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BUREAU OF GEOLOGY
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Report of Investigations No. 60

HYDROLOGIC EFFECTS OF WATER CONTROL AND MANAGEMENT OF SOUTHEASTERN FLORIDA

By
S.D. Leach, Howard Klein, and E.R. Hampton
U.S. Geological Survey

Prepared by the
U.S. GEOLOGICAL SURVEY
in cooperation with the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT,
the
BUREAU OF GEOLOGY
FLORIDA DEPARTMENT OF NATURAL RESOURCES,
and
OTHER STATE, LOCAL AND FEDERAL AGENCIES

TALLAHASSEE, FLORIDA
1972

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LETTER OF TRANSMITTAL

Bureau of Geology
Tallahassee
December 7, 1971

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

Dear Governor Askew:

Since about the turn of the century the natural hydrologic regimen in southeastern Florida has been modified by man. The higher, dryer land was the first to be utilized and progressively more of the lower, wetter lands have been utilized through water control and management.

This report very adequately portrays the effects of this management n the hydrology of southeastern Florida, and it is a significant contribution to an understanding of the water resources in this part of Florida.

Respectfully yours,

Charles W. Hendry, Chief
Bureau of Geology

Completed manuscript received
November 23, 1971
Printed for the Florida Department of Natural Resources
Division of Interior Resources
Bureau of Geology
by News-Journal Corporation
Daytona Beach, Florida

Tallahassee
1972

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ABSTRACT

Most of the land in southeastern Florida presently utilized for urban, suburban, and agricultural purposes was inundated all or much of the time under natural predevelopmental conditions. Early settlement was on the higher ground, where flooding during the rainy season was less probable. Major urban expansion in the 1900's occurred in the vicinity of Miami, Fort Lauderdale, and West Palm Beach. Drainage canals were extended inland along natural drainageways, and through transverse glades. Urban areas expanded westward on land formerly inundated or used for agriculture, displacing agriculture to land farther inland to the east edge of the Everglades.

The hydrologic regimen of the Lake Okeechobee-Everglades area has undergone continuous modification since settlement began late in the nineteenth century. Before drainage and land reclamation in the northern part of the Everglades, water levels in Lake Okeechobee and those in the Everglades adjacent to the lake were about the same during periods of high water; overflow occurred first at two low places when water stages reached 15 feet — outflow along the south shore became general at a stage of about 18 feet. Modification of overland flow in the Everglades began when drainage canals and levees were built around Lake Okeechobee beginning in 1881. Most of the excavation for major drainage canals along the lower east coast was completed by 1932 — canals were either uncontrolled or inadequately controlled, and continuous drainage resulted in lowered ground-water levels and sea-water intrusion into the Biscayne aquifer in the Miami area. After the 1943-45 drought, major canals through the coastal ridge were equipped with control structures, which prevented overdrainage during dry periods and prevented additional or reduced existent sea-water intrusion.

Extensive flooding which followed the heavy rains of 1947 demonstrated the need to improve the water-control systems. The 1947 flooding led to the establishment in 1949 of the Central and Southern Florida Flood Control District, whose functions were to furnish flood protection to urban and agricultural lands during rainy seasons and to provide facilities for conserving water for alleviation of the effects of drought. Work on new water-control facilities in collaboration with the U. S. Army Corps of En-

gineers proceeded during the 1950's; water Conservation Areas 1 and 2 were enclosed by levees in Palm Beach and Broward counties, and a large area southeast of Lake Okeechobee was made useable for agriculture by the system of levees, canals, and pumping stations. By the end of 1962, water Conservation Area 3 was enclosed on the south side and for the first time, surface flow in the Everglades north of the Everglades National Park could be fully controlled. Conservation Area 3 was considered fully enclosed by July 1967 except for a 7.1 mile stretch of levee between L-28 interceptor levee and the L-28 tieback levee on the west side. Additional changes and modifications in the water-management structures are planned for construction as needed.

The prime effect of the water-control works in south Florida has been to facilitate the flow of water out of the Everglades by means of the canal system, thereby changing the spatial and temporal distribution of runoff from the Everglades. Prior to 1961, flow southward toward the Everglades National Park and south Dade County through the Tamiami Canal outlets, based on the 1941-61 record, averaged 252,600 acre-feet per year through the Levee 30 to Levee 67A section, 128,900 acre-feet per year through the Levee 67A to 40-Mile Bend section, and 201,000 acre-feet per year through the 40-Mile Bend to Monroe section. During 1962-68, average annual discharge through the Levee 30 to Levee 67A section was reduced to about 63,200 acre-feet, the discharge through the Levee 67A to 40-Mile Bend section increased to about 323,600 acre-feet, and the discharge in the 40-Mile Bend to Monroe section remained about the same. Adjustments in operation of canals and control structures to meet changing needs have changed the amount, timing, and distribution of seaward discharge of the Miami, North New River, Hillsboro, and West Palm Beach canals which drain the Everglades and transect the coastal ridges. Reduction in flow to the ocean began with completion of the levee systems east of the three conservation areas in 1953. Discharge to the ocean through Miami Canal was reduced an average of 185,000 acre-feet per run-off year for 1956-65, and combined discharge from North New River, Hillsboro, and West Palm Beach canals was reduced about 294,600 acre-feet per runoff year for 1953-65, from the average discharge of 1940-52. Overall reduction of fresh water flow to the ocean since 1953 as a result of flood and water-control measures is about 20 percent of the fresh water that otherwise would have been discharged to the ocean in southeastern Florida.

Before drainage, water levels were near or at land surface along much of the coastal ridge area. One principal effect of pre-1945 land-reclamation practices was the lowering of ground-water levels throughout the coastal ridge and interior areas. Overdrainage of many coastal areas allowed sea-water intrusion of canals and the Biscayne aquifer, the source of nearly all potable water in the area. The overdrainage has been arrested and, since 1954, water levels have tended to stabilize in most of Dade

County. Yearly peak water levels are considerably lower than in pre-flood-control times, and yearly low water levels are higher than in pre-management times. Thus, during 1945, after a prolonged drought, salty water moved up the Miami Canal and intruded the Biscayne aquifer in the vicinity of the Miami well field, when water was being withdrawn at 30 mgd (million gallons per day). In 1966, in a similar dry season, water was being withdrawn at 80 mgd; minimum water levels near the center of the field were about the same as in 1945, but sea-water intrusion was controlled. The improved conditions of well-field production and salinity control are results of salinity barriers in canals and replenishment of water in well-field areas from canals. Similar conditions prevail at other near-shore well fields in the southeast Florida area.

Additional improvements in the hydrologic situation in places in southeast Florida can be achieved by applying existing hydrologic management practices to smaller, specific areas of need, generally by installing additional salinity and water-control structures at key places in canals and by carefully manipulating these to maintain ground water at the maximum levels that allow flood protection to urban and suburban areas. Management practices of this sort will aid prevention of sea-water intrusion during dry periods and allow increased withdrawals of potable water from well fields. Continuous replenishment of water in well fields will be from canals in the dry season, requiring careful attention to the overall quality of water in the canals.

INTRODUCTION

Southeastern Florida is considered in this report to include that part of the State, from the northern shore of Lake Okeechobee and the mouth of the St. Lucie Canal southward to the tip of Florida and from the east coast westward to about the middle of Hendry and Collier Counties (fig. 1). This area is one of rapid urban expansion, where increasing quantities of water are needed to satisfy growing requirements for municipal and industrial supplies and other uses. The region could not have urbanized were it not for programs, started in the early 1900's, aimed initially toward land reclamation, later toward flood control and water control, and finally toward water management. Implementation of these programs has caused major hydrologic changes throughout southeastern Florida. These changes were characterized by modification in rates and duration of fresh-water runoff, impoundment of water in water-storage areas, diversion of water from historical flow patterns, adjustment in water-level gradients and ranges in fluctuations, and changes in water quality. The area of south Florida affected by drainage and reclamation encompasses about 5,800 square miles and is shown on figure 1. Included in the area of investiga-

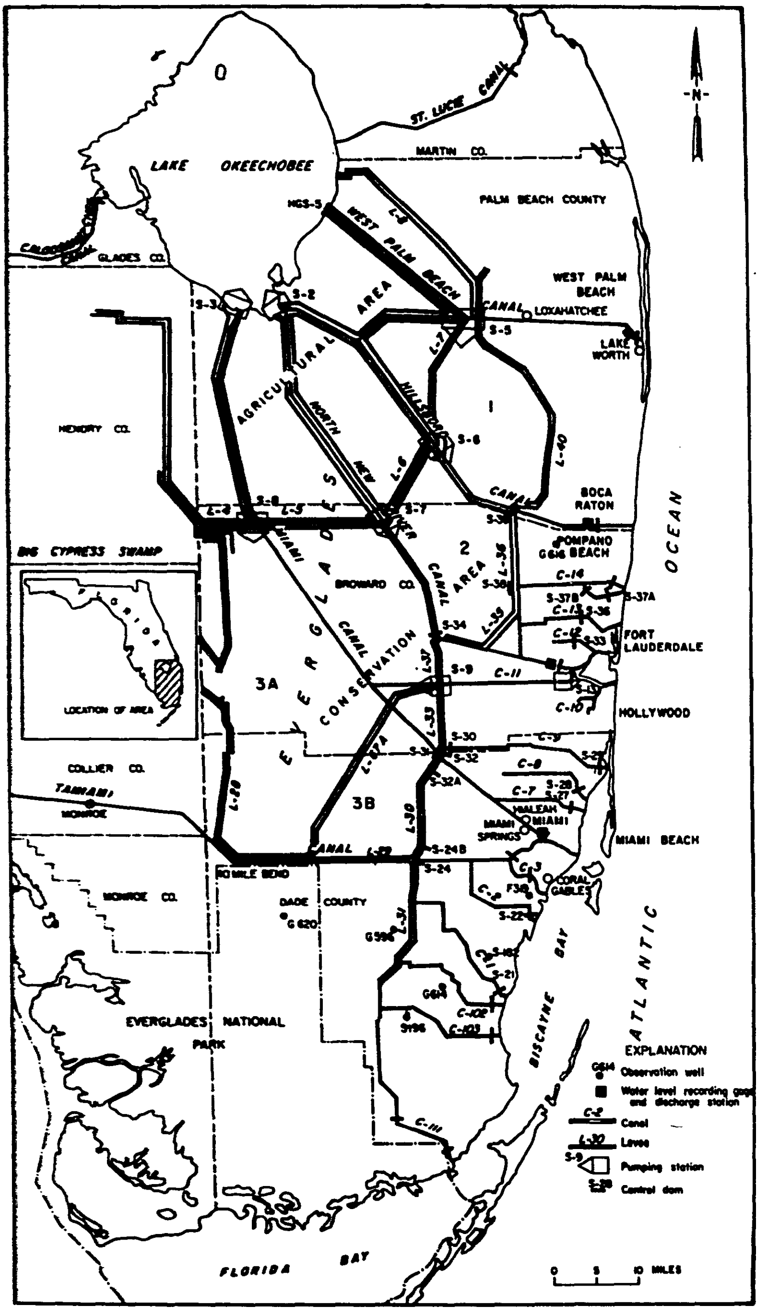

Figure 1. Map showing the Central and Southern Florida Flood Control project structures and hydrologic features in southeastern Florida, 1968

tion, which is coexistent with southeastern Florida as defined above, are project structures and other control features of the Central and Southern Florida Flood Control District (C&SFFCD).

PURPOSE AND SCOPE

This report was prepared by the U.S. Geological Survey in cooperation principally with the Central and Southern Florida Flood Control District (C&SFFCD) as part of the statewide program of water resource evaluation. In addition, the Bureau of Geology, Florida Department of Natural Resources, Broward, Dade, and Palm Beach counties, the cities of Fort Lauderdale, Miami Beach, and West Palm Beach, the Miami Department of Water and Sewers, the National Park Service, and the U.S. Navy extended financial support for the report. All of these agencies are interested in the hydrologic effects of drainage and reclamation of southeast Florida.

Although the results of several water-related investigations have been published, the total hydrologic effects of drainage and reclamation have not been clearly portrayed. The purpose of this report is to describe and evaluate from the mass of hydrologic information the effects that man's activities have had on the hydrology of southeast Florida. Analysis of the data collected, together with an evaluation of the effects of water management provide answers to such questions as:

1. What gross effects have the works of the C&SFFCD had on the hydrologic regimen of southeast Florida?
2. What are the climatic conditions in the southeast Florida area today, and how do they compare with conditions in the past?
3. Will the present and proposed flood-control system be adequate to prevent flooding and to halt sea-water intrusion into the Biscayne aquifer in coastal areas and to provide water to meet the demands of the growing population and other demands?

In the process of answering the above questions, the history of the construction of C&SFFCD works was compiled, the seepage beneath various levees was determined, a generalized water budget was estimated for the conservation areas, and projection of water needs by the year 2000 have been made.

ACKNOWLEDGMENTS

Thanks are given to William V. Storch, Director, Engineering Division, and Robert L. Taylor, Chief of the Hydrology and Hydraulics Branch, C&SFFCD; F.D.R. Park, Water Control Engineer, Dade County Department of Public Works; Garrett Sloan, Director of the Miami Department of Water and Sewers; J. Stanley Weedon, Water Control Engineer, Broward County; John G. Simmons, Director of Utilities, West Palm Beach; and Frank Nix, Hydraulic Engineer, Everglades National Park, for furnishing hydrologic data, and other information. Thanks are also given to the Corps of Army Engineers, Jacksonville, for furnishing discharge information on seepage through levees. The authors are indebted to D. F. Tucker, the Florida District Cartographer, for the many useful suggestions concerning the layout of the illustrations. This report was prepared under the general supervision of C. S. Conover, District Chief, Florida District.

PREVIOUS INVESTIGATIONS

Information concerning the water resources and geology of southeastern Florida is contained in many published reports. Three of the earlier reports that provided the authors with background material are: Matson and Sanford's 1913 report and those of Stringfield in 1933 and 1936.

A comprehensive report on the geohydrologic environment of south Florida based on data collected through 1946 by Parker, Ferguson, Love, and others (1955) provided much background material for establishing the hydrologic setting for the early years during the Everglades Drainage District period, established in 1905, and was used as an aid in determining the effects of changes by the Central and Southern Florida Flood Control District. Several other reports bear on the hydrology of the southeast Florida area. Reports by Schroeder, Klein, and Hoy (1958); Sherwood and Klein (1963); and Sherwood (1959) provide considerable background information on the Biscayne aquifer and the geology. Reports by Klein (1959) and Appel and Klein (1969) on fresh-water supplies provided information on the effects of pumping from the highly permeable Biscayne aquifer.

Reports by Sherwood and Leach (1962), Leach and Sherwood (1963), Kohout and Leach (1964), and Leach and Grantham (1966) provide background information on canal hydrology, sea-water intrusion, and the interconnection between the aquifer and the canals.

Information on seepage through levees was presented by Klein and Sherwood (1961) and a general background on hydrology in segments of the study area were provided by Hartwell, Klein, and Joyner (1963) and Kohout and Hartwell (1967).

GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY AND DRAINAGE

Southeastern Florida generally is flat and low-lying. It has been divided into the Atlantic coastal ridge, sandy flatlands, the Everglades, the Big Cypress Swamp, and the mangrove and coastal glades topographic-ecologic (physiographic) provinces as shown on figure 2. The report area includes all of south Florida generally east of the Big Cypress Swamp—Everglades

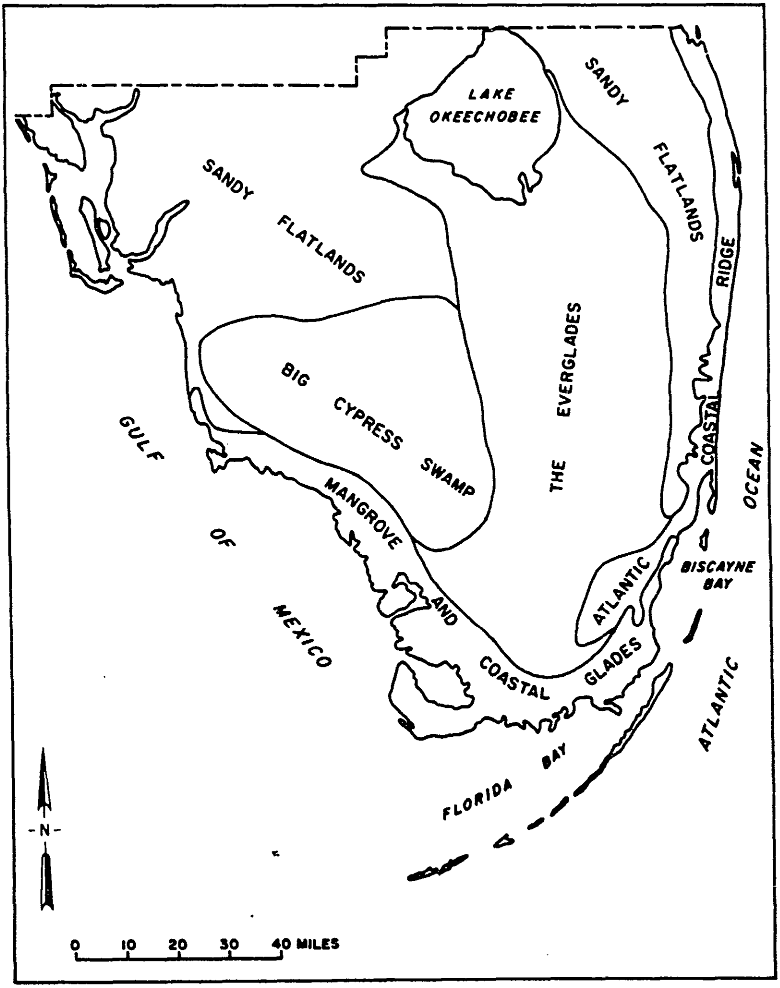

Figure 2. Physiographic provinces of southern Florida

boundary shown on figure 2. A more comprehensive description of the physiographic areas shown on figure 2 is given by Parker, Ferguson, Love, and others (1955, p. 141-155).

The Atlantic coastal ridge is about 5 miles wide, ranges from about 8 to 24 feet above mean sea level, and occupies about 600 square miles. It is breached in many places south of Boca Raton by transverse glades most which are sites of canals. The sandy flatlands province is between the Atlantic coastal ridge and the Everglades, and in the report area it slopes gently southward. Altitudes range from about 20 feet adjacent to Lake Okeechobee to about 6 feet near Miami. It occupies about 1,200 square miles of the report area. The Everglades is slightly lower than the sandy flatlands; it is a seasonally inundated 4,000-square-mile area of organic soils covered predominantly by sawgrass marsh and broken by elongate "tree islands." The Everglades area ranges in altitude from about 14 feet near Lake Okeechobee to about sea level near Florida Bay. The mangrove and coastal glades are mostly tidal flatlands subject to inundation during high tide, particularly when winds are from the southwest. They occupy an area of about 1,100 square miles. They are not a part of the fresh-water system described in this report.

Natural drainage in the report area was generally southward within the Everglades and eastward from the Everglades across the sandy flatlands and through the Atlantic coastal ridge via transverse glades. Present-day drainage through the transverse glades is largely by way of canals.

CLIMATE

The climate of south Florida is subtropical. Average daily temperatures range from about 82° F in the summer to about 68° F in the winter.

Rainfall was determined from the records of 11 National Weather Service (U.S. Weather Bureau) gages selected as index stations because of their long continuous operation (since 1940) and their adequate distribution. Missing record for a particular index station was estimated from one or more of the nearby stations. Table 1 lists the long-term index rain gages, the annual total rainfall for each, the average rainfall for the period of record for each, and the annual average for all gages. Also shown is high and low annual rainfall for each gage.

The annual rainfall in southeastern Florida occurs in distinct cycles. The rainy season, normally June through October, contributes about 70 percent, or about 41 inches of the 59-inch annual total, based on the 20-year average of the index gages. The remaining 18 inches is distributed throughout the other seven months.

Table 1. Annual rainfall, in inches, for the eleven long-term index rain gages in the area of investigation for 1940-65. Also tabulated are the annual averages for all stations and the highest, lowest, and average values at each gage.

Year	Belle Glade	Canal Point	Dania 5 mi. w.	Ft. Lauderdale	Hialeah	Homestead	Loxahatchee	Miami Airport	Stuart	Tamiami Canal at 40-Mile Bend	West Palm Beach Airport	Average
1940	54.94	59.42	64.28	70.75	64.28	70.37	64.28	66.22	58.98	64.28	69.30	64.28
1941	63.53	70.23	65.37	55.01	57.37	76.47	74.00	63.34	64.79	64.74	72.88	66.16
1942	65.82	51.51	65.45	53.05	65.39	63.31	63.25	68.87	58.54	54.43	69.47	61.74
1943	43.20	43.52	48.55	47.38	58.39	56.80	52.78	62.86	46.97	58.96	51.95	51.94
1944	52.12	40.56	44.75	43.09	39.29	51.15	57.51	40.19	45.68	41.60	41.42	45.21
1945	50.65	53.02	60.31	51.99	40.98	54.28	54.12	42.28	54.75	53.55	62.69	52.60
1946	70.94	64.86	62.23	47.70	55.04	64.27	60.53	54.93	49.50	46.67	61.47	58.01
1947	84.68	88.11	106.08	102.36	78.25	94.07	97.20	78.39	73.11	82.76	105.22	90.02
1948	62.98	49.24	74.96	70.87	73.03	70.67	71.50	78.87	48.59	58.47	63.62	65.71
1949	53.53	56.29	68.97	56.75	64.86	65.32	67.91	62.14	52.15	69.26	54.67	61.08
1950	51.03	36.89	60.91	59.30	52.03	55.96	58.57	49.47	44.86	56.96	51.92	52.54
1951	62.18	56.22	43.72	37.34	44.41	45.64	64.95	38.67	47.96	39.21	52.83	48.47
1952	57.75	53.26	46.21	45.61	53.35	58.24	60.48	48.94	55.11	56.54	50.87	53.31
1953	62.31	68.13	72.80	76.75	70.82	63.99	80.61	65.15	74.36	63.49	71.15	69.96
1954	54.18	59.05	72.62	85.80	74.09	67.76	78.23	62.26	70.08	49.99	73.21	67.93
1955	51.40	46.92	35.88	41.20	51.29	52.59	46.69	41.35	43.52	46.13	37.31	44.93
1956	39.55	42.07	29.02	39.25	47.08	45.37	43.93	37.00	40.68	42.97	38.40	40.48
1957	71.26	69.91	69.41	72.15	67.16	63.22	79.73	70.87	61.96	68.22	62.93	68.80
1958	62.40	63.67	61.41	74.75	75.28	73.00	62.32	71.92	60.63	59.33	65.18	66.35
1959	72.99	70.15	84.76	79.70	89.90	87.09	95.63	89.33	87.78	67.18	68.64	81.20
1960	69.50	53.55	72.04	60.48	68.84	82.12	77.74	70.26	60.90	73.91	66.77	68.74
1961	40.85	49.28	40.23	35.54	41.10	45.75	36.64	41.70	43.76	44.05	37.76	41.51
1962	61.51	47.72	41.92	56.11	50.67	55.56	55.70	42.27	51.59	56.06	48.56	51.61
1963	49.87	41.10	46.65	59.34	54.94	62.65	45.29	46.08	54.63	62.41	53.31	52.39
1964	45.13	60.26	47.67	66.99	69.67	61.09	59.46	60.20	62.23	55.28	79.30	60.66
1965	55.56	61.83	55.99	59.76	60.84	46.30	58.23	58.40	40.57	49.49	58.26	55.02
Average	58.07	56.03	59.32	59.58	60.32	62.81	64.13	58.15	55.91	57.15	60.35	59.26
High	84.68	88.11	106.08	102.36	89.90	94.07	97.20	89.33	87.78	82.76	105.22	90.02
Low	39.55	36.89	29.02	35.54	39.29	45.37	36.64	37.00	40.57	39.21	37.31	40.48

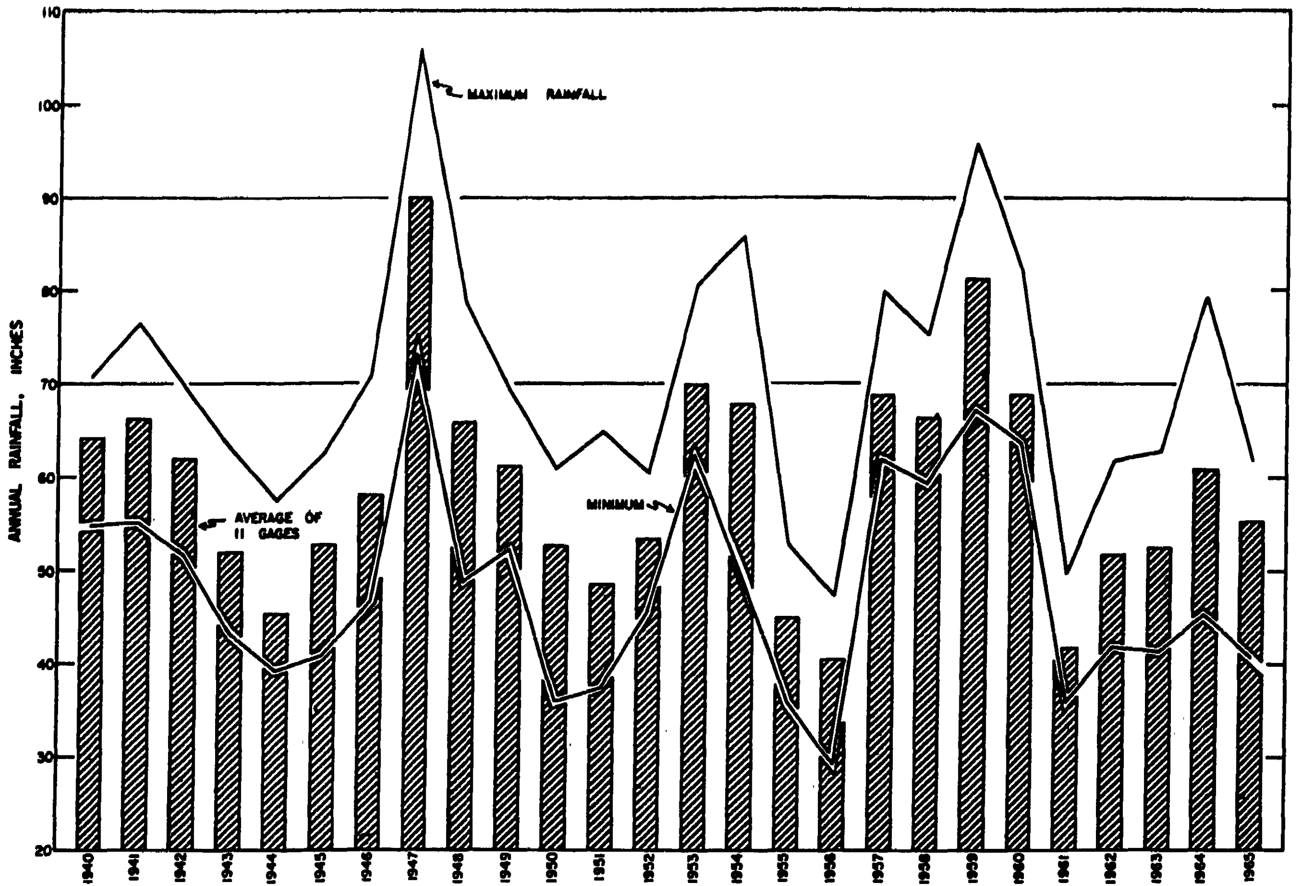

Figure 3. Graph of maximum, minimum, and average annual rainfall of the eleven long-term index gages in southeast Florida, 1940-65

The extremes in annual rainfall for 11 long-term index stations (table 1) range from 106 inches in 1947 to 29 inches in 1956. Both extremes were at the station 5 miles west of Dania in Broward County. The maximum and minimum rainfall recorded each year at any one of the 11 stations is shown in figure 3, along with a bar graph to show the average by year of the 11 stations. Extremes in rainfall range from about 19 inches greater than the yearly average of the 11 stations to about 18 inches less than the yearly average of the 11.

Rainfall patterns for a dry year, 1956, and a wet year, 1947, are shown in figures 4 and 5. A comparison of the figures shows the wide range in rainfall between the dry year and the wet year. The isohyetal lines of rainfall for 1956 shown on figure 4 used data from 33 rain gages for which records for the year were complete. The 1956 year is a typical dry year as compared with other dry years except for the wet cell near the intersection of the Miami and North New River canals. In 1956, the coastal and interior areas received about the same amount of rainfall.

The isohyetal lines of rainfall for 1947, shown in figure 5, used data from 47 rain gages for which records for the year were complete. In 1947 a hurricane in September and one in October crossed south Florida and yielded much of the excessive rainfall along the coast. In other years of above-normal rainfall, the data show that the coastal ridge generally receives more rainfall than the interior.

The deviation from the 1941-60 average rainfall (57.34 inches) for the 24 rain gages that have complete records is shown in figure 6. Several rain gages outside the area were also used to aid in determining the shape of the isohyetal lines. These lines show the deviation from the average of all 24 gages and indicate that the coastal ridge annually receives several inches more rainfall than the Everglades.

A further examination of figure 6 reveals that Lake Okeechobee received on the average about 7 inches less per year than the average of the 24 rain gages. Also, the rainfall deviation has a gradient over the lake from near average along the southeastern shore (zero isohyetal) to 11 inches below average (-11 isohyetal) along the northeastern shore.

The figure shows a wide variation in rainfall over the three water conservation areas. Rainfall averaged about 2 inches per year above the 57-inch 24-gage average in Conservation Area 1, 1 inch below the average in Conservation Area 2 and about 4 inches below the average in Conservation Area 3.

