graph showing fluctuations of chloride content at well stations 1, 2, and 3, 1960-61.

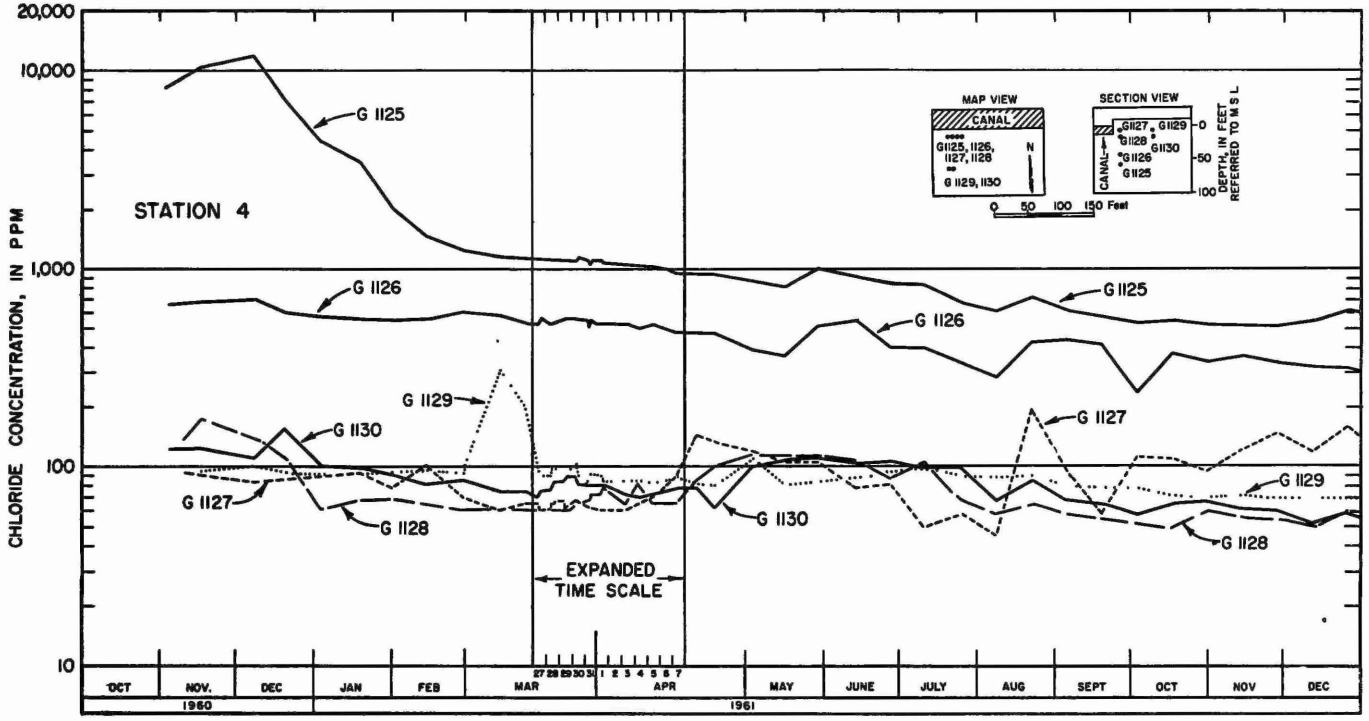



Figure 17. Graph showing fluctuations of chloride content at well station 4, 1960-61.