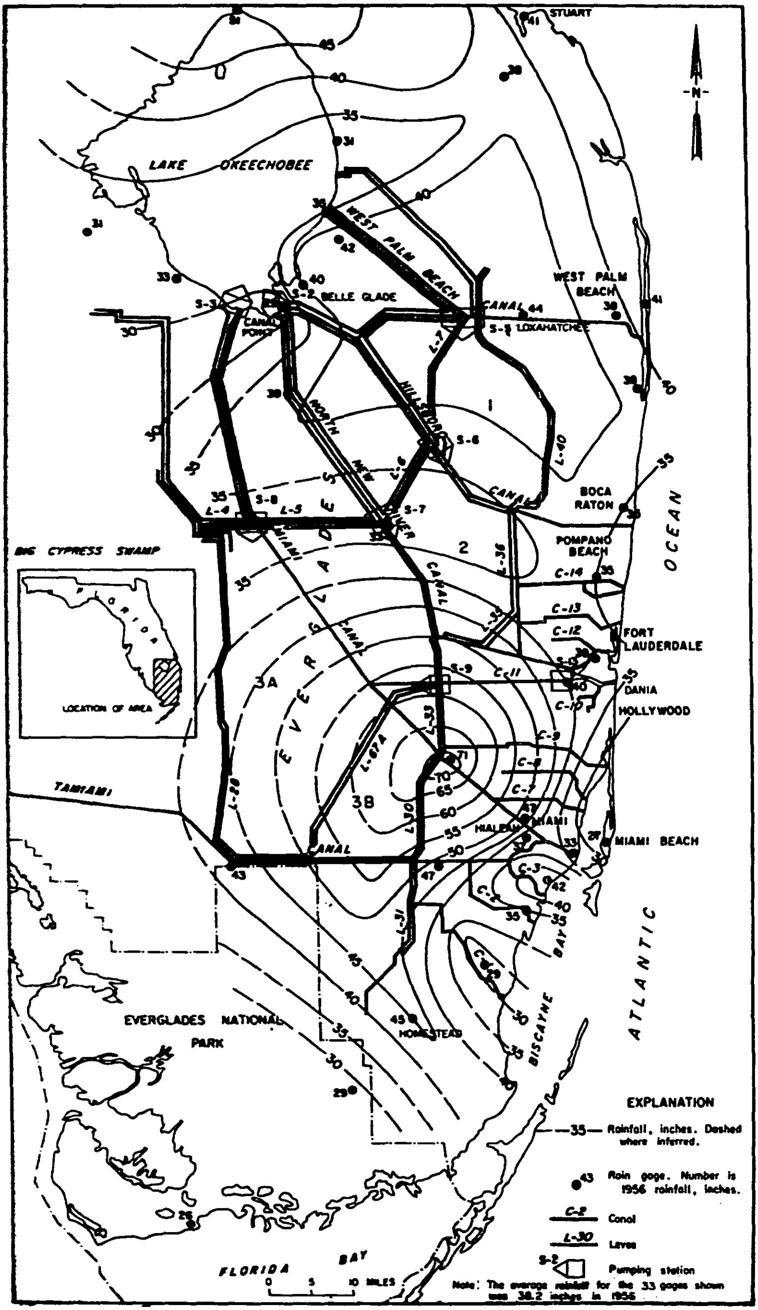

Figure 4. Map of annual rainfall in the area of investigation for 1956, a relatively dry year, using U.S. Weather Bureau data

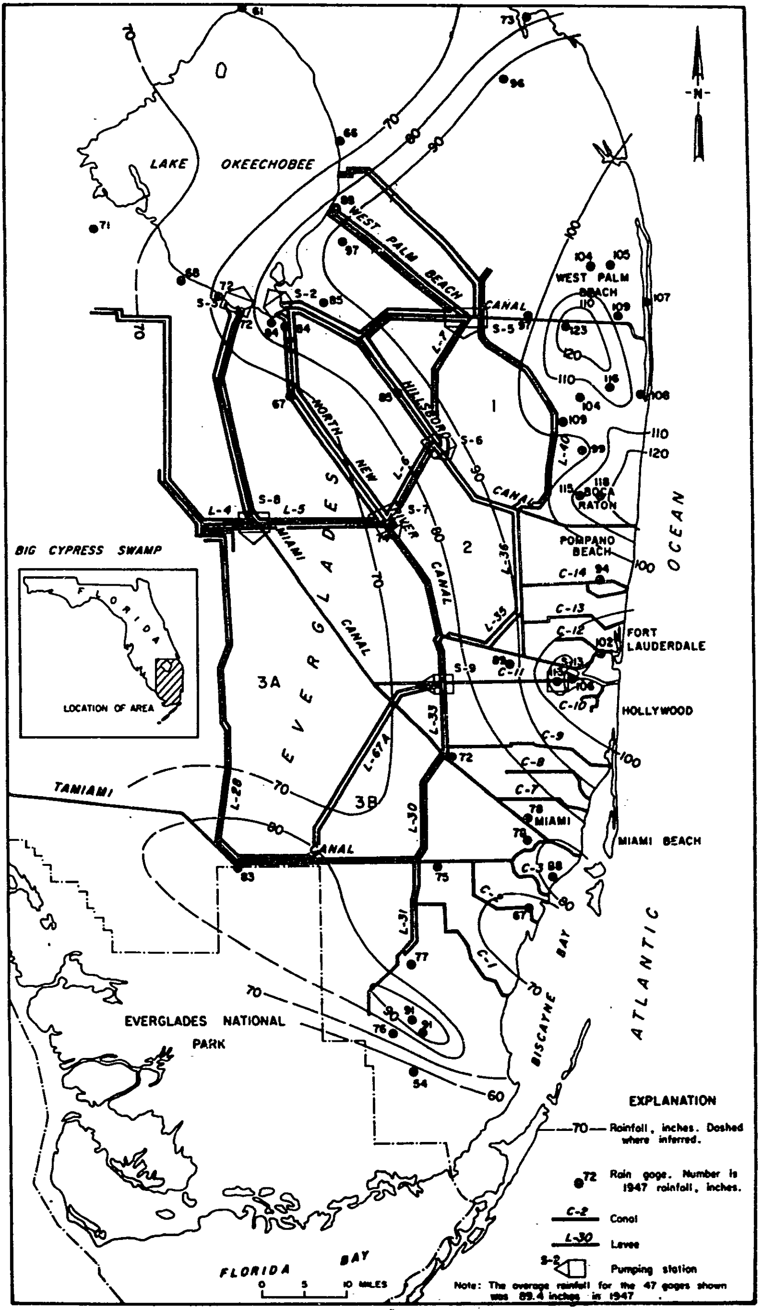

Figure 5. Map of annual rainfall in the area of investigation for 1947, one of the wettest years of record, using U.S. Weather Bureau data

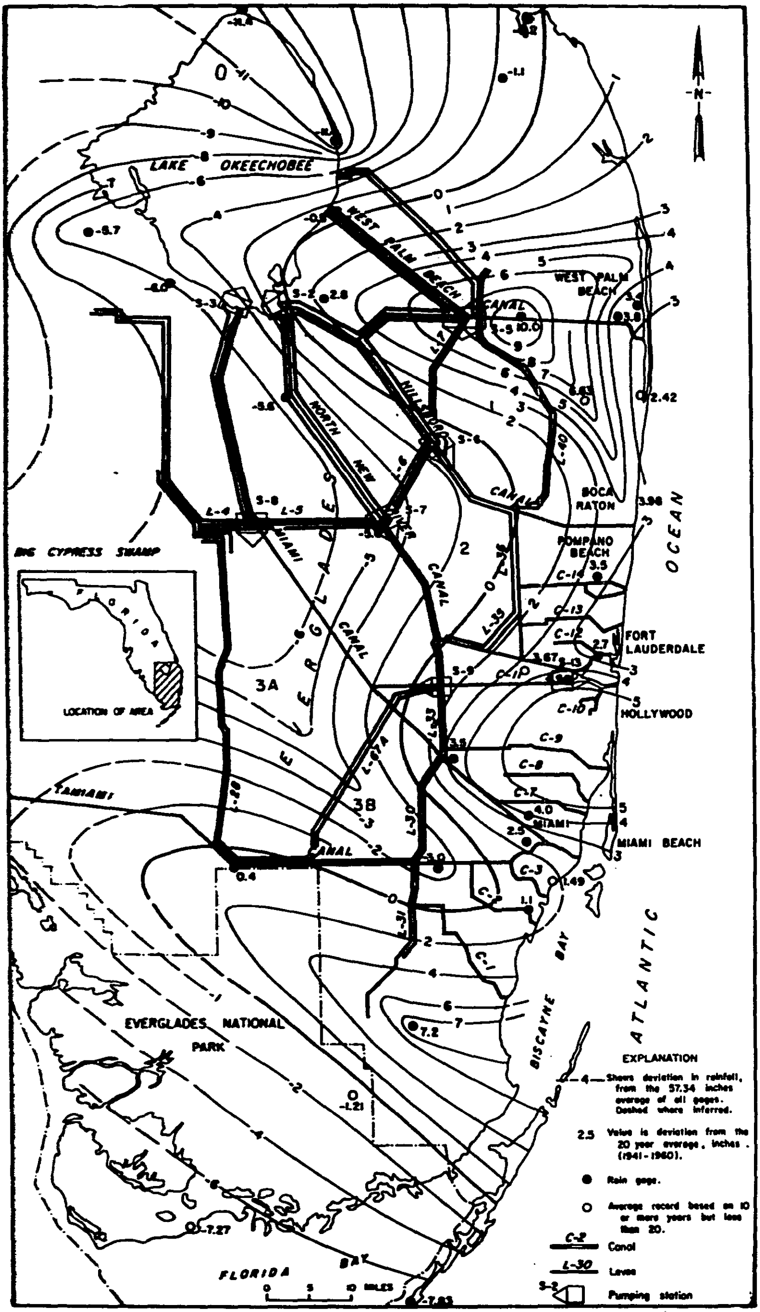

Figure 6. Map showing deviation from the annual average raintall at 24 U.S. Weather Bureau gages, 1941-60. The records of several rain gages located outside the area were also used to aid in determining the shape of the isohyetal lines

GEOLOGY

Sedimentary deposits, mostly sand and limestone, underlie southern Florida. The geologic units of particular importance to the water resources of the area are the highly permeable limestone and sandstone units that compose the Biscayne aquifer and the younger deposits of sand that underlie beach and dune ridges and some terraces.

The Biscayne aquifer underlies most of Dade County, central and eastern Broward County, and southeastern Palm Beach County; it ranges in thickness from a few feet in the central parts of the Everglades to more than 250 feet in coastal Broward County. The aquifer yields all the fresh ground water used in the three counties, except for eastern and northeastern Palm Beach County, where supplies are obtained from sediments of lower permeability.

The rocks that compose the Biscayne aquifer of southern Florida overlie a thick sequence of relatively impermeable clayey materials which in turn overlie the permeable limestone formations of the Floridan aquifer. Beneath much of southern Florida, the Floridan aquifer contains water under sufficient artesian pressure to flow at the surface, but the water generally contains dissolved constituents in excess of the limits recommended for drinking water by the U.S. Public Health Service (1962).

A comprehensive description and discussion of the geology of southern Florida is presented by Parker, Ferguson, Love, and others (1955).

POPULATION DISTRIBUTION AND WATER USE TRENDS

Early settlement in southeastern Florida was on the higher ground of the Atlantic coastal ridge (figure 2) because flooding during the rainy season was less probable there. The areas of major urban expansion were in the vicinity of Miami, Ft. Lauderdale, and West Palm Beach. As drainage canals were extended inland and improved, water levels were lowered sufficiently to permit construction along the transverse glades, the natural drainageways that traverse the coastal ridge, and in areas immediately west of the coastal ridge. Figure 7 shows that alignments of several of the major canals generally follow the natural drainageways through the coastal ridge. As drainage progressed, urban areas expanded to the west along the drainageways on lands formerly used for agriculture, displacing agricultural lands farther inland to the eastern edge of the Everglades.

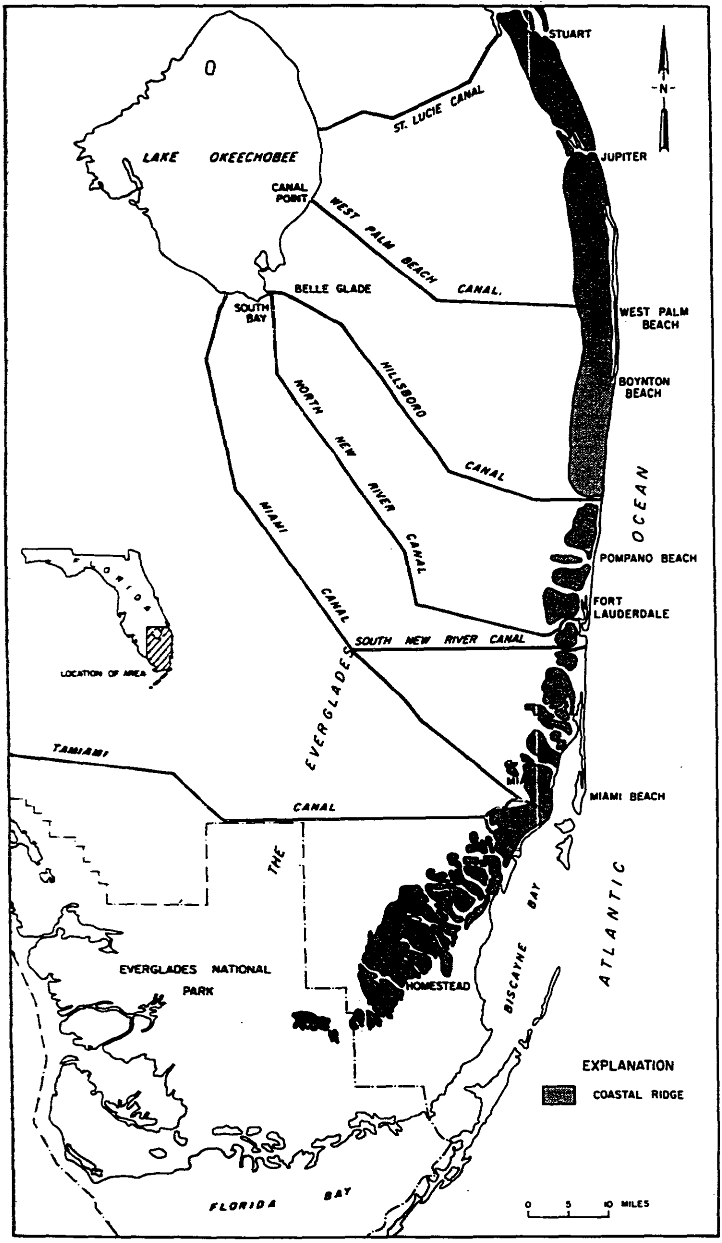

Figure 7. Map of Florida's lower east coast showing the configurations of the natural drainageways (transverse glades) and locations of major canals through the coastal ridge

POPULATION

The region is one of extremely rapid growth in population and economy since 1940. Local planning agencies estimate that the growth

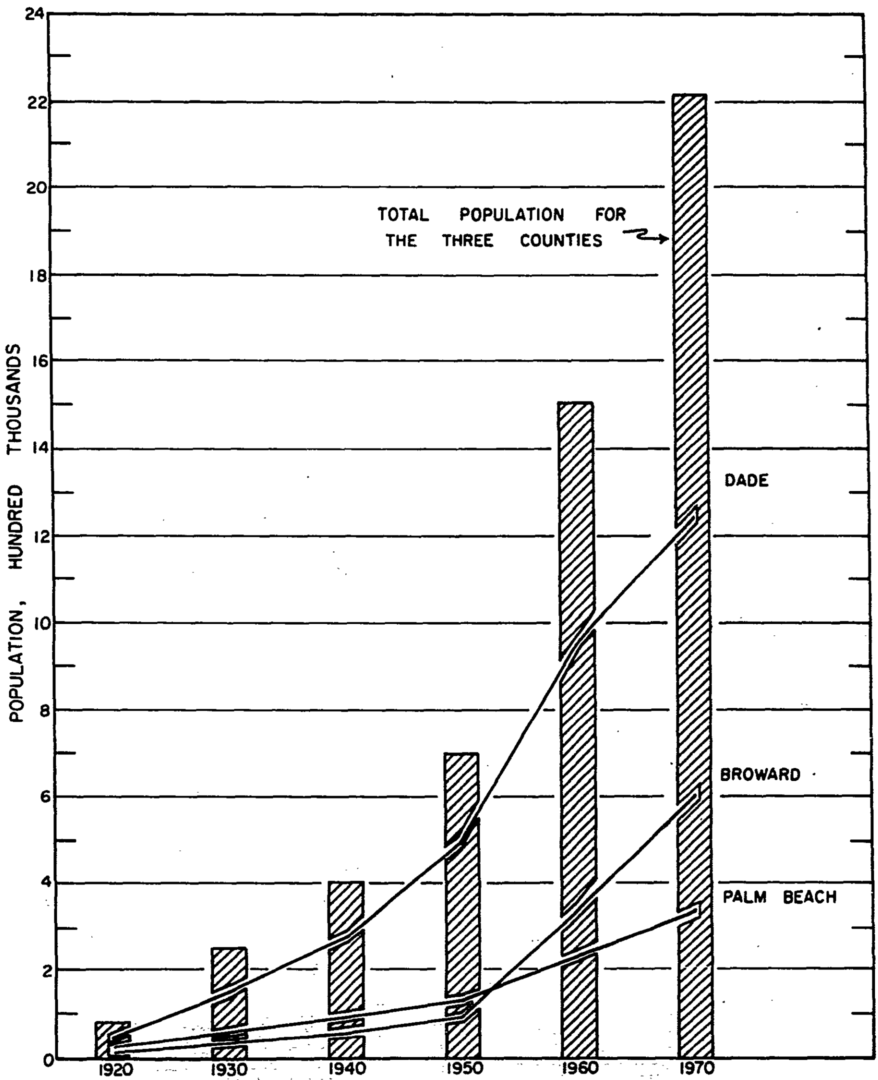

Figure 8. Comparison in population trends in Dade, Broward, and Palm Beach counties of Florida's southeast coast

rate will continue. The following tabulation shows combined population increases for Dade, Broward, and Palm Beach Counties:

1940	390,000
1950	695,000
1960	1,500,000
1965	1,870,000
1970	2,217,000

By the year 2000 the population of the three counties is expected to approach 4.2 million. Figure 8 shows the long-term rate of population growth in three counties of Florida's lower east coast. In addition many tourists visit the lower east coast each year. The major influx has been during the winter, but in recent years summer tourism has increased substantially.

WATER USE

MUNICIPAL

Rapid population increases and the periodic influx of millions of tourists have created major fluctuating stresses on municipal water-supply systems. The municipal systems have succeeded in meeting these demands by planning 10 to 15 years in advance of current needs. Fortunately, the water resources of the region have been adequate despite local problems of contamination by sea-water intrusion and seasonal droughts. Pumpage figures in table 2 show rates of increase in municipal water use for the three largest supply systems—Miami, Fort Lauderdale, and West Palm Beach. All municipal supplies are obtained from ground-water sources except that for West Palm Beach, which obtains its supply from lakes immediately inland from the coast.

Table 2 Pumpage by the three largest supply systems in Florida's lower east coast

City	Year	Average day million gallons	Peak day million gallons	Average for year 1000 Ac/ft
Miami	1960	96.8	137.8	108.4
	1965	131.1	173.7	146.8
	1970	153.1	212.0	171.5
Fort Lauderdale	1960	20.0	35.6	22.4
	1965	28.6	46.9	32.0
	1970	40.7	60.2	45.6
West Palm Beach	1960	11.7	14.6	13.1
	1965	13.9	18.2	15.6
	1970	17.0	29.3	19.0

The Department of Water and Sewers of the city of Miami estimates that by 1980 its daily pumpage during the peak of the tourist season (January-March) will be about 250 mgd (million gallons per day). The Department serves Miami, Miami Beach, Hialeah, Coral Gables, and some nearby communities. In addition, many other smaller municipalities such as North Miami, North Miami Beach, Hollywood, Pompano Beach, Boca Raton, and Lake Worth operate separate municipal systems which show comparable increases in withdrawal rates. The graph in figure 9

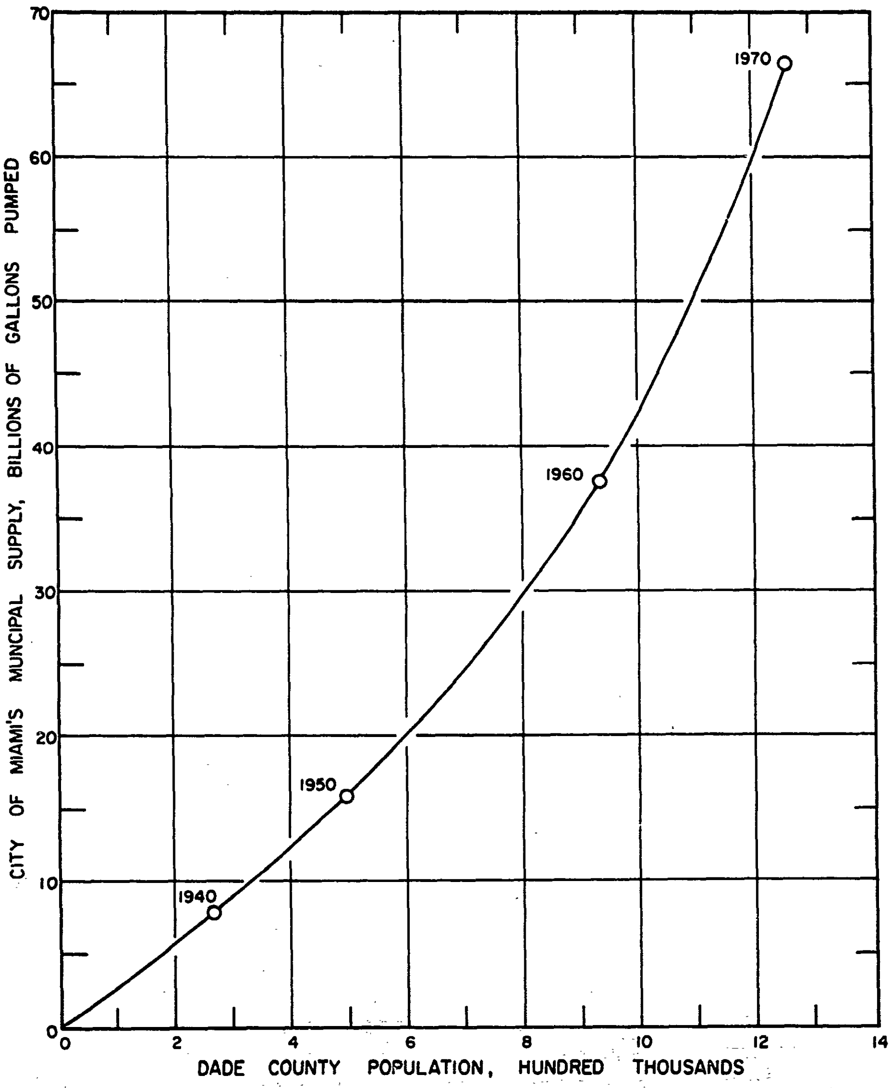

Figure 9. Comparison of city of Miami municipal fresh-water supply and Dade County population over the years.

relates Dade County population growth to the increase in pumping by the city of Miami. The steepening of the curve indicates the per capita use of water in the county has increased over the years.

AGRICULTURAL

Agriculture is the largest user of water in Dade, Broward, and Palm Beach counties. In addition to pumping more water for irrigation than all other users combined, agricultural users consumed about six times more water than the other users in 1965. The supplemental water pumped for irrigation is withdrawn directly from canals and from the Biscayne aquifer. As noted in table 3, irrigation use is projected to increase nearly two and a half times by the year 2000.

The fresh-water demand for the year 2000 for Dade, Broward, and Palm Beach Counties, the three largest counties of Florida's lower east

Table 3. Population for the three largest counties of Florida's lower southeast coast and the amount of fresh water (in 1000 Ac-ft per year) pumped and consumed for municipal, industrial, and agricultural uses in 1965, and as estimated for the year 2000.

County	Population[1]	WATER USE 1965 [2]					
		Municipal		Industrial		Agriculture	
		Pumped	Consumed	Pumped	Consumed	Pumped	Consumed
Broward	480,000	83	21	3.3	0.1	95	40
Dade	1,100,000	225	22	8.5	4.6	214	86
Palm Beach	290,000	43	8.5	6.3	1.1	654	262
Totals	1,870,000	351	51.5	18.1	5.8	963	388

County	Population[3]	WATER USE 2000 [4]					
		Municipal		Industrial		Agriculture	
		Pumped	Consumed	Pumped	Consumed	Pumped	Consumed
Broward	1,370,000	237	60	9.4	0.3	271	114
Dade	1,970,000	403	39	15	8.2	383	154
Palm Beach	910,000	135	27	20	3.4	2,050	822
Totals	4,250,000	775	126	44.4	11.9	2,704	1,090

[1] Adapted from Florida Development Commission data.

[2] Written communication on Water Use 1965, R. W. Pride.

[3] County population projections developed by the Florida Social Sciences Advisory Committee (total occupants less tourists).

[4] The 2000 year water-use estimates are based on water use in 1965 and population projections.

coast, was estimated on the basis of a comparison of the total amount of fresh water pumped and consumed in 1965 (table 3), assuming that per capita use will remain constant and the ratio between water pumped and water consumed also will remain constant. Estimates for the year 2000 show that Dade, Broward, and Palm Beach Counties will pump 3,523,000 and consume 1,230,000 acre-feet of fresh water annually. The consumptive use of water in the year 2000 will be 782,600 acre-feet more than the 445,300 acre-feet consumed by the three counties in 1965. Water consumed is water removed from the local hydrologic system and no longer immediately available for man's use. This increased consumption equals about 700 mgd, or about one and three quarter times the consumption in 1965 for all uses. Most of this additional consumption of water occurs during the dry season each year.

WATER CONTROL AND MANAGEMENT

HISTORY OF WATER CONTROL WORKS

The hydrologic regime of the Lake Okeechobee-Everglades area has undergone continuous modification since settlement began late in the nineteenth century.

The northern part of the Everglades immediately south of Lake Okeechobee was covered by a thick layer of peat that supported dense vegetation, chiefly sawgrass. During the rainy seasons and for several months afterward, water stood above the surface at varying depths, and large losses by evapotranspiration resulted (Parker, Ferguson, Love, and others, 1955, p. 333). Overland flow through the dense vegetation was nearly imperceptible and resembled flow through a permeable aquifer, rather than the surface flow of a wide river. In the southern part of the Everglades, the soil is thin, rocks crop out in many places, and vegetation is less dense; consequently, overland flow there is more rapid. Under natural conditions, most of the water in a particular area of the upper (northern) Everglades was derived from rain on that area or inflow from the area immediately to the north.

In the northern part of the Everglades, before land was drained and reclaimed, water levels in Lake Okeechobee and those in the Everglades adjacent to the lake were the same during periods of high water. When water stages in the area reached about 15 feet, overflow probably occurred first at two low places: part of the water flowed westward into the headwaters of the Caloosahatchee River and part southward into the

Everglades in a narrow reach. Outflow along the south shore became general at a water stage of about 18 feet and "sizeable volumes of water moved slowly in flat, broad sloughs toward tidewater" (Parker, Ferguson, Love, and others, 1955, p. 332).

Modification of the overland flow in the Everglades began when drainage canals and levees were built around Lake Okeechobee. Deepening of the natural flood channel from Lake Okeechobee to the Caloosahatchee River was an early venture. Drainage operations began in July 1882, and by early 1883 a shallow canal connected the Caloosahatchee River to Lake Okeechobee (Parker, Ferguson, Love, and others, 1955, p. 328).

Land drainage and reclamation in the Everglades during 1905 under the Everglades Drainage District began with the construction of two dredges on the banks of New River where Ft. Lauderdale now stands. The dredges were used to excavate four major channels from Lake Okeechobee to the Atlantic Ocean, and by 1913, the North New River Canal was open from Ft. Lauderdale to Lake Okeechobee. The Miami Canal was open except for the lower 6-mile section that was completed by May 1, 1913, the Hillsboro Canal was completed except for a 5-mile section, and the West Palm Beach Canal was under construction. The above four canals were completed and fully operational by 1921; they extended from the southeast shore of the lake across the Everglades and coastal ridge to the ocean. Hurricane gates were constructed at the lake ends of the canals. The gates were closed during hurricanes to minimize water damage to nearby agricultural land in reclaimed parts of the Everglades from the storm tides generated in the lake. The gates were also closed when the water level of the lake was higher than that of the drainage canals adjacent to the lake.

Construction of the St. Lucie Canal began in 1916, and water first flowed through the canal in 1924. During 1935-46, the St. Lucie Canal was the main controlled outlet for the regulation of the water level of the lake.

Construction of a low muck levee on the south and east sides of Lake Okeechobee was begun in 1921 and completed in 1924. This levee was overtopped and breached in 1926 and 1928 by hurricane-driven storm surge. A second, higher earth levee was constructed between 1924 and 1938 on the east, south, and west sides of the lake. The total length of this levee was 85 miles, and the top elevations ranged from 34 to 38 feet.

As new land southward and eastward from Lake Okeechobee and along the east edge of the Everglades in Palm Beach, Broward, and Dade counties was used for agriculture, greater areas came under water control, and drainage facilities were improved through efforts of several drainage districts. These lands were effectively drained, and flood waters were disposed of rapidly. Thus a large part of the overland flow from the Everglades was diverted through the canal systems to the ocean.

Most of the excavation for major drainage canals along the lower east coast was completed by 1932. The canals were either uncontrolled or inadequately controlled, and the continuous drainage to the ocean during dry seasons resulted in intrusion of sea water into the Biscayne aquifer, which threatened municipal water supplies in Miami. After the 1943-45 drought, the major canals through the coastal ridge were equipped with salinity-control structures, which could be opened to discharge flood water during the rainy season and closed to prevent overdrainage of fresh water from the Biscayne aquifer and consequent salt-water encroachment during dry periods.

The heavy rains of 1947 resulted in extensive flooding of the urban and agricultural areas of southeast Florida, which demonstrated the need for improvement in the water-control systems. As a result, more effective programs to handle flood waters were developed, which led to the establishment in 1949 of the C&SFFCD, whose functions were to furnish flood protection to urban and agricultural lands during rainy seasons and to provide facilities for conserving water for alleviation of the effects of drought and for control of salt-water encroachment.

Work on the C&SFFCD facilities in collaboration with the U.S. Army Corps of Engineers proceeded on an intermittent basis during the 1950's. Water Conservation Areas 1 and 2 were enclosed by levees in Palm Beach and Broward Counties, and a large area southeast of Lake Okeechobee was zoned for agriculture and made useable by the system of levees, canals, and pumping stations (fig. 1).

WATER MANAGEMENT PRACTICES AND PROBLEMS

Water control to protect agricultural areas from flooding was either by gravity flow or by pumping from canals toward Lake Okeechobee and by pumping into the water conservation areas. Water flowed southward by gravity through canals and control structures or was pumped to Conservation Area 3 where it moved slowly southward toward the Everglades National Park. Also, that part of the water in Conservation Area 1 which was in excess of the regulation level was diverted to Conservation Area 2, and the excess in Conservation Area 2 was moved to Area 3 through spillways. Establishment of the levees and water conservation areas in the Everglades and the beginning of reductions in the flow of canals to the ocean were the first compensating steps toward reverting toward the original drainage patterns and water conditions in the Everglades. By the end of 1962, Conservation Area 3 was enclosed on the south side, and, for the first time, the surface flow in the Everglades north of the Everglades National Park could be fully controlled. Conservation Area 3 was considered fully enclosed by July 1967 except for a 7.1-mile stretch of levee between the L-28 Interceptor levee and the L-28 tieback levee on the west side. According to plans, additional changes and modifications in water-management structures are to be constructed as needed. A list and description of the various control structures built or operated by the C&SFFCD through 1969 is given in table 7 in the appendix.

During 1946 to 1962 and concurrent with the construction of the flood-control works in the Everglades area, the urban east coast was undergoing accelerated economic development. Housing expanded westward from the coastal ridge in Palm Beach, Broward, and Dade Counties, resulting in new urban areas requiring drainage and protection against flooding.

The need to conserve fresh water, particularly the reduction of discharge of surplus water to the ocean, was emphasized by the regionally low water levels during the droughts of 1955-56 and 1961-65. The ability of the system to cope with flood problems was demonstrated during the extremely wet years of 1957-60, when no appreciable flooding occurred in the areas protected by drainage works. Extensive damage did occur in southern Dade County, where the drainage system was not improved to cope with rainfall of the intensity that accompanied Hurricane Donna in 1960. The south Dade flood-control plan has since been implemented, and the works are nearly complete.

HYDROLOGIC EFFECTS OF WATER CONTROL AND MANAGEMENT

The prime effect of the early water-control works in south Florida has been to increase the flow of water out of the Everglades through canals. Because the source of much of the flow in the canals in southeastern Florida is from Lake Okeechobee and the Everglades, any changes in the hydrology caused by impoundment of water or diversion of water from normal courses in the Everglades will be reflected in the discharge of those canals. In order to evaluate the effects that changes in water-control and flood-control practices have brought about, the rainfall-runoff relation for the primary canals that traverse the Everglades was examined, and the annual discharges of fresh water to the ocean were analyzed.

The history of the development of well fields in the Biscayne aquifer, the relation of reduced water levels to sea-water intrusion, and the relation of municipal well fields along the Atlantic Coastal Ridge to present day water-management practices indicate the extent that natural hydrologic conditions have been altered by water-management practices.

FLOW THROUGH THE EVERGLADES

Before attempts were made to reclaim lands for agriculture southeast of Lake Okeechobee, flow through the Everglades area was moslty southward toward the Gulf of Mexico and Florida Bay, and, during the peak period of the rainy season, to the Atlantic Ocean through the transverse glades (fig. 7). Only during extremely wet years, did water in Lake Okeechobee overflow southward. The extent that the Everglades drainage basin changed from year to year depended upon the amount and distribution of rainfall during each year. During wet years, the effective drainage basin for the Everglades probably extended to or beyond Lake Okeechobee. On the other hand, during dry years and dry seasons, the effective drainage area of the Everglades was greatly reduced and did not include Lake Okeechobee.

RATE OF OVERLAND FLOW

A number of previous workers in the Everglades area have observed that water flows slowly southward out of Lake Okeechobee into the Everglades. Bogart and Ferguson (p. 332, in Parker, Ferguson, Love, and others, 1955), stated, "overflow of the south shore became general at stages of 17 to 18 feet, and sizable volumes of water moved slowly in flat, broad sloughs toward tidewater. The largest slough (known as the Everglades) extends as a grassy marsh, 35 to 50 miles wide, from south and southeast shores of the lake to the end of the Florida peninsula, 100 miles to the south...." On page 333, the above authors state "In its natural state, only a minor part of the rainfall and the overland flow from Lake Okeechobee left the Everglades as surface drainage. Overland flow was extremely slow because land slopes generally averaged about 0.2 ft. per mile, and interconnecting natural drainage channels were extremely shallow and were choked with vegetation. During and after the rainy season, water stood at varying depths over the surface of the organic soils. These conditions naturally led to large losses through evaporation and transpiration."

It is of more than academic interest, therefore, to determine the natural rate of overland flow through the Everglades and the distance water moves in the basin within a runoff year (April 1-March 31). To determine the rate of overland flow, an east-west section was selected immediately north of the Tamiami Canal and extending from Levee 30 westward to Monroe in Collier County (fig. 1). The section was selected because of the availability of semimonthly discharge information from 1940 for the outlets along the Tamiami Canal. Overland flow at this section is probably greater than elsewhere in the Everglades because vegetation is less dense near the Tamiami Trail than it is to the north and evapotranspiration is less there than it is to the south. The discharge information incorporates several prolonged droughts such as 1944-46, 1950-52, 1955-56, and 1961-65 and the extremely wet years 1947-48, 1958-60.

Examination of the discharge records showed that southward flow occurred as soon as water was only slightly above the general land surface of the Everglades. Elevations along the measuring section at which flows occurred initially are referred to as the effective land surface. Effective land surface elevations were determined from each of the water-level gages along the Tamiami Canal. To determine the cross sectional area for the different flow sections, the water depth above the effective land surface was ascertained from the profile gage readings along the Tamiami Canal; the water depth was then multiplied by the length of section represented by each gage. This section extends from half way between two gages, past a given gage, and halfway to the next gage. By using the basic equation $Q=VA$, where Q is discharge through the canal outlets in cubic feet per second and A is the area of flow section in square feet, V, the velocity of water movement in feet per second, can be determined and then converted to feet per day. It is assumed that flow is evenly distributed within each section, as defined above, and that the discharge measured through the Tamiami Canal outlets represents the flow in the nearby section.

Discharge data for 1960, which show a wide range of discharges, and random discharge data from other years were used to determine the rate of flow through the Everglades and the adjoining section of the Big Cypress Swamp. The maximum rates of southward water movement at the Tamiami Canal section were computed to be 1,550 feet per day during October 1947 and 1,480 feet per day during September 1960. The average velocity for the 1960 runoff year (defined as April 1 through March 31) was about 860 feet per day. The minimum rate of southward overland movement is zero, when water levels decline below land surface. Figure 10 shows the relationship between the rate of water movement, in feet per day, and the total instantaneous flow through the Tamiami Canal outlets. The monthly cumulative distances of water movement, based on the curve in figure 10, for three wet years and one dry year are shown in figure 11. The distances shown indicate that even during the excessively

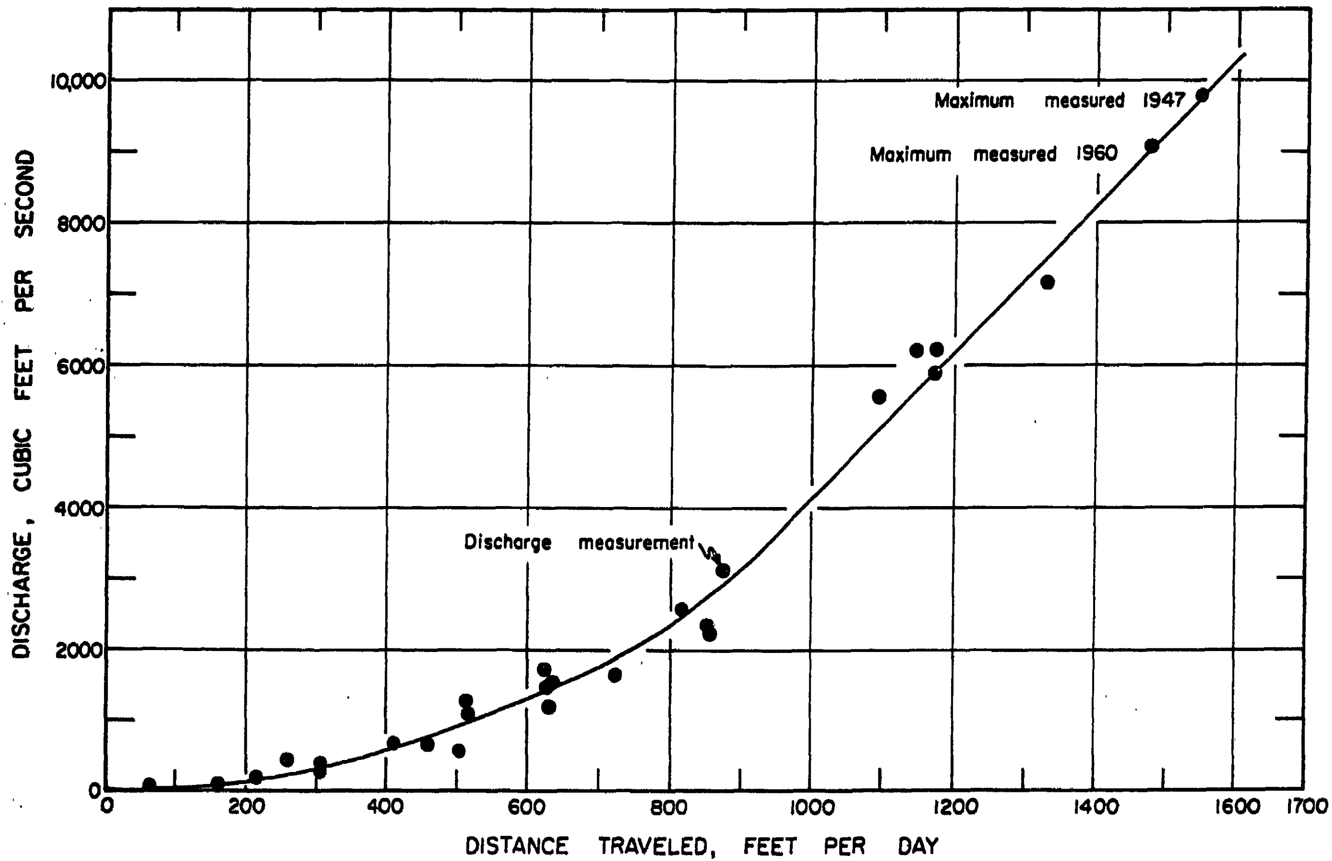

Figure 10. Relation between the Tamiami Canal outlets' discharge and the average distance a particle of water would travel in the Everglades in a day

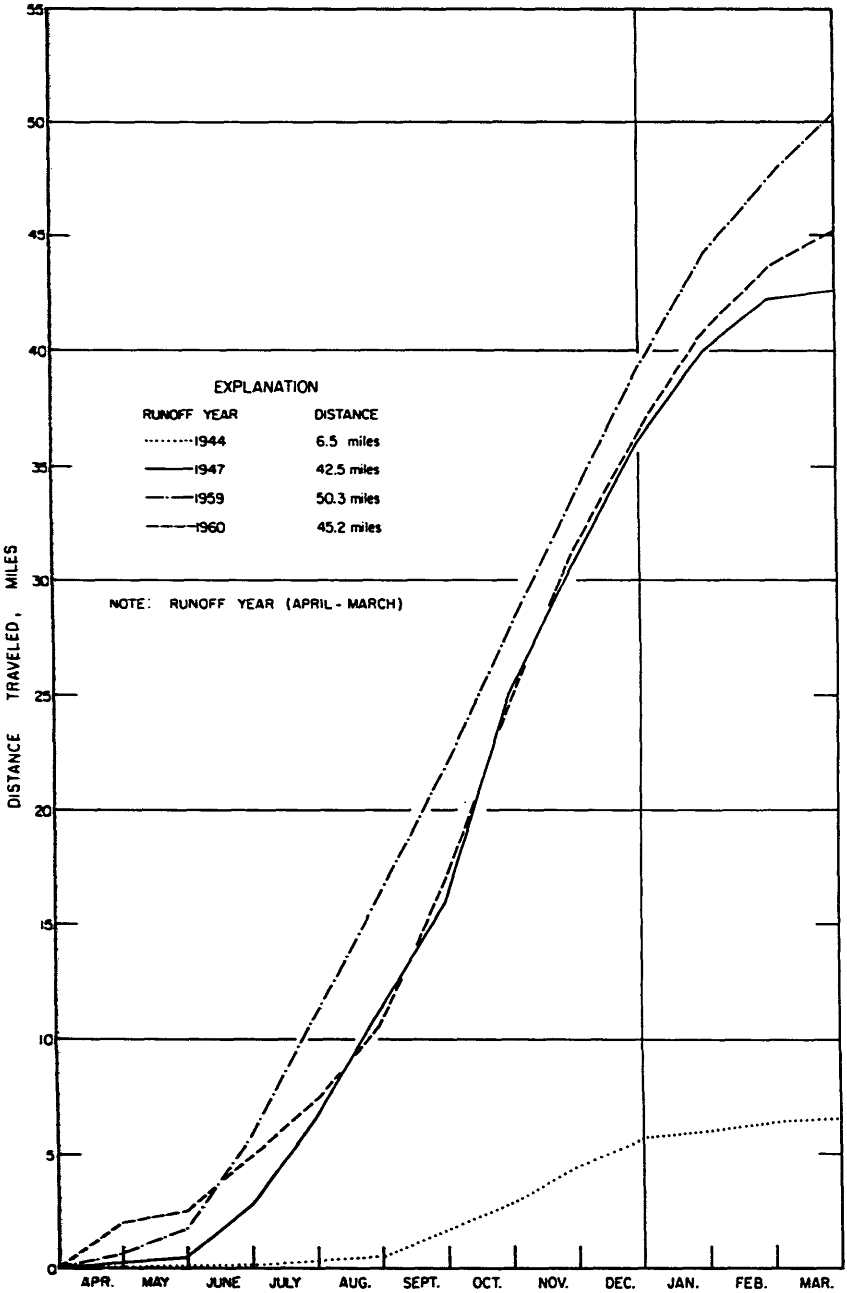

Figure 11. Accumulation of the average monthly distance traveled by a particle of water in the Everglades, based on flow in the measuring section north of the Tamiami Canal

wet years 1947, 1959, and 1960, water from the vicinity of Lake Okeechobee probably did not reach as far south as the Tamiami Canal, because Lake Okeechobee is more than 60 miles to the north. Although it is unlikely that water in the northern part of the basin ever reached the Tamiami Canal, the upbasin water supplies are important because they maintain gradients that sustain the slow southward flow through the Everglades.

The graphs in figure 11 show that the total estimated distance that water traveled in the Everglades during a runoff year was greatest during 1959, the year of greatest total flow. However, the peak flow through the Tamiami Canal outlets for the 1959 runoff year was only about half the peak flow for 1947 or 1960, as shown in figure 12. Comparison of the graph for 1944, a dry year, to those for wet years shows the wide range in hydrologic conditions that occur within the Everglades and Big Cypress basins.

FLOW THROUGH TAMIAMI CANAL OUTLETS

One of the longest continuous records of discharge in southeastern Florida is that of the southward flow through the "Tamiami Canal outlets" beneath the Tamiami Trail between Levee 30, west of Miami, and Monroe, in Collier County. (See figure 17 for location.) This record is of maximum importance because: (1) it shows annual changes in southward movement of water resulting from variations of rainfall within the Everglades and Big Cypress basins; (2) it shows the volume of water along the Tamiami Canal between Levee 30 and Monroe, Florida in the Everglades hydrologic system after all the upstream natural losses and man-imposed diversions are accounted for; (3) it reflects and permits evaluation of significant changes in the system to the north that result from diversions, impoundments, or water use in upbasin areas, and it may be used in defining the historic flows toward Everglades National Park.

The discharge through the Tamiami Canal outlets for 1940-69 is portrayed by the hydrograph on figure 13. The record spans a period of flows through the Everglades during the last part of the period of drainage and land reclamation (until 1946), during the period of flood control and water control (1946-62), and during the beginning of the period of water management.

As shown by the hydrograph on figure 13, the flow southward through Tamiami Canal outlets toward the Everglades National Park fluctuates seasonally and varies greatly from year to year. The annual fluctuation is exemplified by flood years 1947, 1948, and 1960, as compared to drought years 1944 and 1961. Not only does the discharge vary from year to year, as indicated by the annual mean discharge on

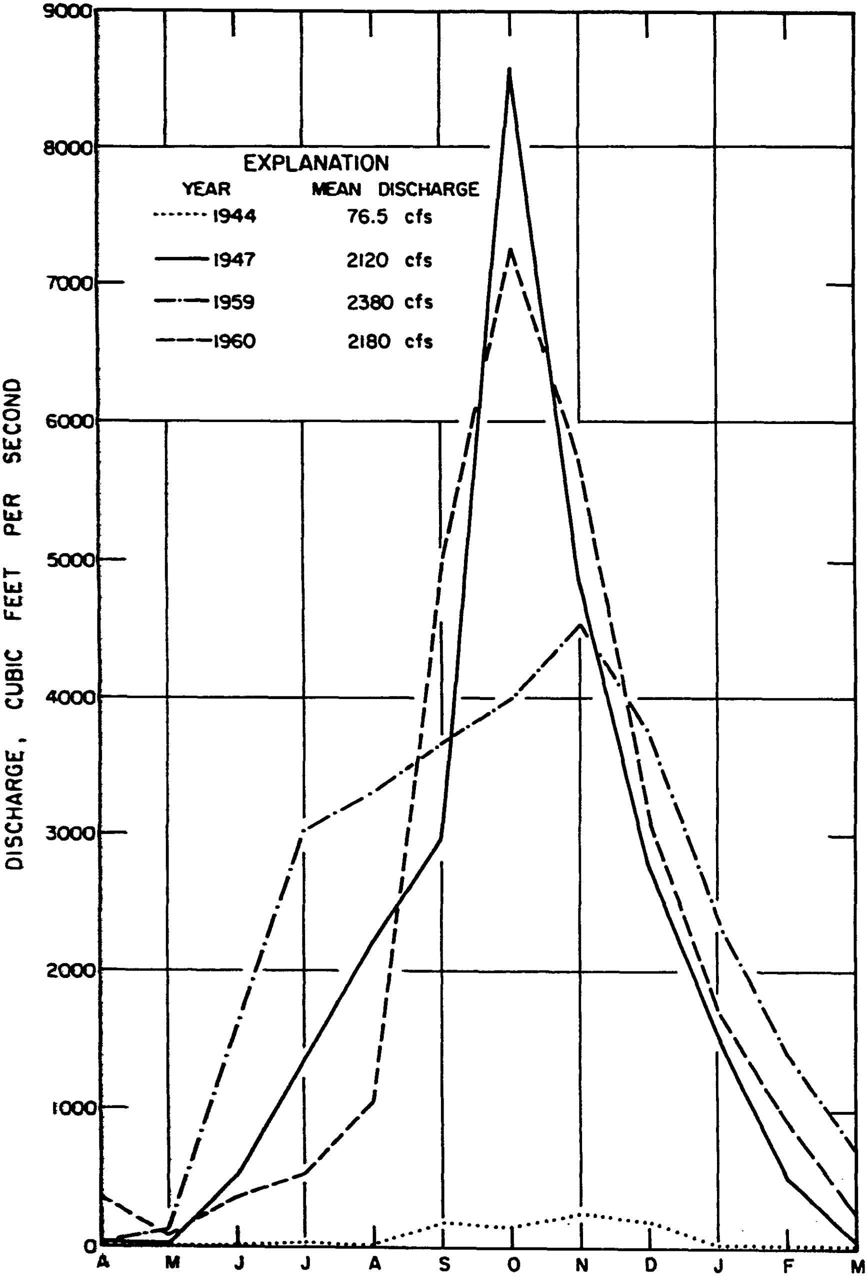

Figure 12. Hydrographs of monthly mean discharge through the Tamiami Canal outlets, showing a comparison of the three wettest runoff years and 1944, one of the driest years of record since 1940

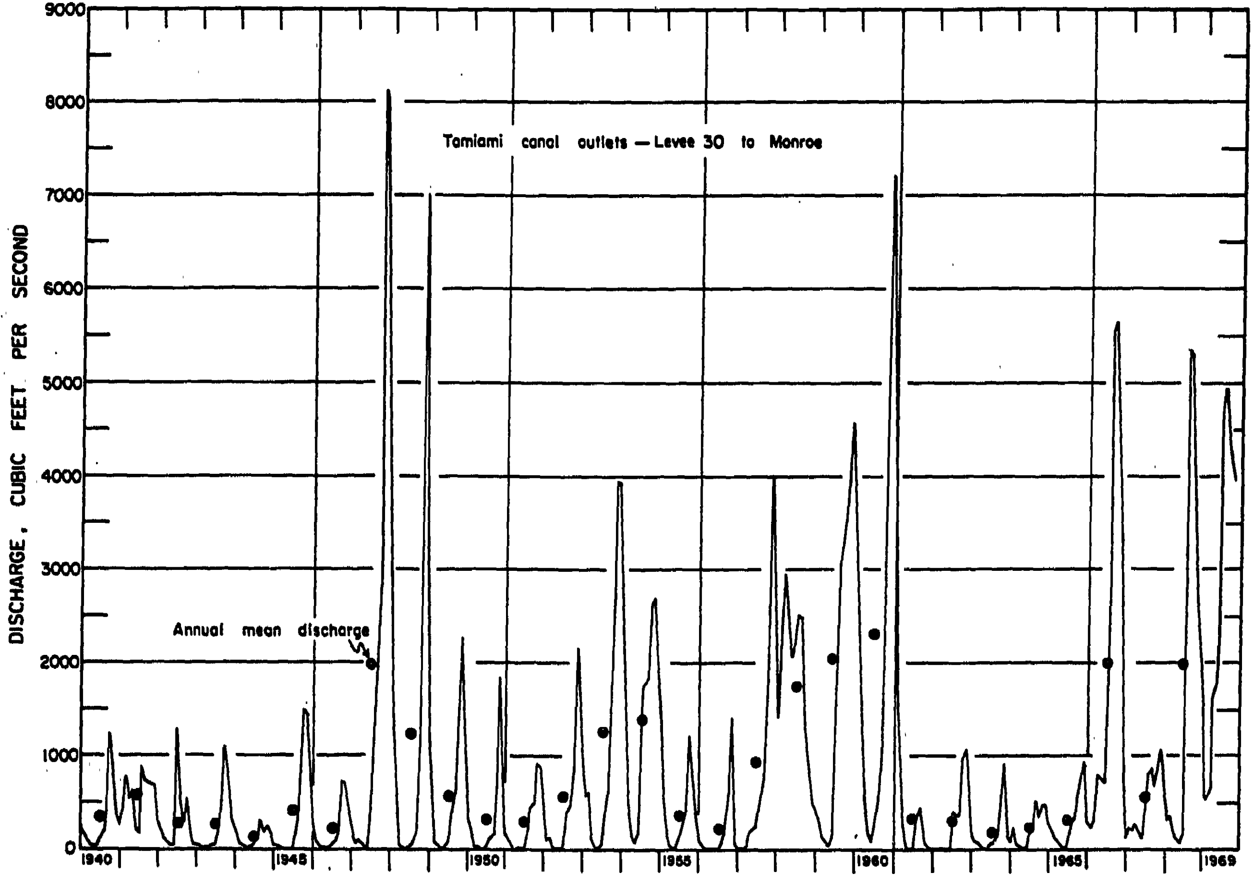

Figure 13. Monthly mean discharge southward toward Everglades National Park through the Tamiami Canal outlets, Levee 30 to Monroe, Florida 1940-69

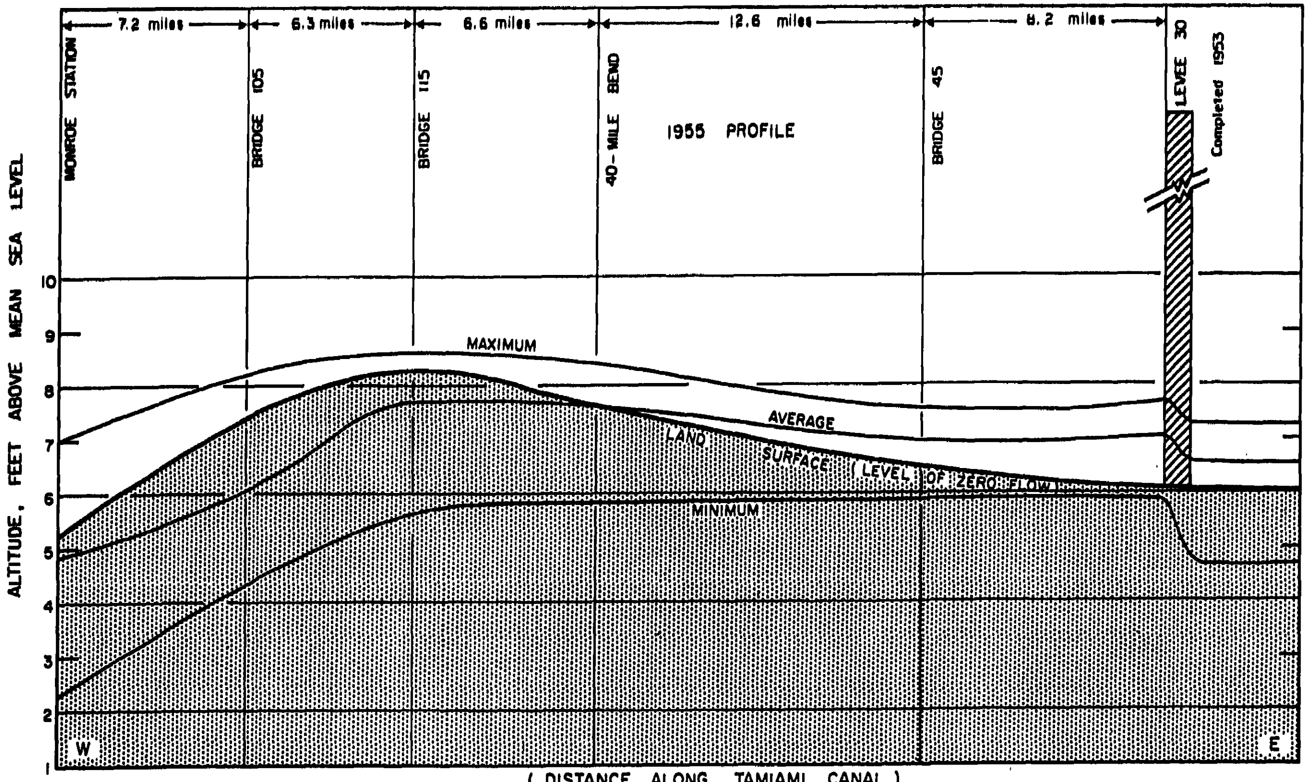

Figure 14. Profiles of maximum, minimum, and average water levels in the Everglades just north of the Tamiami Canal during 1955, a relatively dry year. Also shown is the altitude of zero overland flow southward

figure 13, but the wet and dry seasons may change also from year to year. Annual monthly peak flows usually occur in September or October, but two of the more significant monthly mean peaks that occurred out of phase were the February 1958 peak (2,973 cfs) and the November 1959 peak (4,560 cfs). For all years except 1956 and 1961, discharge through the Tamiami Canal outlets continued through March of the following year. The two most significant periods of zero flow were the 114 days from March 5 to June 26, 1956, and the 189 days from December 6, 1961 to June 12, 1962.

The annual mean discharge in figure 13 indicates there have been two significant extended dry periods. The first was noted from the beginning of record November 1939 (not shown) to May 1947, and the second was from April 1961 through mid-1966. In 1947 the peak of record flow was recorded following one of the driest years, whereas in 1960 the second highest peak of record followed several years of above-normal flow. Also in 1961 the discharge was substantially below normal except for January through March, during which time discharge was basically runoff from the preceding year. Examining the past record and the foregoing examples indicates that in the Everglades area there is very little residual effect from one year to the next. The main reason for this is that historically about 70 percent of the rain each year comes normally June through October and the remaining 30 percent falls November through May each year, the period when evapotranspiration almost always exceeds rainfall. It is during this dry period each year that surface storage in the Everglades is generally depleted.

The high and low water levels along the measuring section of the Tamiami Canal outlets are compared with the effective land-surface elevations during a dry and wet year on figures 14 and 15. The profiles for 1955 (fig. 14) show that only during the period of high water levels during the wet season did overland flow occur through the entire measuring section. At times of average conditions in 1955, flow occurred only through the section between Levee 30 and 40-Mile Bend. At the lowest water-level condition during the dry season, water levels were below the land surface, and no flow occurred through any of the outlets.

The impounding effect of Levee 30 on water west of the levee and the changes in head across the levee that occurred under the different conditions are also shown on figure 14. The higher water levels west of Levee 30 were caused by the flow diverted southward along the levee system.

In contrast to the conditions during a relatively dry year shown on figure 14, the water-level profiles on figure 15 for 1960, a wet

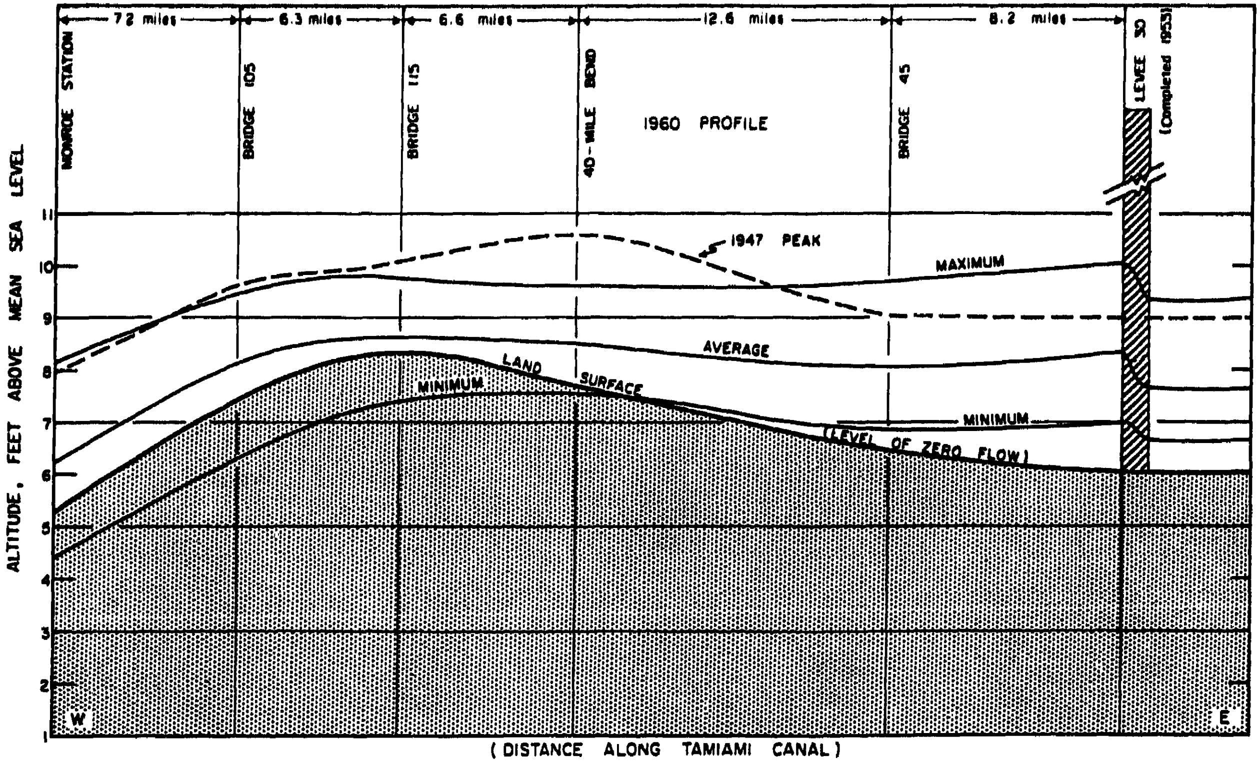

Figure 15. Profiles of maximum, minimum, and average water levels in the Everglades just north of the Tamiami Canal during 1960, a relatively wet year. Also shown is the altitude of zero overland flow southward and the peak profile of 1947 prior to the construction of Levee 30

year, show that southward flow occurred during the entire year through the eastern part of the flow section and during all but the minimum or near minimum conditions through the western part of the flow section. In order to compare pre-Levee 30 high water-level conditions with conditions after the completion of Levee 30, the maximum profile for 1947 (before levees) is superimposed on the 1960 profiles (fig. 15).

An important feature of the profiles in figures 14 and 15 is the rise of the effective land surface west of 40-Mile Bend. Although the maximum elevation west of the 40-Mile Bend site is only slightly more than 2 feet higher than the elevation at the west toe of Levee 30, the difference is sufficient to cause most of the flow during wet years to occur through the eastern part of the section. An analysis of the distribution of discharge through the Tamiami Canal outlets for 1940-60 showed that for most runoff years when discharge was less than 300,000 acre-feet, the percentage of discharge through the western section (Monroe to 40-Mile Bend) was greater than that through the eastern section (40-Mile Bend to Levee 30). However, when the runoff-year discharge exceeded 725,000 acre-feet, about 70 percent of the discharge occurred through the eastern section. The relation between runoff-year

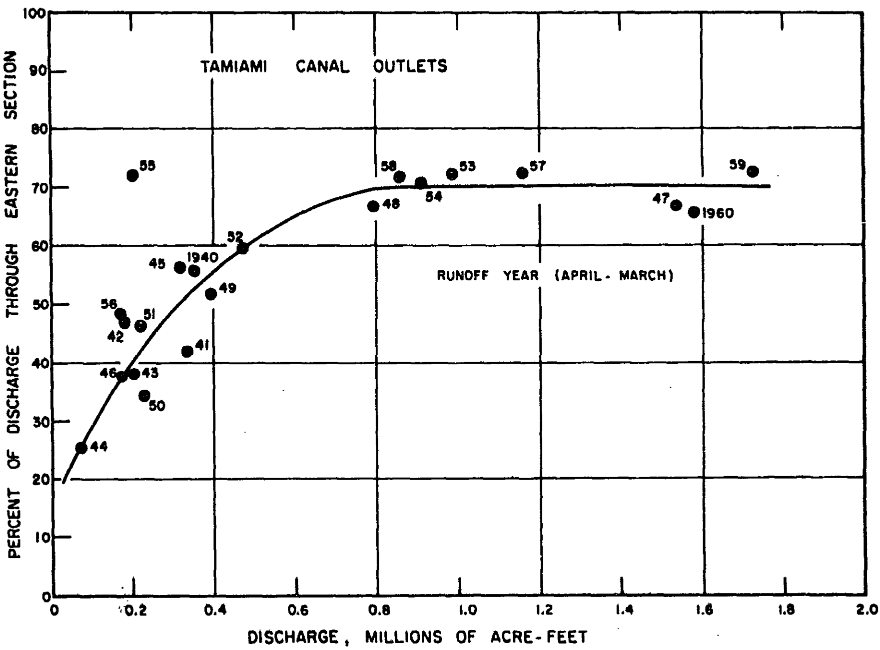

Figure 16. The relation between the annual discharge through the Tamiami Canal outlets, Levee 30 to Monroe, and the percent that flowed through the eastern section, Levee 30 to 40-Mile Bend

discharge through the Tamiami Canal outlets and the percentage that flowed through the eastern section, 40-Mile Bend to Levee 30, is shown on figure 16. Water that flows through the eastern section is from the Everglades basin, whereas water that flows through the western section is from the Big Cypress Swamp.

CHANGES IN FLOW THROUGH TAMIAMI CANAL OUTLETS

In order to describe and evaluate the changes in flow through the Everglades as a result of drainage, water control, and water management within the drainage basins, the Tamiami Canal outlets were subdivided into three flow sections, as shown in figure 17. The monthly mean discharge for the three sections for the period of record is given in tables 7 to 10, and the Tamiami Canal outlet bridge numbering system and mileage is given in table 11 in the appendix.

The western section, 40-Mile Bend to Monroe, is the flow from the Big Cypress Swamp, the only section whose drainage basin has remained relatively unchanged through the period of record. Therefore, the flow through that section is used as the index of natural runoff. The middle section extends from 40-Mile Bend to Levee 67A, and includes the discharge of the four spillways (S-12A, B, C, and D) at the south end of Conservation Area 3A, operational after 1962. These spillways control the direct surface flows into the Everglades National Park. The third or eastern section extends from Levee 67A to Levee 30. After 1962, the discharge through this section has been limited to seepage through Levee 29 on the south side of Conservation Area 3B (figs. 1 and 17). The monthly mean discharge through the three reaches during 1941-69 is shown in figure 18.

The discharge hydrograph for the reach 40-Mile Bend to Levee 67A before 1962 shows the normal flow conditions before completion of Levee 29 and the associated S-12 spillways and completion of Levee 67A in 1962. After 1962 a distinct change in flow pattern is apparent by comparison with the index flow section 40-Mile Bend to Monroe, for the same period. No discharge occurred through S-12 spillways into the Everglades National Park from Conservation Area 3A during 1963, and only a small amount was discharged in 1964. However, the flow through that reach into the Park for 1966 and 1968 was inordinately large in relation to the annual rainfall and to the flow through the index section for that year; furthermore, the flow in 1966, 1968 and 1969 greatly exceeded the prior record flow of 1947 through that section.

Other effects of managing the water in Conservation Area 3A through the manipulation of S-12 spillway gates, constructed in 1962, are shown in figure 18 by the hydrograph of the Levee 67A to 40-Mile

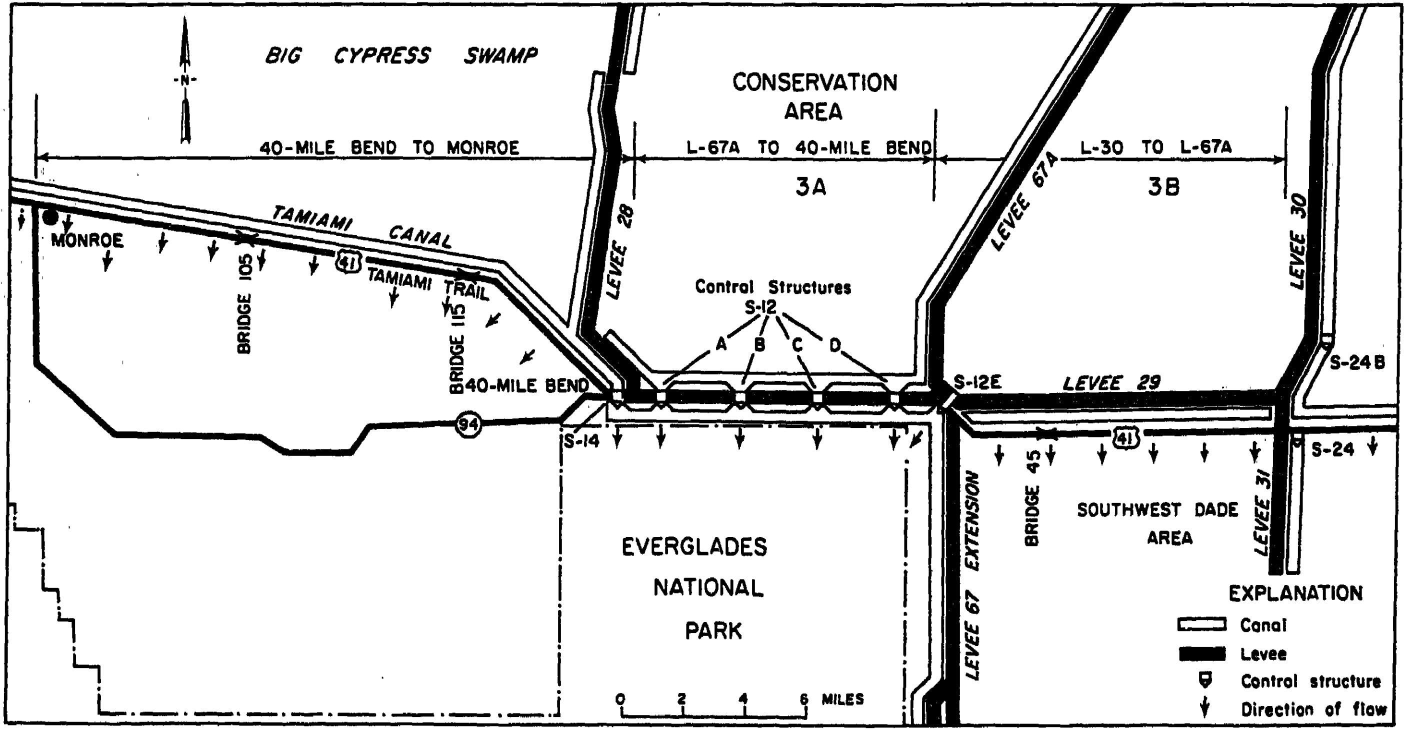

Figure 17. Map showing detail of the Tamiami Canal outlets sub-divided into the three flow sections (Levee 30 to Levee 67A, Levee 67A to 40-Mile Bend, and 40-Mile Bend to Monroe, Florida)

Bend section during 1966, 1968, and 1969. The rate of rise and decline of the discharge after the 1966-68 wet season was greater than it was for any prior year of record. This sharp decline in 1966 was caused by closing the spillway gates in November to retard the runoff, thereby storing water for later release to the National Park. The discharge hydrograph of the Levee 67A to 40-Mile Bend section for 1967 shows that flow was maintained throughout the year, except for a brief period in January, despite the fact that 1967 was a year of subnormal rainfall, as indicated by the small discharge through the 40-Mile Bend to Monroe index flow section. At the end of the dry season of 1967, southeastern Florida was the only area in Florida that did not experience excessively low water levels.