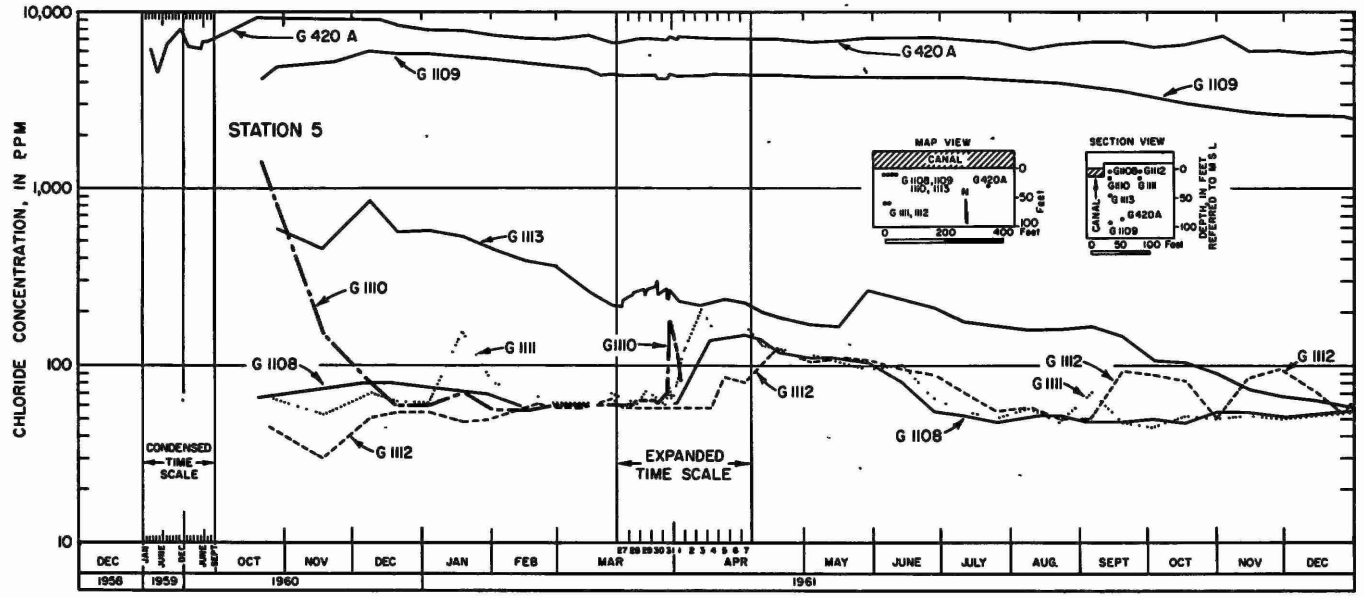



Figure 18. Graph showing fluctuations of chloride content at well station 5, 1959-61.

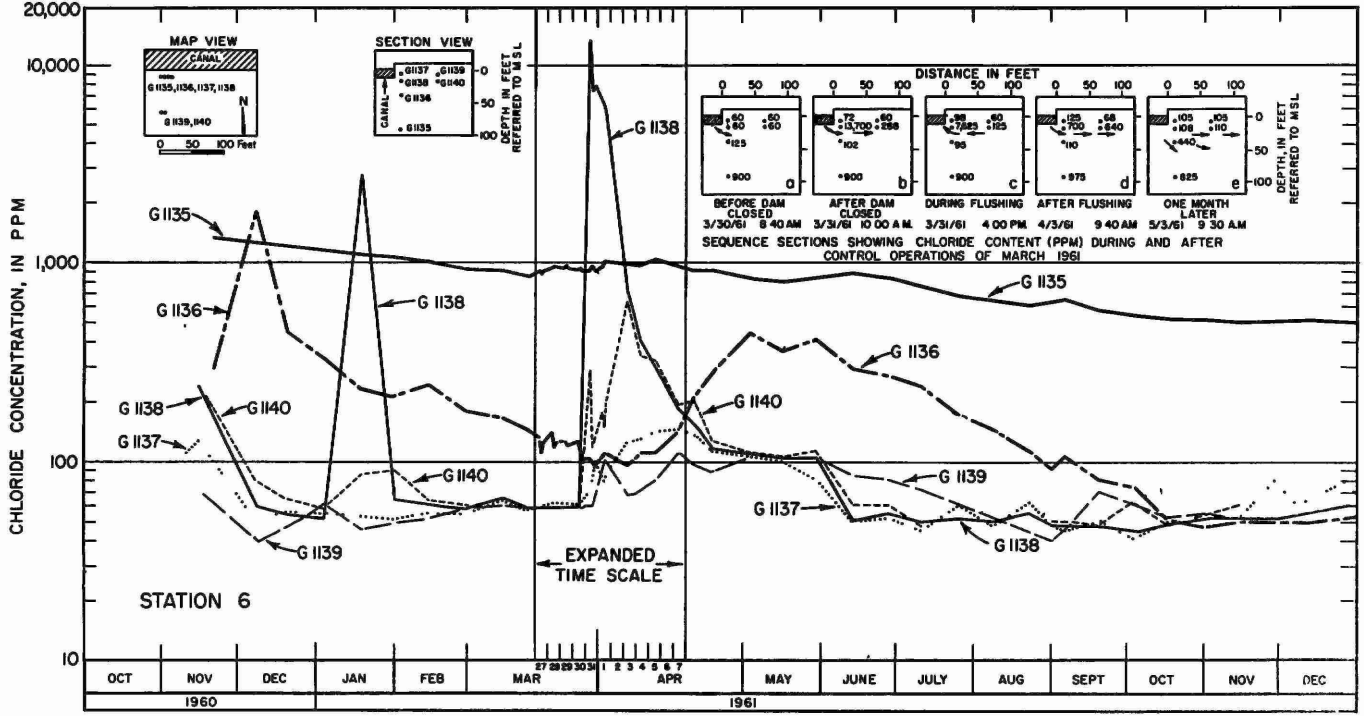



Figure 19. Graph showing fluctuations of chloride content at well station 6, 1960-61.

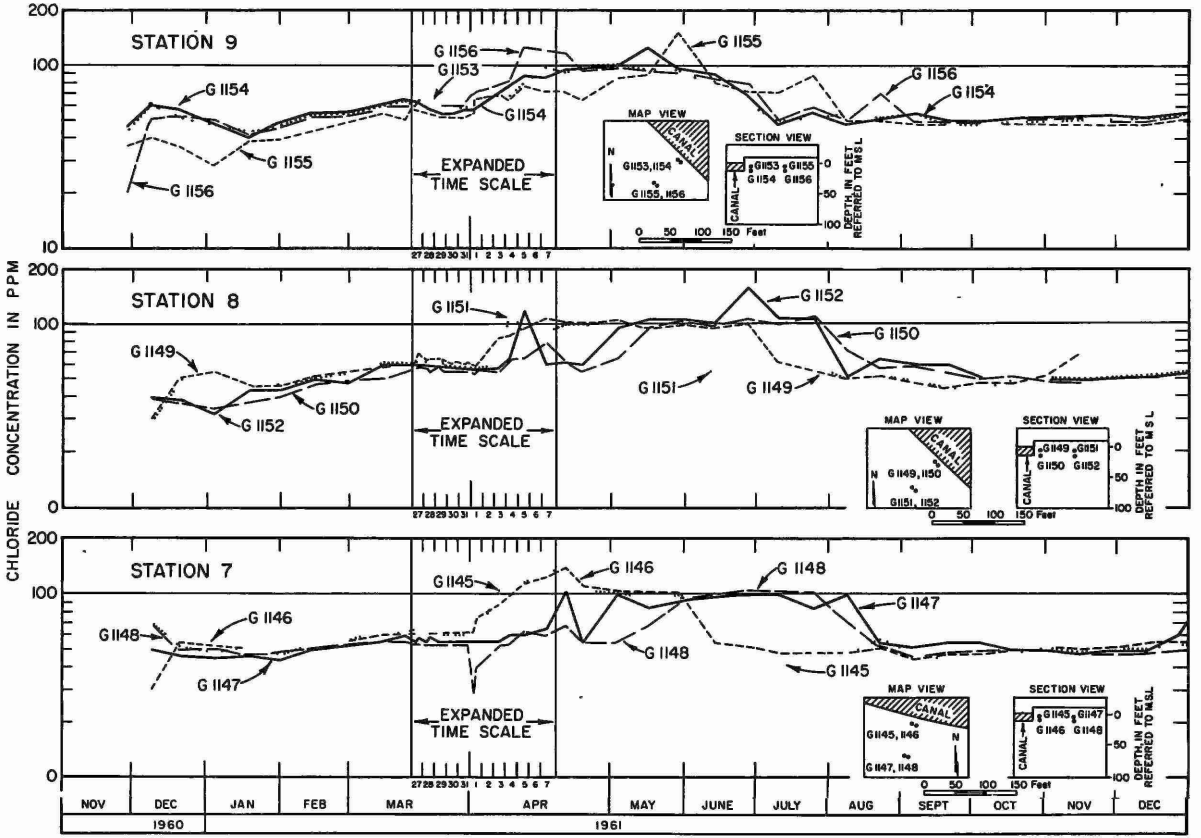



Figure 20. Graph showing fluctuations of chloride content at well stations 7, 8, and 9, 1960-61.

June and October 1960, when the dam was open for hurricane Donna floods (fig. 18).

## RECHARGING THE AQUIFER WITH TRAPPED SALT WATER

The canal is quickly converted from a drainage canal to a recharge canal by closing the control. The water which happens to be in the canal at this time, either fresh or salty, is driven from the canal under hydraulic gradient and appears in wells adjacent to the canal.

All well stations (fig. 16-20) showed an increase of chloride content on the morning of March 31, the day after salt water was trapped. As will be noted by comparing the graphs, the degree of reaction to the recharge of salt water varied. A partial list of the factors involved is as follows: (1) The distance of the well from the canal; (2) the altitude of the terminus of the well in relation to the altitude of salt water in the canal; (3) the concentration of salt water, which varies both vertically and longitudinally along the canal; (4) the amount of dispersion of salt as the water passes through the rock; and (5) the local permeability of the aquifer near the well station.

The relations of salt-water movement at station 6 are shown in the section views of figure 19. Section a for March 30 shows that salt water had not invaded the aquifer during unimpeded tidal oscillation.

In section b (10:00 a.m., Mar. 31), approximately 24 hours after closing the control gates, the chloride content in well G 1138, 5 feet from the canal, had increased from 60 to 13,700 ppm while that in well G 1140, 65 feet from the canal, increased from 60 to 288 ppm. The sharp increase of chloride content in these wells, in contrast to the decrease in well G 1136 (about 22 feet deeper) from 125 to 102 ppm, indicates that the salt water moved nearly horizontally. This is a reasonable observation because the horizontal permeability is generally much greater than the vertical permeability in stratified aquifers.

Section c (4:00 p.m., Mar. 31) shows the flow direction while the canal was being flushed. The sharp decrease of chloride content in wells G 1138 and G 1140 in the fluctuation graph at this time indicates that part of the salt water, that had previously invaded the aquifer, was flushed back toward the canal. After the flushing operation was completed and the dam was closed, the unflushed salt water in the aquifer resumed a flow direction away from the canal (sec. d).