The discharge through the section between Levee 30 and Levee 67A (fig. 18) represents a significant part of the overland flow to eastern and southeastern Dade County. The discharge before 1962 was predomin-

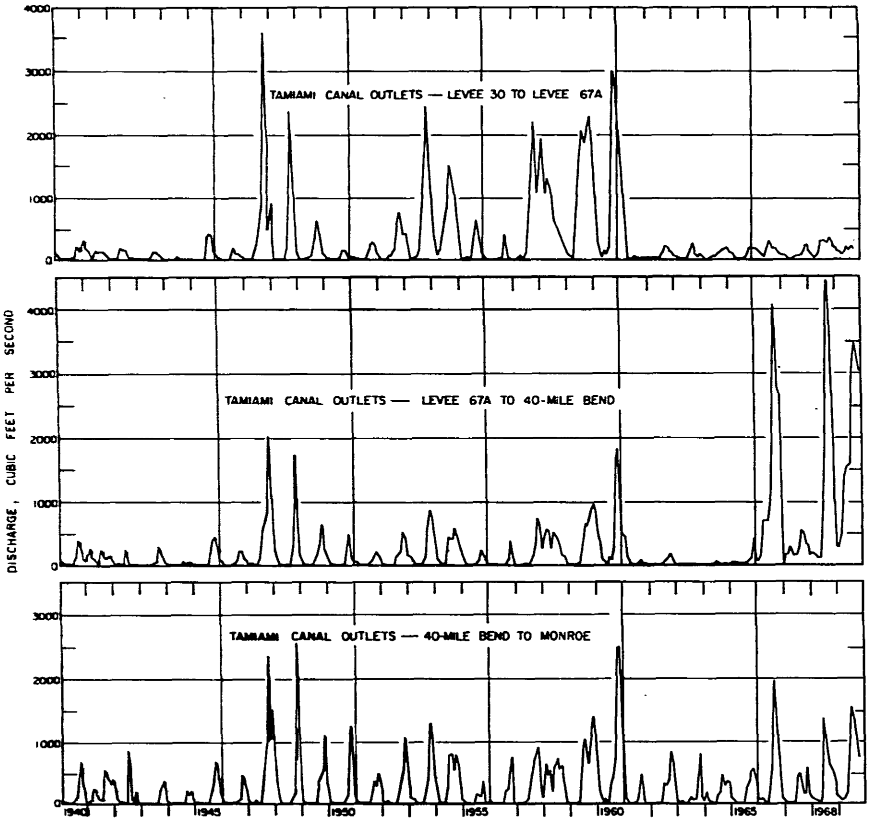

Figure 18. Monthly mean discharge of the Tamiami Canal outlets, Levee 30 to Monroe, Florida, subdivided into three sections, 1941-69

antly overland for periods of high and moderate flow; for periods of low flow, the discharge was chiefly by ground-water flow to the Tamiami Canal and then through the outlets. After 1962, discharge in this reach was a combination of seepage through Levee 29 along the south boundary of Conservation Area 3B and ground-water flow to the Tamiami Canal. The hydrograph shows that during the pre-1962 period, generally more water flowed through the Levee 30 to Levee 67A section than flowed through either of the other sections. After Levee 30 was completed in 1953, the additional water that was routed southward by the levee probably caused the flow to continue for a longer period of time each year. The decrease in flow recession rate is evident when the recession rate for 1947-48 and 1948-49 is compared with the rate for 1959-60 and 1960-61, each following abnormally wet rainy seasons. The decrease in recession rate probably resulted from the southward diversion of flow by the levee system and the impoundment of water behind the levee.

The marked change in flow pattern in the Levee 30-Levee 67A flow section is shown by the hydrographs for 1966 on figure 18. During 1966, water that normally would have flowed through the eastern section was diverted southward by Levee 67A and impounded in Conservation Area 3A. The only flow recorded for the Levee 67A-Levee 30 section was seepage through Levee 29.

Examination of the hydrographs on figure 18 shows that the distribution of flows through the Tamiami Canal outlets has been altered, and the greatest flows now occur through the center flow section, 40-Mile Bend to Levee 67A.

Before construction of Levee 29, the section between Levee 30 and Levee 67A contributed significant quantities of water to south Dade County. Because water is now being stored in Conservation Area 3B or diverted to the west by Levee 67A, the contribution to south Dade County has been altered, and annual peak water levels there have been reduced.

A method was devised to determine changes in the pattern of flow through the three sections of the Tamiami Canal outlets and also the changes in flow in each section during the different periods of construction of the C&SFFCD works. Because the three sections have a related (although undefined) drainage basin, flow through the 40-Mile Bend to Monroe section (which is largely unaffected by control works) was used as a "benchmark" station to determine the changes in the other two related but controlled sections. To use the 40-Mile Bend to Monroe section as an index, its cumulative discharge from runoff year to runoff year was plotted in a straight line by adjusting time, as shown in figure 19. The cumulative discharges of the other two flow sections should

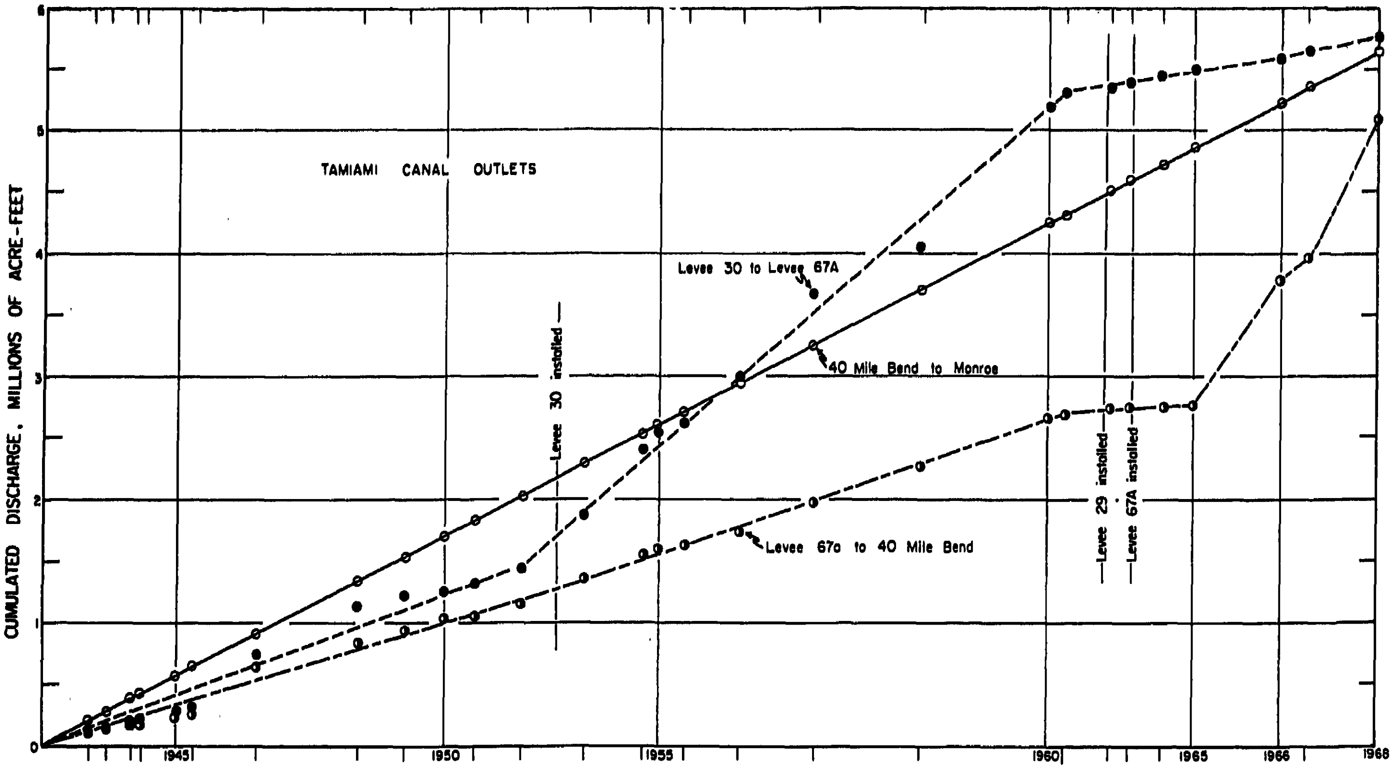

Figure 19. Cumulative annual discharge showing the effects of construction on each of the three sections of the Tamiami Canal outlets between Levee 30 and Monroe, Florida

also plot in a straight line on the same time base as long as they are hydrologically related—that is as long as the hydrologic conditions in the three sections are not changed. Therefore, any departures from a straight-line plot, for the two eastern sections, beyond a normal scattering, will show the time and magnitude of the effects that levee construction and other changes have had on the flow.

The effects of the construction of Levee 30 markedly increased the flow through the section between Levee 30 and Levee 67A, as shown by the increased slope of the time-adjusted plot (fig. 19). The increase in the slope indicates an increase in the flow through the section. The additional water was diverted southward toward Everglades National Park and south Dade County by Levee 30 and other levees east of the three conservation areas, which interrupted the natural eastward flow toward the ocean. The magnitude of the change in flow between 1953 and 1961 can be estimated for the section by projecting a straight line from the initially established trend for 1941 to 1952 to 1961 on figure 19 and determining the difference between the values obtained for 1961. Accumulated discharge would be 3,077,000 acre-feet rather than the 5,274,000 acre-feet shown. The levees to the east of the conservation area thus diverted an additional 2,197,000 acre-feet southward. Based on the 1941-52 trend, the natural discharge through the section would have averaged about 146,500 acre-feet annually rather than 251,100 acre-feet for 1941-61 runoff years. The additional discharge for the section averaged 245,300 acre-feet per runoff year between 1953 and 1961, which was a direct result of the construction of the levee systems. The southward flow for the Levee 30-Levee 67A section for 1953 to 1961 averaged 426,000 acre-feet per runoff year rather than the average of 180,700 acre-feet per runoff year that would have occurred for the period if the levee system had not been built. This was, on the average, 136 percent greater than the flow that would have occurred if the levee system had not diverted runoff southward.

The magnitude of the change in flow between 1953 and 1961 can be estimated for the Levee 67A to 40-Mile Bend section by projecting a straight line from the initially established trend for 1941 to 1952 to 1961 on figure 19 and by determining the difference in discharge between the values obtained. Accumulated discharge would be 2,480,000 acre-feet rather than the 2,684,000 acre-feet shown. The levees at the east side of the conservation areas thus diverted an additional 204,000 acre-feet southward. Based on the 1941-52 trend, the pre-levee natural discharge through Levee 67A to 40-Mile Bend section of the Tamiami Canal outlets would have averaged 118,100 acre-feet annually rather than 127,800 acre-feet for 1941-61 runoff years. The additional discharge for the section averaged 22,920 acre-feet annually per runoff year for 1953-61 as a direct result of diversion by the levee systems. The discharge directly to the Everglades National Park through the Levee 67A to 40-Mile Bend section for 1953 to 1961 averaged 169,000 acre-feet per runoff year rather than 146,100 acre-feet per year if the levee system had not been built — an average of 16 percent greater flow.

The accumulated discharge for the 40-Mile Bend to Monroe section (the index section) based on 1941-61 record was 4,189,800 acre-feet, or an average 199,500 acre-feet per runoff year.

Levee 29 was constructed in 1962 just north of and parallel to the Tamiami Canal from 40-Mile Bend to Levee 30, obstructing southward overland flow. After Levee 29 construction, flow through the Levee 30-Levee 67A section was reduced to seepage through Levee 29, an average of about 66,200 acre-feet per runoff year. Levee 67A, which separates Conservation Areas 3A and 3B, was completed in 1963, routing considerable water westward through the 40-Mile Bend-Levee 67A section. Therefore, the annual average seepage discharge of about 66,200 acre-feet in the Levee 30-Levee 67A section should continue. (See table 9 in the appendix.)

In summary, the flow before 1961 southward toward the Everglades National Park and south Dade County, based on the 1941-61 record, averaged 251,100 acre-feet per runoff year through the Levee 30 to Levee 67A section, 127,800 acre-feet per runoff year through the Levee 67A to 40-Mile Bend section, and 199,500 acre-feet per runoff year through the 40-Mile Bend to Monroe section of the Tamiami Canal outlets. (See table 4 for comparison of flow between the calendar year and runoff year for the three sections of the Tamiami Canal outlets.) The trends of discharge shown on figure 19 indicate that the average for 1962-68 through the Levee 30 to Levee 67A section has been reduced to about 66,200 acre-feet. Although the annual discharge in the Levee 67A to 40-Mile Bend reach has ranged from 0 to 1.1 million acre-feet, the average for 1962-68 was 341,900 acre-feet per runoff year, about 214,100 acre-feet greater than the 1941-61 annual average, and dischage through the 40-Mile Bend to Monroe section has remained about the same.

CONSERVATION AREAS

Three large areas within the Everglades are surrounded by levees and form an important integral part of the water-management system in south Florida—Conservation Areas 1, 2, and 3A and B (figure 1). Effective closure of the conservation areas was accomplished at the end of 1962 except for the west side of Conservation Area 3.

Table 4. Total and average discharge of three flow sections of the Tamiami Canal showing a comparison between runoff and calendar years for the period 1941-68 (for locations of the three sections, see figure 17).

Section	Period	Totals (Thousands of Ac-ft)		Average (Thousands of Ac-ft)	
		Runoff Years [a]	Calendar Years	Runoff Years [a]	Calendar Years
Levee 30 to Levee 67A	1941-52	1,439.5	1,422.5	120.0	118.5
	1953-61[b]	3,834.1	3,881.4	426.0	431.3
	1941-61	5,273.6	5,303.9	251.1	252.6
	1962-68[c]	463.1	442.4	66.2	63.2
	1941-68	5,736.7	5,746.3	204.9	205.2
Levee 67A to 40-Mile Bend	1941-52	1,162.9	1,169.4	96.9	97.4
	1953-61[b]	1,521.1	1,536.7	169.0	170.7
	1941-61	2,684.0	2,706.1	127.8	128.9
	1962-68[c]	2,393.1	2,265.2	341.9	323.6
	1941-68	5,077.1	4,971.3	181.3	177.5
40-Mile Bend to Monroe	1941-52	2,013.3	2,033.8	167.8	169.5
	1953-61[b]	2,176.5	2,187.9	241.8	243.1
	1941-61	4,189.8	4,221.7	199.5	201.0
	1962-68[c]	1,303.9	1,293.6	186.3	184.8
	1941-68	5,493.7	5,515.3	196.2	197.0

[a] Runoff year is defined as period April 1-March 31

[b] After construction of L-30

[c] After construction of L-29

Conservation Area 3 was considered fully enclosed by July 1967 with the exception of a 7.1-mile stretch of levee between L-28 Interceptor levee and L-28 tieback levee. Water in the canal system can flow by gravity or be pumped into the conservation areas, thus delaying runoff from the central Everglades area. During times of intense rainfall, excess surface waters are pumped to temporary storage in the conservation areas, thus reducing the flood-peak water levels east of the conservation areas, especially urban areas along the Atlantic Coastal Ridge. Conditions during a wet period, before and after water-management systems were operational, are shown on figure 20. During dry periods, seepage through levees and regulated releases from the conservation areas sustain water at higher dry-period levels to the east for longer periods than could be maintained before the management system went into operation.

The three conservation areas occupy 1,345 square miles, nearly twice the area of Lake Okeechobee. Although the areas are shallow reservoirs, large volumes of water can be stored temporarily in them, thereby delaying runoff from the interior.

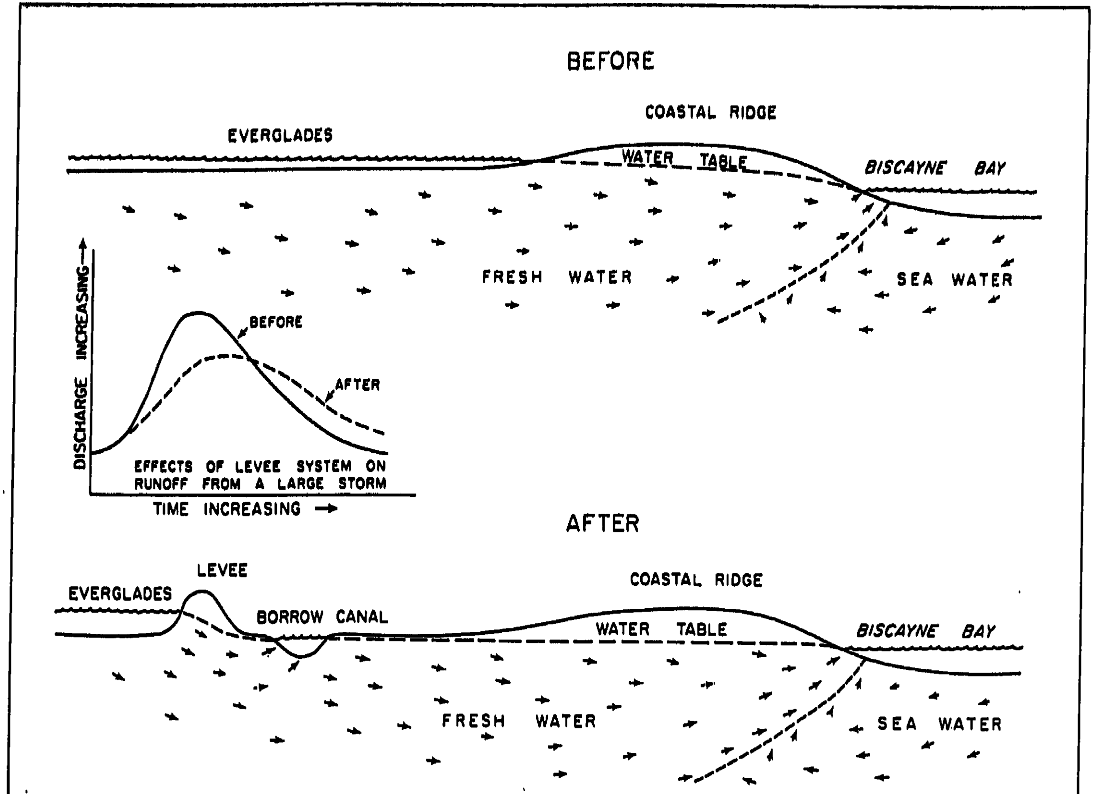

Figure 20. Schematic diagram direction of flow and water levels in a typical west-to-east section, from the Everglades through the coastal ridge to Biscayne Bay. Conditions during a wet period, before and after water management systems were operational, as shown

RAINFALL AND STORAGE

Rainfall differs in intensity over the three conservation areas (fig. 6) and affects the amount of water available for storage in each of the areas. Average rainfall over Conservation Areas 1, 2, and 3 is 59, 56, and 53 inches, respectively.

Most rainfall on the conservation areas evaporates or is transpired to complete the hydrologic cycle. Consequently, the three conservation areas have nearly gone dry several times since being enclosed. In dry years more water enters the conservation areas than is discharged from them through the control structures, as shown by the records for 1961-64, table 6.

The amount of water temporarily in storage in the combined conservation areas as a result of rainfall of a given intensity is shown in figure 21. The amount of storage expected from each storm of a known magnitude is indicated in the illustration. A 6-inch rain, for instance, would add about 430,000 acre-feet, or about 140 billion gallons of fresh water to storage.

SEEPAGE

Considerable water leaves the conservation areas by seeping through the levees. Seepage is generally beneficial because it distributes runoff from severe rain storms at uniformly decreasing rates to the areas east of the conservation areas. The conservation areas retain fresh water from storms until excess water in the coastal area can be removed by canals to the ocean; then seepage through the levees and discharge through the levee control structures help maintain optimum water levels in the areas east of the conservation areas.

Seepage from Conservation Area 1 eastward through Levee 40, from October 1962 to December 1963, is shown in figure 22. The hydrograph of seepage (lower graph) is estimated from a head-discharge relation from Corps of Engineers discharge measurements and from the average head of several gages in the area, shown in the upper graph. The mean eastward seepage for 1963 is estimated to be 109 cfs. This amounts to 3.7 cfs per mile of levee, or a total of about 78,900 acre-feet along 29.2 miles of levee.

The seepage from Conservation Area 2 eastward and southward through levees 35 and 36 is shown in figure 23, and seepage eastward and southward through levees 29, 30, 33, and 37 of Conservation Area 3A and B is shown in figure 24. The estimated seepage during 1963, 180 cfs to the east for Area 2 and 388 cfs to the east and south for Area 3A and B, averages 8.0 cfs and 9.6 cfs per mile, respectively.

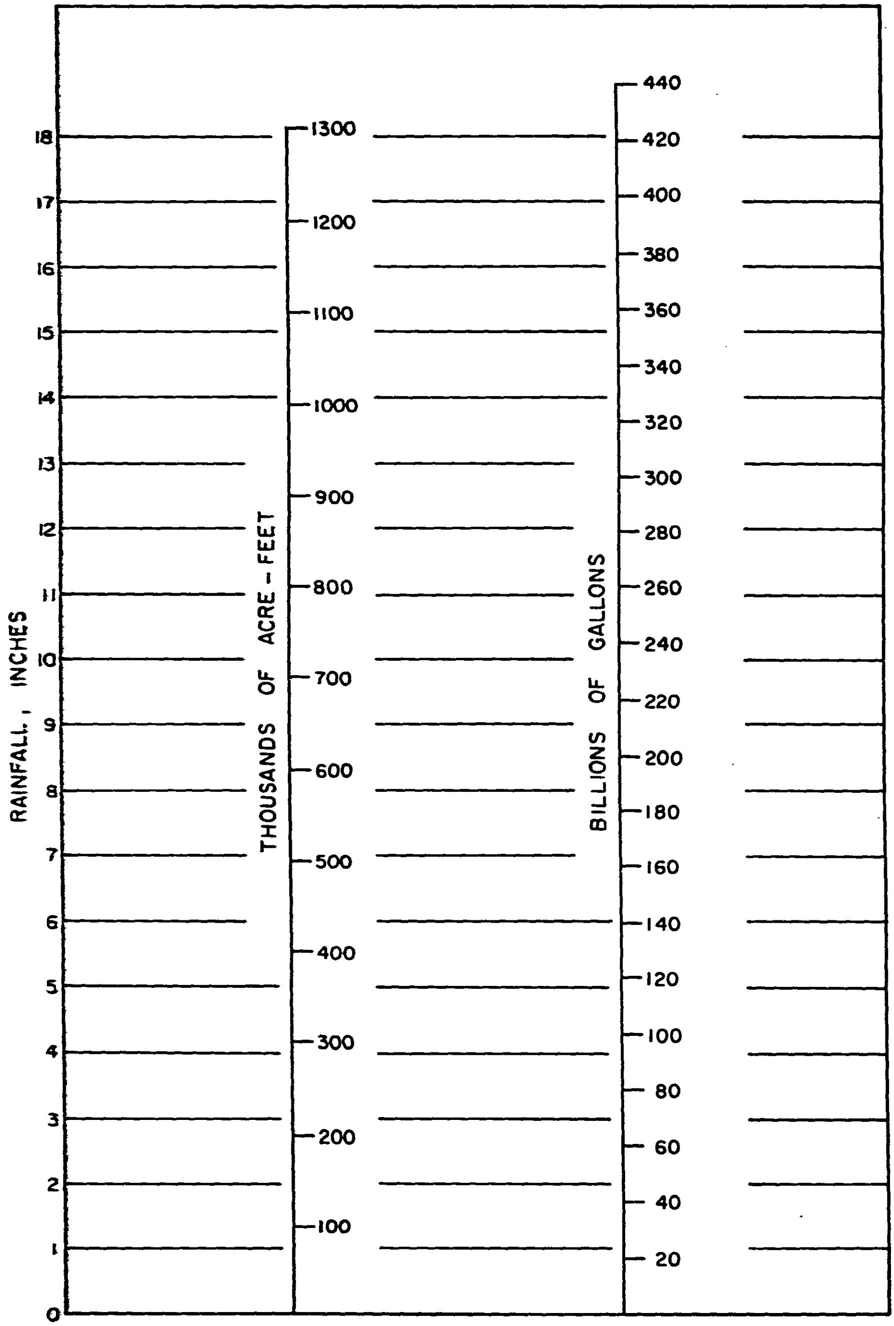

Figure 21. Nomograph of rainfall-storage relation in the three conservation areas

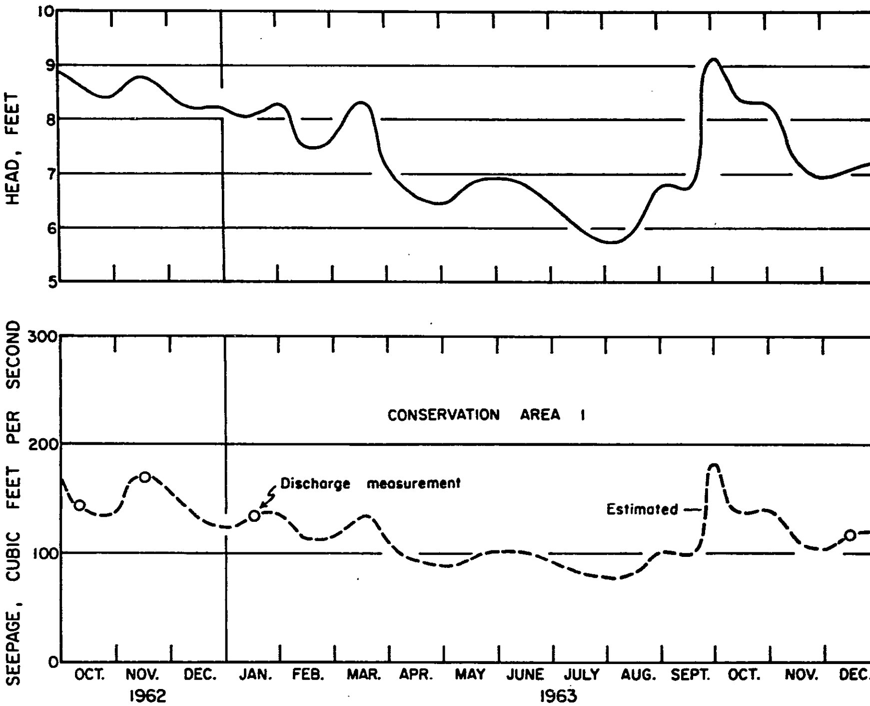

Figure 22. Estimated seepage eastward from Conservation Area 1 through and under Levee 40. Discharge data furnished by the U.S. Corps of Engineers

Using the above values of seepage for 22.5 miles of levee, northeastern Broward County received about 130,300 acre-feet of water in 1963 from Conservation Area 2, whereas, for 40.35 miles of levee, southeastern Broward and eastern and southern Dade counties received about 280,900 acre-feet from Conservation Area 3.

The shallow earth materials have low to moderate permeability in the north and become moderately to highly permeable in the south along the levees on the east side of the conservation areas, as indicated by the seepage rates of 3.7 cfs per mile of levee from Area 1, 8.0 cfs per mile of levee from Area 2, and 9.6 cfs per mile of levee from Area 3. The monthly seepages in table 5 from each of the three conservation areas were derived from figures 22, 23, and 24. Throughout 1963 and 1964, the total amount of seepage for each year was greater during November through February, the dry season, than during June through September, the wet season, because of greater head differential during the dry season. For each of the 2 years, the dry-season seepage was 178,460 and 280,400 acre-feet; the wet-season seepage was 143,360 and 242,200 acre-feet.

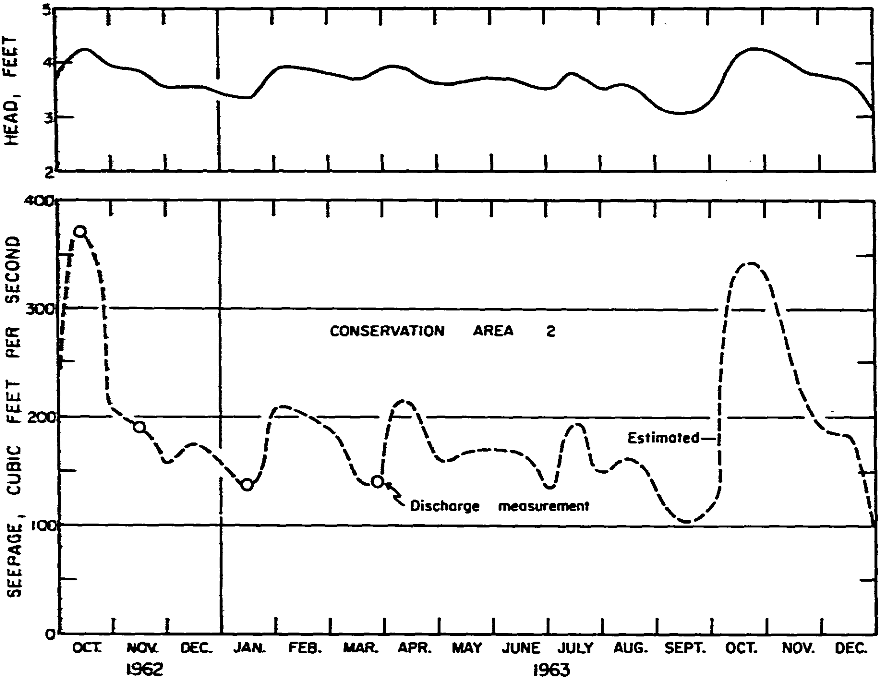

Figure 23. Estimated seepage southward and eastward from Conservation Area 2 through levees L-35 and L-36. Discharge data furnished by the U.S. Corps of Engineers

A generalized water budget was developed for 1963 and 1964 for the combined water conservation areas using the 1963 seepage values to determine the amount of the water that was lost by evapotranspiration. Of the 4 million acre-feet available in 1963, 3.5 million acre-feet (86.8 percent) evaporated and transpired, and 490,200 acre-feet seeped to the east and south. In 1964, of the 5 million acre-feet available, 3.6 million acre-feet (70.5 percent) evaporated and transpired, and 734,500 acre-feet seeped to the east and south.

Major inflow, outflow, rainfall, seepage, change in storage, and evapotranspiration for the three conservation areas are shown in table 6. The discharge data for all the stations in existence during 1958-62 are shown for comparison with the same type of data for these stations in 1963 and 1964. The evapotranspiration for 1963 and 1964 was computed by summation of the inflow, outflow, rainfall, change in storage and the estimated seepage from table 5. For most average years, about 500,000 acre-feet of fresh water may be expected to seep eastward through the levee system.

The prime functions of the conservation areas are to store excess water to reduce flooding of the area east of the levee systems during wet

Table 5 Estimated monthly and annual seepage in acre-feet [1] to the east and south through L-40, L-36, L-35, L-37, L-33, L-30, and L-29 from L-30 to L-67A.

Month	Conservation Areas						Totals	
	1		2		3A and 3B			
	1963	1964	1963	1964	1963	1964	1963	1964
January	8,300	6,760	9,530	3,070	25,820	30,130	43,650	39,960
February	6,660	7,220	11,110	3,060	25,270	26,660	43,040	36,940
March	7,690	8,610	9,530	5,530	20,910	23,670	38,130	37,810
April	5,650	6,840	11,600	8,630	12,500	19,640	29,750	35,110
May	5,840	7,070	10,140	11,070	10,450	23,060	26,430	41,200
June	5,650	6,540	9,520	13,980	14,880	30,640	30,050	51,160
July	4,920	7,690	10,140	8,610	22,140	35,660	37,200	51,960
August	5,230	7,070	9,530	15,060	20,600	37,510	35,360	59,640
September	6,840	7,440	6,540	30,050	27,370	41,950	40,750	79,440
October	8,610	9,220	17,830	36,280	47,960	52,260	74,400	97,760
November	6,840	8,930	15,170	44,330	28,560	48,790	50,570	102,050
December	6,760	7,990	9,840	40,890	24,600	52,570	41,200	101,450
Totals	78,990	91,380	130,480	220,560	281,060	422,540	490,530	734,480

[1] One acre-foot equals 43,560 cubic feet.

Table 6. Generalized water budget in acre-feet showing annual movement of water into the three combined conservation areas.

	Station	1958	1959	1960	1961	1962	1963	1964
Measured flows, cons. areas	S-5	[1] 256,300	557,900	336,300	104,200	188,600	117,200	360,500
	S-6	[1] 189,400	166,000	184,000	43,200	60,300	61,600	148,300
	S-7	—	—	established	[1] 262,600	136,800	74,400	98,200
	S-8	—	—	—	—	[3] established	[1] 90,100	146,800
	S-9	[1] 118,800	117,700	110,600	118,800	35,900	43,700	93,600
	S-12	[2] -939,700	[2] -1,044,700	[2] -1,163,400	[2] -162,200	[4] -32,700	[4] -65,000	[4] -15,400
	S-34	-316,100	-215,700	-123,300	-600	0	-14,400	-3,500
	S-38	0	0	0	0	[5] established	[1] -18,600	-20,700
	S-39	-191,500	-200,500	-84,500	-73,400	-21,300	-19,200	-11,900
Rainfall		4,760,200	5,827,600	4,932,400	2,978,400	3,701,400	3,761,700	4,351,000
						Subtotal	4,031,500	5,146,900
						Storage Change	[6] -43,400	[6] -781,900
						Seepage	-490,500	-734,500
						Evapotranspiration	[7] -3,497,600	[7] -3,630,500

Note: Water budget not computed for 1958-62 due to construction and incomplete data. Negative signs indicate loss from conservation area, except for storage change.

[1] First complete year of record.

[2] Tamiami Canal outlet discharge, Levee 30 to 40-Mile Bend prior to construction of Levee 29.

[3] Established 2/9/62.

[4] Total includes estimated seepage through Levee 29 between L-67-A and 40-Mile Bend.

[5] Established 7/3/61; assumed discharge to be zero for year. Prior record is zero because flow was restricted by Levee 36.

[6] Represents an *increase* in storage in the conservation areas.

[7] Evapotranspiration computed from difference between subtotal and storage change — computed seepage.

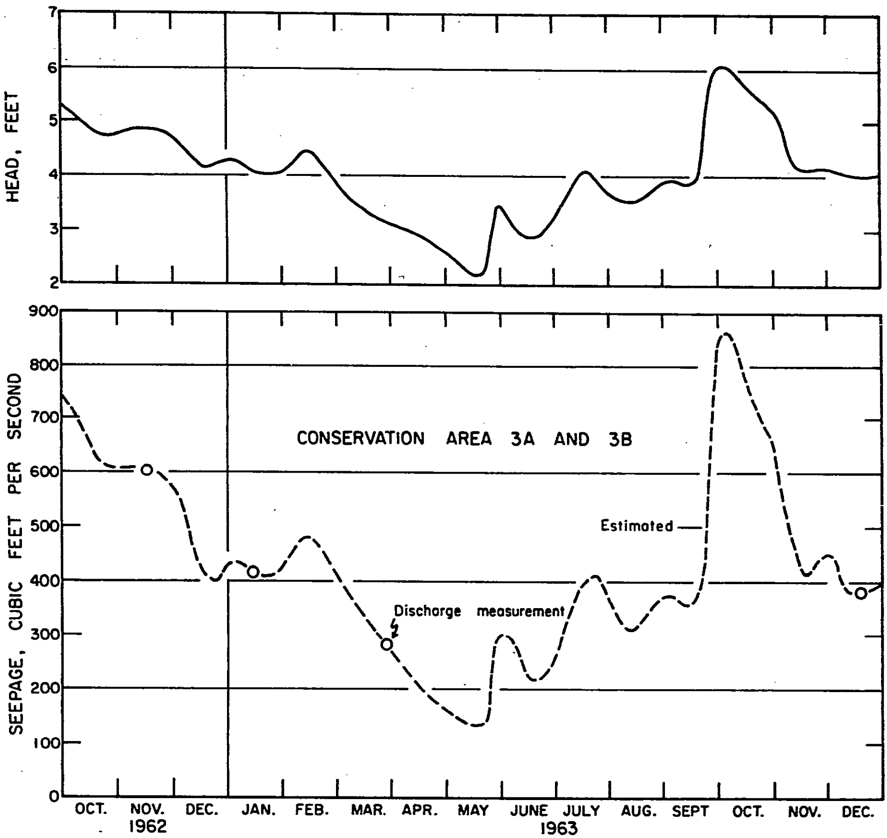

Figure 24. Estimated seepage southward and eastward from Conservation Areas 3A and B through levees L-37, L-33, L-30, and L-29. Discharge data furnished by the U.S. Corps of Engineers

periods and to release water during dry periods to minimize the effects of droughts. Flooding along the urban coastal ridge during the wet years of 1959 and 1960 would undoubtedly have been much greater had it not been for the effectiveness of the drainage and flood-control practices of the C&SFFCD.

In summary, the overall effects of building the eastern levees and establishing the conservation areas are as follows: The levees prevent the overland flow of flood water from the Everglades to the urbanized coastal areas, thereby reducing flooding there. By impounding excess water in the conservation areas, runoff is delayed, and part of the excess is available as direct releases through canals or as seepage from conservation areas during the dry season to maintain water at favorable levels in the coastal areas.

During the period of construction of the C&SFFCD system, urbanization expanded into interior areas, many of which were formerly unsuitable for habitation because of frequent flooding. Much of this low land between the coastal ridge and the Everglades was covered by 2 to 3 feet of water for many weeks during 1947. By 1960, only part of the flood-control works was in operation, but only parts of south Dade County were significantly flooded from hurricane rainfall. Chances for flood conditions comparable with those of 1960 have been minimized since completion of the Flood-control works in south Dade County in the mid 1960's.

CHANGES IN DISCHARGE FROM THE MAJOR CANALS

During the early stages of land reclamation in south Florida, the major canals, including the Miami, North New River, Hillsboro, and West Palm Beach canals, functioned primarily as drains to conduct water out of the Everglades area. As drainage and reclamation progressed, water-control structures and additional canals were constructed (fig. 1) so that discharge from and water levels in the major canals could be controlled and managed.

Adjustments in operation of canals and canal structures to meet changing needs over the years have changed amount, timing, and distribution of discharge from the primary canals since the early days of drainage. Changes in discharge of the major canals constitute one of the principal indicators of the effect of water control and water management on the water resources.

Because the Miami, North New River, Hillsboro and West Palm Beach canals drain the Everglades and transect the coastal ridge, the an-

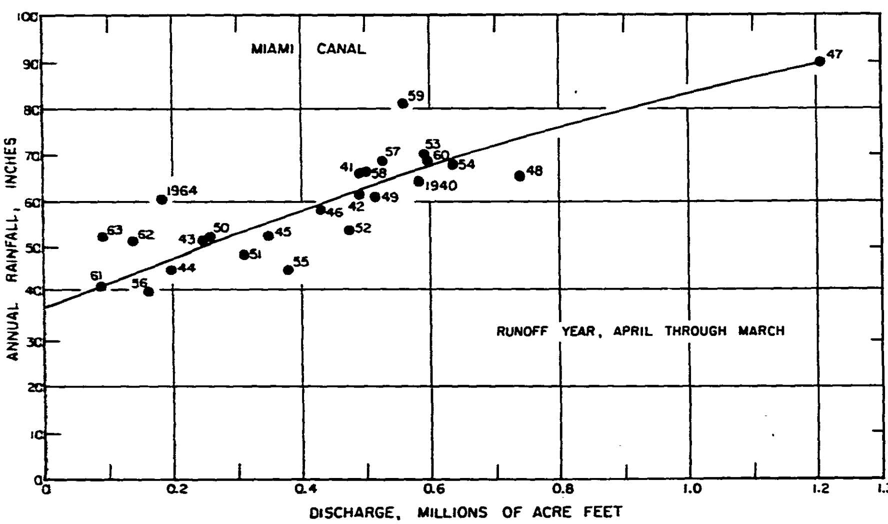

Figure 25. **Generalized relation between annual rainfall at index stations in the area and discharge to the ocean from the Miami Canal for runoff years 1940-64**

nual discharge from each can be used as an indicator of present and past (because of their long records) hydrologic conditions and effects of water management.

A general relationship between annual rainfall and the discharge for a runoff year (April through March) was determined by plotting the average annual rainfall for all index rain gages against the annual discharge of the Miami Canal at N. W. 36th Street, Miami, figure 25. The resulting graph is a rainfall-runoff rating curve that indicates little or no runoff if annual rainfall is less than 37 inches, assuming a normal distribution pattern within the year.

By subtracting 37 inches from the annual rainfall, the double-mass curve relating "adjusted" cumulative rainfall at the index station to cumulative discharge of the Miami Canal at N. W. 36th Street for each runoff year was constructed, figure 26. The relation should plot as a straight line for periods when there were no major water control or flood control changes in the drainage basin. Two changes in slope occur, one around 1955 and the other after 1960, each indicating a significant reduction of discharge in the Miami Canal. The first major break occurred a few years after the completion of the eastern levee system (levees 30 and 33) about 15 miles upstream from the 36th Street control structure, and the completion of

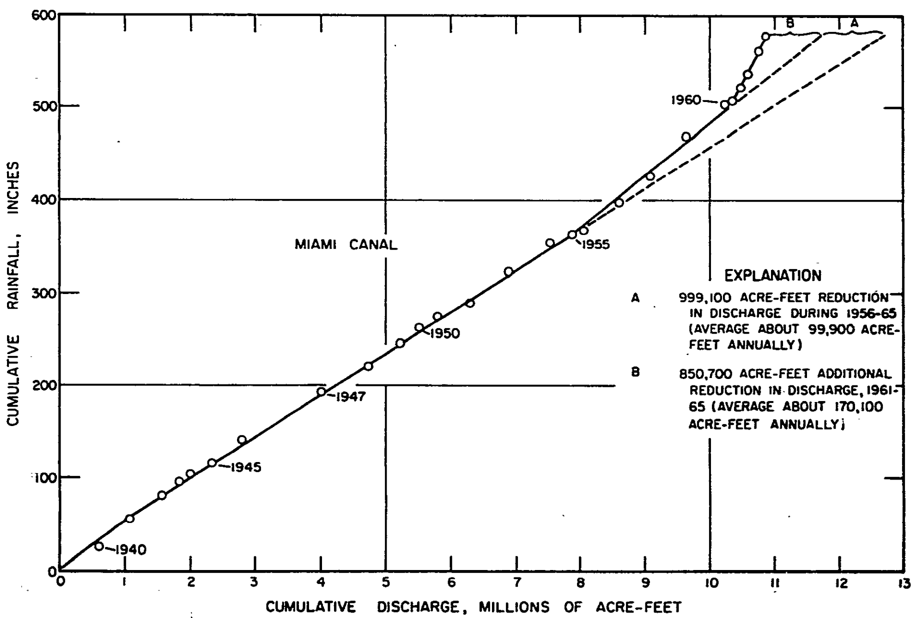

Figure 26. Cumulative runoff-year discharge to the ocean from the Miami Canal related to the adjusted cumulated annual mean rainfall from the eleven index rain gages. Note the change in slope beginning 1955 and 1960

the two control structures (S-32 and S-32A) in the Miami Canal (fig. 1), which regulate flow of the canal. The second break in slope occurred after 1960, when most of the control structures, spillways, and pumping stations of the C&SFFCD system were operational south of Lake Okeechobee, and Levee 67A, which separated Conservation Area 3A from 3B, was completed. The separation was made in order to reduce water levels in Area 3B, thereby minimizing eastward seepage through levees 30 and 33 and seepage southward through the eastern reach of Levee 29.

The two major changes in the slope of the curve indicate reductions in discharge of water to the ocean. The amount of water that would have been discharged to the ocean is indicated in the upper right corner of figure 26 and is labeled A and B. The amount of discharge for the 10-year period "A" (1956-65) was 999,100 acre-feet, averaging about 99,900 acre-feet per runoff year, and the additional amount for the 5-year period "B" (1961-65) was 850,700 acre-feet, averaging about 170,000 acre-feet per runoff year. The total reduction in discharge of Miami Canal for the 10 years 1956-65, as shown in figure 26, was about 1.85 million acre-feet, or about 185,000 acre-feet for each runoff year.

The annual rainfall (average for the long-term index gages) was also compared with the combined discharge of the West Palm Beach, Hillsboro, and North New River canals after adjustments were made to account for inflow from Lake Okeechobee. The relation is shown in figure 27. A wide scattering in the plottings resulted, as did that for the Miami

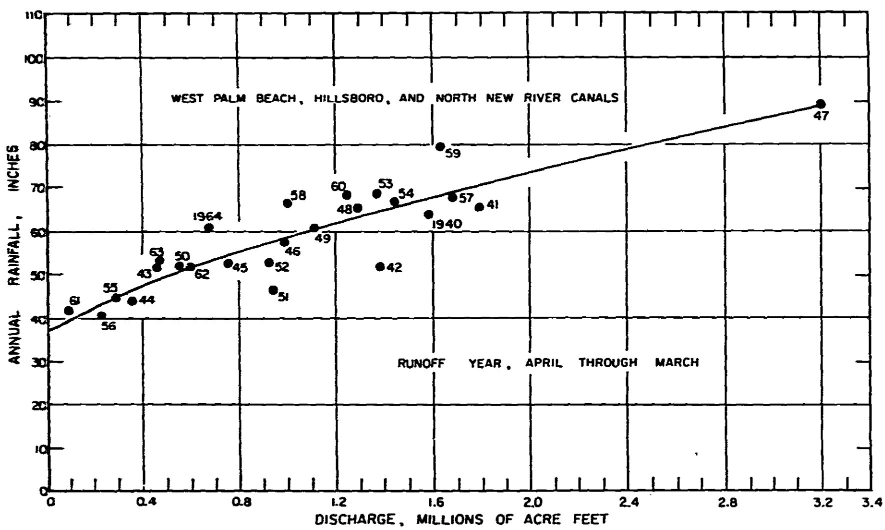

Figure 27. Generalized relation between the annual rainfall at index stations in the area and combined discharge to the ocean from the West Palm Beach, Hillsboro, and North New River canals, for runoff years 1940-64

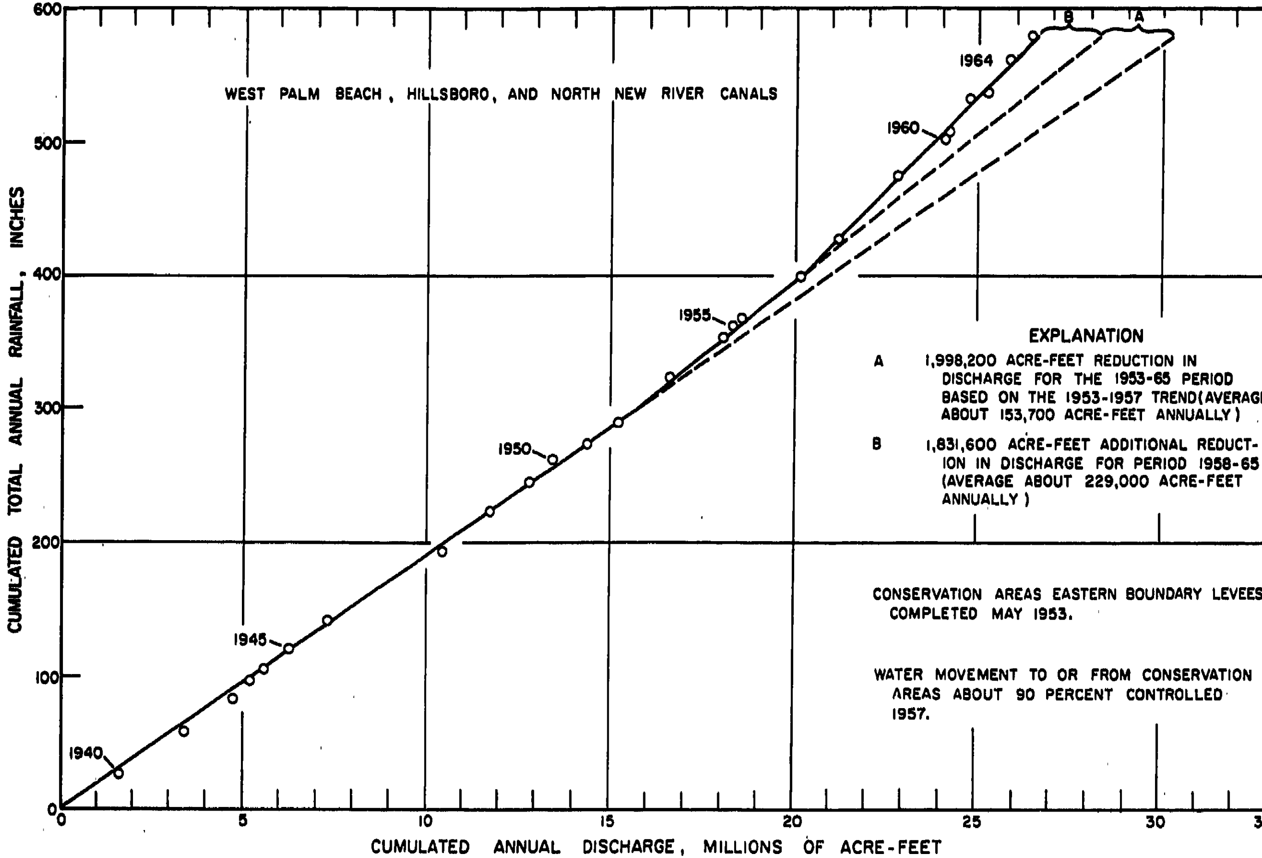

Figure 28. Cumulative runoff-year discharge to the ocean from the West Palm Beach, Hillsboro, and North New River canals related to adjusted cumulated annual mean rainfall from the eleven index rain gages. Adjustments for inflow to and outflow from Lake Okeechobee applied to runoff values

Canal in figure 25, and, similarly, the curve indicated that little or no runoff to the ocean would occur if rainfall was 37 inches or less. As a matter of interest, an examination of several rainfall-runoff relations for other discharge stations in southern Florida showed that flow to the ocean approaches zero when rainfall is about 37 inches, suggesting that for most years evapotranspiration is at least 37 inches.

By subtracting 37 inches from the annual rainfall (average of all index stations) the double-mass curve relating "adjusted" cumulative rainfall to cumulative discharge from the West Palm Beach, Hillsboro, and North New River canals for runoff years 1940 to 1964 was constructed, figure 28.

Similarly, as in the graph for the Miami Canal (fig. 26), the early points plot as a straight line, and the data for more recent years defined two changes in slope, which also indicate reductions in discharge to the ocean. The first change in slope of the curve begins between 1952 and 1953, corresponding to completion of the eastern levees. The second change begins after 1957, when most of the pumping stations and control structures were completed, when the agriculture areas were established, and when Conservation Areas 1 and 2 were enclosed by levees.

The total effects of all the changes in the three canals since 1953 may be summed up in an average and total reduction of discharge to the ocean. The extended straight line on figure 28 shows what the discharge would have been for the West Palm Beach, Hillsboro, and North New River canals if no changes had been made. This projection indicates that an average of 1,167,000 acre-feet would have been discharged for each of the 13 years (1953-65), a total discharge of 15,171,000 acre-feet. The actual total discharge from the three canals to the ocean for the 13-year period was 11,341,000 acre-feet, or about 872,400 acre-feet per runoff year. Therefore, the reduction in discharge over the 13 years was 3,830,000 acre-feet, an average of about 294,600 acre-feet per runoff year. The total amount of discharge would break down into 1,998,200 acre-feet for the 13-year period "A" (1953-65), averaging 153,700 acre-feet per year, and an additional reduction in discharge of 1,831,600 acre-feet for the 8-year period (1958-65), averaging 229,000 acre-feet per year. This total reduction in discharge would indicate a 25-percent reduction of the projected discharge to the ocean. The above discharge values have been adjusted for inflow to and outflow from Lake Okeechobee to the upper Everglades basin.

In summary, the four major canals, Miami, North New River, Hillsboro, and West Palm Beach, drain the Everglades and transect the coastal ridge. The discharge records on the four major canals date back to 1939 before changes by the C&SFFCD projects and can be used to detect changes in hydrologic conditions or effects of water management. One of the more significant changes noted was the reduction in seaward discharge of fresh water coincident with the completion of levee systems east of the three conservation areas. The reduction in flow to the ocean began with the completion of these levees in 1953, resulting in reduction of discharge to the ocean from the Miami Canal of about 185,000 acre-feet per runoff year for 1956-65 and a reduction of discharge from the North New River, Hillsboro, and West Palm Beach Canals of about 294,600 acre-feet per runoff year for 1953-65.

Although the discharge records of the four major canals indicate a 25 percent reduction in annual discharge to the ocean, not all the salvaged water is available for use. Additional canals have been constructed, such as the Cutler Drain (C-100); most of the old canals such as Snapper Creek and Snake Creek canals have been widened, deepened, and provided with new control structures for flood protection. Consequently, the overall reduction of fresh-water flow to the ocean in southeastern Florida since 1953 as a result of flood-control and water-management practices is about 20 percent.

WATER LEVEL CHANGES ALONG COASTAL RIDGE AND VICINITY

One principal effect of pre-1945 land-reclamation practices was the lowering of ground-water levels throughout the coastal ridge and interior areas. Water-level declines resulted from virtually uncontrolled drainage from the four major canals that traverse the Everglades and the coastal ridge. The West Palm Beach, Hillsboro, North New River, and Miami canals conducted large quantities of water from the Everglades to the ocean. In the coastal ridge area, the canals penetrate the permeable Biscayne aquifer, and water from the aquifer drains to the canals when canal levels are lower than the water table. In the early period when drainage continued throughout the dry seasons, some areas were overdrained, allowing sea water to enter the canals and the aquifer and to migrate progressively inland, as shown by Parker, Ferguson, Love, and others (1955, figure 169).

The lowest water levels of record occurred in May and June 1945, the end of a prolonged drought and the end of the period of uncontrolled drainage. The contour map in figure 29 portrays these conditions in Dade County (Schroeder and others, 1958, fig. 14). It was during 1945 that the greatest threat of sea-water contamination of Miami's water supply system occurred, and remedial steps were taken to control flow in the major drainage canals before the next dry season. The important features

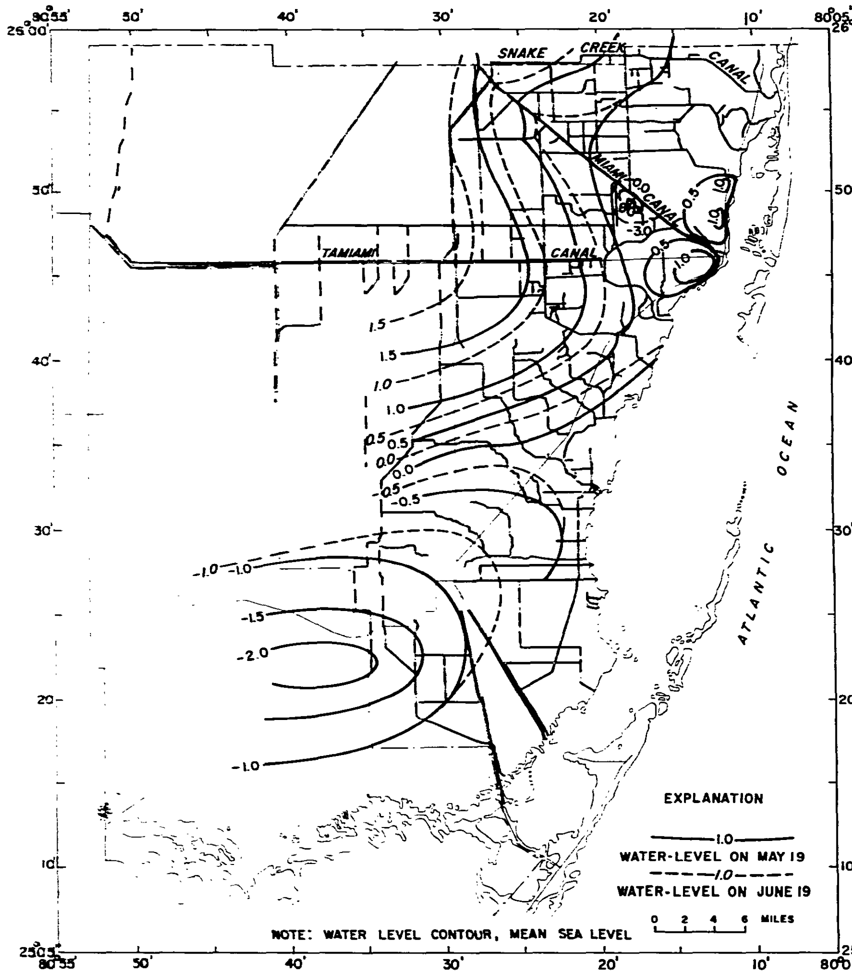

Figure 29. Map of Dade County showing contours of the low water levels of record, May-June 1945 (from Schroeder and others, 1958, fig. 14)

of the contour map are the below sea-level elevations throughout the southeast and southern parts of the county and the low eastward gradient in the northern part.

Marked changes in hydrology took place during the 15-year span beginning in 1950. Canals were extended inland for expanded drainage. New canals were dug through the coastal ridge, and many extended inland to the eastern levee system to accommodate rapid urbanization. Each new major canal was equipped with a gated control structure. The improved drainage lowered peak levels during the rainy season,

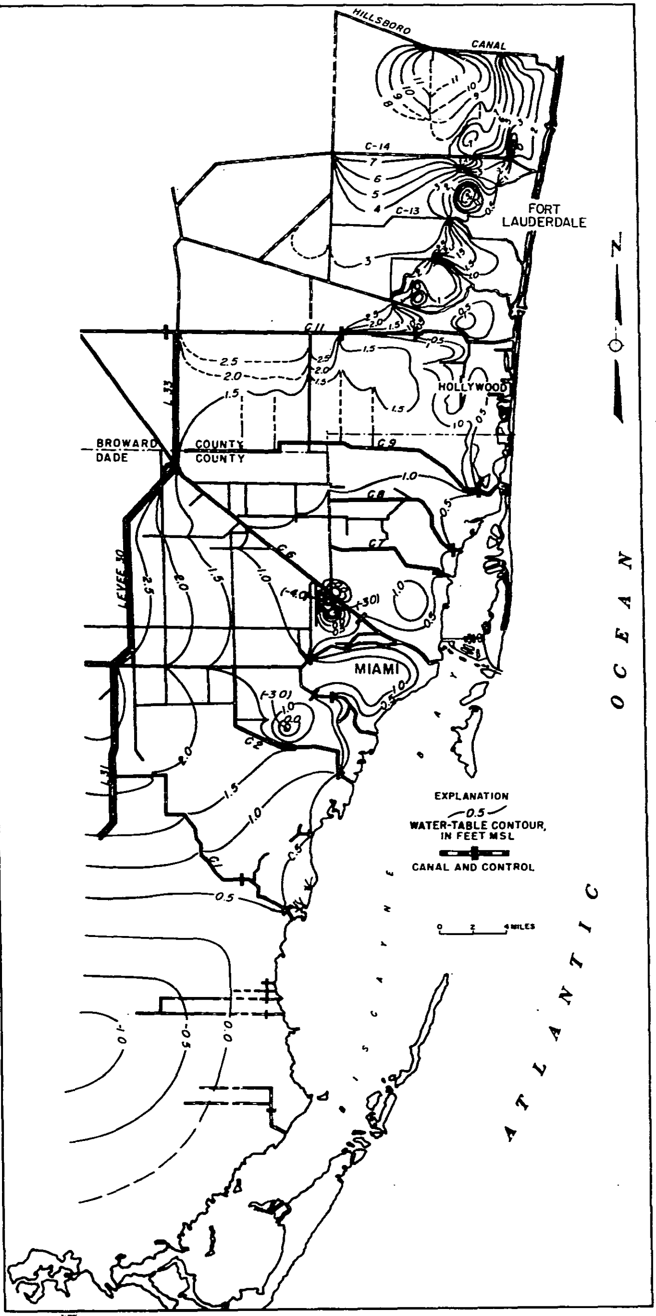

Figure 30. Map of Florida's lower east coast showing contours of low-water conditions in May 1962 (adapted from Sherwood and Klein, 1963, fig. 9 and McCoy and Sherwood, 1968, fig. 8)

and the timely closing of the control structures at or soon after the rainy season prevented overdrainage and excessive lowering of water levels, thereby stabilizing the salt front in the aquifer in most areas. The contour map in figure 30 shows water levels in southeastern Florida in May 1962, the end of a prolonged drought that was comparable in intensity to that ending June 1945 (fig. 29). A comparison of the two maps shows that the low levels in south Dade County in May 1962, although below sea level, were not as low as in 1945 and that the levels in middle and northern Dade County were about 1 foot higher in 1962 than in 1945, despite the fact that water use had multiplied many times during the 17 years.

In 1967 a new system of drainage canals was completed in south Dade County, an area that had experienced flooding in 1947

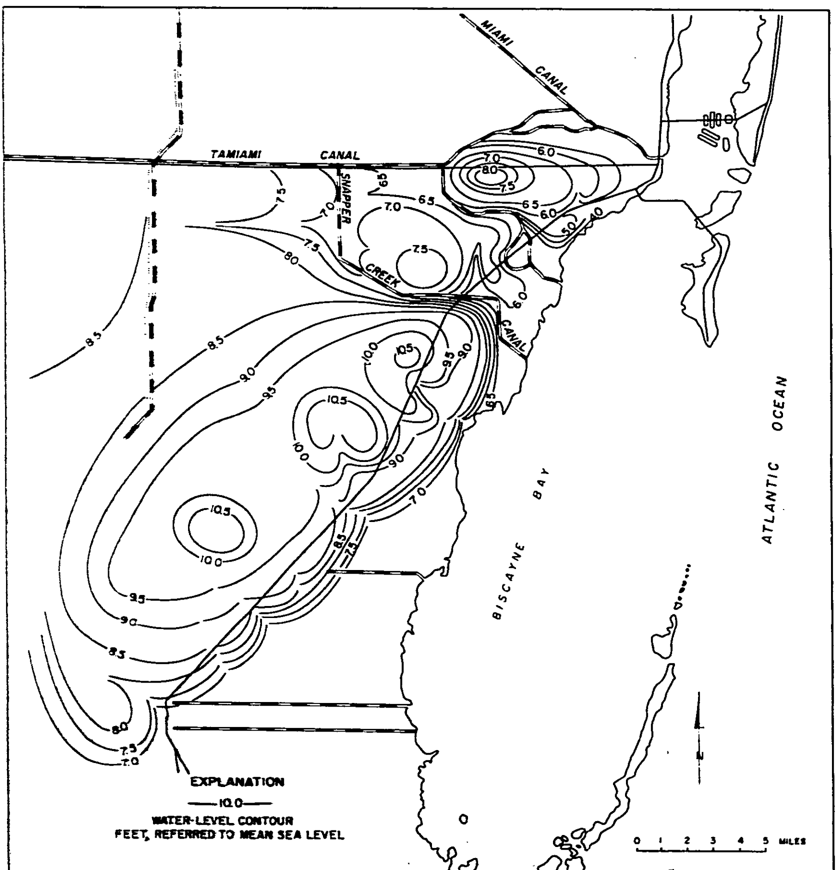

Figure 31. Map of part of Dade County showing contours of the high water conditions of September 1960

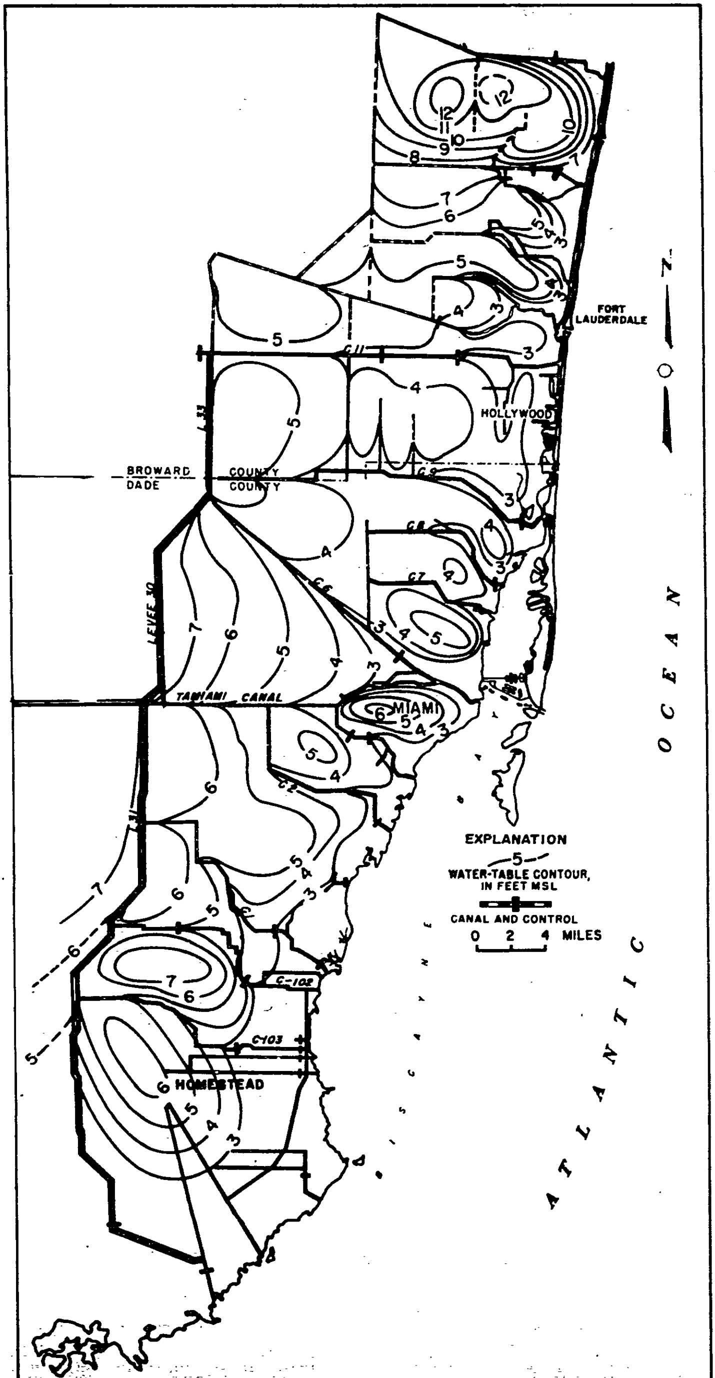

Figure 32. Map of Florida's lower east coast showing contours of the high water conditions of June 1968

and 1948, 1954, and 1960. The high-water conditions resulting from two tropical storms in September 1960 are shown on figure 31. Water-level peaks exceeded 10.5 feet above mean sea level in the high parts of the ridge, sheet flow occurred through the transverse glades, and much of the coastal marsh east of the ridge was flooded.

The flooding in south Dade County brought about a high priority for completing the drainage system there. That system was nearly completed by the end of 1968 and is shown in figure 32 in the area south of Canal 2 (Snapper Creek Canal). The effectiveness of the system in preventing floods is shown by the water-level contours for June 1968 (fig. 32), which show conditions after rainfall of nearly 16 inches in May and more than 15 inches at Homestead during the first 20 days of June 1968. Drainage by the canals resulted in local ground-water mounds in the intercanal areas rather than a high elongate mound, as was shown for September 1960. No flooding resulted from the May-June 1968 rainfall in Dade County, though the rainfall was greater than that during the September 1960 storm.

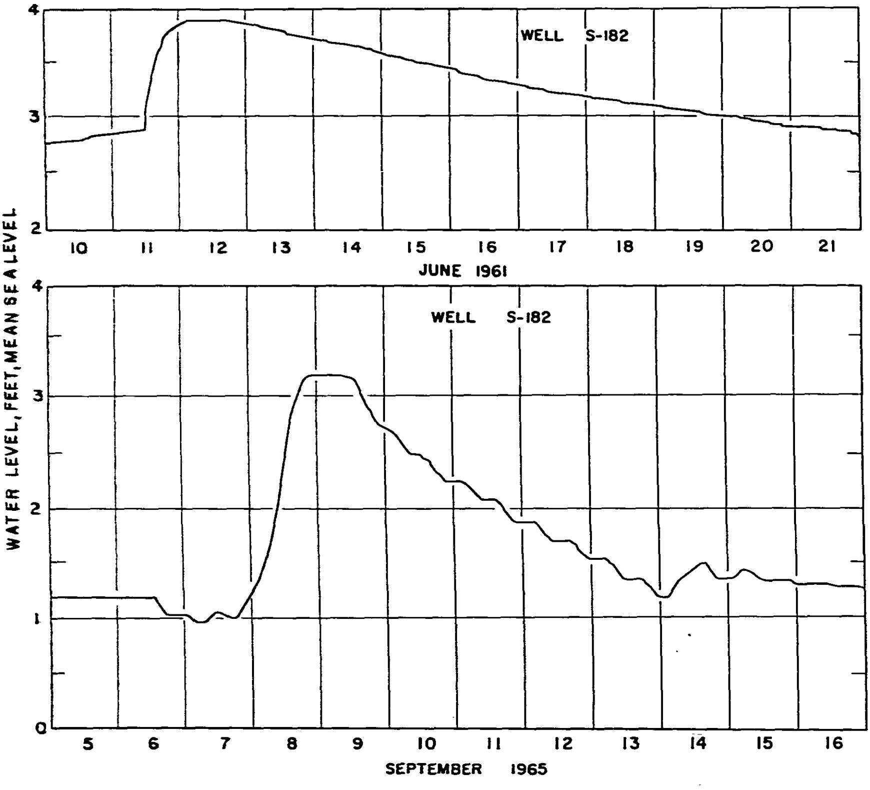

Figure 33. Hydrographs of well S-182 showing water-level recession rates before and after construction of Canal 1

The effects of the new canal system and flood-control practices on the hydrology of south Dade County were also marked by a change in the recession rate of water levels. Figure 33 shows selected graphs of sections of the water level recorded at well S-182, a short distance north of Canal 1 (see figure 1 for location), to contrast the recession rates before and after Canal 1 was completed and the salinity control S-21 was accepted. The graphs show that the rate for part of June 1961 (pre-canal construction) was about 0.2 foot per day, half the 0.4 foot per day rate of September 1965.