In addition, salt water from the salt-water lens, which remained in the downstream reach of the canal after flushing (fig. 12, sec. 15, and fig. 13, sec. 16),moved into the aquifer. The disappearance of the salt-water lens from the canal by April 3 coincided with the sharp decrease in chloride content in well G 1138 on that date; the recharge water in the canal had become relatively fresh but the increase of chloride content in well G 1140 between April 1 and 3 showed movement of the salt-water slug farther from the canal. The low maximum chloride content in well G 1140 as compared to that of well G 1138 indicates dilution of the salt water during movement between the wells.

It is interesting to note that the chloride-content curve for well G 1138 crosses over and becomes lower than that for well G 1140 after April 5 (fluctuation graph, fig. 19). As previously shown, water in the canal continued to freshen with time. Thus, as the slug of salt water passed farther into the aquifer it was followed by relatively fresh water which appeared first in well G 1138, near the canal bank, and then in well G 1140. The reversal of the chloride-content curves shows the cause-effect relation of salinity in the canal on salinity in the aquifer.

The chloride content in well G 1137 reached a maximum on April 7, more than a week after the control was closed (fluctuation graph, fig. 19). During this week, some of the salt water that remained at the bottom of the canal was dispersed upward in the canal by wind agitation (fig. 13, sec. 16, 17). As the shallow wells were recharged by water from the upper part of the canal, the time lag of salinity fluctuation in the shallow wells reflects the changes of salinity in the upper part of the canal. The lower peak chloride content in well G 1139, as compared to well G 1137 again demonstrates the reduction of salinity by dispersion of salt as ground water moves through the pore spaces of the aquifer.

Well G 1136 is 22 feet deeper than well G 1138 so that the vertical component of salt-water movement is identified by the relative fluctuations of chloride content in the two wells. The chloride content in well G 1136 did not reach its maximum until early May, about 1 month after the short-term test, whereas that of well G 1138 reached its maximum 1 day after the control was closed (fig. 19). This great difference in time results from several factors. An important driving force in the vertical direction is the difference in density between the overlying heavy salt water and the underlying light fresh water. In open water, an unstable density condition of this type is corrected rapidly by a massive discrete

overturn of the two fluids. The settling of salt water in the rock pit is an example. However, in an aquifer the pores of the rock are small and the fluid movement is split into similarly small flow filaments. The fresh water rises at the same time that the salt water sinks. The overturn is reduced to slow infiltration wherein dispersion of salt plays an important part in modification of the original concentrations. The effect of trapping salt water in March 1961 is recognizable until October 1961 in the fluctuation curve for well G 1136 (fig. 19).

In the longitudinal sections of figure 7, the downward movement of salt water is depicted as a lens of salt water that appears near the bottom of the canal and progressively drifts downward with time (sections of Mar. 31 to May 16, 1961). At the same time there is a horizontal component of flow perpendicular to and away from the canal; this movement is shown by the arrows in section e of figure 19.

## ULTIMATE LOSS AND FLUSHING OF SALT WATER IN THE AQUIFER

Comparison of the fluctuations of chloride content at all stations (fig. 16-20) shows that the deep wells were little affected by the short-term test but that the shallow wells were affected in a characteristic pattern. This pattern is responsive to the operations of the control dam.

The control gates were closed on March 31, and they remained closed until May 26 (fig. 5). Initially the chloride content in the shallow wells rose sharply and then tended to decrease slightly. At the downstream stations the decrease was somewhat larger because ground-water movement around the control dam and toward the ocean was more rapid there.

At the more inland stations (fig. 20), the aquifer is recharged rapidly until canal water refills that part of the aquifer that is unwatered during drainage. After this, the gradient away from the canal becomes comparatively small as the ground-water flow system approaches a steady state consistent with the boundaries of the aquifer. As the rate of recharge is proportional to the gradient, salt water at first moves rapidly into the aquifer, and subsequently at a much slower pace. The salt water, therefore, remains within reasonable proximity of the canal and is subject to retrieval.

The chloride content in most of the shallow wells decreased sharply after the control dam was opened at the end of May. The

fluctuations at station 7 (fig. 20) are especially interesting. The chloride content in wells G 1145 and G 1146 near the canal decreased sharply, whereas that in G 1147 and G 1148, 60 feet from the canal, remained unchanged. Figure 5 shows that the total gate opening was decreased from 30 feet May 26 to 31 to about 5 feet thereafter. At the 30-foot gate opening, the canal caused drainage and some of the salt water flowed out of the aquifer into the canal. Water levels recovered somewhat after closing to the 5-foot opening (fig. 5), and fresh water from the canal recharged the aquifer. The movement of fresh water into the aquifer was sufficient to freshen the water in wells close to the canal (G 1145-G 1146), although water in the wells farther from the canal (G 1147-G 1148) remained relatively salty. Clearly, part of the salt water trapped in March had been removed but a part still remained as an isolated mass. During the next gate openings on August 20 the remaining salt water was completely flushed from the aquifer and the chloride contents of all four wells became nearly the same. Thus, the low-salinity water trapped in March was recovered from the shallow part of the aquifer by August 1961.