Long-term records of fluctuations of ground-water levels and general water-level trends from observation wells provide the most valuable information to aid in determining changes in water levels caused by the flood-control and water-control practices. Scattered records of water levels and reports of general hydrologic conditions in different areas, as reported by Parker, Ferguson, Love, and others (1955, p. 500-585), indicate that water levels were near or at the land surface along much of the coastal ridge area before drainage. Detailed records of water-level fluctuations since 1940, as reported by Kohout and Hartwell (1967, p. 25-27, fig. 13), show the adjustment of ground-water levels to water-control activities in subsequent years and that water levels are generally several feet below land surface. The records show that in the northern half of Dade County the yearly water-level peaks were lowered, especially after 1954, and a small but gradual rise in annual minimum levels occurred in certain areas.

General changes in water levels and the patterns of fluctuations along and immediately west of the coastal ridge in Broward County are shown on figure 34 by the hydrograph of well G-616, near Pompano Beach. The apparent changes are an increase in the rate of fluctuations

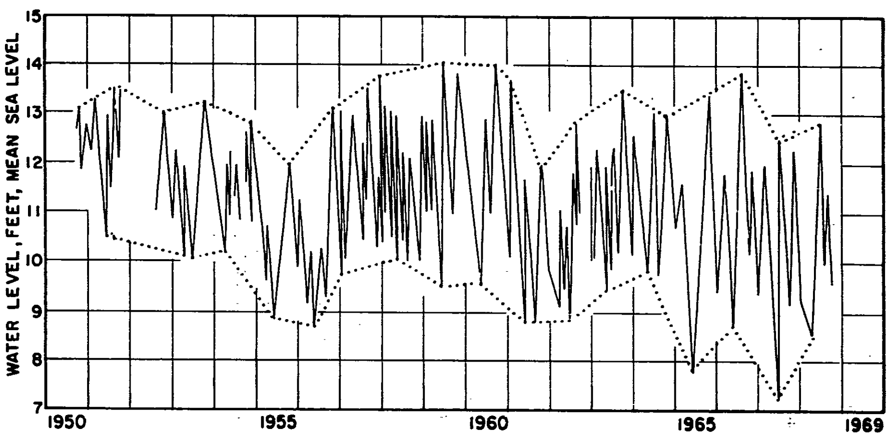

Figure 34. Hydrograph of well G-616 in Broward County

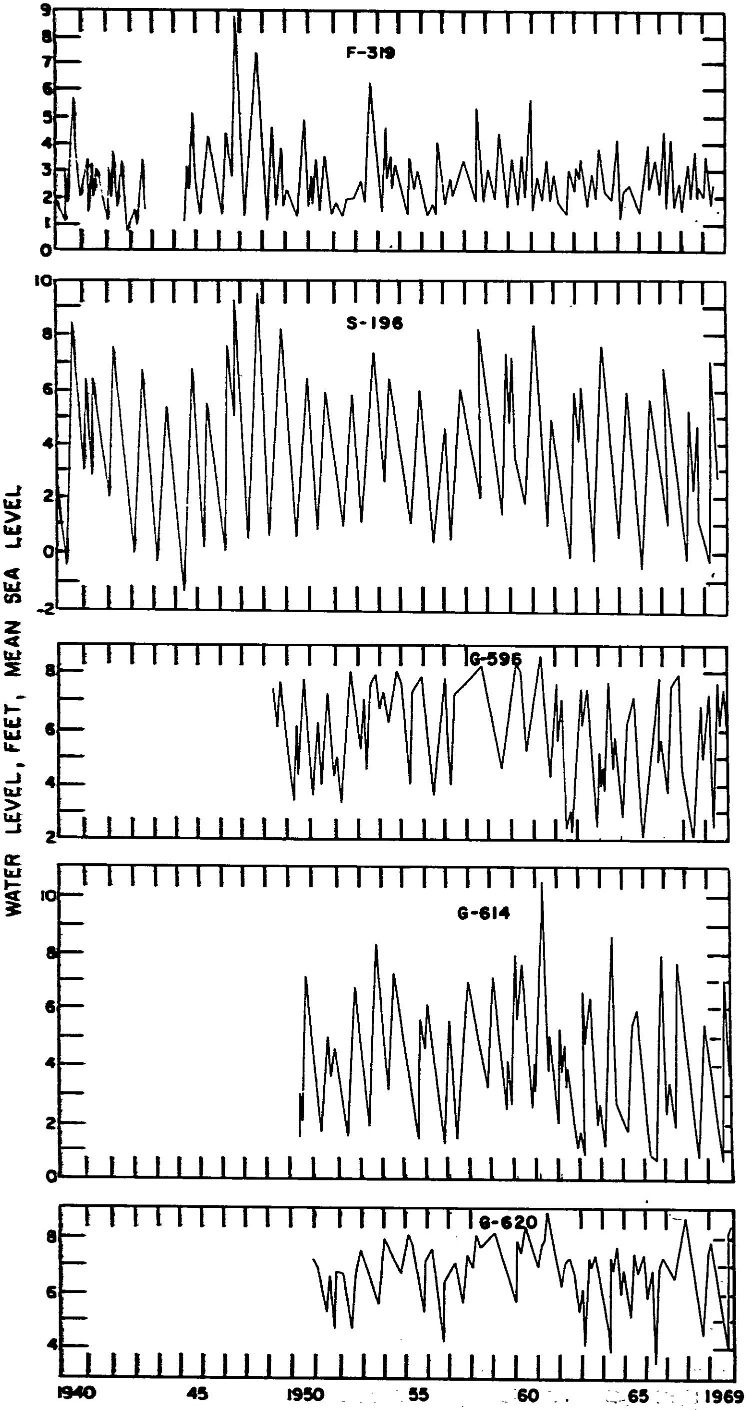

Figure 35. Hydrographs of selected observation wells in southern Dade County

beginning about 1958 and the lowering of the annual minimum levels. The first downward trend in minimum water levels began in 1955 and generally coincides with the completion of the canal system west of Pompano Beach, which connected with the Pompano Canal (C-14). The second downward trend in minimum water levels began in 1965, when the drainage system for a large community northwest of Pompano Beach was connected to the Pompano Canal.

Inspection and analysis of long-term water-level records in other parts of the coastal ridge also show changes in trends, in magnitude of fluctuations, and in recession rates. Figure 35 shows hydrographs of five observation wells in southern Dade County, wells F-319, S-196, G-596, G-614, and G-620. Locations of wells are shown in figure 1.

The hydrograph for well F-319, near the coast south of Miami, shows the marked moderation of the height of annual water-level peaks since the 1947 record high and an upward trend of the minimum levels. These changes in the pattern of fluctuations are a result of water-control practices in Snapper Creek Canal (C-2). Even during the extreme rainfall of September 1960, flooding in the urbanized areas of the Snapper Creek Canal basin was minimal or nonexistent. The upward trend in minimum levels is the result of two factors: (1) the ability of the Snapper Creek Canal and its secondary canal system to pick up ground water in the interior reach and convey it eastward, thereby maintaining relatively high levels in the coastal reach to combat sea-water intrusion; (2) improved water-control practices brought about by increased experience in control-structure operations resulted in a decrease in freshwater discharge to the ocean and a slowdown in the recession rate of water levels.

The hydrograph for well G-596 (fig. 35) west of Levee 31 shows the changes in water level in the interior areas as a result of the construction of the levee system around the conservation areas, the extension of Black Creek Canal (C-1) inland to the levee system, and the subsequent flood-control and water-control practices in the area drained by C-1. The 1952-60 water levels for well G-596 shows a slight rise, probably in part of a result of construction of the eastern levee system and the resultant southward diversion of surface flows. The record for 1962-68 shows a distinct downward trend. The annual minimum levels are as much as 1.0 to 1.5 feet lower than earlier minimums, and the annual peak levels are as much as 0.5 foot lower than those for the preceding period. These lowered water levels are significant because they are the difference between flooding and not flooding in the area, which has enabled the establishment of new farmlands in the vicinity of Levee 31. The annual magnitude of fluctuations for 1962-68 is considerably increased from that observed in the earlier period of record. The downward displacement of water levels and the increase in the magnitude of fluctuations are the result of: (1) below-normal rainfall during part of the period, particularly 1962-63; (2) the draining effect of the Black Creek Canal (C-1), which picks up water from the vicinity of well G-596 and conducts it to the coast; (3) completion (1962) of the eastern section of Levee 29 along the south boundary of Conservation Area 3B, which prevented southward overland flow from Conservation Area 3B.

The hydrographs for wells S-196 and G-614 in southern Dade County indicate a lowering of annual minimum levels during 1962-68; however the lowering was not so pronounced as that observed in the vicinity of well G-596. The lowering of ground-water levels in southern Dade County, as indicated in the hydrographs of wells S-196 and G-614, may have been the result of the drainage by the Black Creek Canal (C-1), because those two wells are south of and, in part, downgradient from the Black Creek Canal (C-1); and lowering of levels owing to drainage by C-1 will be reflected in the levels in areas to the south. Canals 102 and 103 were operational in 1967, but sufficient time has not passed to determine the incremental effect that those canals have had on adjacent ground-water levels.

In the highly permeable aquifer of eastern Dade County, the canal system has effectively lowered water levels, thereby aiding in the prevention of major flooding. Many of the canals extend long distances inland to the Everglades and drain areas of relatively high water levels. Drainage of Everglades water through the canals has resulted in lowering inland water levels and raising levels near the coast. One overall hydrologic result is a reduction of the water-level gradient throughout the area east of the levee system.

A complete evaluation of the effects that water management during 1962-68 had on hydrologic conditions is beyond the scope of this report, but indications are that they have been effective in flood control and water availability and that works in progress will increase its effectiveness. Owing to a prolonged period of below-average rainfall, which began after Hurricane Donna in the fall of 1960, surplus water was not available to manage until 1966, a year of above-normal rainfall. Sufficient water was retained in the management system after the 1966 rainy season to permit major but gradually reduced releases to the Everglades National Park throughout the subsequent dry season and to maintain adequate water levels along the coast.

Flood benefits of the new canal system in south Dade County were realized at the beginning of the rainy season of 1968, when rain in excess of 32 inches fell during May and June. Without the canal system, inundation equaling or exceeding 1947-48 and 1960 conditions would probably have occurred. (Compare figs. 31 and 32 in south Dade County.)

CHANGES IN WELL-FIELD AREAS AND SEA-WATER INTRUSION

A prime objective for water management is to hold additional water in the conservation areas by reducing flood flow to the ocean. This should insure that water deliveries to the coastal sections of the

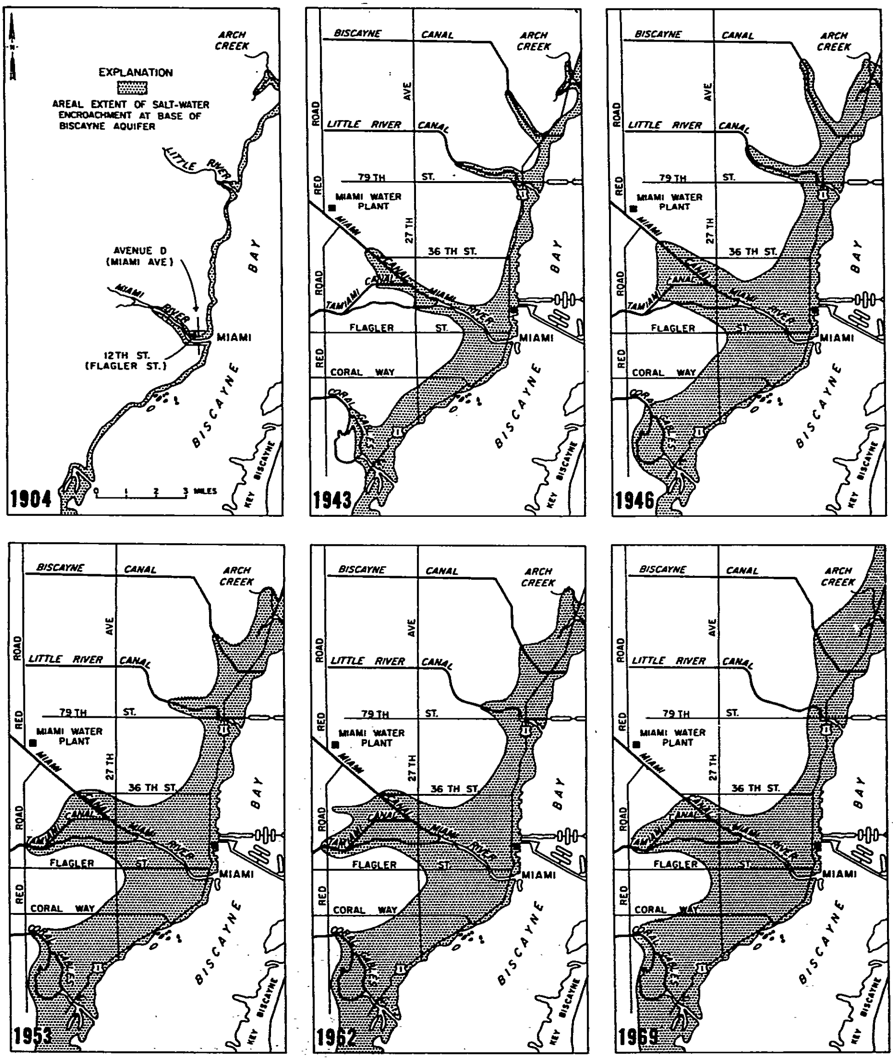

Figure 36. Maps of the Miami area in eastern Dade County showing the sea-water encroachment at the base of the Biscayne aquifer 1904-69 (Parker, Ferguson, Love, and others, 1955, p. 589, Kohout, 1961, Leach and Grantham, 1966) updated

Biscayne aquifer are adequate during dry seasons to prevent further sea-water intrusion and to provide replenishment to well fields by infiltration from the canals. If this objective is satisfied, then hydrologic conditions in inland areas and in the Everglades National Park should improve.

Sea-water intrusion and its control have been problems in developing the water resources of southeastern Florida. Parker, Ferguson, Love, and others (1955, p. 571-711) presented a detailed history of sea-water intrusion in southeastern Florida. Figure 36 updates their presentation (1955, fig. 169) of the progressive movement of salt water into the Biscayne aquifer in the Dade County area. It is apparent that further intrusion has not been significant since 1962, indicating that adequate coastal water levels have been maintained in the aquifer. As water demands increase in the future, however, sea-water intrusion may again become significant unless more water is furnished from interior storage areas, especially during dry periods.

The major long-established municipal well fields are located along the coastal ridge but at sufficient distances from the coast and upstream from water-control structures to be protected from sea-water intrusion. Figure 37 shows the locations of and daily pumping rates in the large municipal well fields in southeastern Florida in late 1970 and their locations with respect to the area affected by sea-water intrusion. Most fields are located upstream from the control structures in canals to facilitate infiltration of fresh water from the canals. Infiltration from the canals to the well fields minimizes drawdown caused by pumping, thereby reducing the possibility of inland gradients and salt-water intrusion in the vicinity of the well fields.

Because of the critical hydrologic conditions in the vicinity of the major well fields and the past experiences of sea-water intrusion in well fields of Miami and Fort Lauderdale, intensive investigations of large well fields have continued for more than 20 years. Analyses of hydrologic conditions in well fields before and after water control and management indicate their effectiveness.

MIAMI MUNICIPAL WELL FIELDS

The Miami municipal well field, adjacent to the Miami Canal at Miami Springs (fig. 37) was placed into service in 1925 and yielded water of low chloride content until April 1939, when wells near the Miami Canal began to yield salty water (Parker, Ferguson, Love and others, 1955, p. 691). The source was salty water that had moved upstream in the uncontrolled canal to the vicinity of the well field and had infiltrated laterally through the aquifer. Contamination in the field

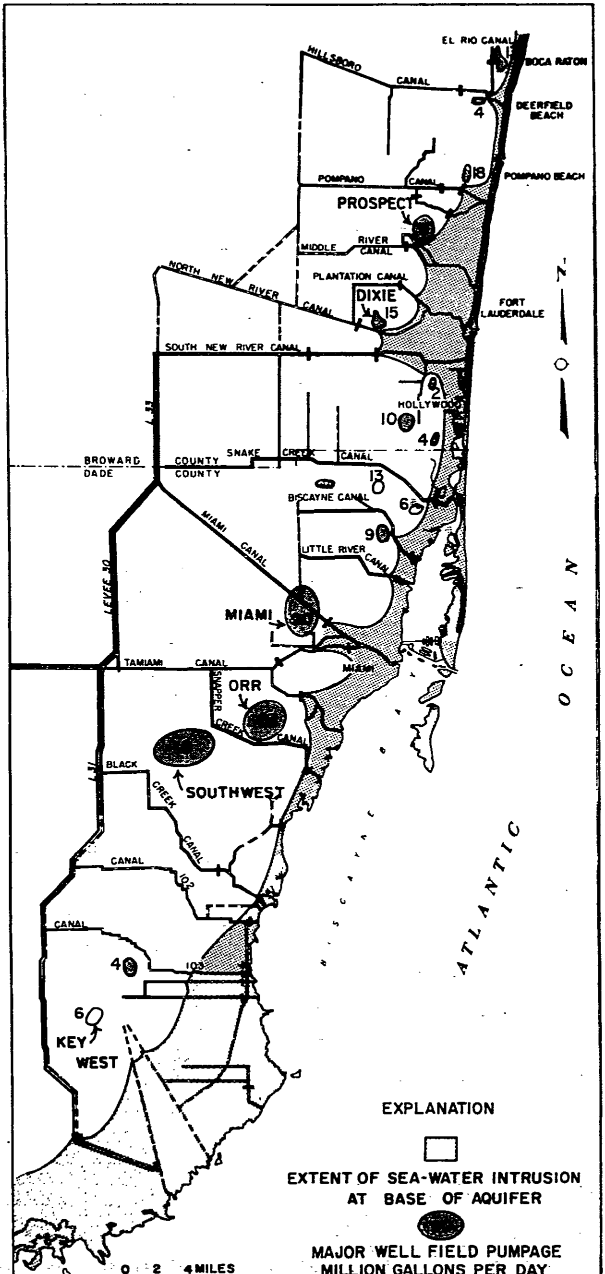

Figure 37. Map of Florida's lower east coast showing the major well fields and their pumping rates in million gallons per day near the end of 1970, and the extent of seawater encroachment at the base of the Biscayne aquifer

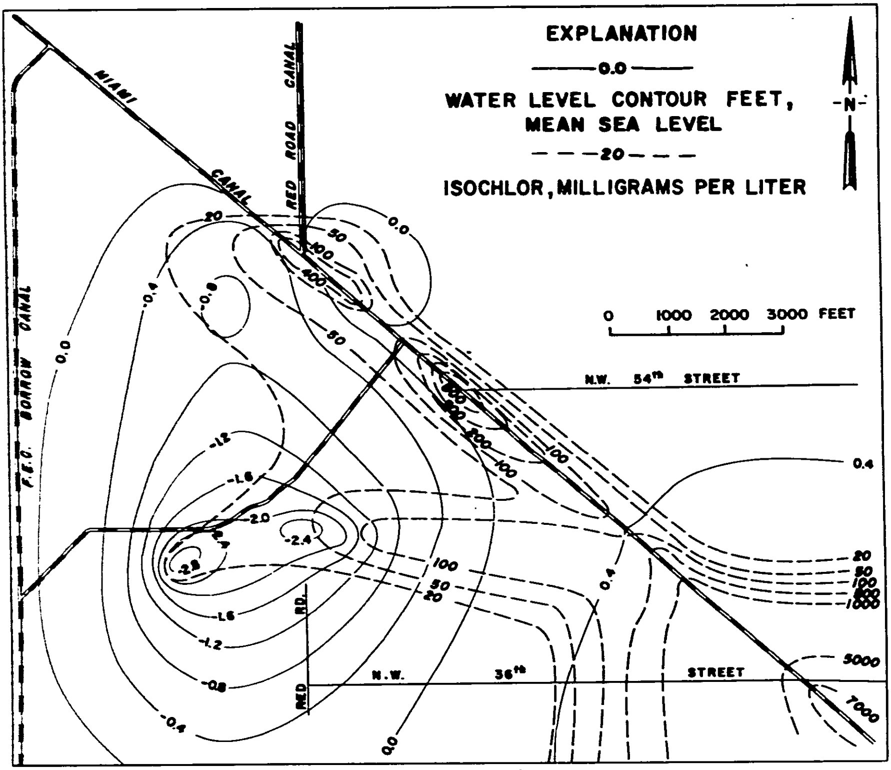

Figure 38. Map of the Miami well field showing water levels and chloride conditions June 29, 1945 during uncontrolled conditions of Miami Canal

remained a problem through 1945. The contour map in figure 38 shows water-level and chloride conditions in the well field on June 29, 1945, the end of a prolonged drought. The highest water level in the well-field area was 0.4 foot above mean sea level, and the hydraulic gradient was inland and toward the centers of pumping, where water levels were nearly 3 feet below sea level. The pattern of the choloride lines shows that tongues of salty water had moved up the uncontrolled Miami Canal and had infiltrated vertically into the aquifer and laterally toward the areas of greatest water-level drawdown. Pumpage in the well field at the time was 30 mgd.

In 1946 a control structure of sheet steel piles was built in the Miami Canal at N. W. 36th Street to prevent the inland movement of salt water. During the rainy seasons the control was opened to permit discharge of surplus water, but after the flood seasons the control was closed to prevent overdrainage and excessive lowering of water levels. As a result, water levels in the well field were maintained at higher levels during dry seasons, and the areas contaminated by salt water were gradually freshened.

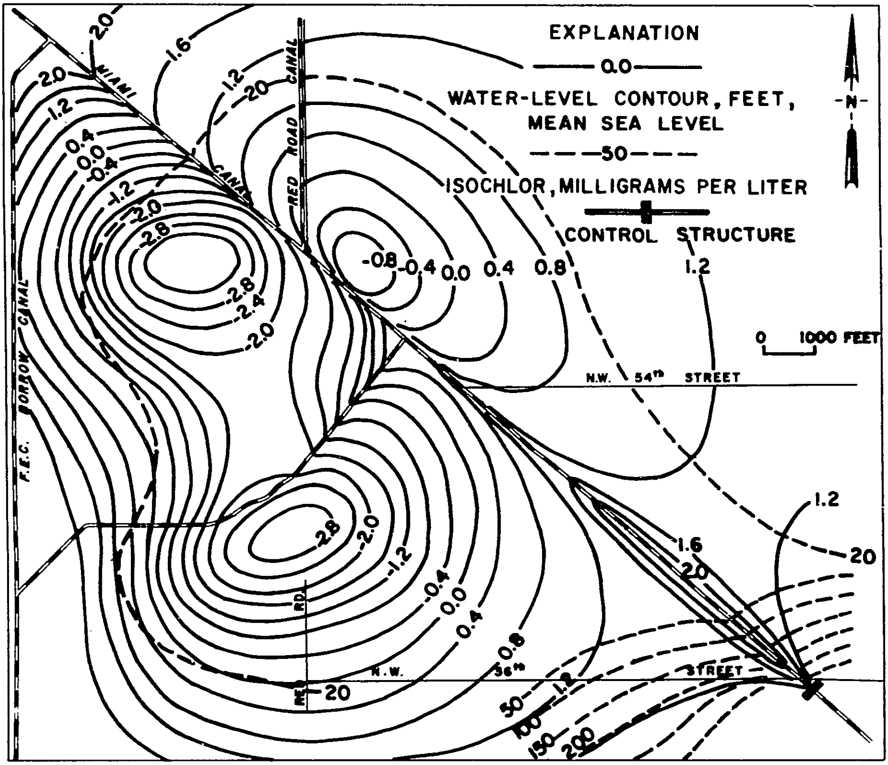

Figure 39. Map of the Miami well field showing water levels and chloride conditions April 7, 1966 during controlled conditions of Miami Canal

Figure 39 is another contour map of the Miami well field area that shows water-level and chloride conditions during the dry season of 1966, so that comparison can be made with the uncontrolled condition in 1945. Pumpage in the well field during the dry season of 1966 was 80 mgd, the control structure at N. W. 36th Street was closed, and a water level of 2 feet above mean sea level was being maintained along the controlled reach of the canal. The contours show that the canal was replenishing the well field by downward and lateral infiltration into the aquifer. A general appraisal shows that as a result of the general rise in water level at the control structure, pumpage of 80 mgd in 1966 produced about the same minimum water level in the withdrawal centers as pumpage of 30 mgd in June 1945. Also, under the 1966 condition, sea water was not intruding the aquifer. Sea water did intrude in 1945.

In 1968 additional supply wells on the north side of the Miami Canal were added to the municipal system, thereby increasing the capacity of the well field from 80 to 130 mgd. Planned modifications and additions to the northwest will boost the yield of the well field to more than 200 mgd in the next few years. As long as adequate quantities of water are available by eastward seepage or by releases from Conservation Area 3 into the upper reach of the Miami Canal to maintain adequate fresh water levels at the 36th Street control structure, the well field is expected to yield its capacity without significant inland advance of salt water in the Miami Canal basin. However, the threat of sea-water intrusion to the well field also persists from the south, from the presently uncontrolled reach of the Tamiami Canal. If no further lowering of water levels occurs in the southern part of the well field, the salt water there should not advance toward the well field. A permanent control structure, to be provided by a recent (1969) decision, in the Tamiami Canal near its confluence with the Miami Canal should give further protection to the well field.

Because the permanence of the well field depends upon replenishment from the inland part of the basin and from the water conservation areas during drought, management of the water in the Miami Canal basin during future years will be a key to the protection of the well field.

Water-level contour maps, such as the map of May 1962 (fig 30), that depict hydrologic conditions in Dade County at the end of prolonged droughts, show characteristic low levels and a nearly flat hydraulic gradient in the northern part of the county from the levee eastward to the coast, about 15 miles. The low gradient is the result of effective drainage by the primary canals and the extensive network of secondary canals connected to the Miami and Snake Creek canals, as shown in figure 30. Water levels are regulated by a single control near the coast in each of the primary canals.

To minimize flooding in low lying residential areas along the coastal ridge, it is necessary to reduce water levels in inland areas thereby reducing the amount of water in aquifer storage available for use during the dry seasons and partly negating the replenishment benefits of rainfall. For several years this method of water control served the basic needs of flood control and the stabilization of sea-water intrusion; however, the practices have resulted in progressively greater reliance on water in the conservation areas each year as the source of aquifer replenishment in the coastal area during dry seasons. The rate at which municipal needs are increasing suggests that in the near future, replenishment from the conservation areas by itself might not be adequate to fulfill all demands required to protect the water resources during prolonged drought.

The Alexander Orr-Southwest well-field complex of Miami was placed into operation in the early 1950's, when moderate quantities of

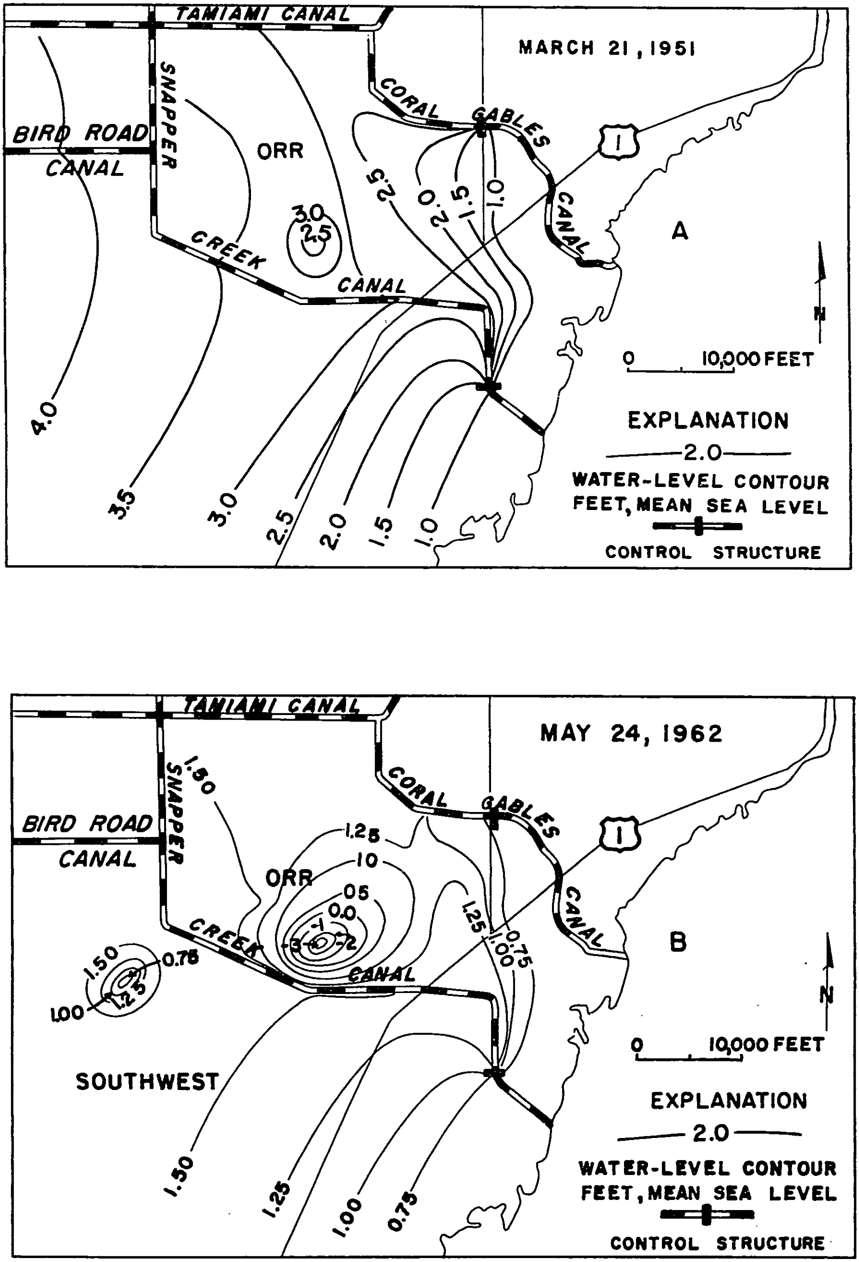

Figure 40. Maps of the Alexander Orr and Southwest well field areas of the City of Miami showing water-level conditions March 21, 1951 (A) and May 24, 1962 (B) (from Sherwood and Leach, 1962, fig. 17 and Sherwood and Klein, 1963, Fig. 8)

water were pumped from a cluster of wells about half a mile north of the Snapper Creek Canal (Canal 2). Figure 40A shows the small cone of depression in the water table that formed as a result of moderate pumping of 6.7 mgd (Sherwood and Leach, 1962, fig. 17) on March 21, 1951, during the dry season. That cluster of wells (Orr well field) served the growing urban area south of Miami; but, because of rapidly increasing demands during the late 1950's, additional high-capacity wells south of the canal and 4 miles west of the original cluster were placed into operation. The well field to the west, the Southwest well field, comprised 6 wells each capable of pumping 10 mgd. The Southwest field was the primary source, and the Orr well field was used as a reserve to make up peak demands during the tourist season and prolonged droughts. However, after Klein (1958) indicated that the Orr reserve field could be pumped at capacity safely on a permanent basis, the bulk of the withdrawals for the increased demands south of Miami was shifted to the Orr well field, and the Southwest field was placed on reserve status. The effect of heavy municipal pumping in the Orr field, 42 mgd, and in the Southwest field, 28 mgd, near the end of a prolonged drought in May 1962 is shown in figure 40B (Sherwood and Klein, 1963, fig. 8).

Since 1962 the capacity of the Orr field has been increased to 60 mgd (10 wells), and plans call for maximum withdrawal of about 300 mgd from the Southwest well field. These quantities can be withdrawn from that area because of the following safety factors related to the Snapper Creek Canal system: (1) The canal extends westward and northward connecting with the Tamiami Canal, which, in turn, extends to Conservation Area 3, thereby assuring a source of replenishment to the canal for maintaining high levels at the coastal control structure and for infiltration to the well field; (2) the coastal control structure has been efficient, and loss of water is minimal during dry seasons (Kohout and Hartwell, 1967, p. 40-42); and (3) because the spur canal east of the Orr field (fig. 40) is connected to the Snapper Creek Canal, its water level is the same as that of the Snapper Creek Canal and, therefore, it is a source of aquifer replenishment, which minimizes the eastward expansion of the cone of depression formed by well-field pumping and stabilizes the movement of salt water in the aquifer between the well field and the coast. Water-level measurements in the Orr-Southwest well-field area in dry seasons during 1966-68 indicated that when pumping was increased to 65 mgd the cone was deepened only by about 1 foot.