The recovery was possible because the density of this low-salinity water (less than 200 ppm) was not great enough to cause a large downward movement. The dense, high-salinity water that percolated downward at station 6 (shown by the graph of well G 1136, fig. 19) obviously was not recovered. It continued to move downward until the density contrast was eliminated by confluence with water of the same density in the deep part of the aquifer.

## MANIPULATION OF THE CONTROL DAM FOR MAXIMUM BENEFIT

The primary function of a canal in the Miami area is to remove surplus floodwaters. As floods in Miami result from heavy rainfall, it is obvious that the floodwaters must always be fresh. If salt water penetrates landward in a canal, the drainage function of the canal is impaired because floodwaters cannot flow seaward through that part of the canal in which salt water flows landward; therefore, the optimum removal of floodwaters occurs when no salt water invades the canal. Whether the flow condition is steady state or transient due to tide, it should be recognized that intrusion of salt water in a canal is an obvious sign of reduced efficiency in the discharge of fresh floodwaters.

All four gates of S-29 were fully open for nearly 2 months after hurricane Donna passed on September 10, 1960 (fig. 3). Only

during September 10 to 14 was the discharge great enough to keep the canal flushed of salt water. At all other times during the period of record shown in figure 5, full openings of the gates permitted salt water to move upstream on a rising tide. This suggests that the control was operated at full-open position much longer than necessary.

## FACTORS AFFECTING INLAND MOVEMENT OF SALT WATER

The manner in which the total gate opening is manipulated has a bearing on the landward extension of salt water in the canal. For example, a gate opening of 30 feet may be represented by a 7.5-foot opening for each of the 4 gates or a 15-foot opening for each of only two gates (the other 2 remaining closed).[1] The schematic flow diagrams of figure 21 illustrate the hydraulic advantage that attaches to uniform distribution of the gate opening. In figure 21a fresh water is forced to flow downward around the obstruction of the gate. This downward displacement of the fresh-water discharge section impedes the upstream intrusion of salt water. Uniform opening and submersion of the four sluice gates (in contrast to fully open gates) can be used as a device to distort the flow pattern deliberately in order to prevent salt-water intrusion.

Questions arise as to whether the movement of salt water into a canal is ever justified on the basis that widest opening of the control gates will cause greatest discharge of fresh floodwater. The critical point of entrance of salt water into a canal is at the control dam, for here is the only place where intrusion can be controlled. The problem involves the total head at the dam, the amount of discharge at various gate openings under these various heads, and the influence of fresh-water head in preventing upstream movement of salt water beyond the control dam.

Using the principle of static equilibrium for fluids of different density, salt water will not move upstream as long as the head differential between the fresh-water and salt-water sides of the control gate is greater than 0.3 foot (for a canal whose bottom is 12 feet below sea level). This value is obtained by balancing the

[1]The values used here only demonstrate a principle; the discharge area for 2 gates opened 15 feet is not equal to the discharge area for 4 gates opened 7.5 feet because the gates at wide-open position may be above the actual water surface by as much as 3 feet.

pressure exerted by fresh water against the opposing pressure exerted by sea water at the bottom of the canal.

$$P_f = \rho_f g l_f \qquad P_s = \rho_s g l_s$$

$$\rho_f g l_f = \rho_s g l_s$$

letting $l_f = h + l_s$ (See fig. 21a):

$$\rho_f (h + l_s) = \rho_s l_s$$

$$h = l_s \frac{(\rho_s - \rho_f)}{\rho_f}$$

$$h = 12 \frac{(1.025 - 1.000)}{1.000} = 0.3 \text{ ft.}$$

$P_f$ = pressure exerted by fresh water
$P_s$ = pressure exerted by sea water
$g$ = acceleration of gravity
$\rho_f$ = 1.000, density of fresh water
$\rho_s$ = 1.025, density of sea water
$l_f$ = length of fresh-water column, in feet
$l_s$ = 12 feet, length of sea-water column
$h$ = head differential between fresh-water and sea-water sides of control dam, in feet.

Referring to the schematic flow diagram of figure 21b, when the gates are fully open, the head loss through the control structure itself is very small. The flood conditions would have to be very severe in order to maintain 0.3 foot of fresh-water head at the control dam near high tide, when the greatest possibility of inland movement of salt water exists. The reason for upstream penetration of salt water on September 15, 1960 (fig. 5), only 5 days after the passage of hurricane Donna, is evident. With fully open gates, the head differential and discharge decrease very rapidly until salt water is able to flow upstream during the rising tide. Submergence of the gates, however, tends to focus all the head loss at the control (fig. 21a). This is very desirable and if the four gates of S-29 are uniformly adjusted to maintain a head differential of 0.3 foot during the rising tide, no salt water will invade the canal.

## DISCHARGE RELATED TO GATE OPENING

The quantity of water discharged under a sluice gate depends on the head differential across the gate and on the cross-sectional area through which the discharge occurs.

Figure 22 shows the approximate discharge related to head differential for various openings of one gate of the control dam in the Snake Creek Canal. The plotted points represent the mean daily discharge at West Dixie Highway and the head differential,

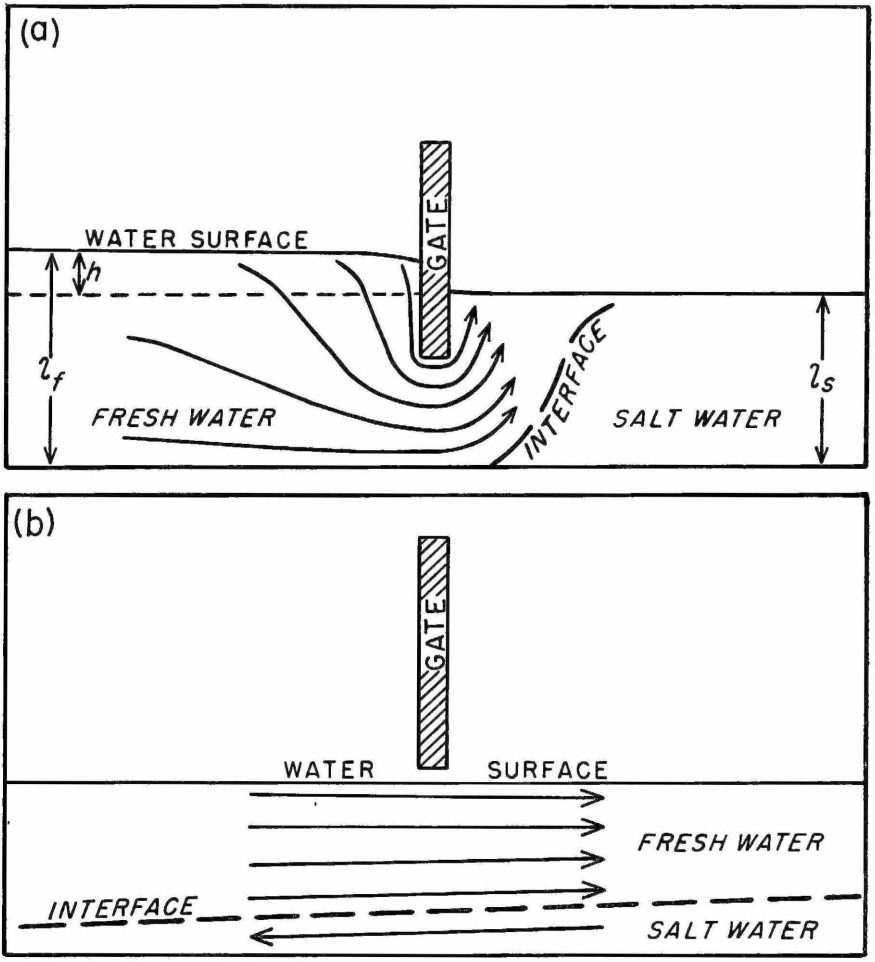



Figure 21. Schematic flow diagrams: a, with gate partially submerged; b, with gate fully open.

as obtained from the difference in mean daily gage height at West Dixie Highway and Biscayne Bay at NE 84th Street. Comparison of past records indicated that the mean daily gage heights of Biscayne Bay at NE 84th Street and the now discontinued gaging station just below the control dam in Snake Creek Canal were comparable when the control dam was closed or the discharge was within the range shown in figure 22.

The curves were calculated by using the formula $Q = AC\sqrt{2gh}$ where Q is the discharge, A is the cross-sectional area, C is the coefficient of friction, g is the acceleration of gravity, and h is the