FORT LAUDERDALE WELL FIELDS

Some of the more marked hydrologic changes over the years have occurred in the Prospect well-field area of Fort Lauderdale, located between the Pompano Canal (Canal 14) and the Middle River Canal

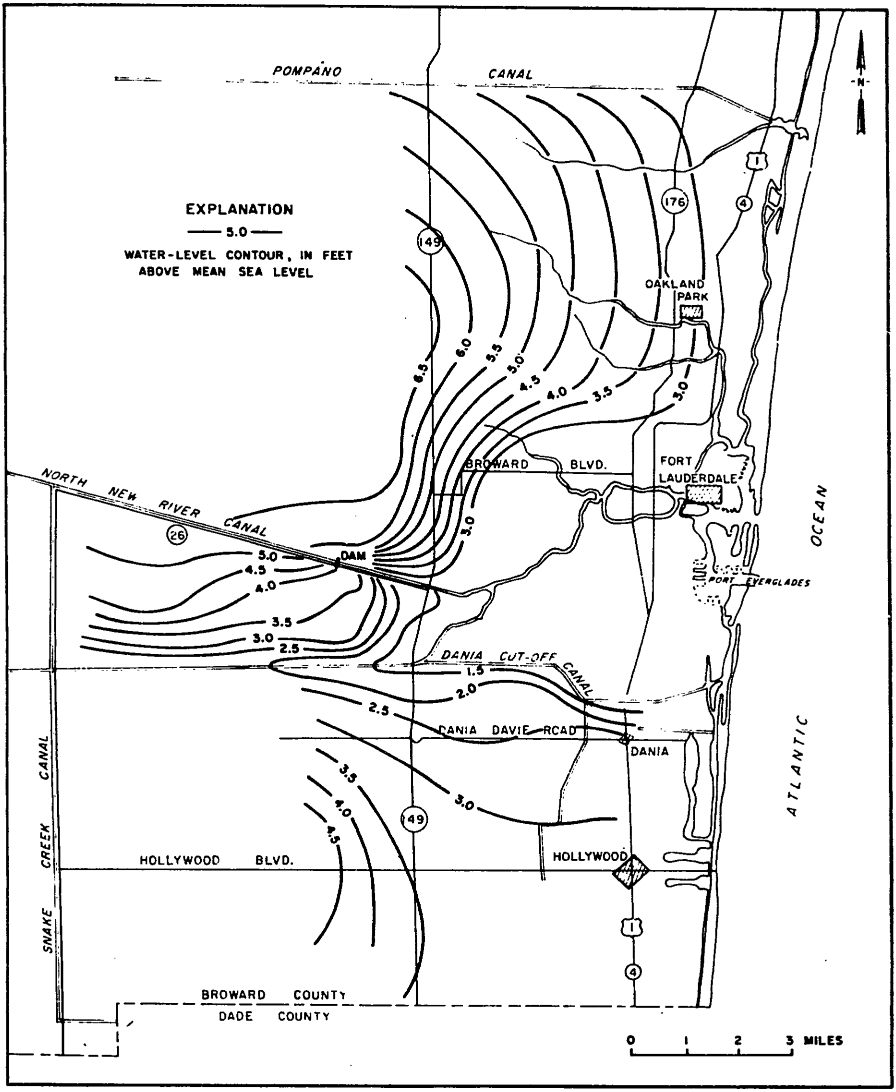

Figure 41. Map of southeastern Broward County showing water-level conditions February 15, 1941 (adapted from Sherwood, 1959, fig. 9)

(Canal 13). Sherwood (1959, fig. 9) mapped water levels in eastern Broward County in 1941 before intensive drainage and urbanization and before establishment of the Prospect well field. Those early levels are shown in figure 41 so that comparisons can be made with levels after development. The Prospect well field was placed in operation

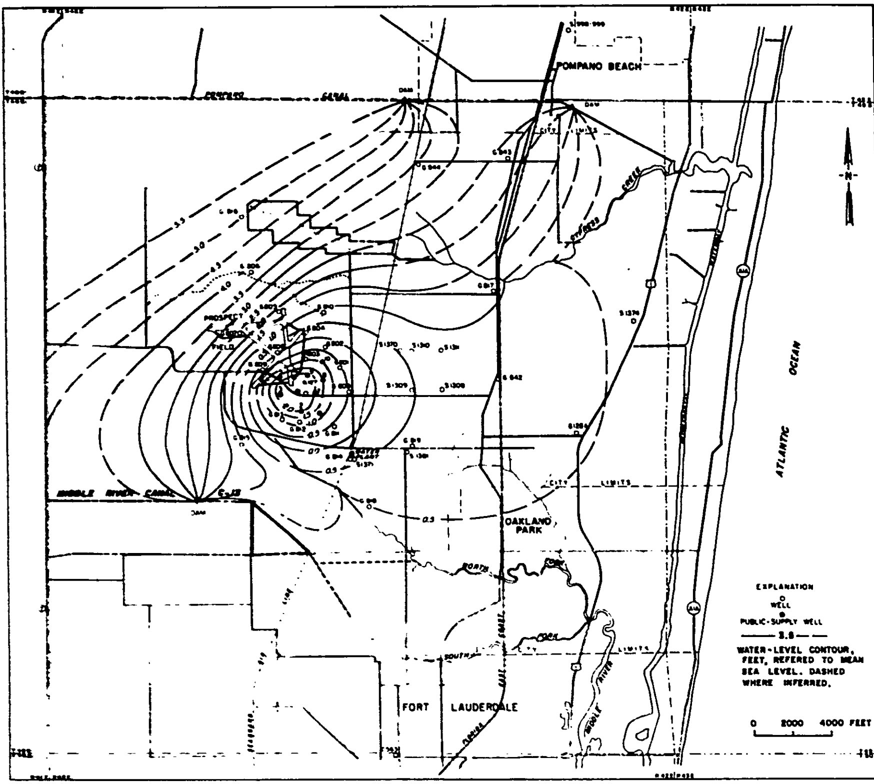

Figure 42. **Map of the Oakland Park area of Broward County showing water-level conditions in the Prospect well field August 7, 1956 (from Sherwood, 1959, fig. 11). The total pumpage for the Prospect well field was 7 mgd**

about 1955 when Fort Lauderdale was experiencing its greatest growth rate. Figure 42 (Sherwood, 1958, fig. 11) shows the effect that canal drainage and pumping the original 10 municipal wells at more than 7 mgd had on water levels in that area in 1956. This map, when compared with that of figure 41 for 1941, and that of figure 43 for 1968, indicates the large changes in water levels and water-table configuration that resulted over the years as a result of increases in withdrawals, changes in the pattern of pumping, and changes in canal systems and control structures. The pumping rates that produced the cones in figure 43 were 30 mgd from the supply wells and 5 mgd from the rock pit in the western part of the field.

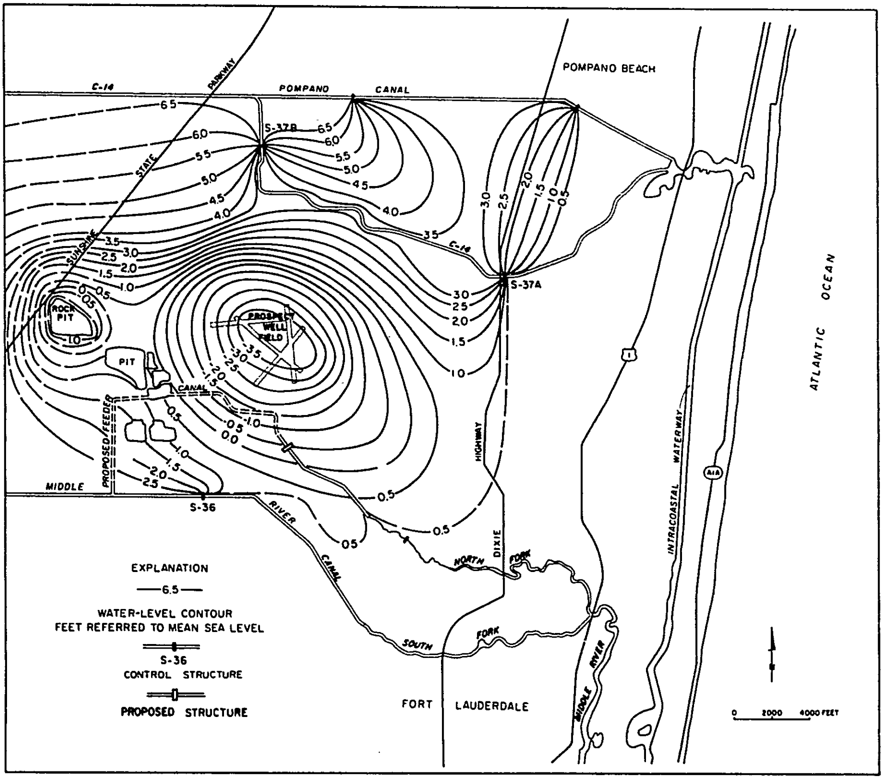

Figure 43. **Map of the Oakland Park area of Broward County showing water-level conditions in the Prospect well field April 18, 1968 (map prepared by H. J. McCoy). The Pumpage from the Prospect well field was 30 mgd and the western rock pit was 5 mgd**

The Prospect well field has had a history of sea-water intrusion (Sherwood and Grantham, 1966) in its southern part; however, structures to combat the intrusion are scheduled for completion in the near future. These structures include a feeder canal (fig. 43), which will connect with the Middle River Canal upstream from the control structure (Sherwood and Klein, 1963, fig. 4). The purpose of the connection is to increase replenishment to the well field, and, because the feeder canal will be controlled at a point seaward of the well field, water levels in the area formerly intruded by sea water will be raised, thereby retarding further inland movement of salt water.

Other municipal well fields of large capacities are shown in figure

37. The map indicates the pumping rate of each of the well fields in November 1970 and shows the position of each field in relation to the inland extent of water containing 1,000 mg/l (milligrams per liter) chloride near the base of the Biscayne aquifer. In addition, other smaller municipal well fields and many supplies for individual housing developments, not shown in figure 37, are scattered throughout the lower east coast.

The capability of maintaining high water levels along the eastern perimeter of the Lake Worth Drainage District in eastern Palm Beach County (fig. 46 for location) during dry seasons through water-control practices, insures that a dependable source of replenishment will be available to the shallow aquifers along the urban coastal area and that ground-water levels sufficient to retard sea-water intrusion can be maintained. Municipal well fields along the 30-mile coastal strip from Boca Raton northward to West Palm Beach, therefore, have a built-in system of ground-water replenishment, whereby the water-control practices that benefit agriculture in the inland area offer concurrent benefits to the expanding urban areas. So long as water-management practices in the area remain effective and the quality of the water that replenishes the shallow aquifer remains acceptable, the ground-water supplies should be sufficient for future needs.

A large part of the water released from Conservation Areas 1 and 2 into primary canals in Palm Beach and Broward counties is channeled into equalizer and lateral canals to maintain water levels for irrigation in the Lake Worth Drainage District and other agricultural districts bordering the eastern Everglades. The water-level map in figure 44 (McCoy and Hardee, 1970, fig. 14) shows the effect that maintaining water levels in canals in the southern part of the Lake Worth Drainage District (area west of Canal E-3) has on ground water in the Boca Raton area. On April 12, 1967, near the end of the dry season, the water level in Canal E-3, was about 10 feet above sea level, and water from the canal was seeping eastward under a high gradient. The contours show that the eastward seepage in the southern part of Boca Raton was being discharged into the uncontrolled reach of the Hillsboro Canal and El Rio Canal, whereas the seepage in the northern part of the city was being discharged to the controlled reach of El Rio Canal (above the control structure), and part of that seepage was being diverted toward the pumping wells in the well field.

The rate of eastward seepage from Canal E-3 depends in part upon the permeability of the shallow water-bearing materials. The quantity of seepage can be estimated by the equation: $Q=TIL$, where Q is the quantity of seepage, in gallons per day, T is the transmissivity of the aquifer, in gallons per day per foot, I is the hydraulic gradient,

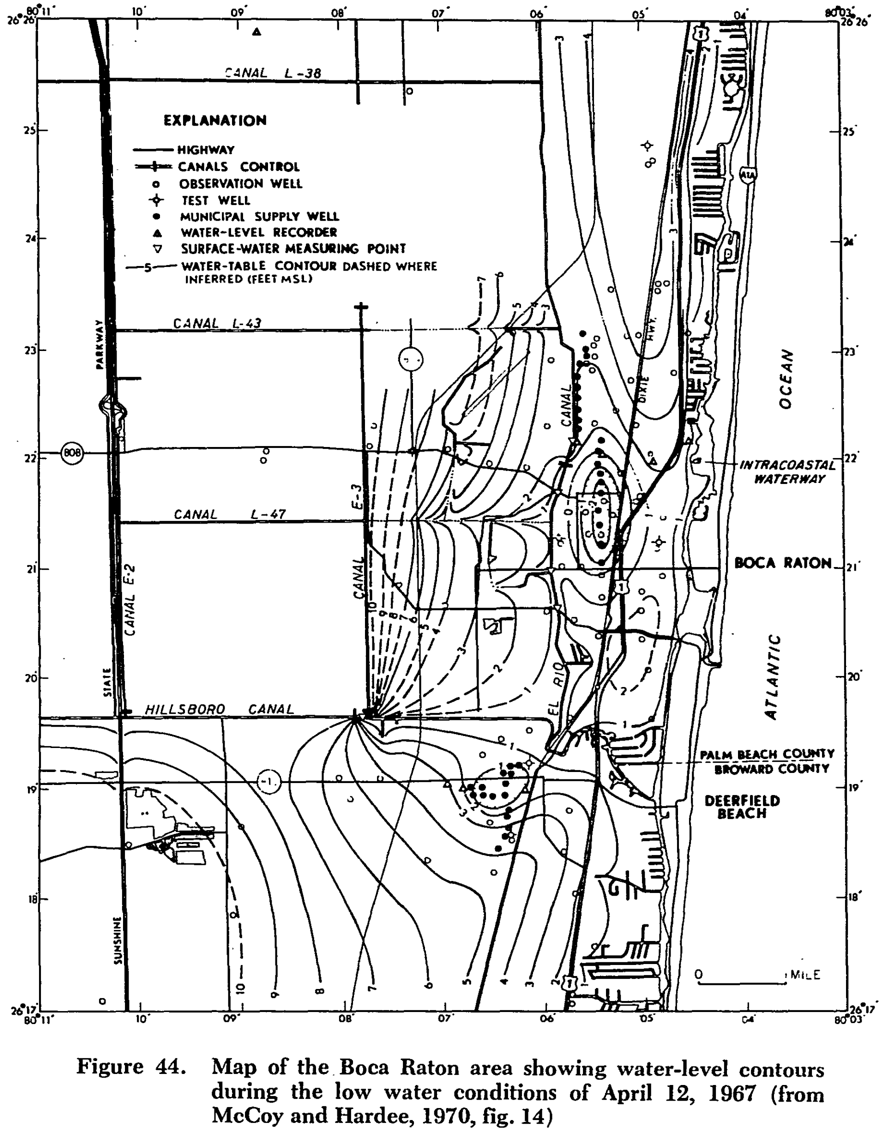

Figure 44. Map of the Boca Raton area showing water-level contours during the low water conditions of April 12, 1967 (from McCoy and Hardee, 1970, fig. 14)

in feet per foot, and L is the length of the flow section in feet. McCoy and Hardee, (1969, p. 25) determined that the transmissivity of the shallow aquifer west of Boca Raton is about 380,000 gpd/ft. Substituting that value in the equation and inserting the water-table gradient that prevailed east of Canal E-3 on April 12, 1967 (7 feet in 11,000 feet) it was determined that the rate of eastward underflow along the 5-mile section between Canal L-38 and Canal L-47 was 6.4 mgd near the end of the dry season of 1967.

Schroeder and others (1954, p. 11-14) determined that the transmissivity of the shallow aquifer in Delray Beach to the north is appreciably less than in the area of Boca Raton, indicating that the ability of the shallow aquifer to transmit water decreases northward from Boca Raton. Therefore, eastward seepage from the Lake Worth Drainage District probably is proportionately less in the north than it is in the south, and the yield of wells is smaller in the north.

The annual quantity of fresh water discharged to tidewater by the West Palm Beach Canal represents excess water within the drainage basin under management operations. Figure 45 graphically relates between the average discharge to the ocean of the West Palm Beach Canal and the average rainfall measured at Loxahatchee and the West Palm Beach Airport. The discharge ranged from about 220 cfs in 1956 to more than 1500 cfs in 1947 and 1948. It is apparent from the graph of the discharge, that a reduction of total flow to the ocean occurred after 1955, when Pumping Station 5A began operation. The graph also shows that the increment of flow brought in by agricultural and drainage canals and by ground-water inseepage along the 20-mile reach east of the pumping station constitutes a significant part of the total canal flow.

Even during years of deficient rainfall, such as 1955-56 and 1961-63, some discharge to the ocean took place. The discharge from the West Palm Beach Canal also represents a part of the fresh-water potential of the basin and is the quantity of water that can be used for municipal and other purposes without causing further decrease of fresh water in storage under present conditions. As water requirements increase with time, water-management practices will be directed toward incremental decreases in discharge of the West Palm Beach Canal and the probable increase in utilization of Lake Okeechobee and Conservation Area 1 for water storage and delay of runoff by backpumping.

THE COURSE AND COMPROMISES OF FUTURE WATER DEVELOPMENT

Earlier parts of this report describe the sequence and nature of past water-development works and how each has altered the manner in which water occurs, moves, is stored and released, is lost to the atmosphere, is utilized by man, and is disposed. Increasing water requirements will require new works and further changes in hydrologic patterns. As with existing canals, control works, levees, pumps, well fields, treatment plants, and pipe lines, each new facility will be designed to improve land use and (or) make greater quantities of water of adequate quality available in certain areas during drought. Many of the new facilities, in addition, will be placed or designed with a new purpose: that of protecting or enhancing the environment.

The design and location of many of the new facilities will be difficult. Greater water storage for dry periods often is accomplished only at some sacrifice to land use. During extreme drought the competition for water among localities will be more severe. Public demands for environmental protection will require allocation of water to sustain the ecology in specified areas. New works interspersed with the older will certainly add to the complexity of water management.

Successful location, design, and operation of facilities also will require greater knowledge of the water system on which it is imposed and will alter it to varying degrees. Hydrologic knowledge gained in one water system may be utilized beneficially in considering further works affecting another system.

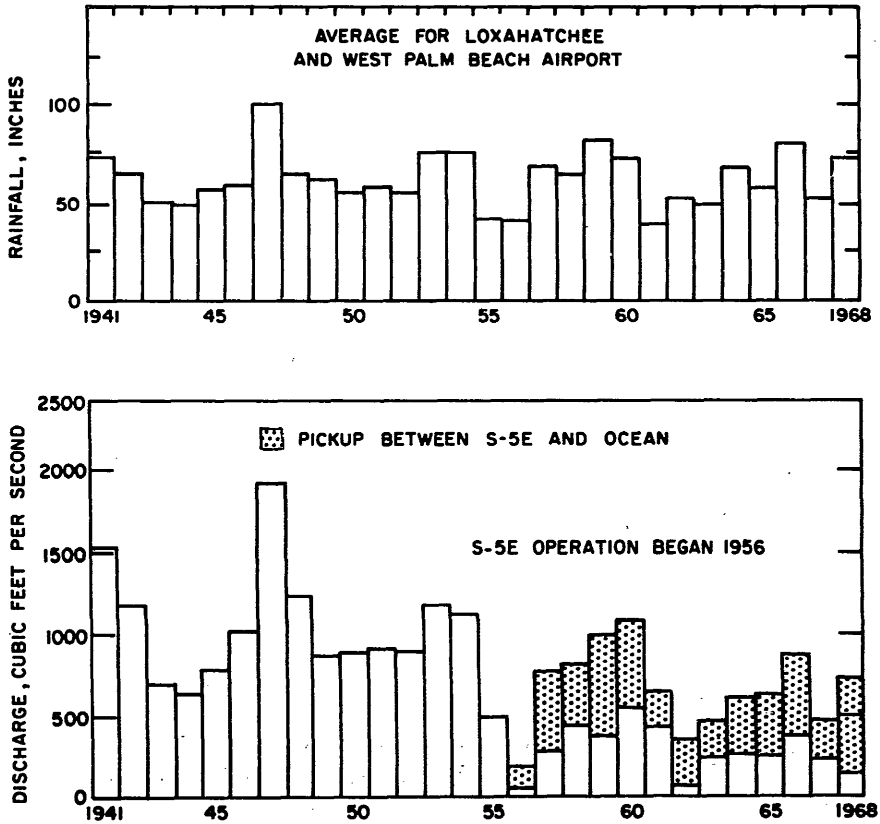

Figure 45. Graphs relating rainfall to the discharge of the West Palm Beach Canal to the ocean, 1941-69. Also shown is the pickup of flow in the canal reach below S-5E from 1956

The primary purpose of this chapter is to relate previous experience with the hydrologic characteristics of water systems in south Florida to some of the alternatives for further water-development works. No recommendations are made by the authors for or against specific development works. Their only contribution is to report upon the hydrology of the present system and to predict the changes that may result from various types and locations of new works under consideration.

Certain segments or features of actual development plans or proposals for water-development works in particular locations have been selected to illustrate the probable impact of specific works on water systems.

DEVELOPMENTAL PLANS

Several plans of improvement for drainage and enhancement of the water resource through careful management have been proposed from time to time.

IMPLEMENTATION OF AREA B AND EAST COAST BACKPUMPING PLANS

The plan by the Corps of Engineers (1958) for development of Area B, the area east of the levee system in northern Dade and southern Broward Counties (fig. 46), is basically a flood-control plan. Nonetheless, the plan for Area B ". . . will have considerable potential for conservation of fresh water," (Kohout and Hartwell, 1967, p. 59). Backpumping to the conservation areas — a part of the plan — would reduce canal discharge to the ocean. Some hydrologic effects of backpumping, disregarding the quality of the backpumped water, would be as follows: (1) reduction in amount and duration of wet-period discharge to the ocean; (2) lowering of peak levels and an equalization of water levels east of the levee system; (3) reduction of total runoff to the ocean; (4) delay in water-level recession in the conservation areas; (5) early closing of coastal control structures; (6) ability to maintain proper water levels at coastal structures for longer periods to retard sea-water intrusion; and (7) utilization of the aquifer system as a water-storage reservoir. Kohout and Hartwell (1967 p. 42) suggested the use of supplemental pumps (100-400 cfs capacity) at the west and east sides of Area B and control structures in canals at the east side of Area B for flexibility of water control during periods of intermediate water-level conditions. They further suggested that when Conservation Area 3 is dry, the east-side pumps would help maintain levels along the urban coast by pumping seaward from the Area B canals.

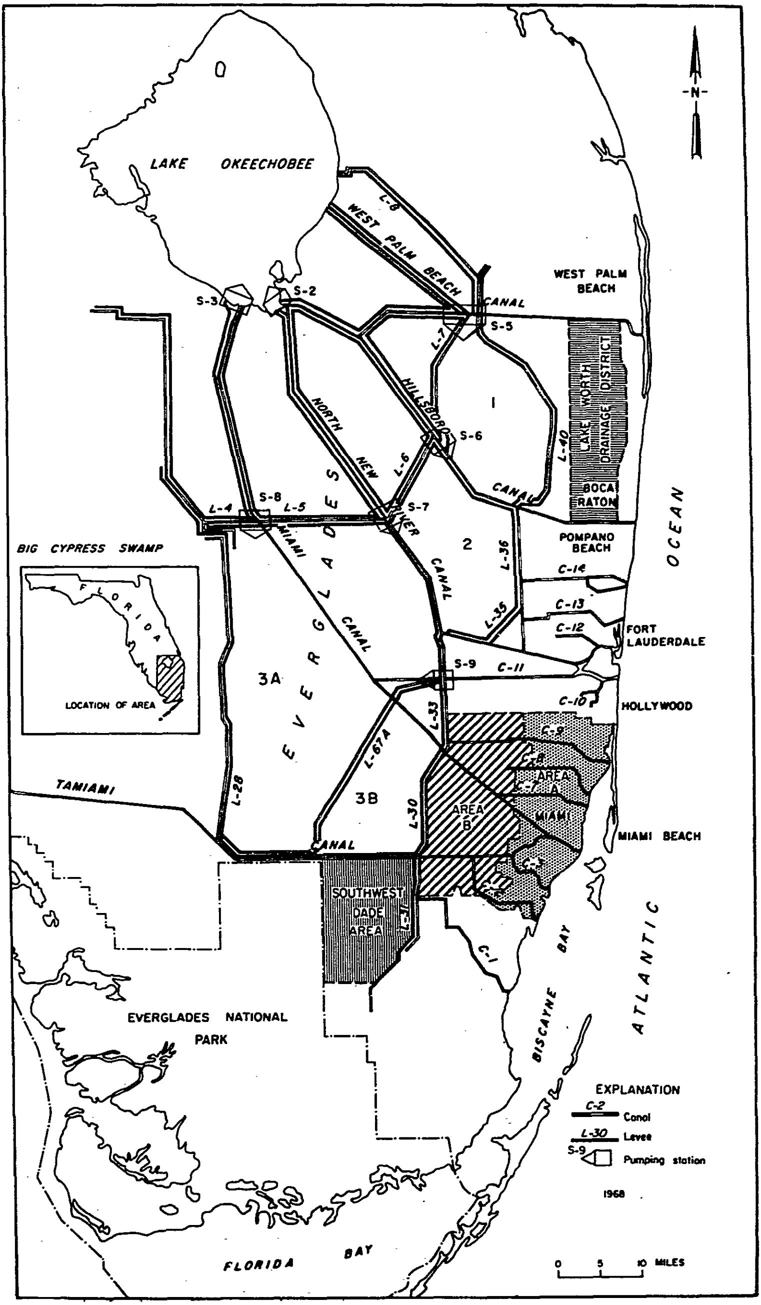

Figure 46. Map of southeastern Florida showing locations of the Area A, Area B, and southwest Dade area in relation to the Central and Southern Florida Flood Control District works

During prolonged drought after urbanization is completed, it may be necessary to pump water from aquifer storage west of the levee system into the Area B canals to furnish water to the coastal area. Possibly, pumping from aquifer storage west of Levee 30 could replace pumping from the east end of the Area B canals. The capacity of the pumps would be adequate to sustain proper water levels at the coastal control structures, most importantly the structures in the Snake Creek, Miami, and the Snapper Creek canals. The quantities would be equivalent to the normal losses by seepage around each structure along the controlled easterly reach of each of these canals, about 40-50 cfs per canal, plus the quantities diverted from the canals by well field withdrawals.

CONVEYANCE CANALS TO SOUTH DADE COUNTY

An area of perennial water deficiency is the south Dade County area, where water levels approach or decline below sea level by the end

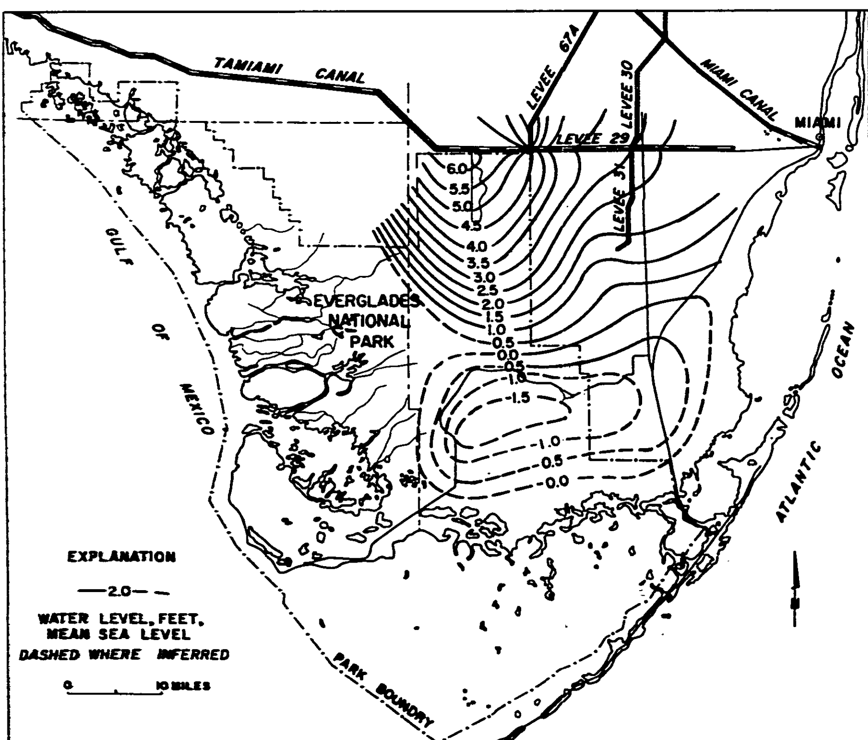

Figure 47. **Map of the southern tip of Florida showing contours of water-level conditions in May 1962, a near record low-water condition**

of each dry season, as shown in figure 47. The south Dade area is probably the most water deficient area in dry periods because it is at the southern tip of the hydrologic system and is the most difficult area to replenish. The plan proposed by the Corps of Engineers (1968) to replenish south Dade County by means of conveyance canals connected to Conservation Area 3 would, if effected, reduce the rate of water-level recession. Any water that can be shunted southward during prolonged drought will slow, or possibly stop, the recession in water levels, even though evapotranspiration will increase. Hartwell and others (1963) estimated that in May 1962, a near-record low-water period, evapotranspiration within a 275-square-mile area of low water levels in south Dade County was about 790 cfs (1,580 acre-feet per day).

The Corps of Engineers has indicated that a total of 1,400 cfs (2,800 acre-feet per day) might be available for dry-season distribution to the south Dade area and the Everglades National Park and to the eastern part of Dade County.

Replenishment from Conservation Area 3 through conveyance canals to the south would be needed only during dry periods. Part of the replenishment at other times might be lost to the ocean through automatic operation of coastal control structures in the south Dade canals. One proposed conveyance-canal route is southward along the eastern boundary of the Everglades National Park and then eastward to the Levee 31 Canal, where water would be distributed northward, eastward, and southward. (See fig. 1.) An alternate route might be directly southward through the Levee 31 Canal, a part being diverted eastward and part southward.

Water carried southward through the Levee 31 Canal would be delivered directly to critical areas — the coast of south Dade County and the southern panhandle of the National Park. Because of the long distance involved in moving water from the north end of Levee 31 Canal to the panhandle area, pumping facilities may be required to assure replenishment to the southern terminus of the canal system. Replenishment to the southern terminus also would raise water levels in the U.S. Navy's Key West well field near Florida City. (See fig. 37 for location.)

Recharging the aquifer in south Dade appears to be of high priority. Therefore, early investigations may be warranted to determine the effect that releases of water into the Levee 31 Canal might have on canal levels and on ground-water levels to the south and southeast. If results show that levels can be maintained in south Dade, consideration could be given to utilizing the method each year until the subsequent rainy season begins. Included also might be the possibility of ground-water pumping from Conservation Area 3B to Levee 31 canal when low-water conditions in the South are prolonged.

SOUTHWEST DADE PLAN OF IMPROVEMENT

The southwest Dade plan of improvement (Corps of Engineers, 1963) proposes to pump water at 15 inches per month from the area between Levee 31 and the eastern boundary of Everglades National Park. (See fig. 46.) As a result of the pumping, water levels would be lowered below the land surface far enough to permit preparation of fields for farming by early November of each year. Under present conditions most of that area normally remains inundated or swampy through December.

Hull and Galliher (1970, fig. 8) showed that, even during low-water conditions, water levels in the northern part of the southwest Dade area are 4-6 feet above msl; and, therefore, that this area serves as the source of part of the water replenishment for southeastern and southern Dade County. Because the plan is designed to lower peak water levels in the southwest Dade area, the lowering also would affect levels in areas downgradient, to the east and the south.

Actually the improvement plan would accelerate runoff from the southwest Dade area, in turn accelerating recession of water levels in adjacent areas. Implementation of the completed south Dade flood-control plan has already lowered peak levels in the lower east coastal and southern parts of the county. Any additional lowering occasioned by implementing the improvement plan would then be superimposed on the previous lowering, thus facilitating the possibility of salt-water encroachment.

Because the Southwest Dade plan is designed specifically to enhance agriculture, fertilizers and pesticides will be involved. Through years of operation, pesticides could build up in the soils. As the plan calls for pumping the excess water westward into the Everglades National Park, the Park officials may choose to reject the excess water if it proved to be detrimental to wildlife. No other outlet for the excess water is provided for in the plan. On the other hand, if the pesticide content of the water proved to be harmless to wildlife, the Park officials might accept the excess water as part of the annual release from the water-conservation system. Then part of the water from the conservation areas normally earmarked for discharge to the Park could be retained in the Conservation Area 3 for later use.

Land-use studies in southeastern Florida have shown that much land made suitable for agriculture through improved drainage has been later converted to urban use. If this were to happen in Southwest Dade, year-round flood protection, of course, would be required. The hydrologic effects of such urbanization would be an accelerated lowering of levels to the east and south and an increase in seepage through and under the levees southward from Conservation Area 3. A pre-urbanization alternative to improved drainage would be filling the land to higher elevations and installing related secondary and tertiary control structures in canals to delay runoff.

LOWER EAST COAST AGRICULTURAL AREAS

The Central and Southern Florida Flood Control District is committed to provide flood protection to the agricultural lands along the lower east coast of Dade County, where the land surface is generally at an altitude below 3 feet. Ground-water levels there must be maintained below the land surface to prevent crop damage during the growing season, which starts in October. The optimum canal level at the coastal structures in canals 1, 102, and 103 is 1.4 feet above msl during the growing season. In order to maintain that level during the early part of the growing season, when water levels are usually high, the automatic gates in the structures open and close repeatedly, depending upon the rate of ground-water flow to the lower reaches. The operations for flood and salinity control, which are necessary along the coast, constitute a drain on the water resources of the interior, and the repeated operations are decreased in frequency as water levels in the interior decline.

Continued growth in population suggests that agriculture along the lower east coast may be gradually phased out in favor of urban use of land. To accommodate urban expansion, the lower east coast properties would have to be raised to elevations adequate for protection against tidal inundations. At that time, the optimum water levels at the coastal control structures could be raised to levels corresponding to those in canals in urban areas to the north, 2.5 to 3 feet above msl. The controls would be used to remove flood peaks, but they could be closed earlier and kept closed during the entire dry season. As a result, much of the water presently being lost during the early months of the dry season could be retained in the Biscayne aquifer.

Raising ground-water levels behind control structures along the coast will result in a decrease in water-table gradient within the controlled sections of the Biscayne aquifer. In turn, this will moderate the lowering of levels in the interior and thus reduce seepage southward and southeastward from Conservation Area 3. An increase in levels along the coast also could result in a seaward movement of the salt front in the aquifer.