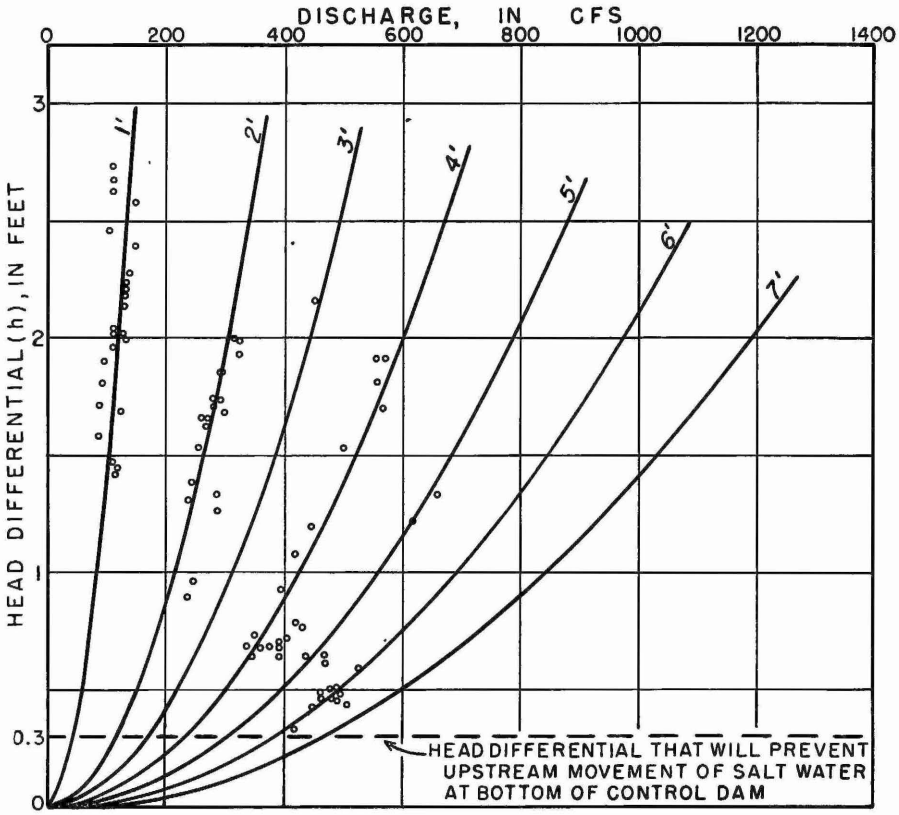



Figure 22. Graph showing relations of head differential and discharge for various openings of one gate of the control dam in the Snake Creek Canal.

head differential through the gate. As Q, A, and H were known for each of the points in figure 22, the coefficient of friction (C) was evaluated for the different gate openings. Then, using the average value of C and holding the area (A) constant for the individual gate openings, the curves were constructed through the mean value of the plotted points by solving the formula for Q while letting the head differential (h) vary.

The curves may be used to estimate low discharge for the control structure provided the upstream tidal range is less than 0.5 foot. The accuracy decreases when the tidal range of the upstream stage recorder exceeds 0.5 foot during a given day.

The following table shows the recession of discharge following the passage of hurricane Donna on September 10, 1960.

| Date (September) | Mean daily head differential (feet) | Mean daily discharge (cfs) |
|---|---|---|
| 11 | 0.48 | 2,430 |
| 12 | .38 | 2,180 |
| 13 | .31 | 1,800 |
| 14 | .28 | 1,660 |
| 15 | .23 | 1,510 |
| 16 | .17 | 1,290 |
| 17 | .19 | 1,240 |
| 18 | .22 | 943 |

Salt water invaded the canal on a rising tide on September 15. A comparison of the measured discharges in the table (all gates fully open) with the plotted points in figure 22 (only one gate partially open) indicates that the four gates can be partly closed within a week after a flood peak has occurred to maintain a head differential of at least 0.3 foot. This would keep the salt water out of the canal. The small increase in head required to maintain the same discharge would be insignificant from the standpoint of flood height above the dam.

There is a distinct difference between holding salt water back, as shown in the schematic flow diagram of figure 21a, and allowing salt water to invade the canal, as in figure 21b. Inland penetration of salt water does not contribute to seaward discharge because, as previously defined, true removal of floodwaters must only mean removal of fresh floodwaters. Salt water which penetrates landward in the canal merely replaces fresh water; once it has gained entry, energy must be expended to remove it. In the velocity profiles of figures 8A and 8B, the velocities near the bottom of the canal are landward during the rising tide, and are small relative to the seaward velocities in the upper part of the canal during the falling tide. These velocities reflect two things: (1) Sea water provides back pressure which is greatest at the bottom of the canal. (2) Energy is expended in driving the intruded salt water back to the ocean on the falling tide. As the noncontributing landward flows and the reduced seaward flows of salt water must be integrated with the positive flow of fresh water to yield the mean daily discharge, the mere presence of salt water in the canal, in effect, reduces the mean daily discharge of true (fresh) floodwaters.

In some respects, salt water acts as a movable dam in the bottom of the canal; it effectively reduces the depth of the canal

through which fresh water can flow seaward. For example, if salt water occupies the lower 6 feet of the canal when the control is fully open (fig. 8), the effective flow section for fresh water is reduced to a thickness of about 6 feet (total depth of canal is 12 feet). If the gates are lowered to an opening of, say, 7 feet, the fresh-water discharge will be impeded and this will cause the fresh-water head to rise until salt water is driven out of the lower part of the canal. Conceivably, the head might build up sufficiently so that the fresh water would flow through the full 7-foot section below the sluice gate. However, there is no assurance that this will occur—fresh water may discharge through only the upper part of the 7-foot thick section while salt water continues to flow landward through the lower part.

This leads to an important point. The effect upon head and discharge caused by constriction from lowering the gates, as opposed to constriction and back-water effect from salt water in the bottom of the canal, is indeterminate without controlled tests. The optimum gate opening probably occurs when the salt-water wedge is held just downstream from the control and only fresh water is flowing beneath the sluice gates. This gate opening will discharge the maximum amount of water without permitting salt water to invade the canal and aquifer above the control.

Future studies should be directed toward evaluation of the relations of fresh-water to salt-water discharge with various gate openings, in the immediate vicinity of the control dam.

## SUMMARY

The Snake Creek Canal cuts through highly permeable limestone of the Biscayne aquifer of southeastern Florida. The canal extends inland about 18 miles from the salinity-control dam located near the shoreline. The canal is somewhat representative of a number of canals in the area and information learned during the study is generally applicable to other canals.

Salt water was traced in the Snake Creek Canal under various circumstances of control-dam operation during a special test in March 1961. In the first phase of this test all four gates of the control dam were opened wide. Salt water moved inland about 2 miles during the rising tide and seaward during the falling tide. Salt water penetration into the aquifer was negligible during the 3 days the gates were fully open.

In the second phase of the special test the control was completely closed at high tide, trapping salt water above the dam. A density

current developed in the trapped salt water, which caused it to flow inland along the bottom of the canal at a rate of about 900 feet per hour until it reached a deep rock pit which acted as a hydraulic sink. A flushing operation removed salt water from the canal, but not that in the rock pit. Measurements of electrical conductivity during the subsequent months in the rock pit showed that the salt dispersed upward by a combination of wind, tidal mixing, and molecular diffusion. After reduction of salinity by this upward dispersion, the salt water in the rock pit was flushed seaward through the canal.

When salt water is trapped in a canal by control-dam operation or by overtopping the dam during abnormally high tides, it is not necessary to wait for nor to have high fresh-water head behind the dam in order to perform a flushing operation. The falling tide (level) of the ocean creates a seaward hydraulic gradient and a condition favorable for a high rate of discharge from the canal. Calculations and observations show that flushing of 2 to 3 miles of the downstream reach of a canal is feasible during one falling tide. The canal should tap a reasonably large reservoir of fresh water and the control dam should be the type that permits rapid operation so that the gates can be opened just after high tide and closed at low tide. Although some fresh water is lost during flushing, good water management is better served by wasting a small portion of a vast reservoir of fresh water than by allowing a small volume of salt water to move inland to contaminate a much larger volume of fresh water.

The movement of salt water in the aquifer adjacent to a canal is closely related to happenings in the canal itself. When the gates are closed, the downstream controlled reach of the canal is immediately converted from a condition of drainage to a condition of recharge. Salt water trapped behind the dam during the test entered the aquifer and quickly appeared in wells adjacent to the canal. Sections perpendicular to the canal showed that the salt-water outseepage from the canal moved much more rapidly horizontally than it did vertically. The residual effect of downward movement of salt water in the aquifer was recognizable for 6 months at one of the observation stations. The fluctuations of chloride content in shallow wells indicate that some of the low-salinity water in the upper part of the aquifer was eventually recovered and flushed seaward through the canal during subsequent gate openings.

The movement of high salinity water deep in the aquifer responds to head changes related to long-term operations of the control dam. The chloride content in deep wells increased during the fall of 1960 when the control remained open because of flood conditions. The year of 1961 was abnormally dry; infrequent opening of the control caused heads to remain sufficiently high so that general expulsion of salt water from the aquifer occurred throughout 1961. It is a contradictory situation that the greatest inland movement of salt water took place in a wet year and the greatest expulsion of salt water took place during a dry year. Nevertheless, this fact indicates that the means are available for very effective control of the movement of salt water in the Biscayne aquifer.

## CONCLUSIONS AS TO OPERATING CRITERIA

The data in this report indicate that salt water need not and should never be trapped in a canal. As the position of salt water in a canal has only a tenuous relation to head, the following conclusions are made with regard to the operation of the gates:

(1) Control gates, which operate automatically by sensing the head differential between the upstream and downstream sides of the dam, cannot be operated effectively on an automatic basis until the relations of salt-water movement and head are properly evaluated. It is entirely possible for the automatic operations to trap salt water inadvertently.
(2) In addition to the upstream and downstream stage recorders which are being installed at the new automatically controlled dams, a conductivity recorder should be installed in each canal slightly upstream from the control dam. Data from these three sources will permit future evaluation of the relation of salt-water movement to total head in the canal and to head differential through the control dam.
(3) Persons responsible for gate operation should be furnished a portable conductivity instrument to determine the salinity at the bottom of the canal at different points. Knowledge of the presence and movement of salt water in the canal will aid greatly in proper operation of the control.

The following suggestions are made for operation after heavy rainfall:

(1) After the first inland penetration of salt water during a rising tide (which may occur within a week after a flood

peak), the gates should be partly closed as conditions permit.

(2) The gates should always be opened uniformly so that maximum fresh-water pressure is applied against the intruding salt water by increased velocities of the fresh water as it flows under the submerged sluice gates.

(3) The instantaneous dynamic head that will prevent inland movement of salt water cannot be determined without controlled tests. However, the calculated hydrostatic head that will prevent intrusion at the bottom of S-29 is 0.3 foot. Therefore, salt water will not enter the bottom of the canal above the control structure if an instantaneous head of 0.3 foot is maintained between upstream and downstream sides of the dam at the time of minimum head differential, about 2 hours before high tide.

Some experimentation will be necessary to establish specific operating criteria. Closing the control gates so that 0.3 foot of head will be maintained during the rising tide will tend to increase the stage in the upstream part of the canal by an amount not greater that 0.3 foot. This is a tolerable increase in stage even during floods.

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