With the demands for water increasing at unprecedented rates, strict water management will be necessary to protect the water resource. In the particular area of coastal Dade County, agriculture does not seem to be hydrologically compatible with urban development. In other agricultural areas, for example the Lake Worth Drainage District and adjacent agricultural districts in Palm Beach and Broward Counties, water control is beneficial because it insures that water levels will be maintained at high levels, thereby furnishing constant replenishment to the urban coastal strip.

ALTERNATIVES FOR FURTHER WATER DEVELOPMENT

Analysis of the hydrologic effects of water-develoment plans and operation of the water-management system indicates that management and control might be improved in the future. Accomplishing the improvements involves operations, proposed plans for development works, and long-range goals.

Experience in the operation of works shows that the levees and the system of primary and secondary canals can adequately protect most urban areas from flooding. As indicated previously, however, a few areas in northern Broward and Palm Beach Counties are subject to inundation locally during sustained heavy rainfall because of the low permeability of the shallow sediments.

A major objective of water-resources planning agencies is to conserve water resources, primarily by reducing or delaying runoff to the ocean. Gradual reduction of canal discharge to the ocean is feasible and can be accomplished in some places (1) by adjustments in timing of control-structure operations, (2) by adding secondary control structures—a feature that would also reduce the depth of water and the time it remains in canals locally, (3) by raising optimum water-control elevations in selected canals, and (4) by implementing plans for back-pumping excess water into conservation areas. Net usable supplies may also be increased by raising design levels in the surface reservoirs, such as Lake Okeechobee and the conservation areas, without increasing evapotranspiration.

REDUCTION OF LOSSES TO THE OCEAN

As urbanization continues, increased water requirements can be met in part with water salvaged by reducing canal discharge to the ocean, either by earlier control closings or by fewer releases of water to the ocean. Whether such changes in control operations are possible can be determined by monitoring and analysis of the results of the operations and by review of past operations. Adjustments can then be made in operations for optimum results.

The most vulnerable area in southeastern Florida during drought is southern Dade County, because it is remote from any major surface source of fresh-water replenishment. Therefore, careful water-management practices will be required there to assure ample water for all users during drought. A second vulnerable area is northern Dade County, particularly the Miami Canal area, where sufficient water must be retained to replenish the Miami well field and to maintain canal levels to prevent encroachment of sea water into the Biscayne aquifer. Any method that would delay the runoff from those two areas, such as raising the optimum water levels at coastal and secondary control structures in major canals at or before the end of the rainy season would increase the water resource.

Increased flexibility in controlling runoff would, on a long-term basis, reduce losses to the ocean and, hence, will probably become a part of overall water-management plans. Flexibility can be gained in several ways. A few ways that might be applicable, depending on location, are as follows:

(1) Installation of additional secondary control structures: Such structures might, to advantage, be placed on Snake Creek Canal, Miami Canal, Snapper Canal, or Bird Road Canal. Of these, Snake Creek (C-9) and Miami Canals (C-6) are equipped only with coastal salinity control structures, so that the base level of their inland reaches is the same as the coastal control; under these conditions, steep groundwater gradients inland induce large water pickup to canals, causing water to move eastward to the coastal salinity control structures. Stepped-up levels by use of secondary structures in both canals to raise water levels in inland reaches would reduce hydraulic gradients to canals in inland reaches. This reduction would delay runoff from upstream reaches and would retain significant quantities of water in upbasin storage, over and above quantities stored in canals and the aquifer upgradient from the single structures at the coast. The quantities salvaged would be the water retained in the aquifer resulting from the higher level maintained behind the secondary control structures plus the water contributed from Conservation Area 3B and vicinity to the canal discharge that is lost in urban flood protection under current operating conditions.

If secondary structures were to be placed on the two canals they might be located—from a water-conservation standpoint—9 to 11 miles downstream from Levee 33 in the Snake Creek Canal and 7 to 8 miles downstream from the levee system in the Miami Canal. Those locations may not be feasible physically, however, because of low land elevations in parts of the canal reaches upgradient from these suggested sites. By installation of the secondary control structure in the Miami Canal, water could be released as needed to replenish the Miami well field and to maintain adequate levels in the canal at the 36th Street control structure.

If a secondary control structure were to be constructed in the Snapper Creek Canal, say, downstream from its confluence with the Bird Road Canal (2 miles south of the Tamiami Canal), or in the Bird Road Canal near its outlet, runoff from the interior part of the basin would be delayed. Adjustments in control operations would permit releases to replenish the Alexander Orr and Southwest well fields of Miami and to maintain levels at the salinity-control structure near the coast. These suggested controls should be effective because the Bird Road Canal and its connections with the Tamiami Canal at 132nd Avenue and 157th Avenue contribute a large percentage of the flow in the Snapper Creek Canal during the dry season.

(2) Installation of tertiary controls. For example, if the Black Creek Canal (Canal 1) could be regulated near its confluence with the Levee 31 Canal, seepage into the northern reach of the Levee 31 Canal would be reduced. Simultaneous with this, the reduced contribution to the downstream reaches of the Black Creek Canal would result in fewer operations of the automatic coastal structure (S-21) during dry seasons.

(3) If a decision is made to construct a boat lock in the Miami River downstream from the existing N.W. 36th street structure protective procedures could be devised to prevent excessive loss of water from boat locks and to retard sea-water intrusion. Boggess (1970, fig. 7) sampled water containing 250 mg/l chloride at the bottom of the Caloosahatchee River channel about 11 miles upstream from boat lock S-79 near Fort Myers at the end of the dry season of 1968. The source of chloride was slugs of salty water from the tidal reach of the river that moved upstream as a result of lockages.

Under conditions of inland low water and frequent boat lockages, slugs of salt water could migrate upstream in the Miami Canal into the area of influence of the Miami well field. Because the well field depends heavily upon the Miami Canal for its replenishment, salt water in the canal upstream from the 36th Street structure for an extended period of time could be extremely damaging.

On the Tamiami Canal, where a boat lock is scheduled for construction near its confluence with the Miami Canal, protective devices and careful scheduling of lockages should assist in suppressing sea-water intrusion. The main purpose of the lock on Tamiami Canal would be to reduce the threat of salt-water intrusion on the south flank of the Miami well field by retaining more fresh water in that part of the Tamiami Canal basin than is being retained currently. That reach of the canal through the basin has been uncontrolled in the past, and at times salt water has moved inland to the downstream side of the control structure at N.W. 67th Avenue. The effect of this lock, as far as prevention of sea-water intrusion is concerned, would be negated if it is not operated carefully. If restrictions on lockages cannot be imposed, the control near 67th Avenue would need to be retained. If the control at 67th Avenue is abandoned and replaced by the downstream lock and no lockage restrictions are imposed, water could be diverted southward from the Miami Canal basin. Water levels in the vicinity of Miami's municipal well field, thus, could decline excessively.

(4) Canal discharge to the ocean could be reduced by decreasing the number of automatic operations of coastal control structures. At the beginning of the growing season, October or early November, particularly in the low coastal agricultural areas of south Dade County, some discharge is necessary to keep water levels low enough to prepare fields and to prevent crop damage by flooding. Water-level data indicate that discharge may continue for several weeks into the dry season. For example, continuous data collected in 1968 at coastal control structure S-21 in Canal 1 show that the control was opened several times each day during January 1 through mid-April, the dry season. The openings were in response to the pickup of ground water from the interior part of the Canal 1 basin. A large contribution of discharge to the coastal reach in Canal 1 is the result of seepage around the secondary control structure near U.S. Highway 1.

Decreasing the number of automatic operations would be easier if seepage could be decreased. One way in which seepage could be decreased would be to install an impermeable liner along the canal upstream from the structure or possibly a grout curtain flanking the structure.

Water-level contours prepared by Flood Control District personnel show that the bulk of the seepage occurs within 200-300 feet upstream from the structure. Hence, an impermeable canal liner or grout curtain there would lengthen the flow lines in the vicinity of the structure, thereby decreasing the gradient. The resulting decrease in the number of automatic operations at the coastal control structure would delay the recession of water levels in the basin.

Consideration also might be given to impermeable canal liners upstream from other secondary control structures. The resulting water levels in the upper reach would approximate those before canal construction, but the peak levels would be reduced by operation of the structures.

(5) Lowering ground-water levels unduly could be avoided to minimize further loss. In past years, lowering water levels adjacent to

the west edge of the coastal ridge has given strong impetus to the inland expansion of urbanization. Adequate drainage made it possible to build on areas of low altitude, thereby lowering the cost of preparing the land for housing. Were it not for the effective drainage by the canal systems and water diverted from the urban areas by the levees, much of the area immediately west of the coastal ridge would have required filling to raise land elevations which would have added to the cost of the housing units. However, once the drainage system is in operation, the houses built, and a residence environment established, floods, of course, must be prevented. A result of urban expansion was the lowering of water levels along the ridge and the east edge of the Everglades. It is to be expected that as expansion continues, pressure will be exerted to continue with this pattern of drainage and water-level lowering. To minimize further loss of water, particularly in inland areas where water levels are normally high, minimum allowable land-surface altitudes could be established at the highest levels practicable, perhaps in combination with raising the altitude of the land by filling and back-pumping excess water to conservation-area storage.

Locally, where land altitude is low, as in the Miami, the Little River and the Biscayne Canal basins and parts of southern Broward County, the rainy seasons are chronically troublesome because these areas are prone to flooding. As some of the houses in those low areas were built before the establishment of minimum elevation standards, below which construction is not considered advisable, the control structures must be operated in such a way that these older houses are protected. Water levels in much of the basin areas, thus, are lower than they need be, consistent with effective management practice.

MAINTAINING WATER QUALITY

Two major problems of water quality confront the water-management agencies of southeastern Florida. One problem, long standing contamination resulting from sea-water intrusion, will continue to threaten water resources as water needs increase. The protection of all well fields from sea-water intrusion is essential. The other problem, pollution, is emerging and may become a great threat as urbanization continues, with its concurrent demand for water and waste-water systems.

Fort Lauderdale plans to increase withdrawals from its Prospect well field between the Pompano Canal and the Middle River Canal. This well field's history of sea-water intrusion is well known (Sherwood, 1959, p. 26). Because of intrusion, any further expansion would be safer in the southern part of the well field, in the vicinity of the Middle River Canal and west of the salinity-control structure, S-36. There, the upper part of the aquifer is permeable, facilitating artificial recharge from the canal by infiltration of fresh water when the wells are pumped. By developing this part of the field, drawdown would be minimized as a result of infiltration from the canal, and the possibility of further sea-water intrusion would be reduced. Sufficient water for induced recharge to the well field from the Middle River Canal would probably be available were the canal to be extended into Conservation Area 2. By so extending the canal to Area 2, not only would a supplemental supply from Conservation Area 2 be available, but the canal would tap, and partly drain, shallow ground-water bodies in the intervening reach.

The capacity of Fort Lauderdale's Dixie well field between the North New River Canal and the Plantation Canal (C-12), is small. Because of its proximity to the uncontrolled salt-water reach of the North New River Canal, heavy pumping of the field would lower water levels between the well field and the canal during the dry season and would induce recharge of salt water. Extension of a connector canal from the controlled reach of the Middle River Canal to the Plantation Canal would raise the stage in both canals and, as a result, would raise groundwater levels in the northern part of the Dixie well field. The freshwater recharge would permit greater withdrawal of water.

The southern part of the Dixie well field, however, will continue to be subject to sea-water intrusion from the North New River Canal during extreme drought, and, therefore, increased withdrawals in that part of the field is not likely. Grantham and Sherwood (1968, fig. 15) show that the chloride content of water in the North New River Canal increases markedly below the salinity-control structure (Sewell Lock) when discharge through the structure declines below 50 cfs for several weeks. Because water-management practices in the future will tend to reduce discharge to the ocean, water below the structure for long periods would have high chloride content. This would increase the threat of intrusion of salt water into the shallow aquifer underlying the southern part of the well field. A control structure placed in the canal downstream from the area of influence of the well field might, however, tend to alleviate the threat.

The problem of sea-water intrusion in the Hollywood Canal basin (C-10) in southern Broward County will intensify as the area continues to be drained and pumping increases from the Hollywood municipal well field. Municipal wells in the Dania well field in the vicinity of the canal have begun to show salt-water contamination from the canal, and plans are underway to move the field farther from the canal. Saltwater contamination also may threaten the Hollywood well field adjacent to the Hollywood Canal, about 3 miles upstream from its confluence with Canal 11. Drainage by the Hollywood Canal is uncontrolled, water levels are perennially low, and, thus, the possibility of salt-water intrusion would be enhanced by major increases in withdrawals from Dania and Hollywood municipal well fields.

The western spur of the Hollywood Canal is being extended inland to improve local drainage for additional housing. The spur is to be controlled, but the structure will prevent only the westward movement of salt water in the channel. Because the spur canal will be dead-ended and will have no perennial source of replenishment, a head of fresh water cannot be maintained on the upstream side of the control structure during the dry season to prevent salt-water intrusion into the aquifer. A connection between the upstream end of the spur canal with one of the primary canals, possibly the Snake Creek Canal, would furnish a source of replenishment to the controlled reach of the spur, thereby raising and maintaining a higher water level in the area. A secondary control structure may be required along the connecting canal. General resultant benefits would be stabilizing of the salt front in the aquifer and raising average water levels in the Hollywood well field, where withdrawals are steadily increasing.

A rapidly developing problem in the urbanizing areas and probably the most critical problem to be faced in the future is the disposal of sewage, storm runoff, and other wastes. Agencies involved in waste disposal and pollution control seem oriented at the present time toward discharge of treated wastes to ocean outfalls, but, as discharge to the ocean involves the outflow of the resource from the area of potential use, the orientation may change in the future.

If anticipated large future water demands (table 3) are to be satisfied, it may become necessary to retain increasing quantities of storm runoff and properly treated sewage instead of discharging them to the ocean.

At the end of 1968 nearly 400 million gallons per month of partly treated effluent was being discharged into the controlled reaches of four major canals in Dade County. The effluent represents recharge to the system because it not only enters the aquifer for reuse but helps in maintaining water levels at the coastal control structures, thereby aiding the control of sea-water intrusion into the aquifer. In the future, the effluent will be treated to meet water quality standards for potable water supplies, particularly during dry seasons, because then canals do not discharge to the ocean, and controlled reaches of major canals are the source of recharge to municipal well fields and other water supplies along the coastal ridge.

Before sewer systems are installed in areas presently served by septic tanks, the impact of this alternative on the total available fresh-water supply should be evaluated. The largest concentration of septic tanks in southeast Florida is in Dade County, where large areas have been served by septic tanks for years. Suburban developments in Broward and Palm Beach Counties have, of necessity, relied chiefly upon treatment plants rather than septic tanks because in many areas water levels were near the land surface, and the permeability of the shallow sediments is lower than in Dade County.

Other potential pollutants to the water resource are mainly related to application of fertilizers and pesticides for agricultural activities and sanitary landfills. The urban lower east coast differs from many urban areas in that it comprises scattered centers of populations, and there are few massive paved areas to restrict infiltration of rainfall to the aquifer. Residents take pride in the appearance of their homes, and each home has a well-kept lawn and shrubbery requiring continuous maintenance. So the city dweller regularly uses fertilizers and pesticides and irrigates at regular intervals. A variety of fertilizers and pesticides, therefore, may infiltrate to the aquifer. Water in many of the canals and the water-storage areas represents, in part, drainage from agricultural lands, including pastures and dairies. The drainage water probably contains organisms and dissolved chemicals derived from the agricultural operations, and the situation is unevaluated but potentially hazardous.

Pesticide and nutrient buildups, generally in nontoxic concentrations, are beginning to appear in some of the canal water, surface-water bodies, and bottom sediments in Palm Beach and Broward Counties and in the Everglades National Park. Fortunately, excessive buildup seems to be minimized by the annual flushing each rainy season. With implementation of water-conservation plans and reduction of discharge through canals to the ocean, however, further buildup could be expected in the controlled canal reaches and in the major water-storage areas.

Of special interest would be the canals, streams, or lakes from which a few of the municipalities obtain water supplies, such as West Palm Beach from Clear Lake, immediately inland from the city, and Ft. Myers (on the Gulf Coast) from the controlled reach of the Caloosahatchee River. Each source has a potential problem of pesticides, nutrients, and buildup of dissolved minerals. Urbanization is expanding inland from West Palm Beach and soon could envelop Clear Lake unless zoning laws prevent it. If residences were to surround the lake, runoff water could carry undesirable amounts of nutrients into the lake. Although there is some mixing of water within the lake, relative stagnation would be expected during prolonged drought, and pollutants may accumulate to excess periodically. Monitoring hazardous water constituents not only in urban areas but also in major canals that traverse agricultural areas and urban areas and which contribute water to well fields could serve as an early-warning system.

Contaminants leached from sanitary landfills pose a lesser problem to potable water supplies at the present time than pesticides and nutrients because the landfills are small, widely scattered, and are generally some distance from well fields. No information is available concerning the occurrence of pollutants in the Biscayne aquifer caused by leaching of landfills, but the variety of materials deposited in landfills is great and represents a potential hazard.

SUMMARY

During the early years of development in southeastern Florida, emphasis was placed on drainage and flood-control works to accommodate rapid urbanization and also agriculture. The installation and operation of these works to prevent flooding lowered water levels in large areas by facilitating the rapid removal of water from inland areas. By 1962, most of the major works of a complex system of canals, levees, pump stations, control structures, and water-conservation areas was completed. As a result, large quantities of water were discharged through canals to the ocean. The severe drought of 1961-65, together with increasing water demands and a renewed threat of sea-water intrusion, shifted the emphasis to curtailment of canal discharge to the ocean and increased management of water resources.

The hydrology of southeastern Florida was affected significantly before 1945, when land drainage and reclamation was a principal objective. The prime effect was a lowering of water levels along the coastal ridge and in the interior as a result of: (1) completion of several coastal drainage canals along the urbanizing coastal ridge to provide dry land for housing developments; (2) completion of the West Palm Beach, the Hillsboro, the North New River, and the Miami canals, which intercepted or diverted water from the Everglades to the ocean; (3) construction of the levee on the south shore of Lake Okeechobee, which prevented southward spillage from the lake during the hurricane season.

Adequate hydrologic data for the early 1900's are lacking, but estimates indicate that water levels were lowered generally 5 or 6 feet throughout southeastern Florida as a result of uncontrolled drainage. An adverse hydrologic effect was intrusion of sea water into canals and the shallow Biscayne aquifer along the coast. Sea-water intrusion contaminated Miami's main well field in the Hialeah-Miami Springs area during the drought in 1945.

The initial work of the Central and Southern Florida Flood Control District, established in 1949 after the disastrous flood of 1947, was the construction in 1953 of the levee system along the east edge of the conservation areas, which prevented the eastward flow of flood water from the Everglades. Construction continued on an intermittent basis through 1962. By then, the three water conservation areas were enclosed by levees except the west part of Conservation Area 3. Most major canals were equipped with modern gated control structures, the system of interior pumping stations and spillways was built and became operational, and large agricultural acreage was opened south of Lake Okeechobee.

The period 1946-62 was one of water control as well as flood control. The water-control practices were an attempt to prevent further damage to water resources caused by the earlier uncontrolled drainage. Flood control was of higher priority because urban areas were expanding inland, and drainage systems had to be improved. Control structures were built in all major canals to allow the expeditious discharge of large quantities of water during the rainy season and to retain fresh water in the canals and aquifer upgradient from controls during the dry season. The control structures also effectively halted the intrusion of sea water despite the fact that water use by municipalities and for irrigation increased several fold during 1946-62.

Analysis of data collected during the flood-control and water-control phase (1946-62) shows that hydrologic conditions were more favorable than during the period of land reclamation. Personnel guiding the operations became increasingly cognizant of the different water-condition requirements of the several interests, and operations became more efficient. The increased need for water conservation, particularly the reduction of canal discharge to the ocean, became apparent after the occurrence of regionally low water levels during 1955-56 and 1961-65. The ability of the system to cope with flood problems was demonstrated during the extremly wet years of 1957-60, when no appreciable flooding occurred. The exception was in southern Dade County, where the system was inadequate for Hurricane Donna in 1960. Flood control in south Dade County has since been provided.

The major effects upon the hydrology during 1946-62 were:

(1) A southward diversion of some of the flows that previously had moved eastward through the transverse glades by construction of the east coast levee system.

(2) A marked reduction in discharge to the ocean by the West Palm Beach, the Hillsboro, and the North New River canals. The first reduction occurred in 1953 with the completion of the eastern levee system. The second reduction occurred in 1958, when most of the pumping stations

and spillways in the conservation areas were completed. The total reduction in discharge to the ocean from the three canals was about 294,600 acre-feet per year, or an average salvage of 25 percent of previous total flow to the ocean.

(3) Modification of flow through the Everglades after enclosure of Conservation Areas 1 and 2 and completion of the protective system of levees encircling the agricultural areas southeast of Lake Okeechobee. Establishment of Conservation Areas 1 and 2 and the Everglades agricultural area has modified the natural Everglades drainage basin.

(4) Initially, a large decrease in coastal canal discharge occurred, as compared with pre-1946, as a result of operation of coastal control structures; subsequently, the discharge gradually increased in Dade County and part of Broward County as a result of expanded urbanization and the need to drain land for housing in inland areas. Overall, discharge decreased as compared with the earlier period.

(5) Delay in recession of water levels during the dry season in conservation areas as a result of pumping part of the surplus water salvaged by decreased canal discharge into conservation areas.

(6) Increase in gradient between the conservation areas and areas immediately east of the levee system as a result of lowering peak levels in urban areas. Increased reliance was placed on the conservation areas for replenishment of ground water in urban areas during the dry season.

(7) An increase in the rate of recession of water levels along the coastal ridge and vicinity after the rainy seasons, as a result of improved canal systems and their inland extension to the levees.

(8) Lowering of annual peak water levels for flood protection on the coastal ridge and vicinity, as a result of regulated openings of control structures in the improved canal system, which permitted rapid discharge to the sea.

(9) Raising of annual low water levels along the coast, chiefly in areas adjacent to control structures, as a result of closed control structures and ground-water pickup by canals from inland reaches.

(10) Decrease in water-table gradient throughout the coastal ridge and vicinity.

(11) Stabilization of the salt front in the aquifer, as a result of the rise in minimum water levels along the coast, enabled large increases in municipal withdrawals without further threat of salt-water intrusion.

By the end of 1962, Conservation Area 3 was enclosed on the south side, and, for the first time, flow through most of the Everglades could be regulated. The enclosure marked the beginning of the capability for nearly complete management of the water resources within the flood-control project from Lake Okeechobee southward.

The year 1962 also marked the beginning of a system of controlled canals in south Dade County designed to protect that area from recurrence of floods of the magnitude of those of 1947-48 and 1960. The canal system was nearly completed and operational by the end of 1967. The most pronounced effects of the south Dade canals were the lowering of annual peak water levels and faster water-level recession after storms except in coastal areas. The movement of water from the inland area to the coast through the canals raised levels along the coast and helped prevent seawater intrusion.

Water management since 1962 has been highly effective, and works in progress, particularly those related to water conservation, should increase its effectiveness. Owing to a prolonged period of low rainfall, which began after Hurricane Donna in the fall of 1960, surplus water was not available to manage until 1966, a year of above-normal rainfall. Sufficient water was retained in the flood-control system during the months following that rainy season to permit both major releases to the Everglades National Park throughout the subsequent dry season and maintenance of adequate water levels along the coast. The southeast coast was the only area in Florida that did not have critically low water levels during the nearly rainless winter and spring of 1966-67.

The new canal system in south Dade County was dramatically tested at the beginning of the rainy season of 1968 when flooding was avoided despite more than 32 inches of rain which fell during May and part of June. Heavy flood damage might have resulted without the new canal system.

Water management should become even more effective with the completion of canals capable of moving excess water from Lake Okeechobee through the conservation areas to the south end of the system and to the Everglades National Park. Raising the level of Lake Okeechobee in future years would increase the water supply to provide for more demand. In addition, implementing plans for backpumping of excess water to the conservation areas would further increase the quantity of water available, but not necessarily its quality.

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APPENDIX

Table 7. Control structures in the area of investigation maintained and operated by the Central and Southern Florida Flood Control District.

Structure Number	Date Accepted	Remarks
S-2	2-1-57	Pumping station above the fork in the North New River Canal and Hillsboro Canal and 3 miles north of South Bay, Palm Beach County. The structure has four vertical lift pumps to discharge water into Lake Okeechobee. Also, at the same site is Hurricane Gate Structure No. 4 which at times discharges water either to or from the lake by gravity. Daily water levels and discharge measured by the U.S.G.S. since February 1957.
S-3	10-26-59	Pumping station in the Miami Canal at Lake Okeechobee and 0.4 miles upstream from U.S. Highway 27 in Lake Harbor, Palm Beach County. The structure has three vertical lift pumps, to discharge water from the Miami Canal to Lake Okeechobee. Also at same site is Hurricane Gate Structure No. 3 which at times discharges water to or from the lake by gravity. Daily water levels and discharge measured by the U.S.G.S. since October 1957.
S-5A	5-21-55	Pumping station is in Levee 7 and 6 miles west along U.S. Highway 441 from Loxahatchee, Palm Beach County (see fig. 14 for detail). The structure has 6 horizontal pumps to discharge water from the West Palm Beach Canal to Conservation Area No. 1. Diversion to Conservation Area No. 1 at same site (see S-5A-S). Daily water levels and discharge measured by the U.S.G.S. since October 1957.
S-5A-E	4-15-54	The control structure is in West Palm Beach Canal, 6 miles west along U.S. Highway 441 from Loxahatchee, Palm Beach County. The structure has two vertical lift gated concrete culverts to discharge water down the West Palm Beach Canal from the S-5 complex. Daily water levels and discharge have been measured by the U.S.G.S since October 1957.
S-5A-S	4-15-54	The control structure is in Levee 40 borrow canal, 6 miles west along U.S. Highway 441 from Loxahatchee, Palm Beach County. The structure has two bays with vertical lift gates to discharge water through Levee 7 from the S-5 complex to Conservation Area No. 1. Diversion to Conservation Area at same site (see S-5A). Daily water levels and discharge measured by the U.S.G.S. since October 1957.
S-5A-W	4-15-68	The control structure is in West Palm Beach Canal, 6 miles west along U.S. Highway 441 from Loxahatchee, Palm Beach County. The structure has two vertical lift gated concrete culverts to discharge water downstream in the West Palm Beach Canal by gravity. Also may reverse when the downstream water level is high and the upstream is drawn down by S-5A pumping. Daily water levels and discharge is measured by the U.S.G.S. since October 1957.
S-6	4-25-57	Pumping station in the Hillsboro Canal at junction between levees 6 and 7 and about 23 miles southeast from Belle Glade, Palm Beach County. The structure has three vertical lift pumps to discharge water from the Hillsboro Canal to Conservation Area No. 1. Daily water levels and discharge measured by the U.S.G.S. since October 1957.

Table 7—Continued

Structure Number	Date Accepted	Remarks
S-7	1-15-60	Pumping station in the North New River Canal at junction between levees 5 and 6, on the Broward-Palm Beach County line and on U.S. Highway 27 about 25 miles south, southeast of South Bay, Palm Beach County. The structure has three horizontal pumps to discharge water from North New River Canal to Conservation Area No. 2A. Also, the structure is equipped with a vertical lift gated control which can discharge water in either direction to or from the Conservation Area by gravity. Daily water levels and discharge measured by the C&SFFCD.
S-8	2-9-62	Pumping station in the Miami Canal at junction between levees 4 and 5 and the Broward-Palm Beach County line about 26 miles south of Lake Harbor, Palm Beach County. The structure has four horizontal lift pumps to discharge water from the Miami Canal to Conservation Area No. 3A. The structure is also equipped with a vertical lift gated control that flows into the Conservation Area by gravity, but may reverse if conditions dictate. Daily water levels and discharge measured by the U.S.G.S. since March 1962.
S-9	8-9-57	Pumping station is in the South New River Canal (C-11) at the junction between levees 33 and 37, half a mile west of U.S. Highway 27 and about 13 miles west of Davie, Broward County. The structure has three vertical lift pumps to discharge water from South New River Canal west to Conservation Area No 3A. Daily water level and discharge measured by the U.S.G.S. since October 1957.
S-10-A,B,C	—	Three control structures along Levee 39 between S-6 and S-39 in Palm Beach County. The gated controls discharge water from Conservation Area No. 1 to Conservation Area No. 2A. Water levels and discharge measured by C&SFFCD.
S-11-A,B,C	—	Three control structures in U.S. Highway 27 and along Levee 38 and between S-34 and 26-Mile Bend in Broward County. The structures each have 4 bays with vertical lift gates to control the flow from Conservation Area No 2A. to Conservation Area No. 3A. Water levels and discharge measured by C&SFFCD.
S-12-A,B,C,D	—	Four control structures in Levee 29-U.S. Highway 41 (Tamiami Trail) and located between Levee 67A and 40-Mile Bend, Dade County. The structures each have 6 bays with vertical lift gates to control the discharge from Conservation Area No. 3A to the Everglades National Park. Daily water levels and discharge measured by the U.S.G.S. since October 1963, water levels at S-12-A and S-12-D collected by the Corps of Engineers. Prior records of Tamiami Canal Outlets, Miami to Monroe, Florida, collected by U.S.G.S. since November 1939.
S-12-E	—	The control structure is in Levee 29 and U. S. Highway 41 at junction of Levee 67A west of Miami, Dade County. The structure has four vertical lift gated bays to discharge water from Conservation Area No. 3B to the Everglades National Park. Daily water levels and discharge contained in the discharge station Tamiami Canal Outlets, Levee 30 to Levee 67A, near Miami, Florida. Prior records of Tamiami Canal Outlets, Miami to Monroe, Florida, collected by U.S.G.S. since November 1939.
S-13	11-1-54	Pumping station is in the South New River Canal (C-11) just west of U.S. Highway 441 and 1.5 miles east of Davie, Broward County. The structure has three vertical lift pumps to discharge water downstream in C-11 to the sea. The structure also has an automatic operated vertical lift gated control to discharge water by gravity to the sea. The downstream side of the structure is effected by tide. Daily water levels and discharge measured by the U.S.G.S. since March 1957.

Table 7—Continued

Structure Number	Date Accepted	Remarks
S-13-A	11-15-56	The control structure is in the South New River Canal (C-11) 4.5 miles upstream from S-13. The structure has four vertical lift gated corrugated steel culverts in an earthen structure to control of the flow downstream in C-11. Water levels collected by C&SFFCD.
S-14	1-31-63	The control structure is in Levee 29 and U.S. Highway 41 at 40-Mile Bend, about 40 miles west of Miami, Florida, Dade County. The structure has two vertical lift gated culverts to discharge water from Big Cypress Swamp to the Everglades National Park. Daily water levels and discharge is contained in the discharge station 40-Mile Bend to Monroe by the U.S.G.S. since October 1963 and prior records of Tamiami Canal Outlets, Miami to Monroe, Florida, collected by U.S.G.S. since November 1939.
S-18C	4-15-66	The salinity control structure is in Canal 111 about 10 miles south of Homestead, Dade County. The structure has vertical lift gates to control the flow in C-111.
S-20-G	7-12-66	The control structure is in Levee 31 (east) about 7 miles east of Homestead, Dade County. Discharge is to Biscayne Bay. Downstream side of control is effected by tide.
S-21	12-8-61	The salinity control structure is on Black Creek Canal (C-1) and on Levee 31 (east) and 3½ miles east of Goulds, Dade County. The structure is controlled by automatic vertical lift gates to discharge water from C-1 to Biscayne Bay. Daily upstream water levels collected by the U.S.G.S. since March 1957.
S-22	6-15-56	The control structure is in Snapper Creek Canal (C-2), 2½ miles south of South Miami, Dade County. The structure has two bays controlled by vertical lift gates to discharge water downstream in C-2 to Biscayne Bay. Daily water levels and discharge measured by the U.S.G.S. since February 1959. Prior records of water levels collected by U.S.G.S. at same site.
S-24	10-15-52	The structure is in U. S. Highway 41 east of Levee 30. The structure is a single gated culvert to discharge water from L-30 borrow canal and Tamiami Canal to the south through Highway to the L-31 (north) borrow canal. Twice monthly staff gage readings by the U.S.G.S.
S-24-A	10-15-52	The structure is in Levee 31 (north) 2½ miles south of U. S. Highway 41 and Tamiami Canal. The structure has two culverts controlled by vertical lift gates to discharge water between L-31 (N) borrow canal and the Everglades to the west.
S-24-B	7-12-63	The structure is the Levee 30 borrow canal, 2½ miles north of U. S. Highway 41 and Tamiami Canal. The structure is gated culverts to control the flow of water southward in the borrow canal.
S-27	—	The structure is in Little River Canal (C-7), 1.2 miles upstream from mouth at Biscayne Bay. The structure has automatic vertical lift gates to control the discharge of water downstream in C-7 to Biscayne Bay. Daily water levels and discharge measured by the U.S.G.S. since November 1959. Prior records of water levels collected at a site upstream by the U.S.G.S.
S-28	4-26-62	The structure is in Biscayne Canal (C-8), 1 mile upstream from the mouth at Biscayne Bay and located in Miami, Dade County. The control has two bays with automatic vertical lift gates to control the discharge in C-8 to Biscayne Bay. Downstream side of control is tidal. Daily upstream water levels and discharge measured by the U.S.G.S. since April 1962. Prior records of water levels collected at a site upstream by the U.S.G.S.

Table 7—Continued

Structure Number	Date Accepted	Remarks
S-29	12-11-53	The structure is in Snake Creek Canal (C-9), 0.1 mile upstream from mouth at Biscayne Bay and in North Miami Beach, Dade County. The structure has four bays with vertical lift gates to control the discharge from C-9 to the Bay. Daily upstream water levels and discharge measured by the U.S.G.S. since January 1959. Prior records of water levels collected at site upstream by the U.S.G.S.
S-30	11-23-60	The control structure is in the western end of the Snake Creek Canal (C-9), 100 feet east of U. S. Highway 27 and 13.5 miles northwest of Hialeah, Dade County. Daily water levels and discharge measured by the U.S.G.S. since May 1963.
S-31	7-12-63	The control structure is in the Miami Canal between the junction between levees 30 and 33 and 15 miles northwest of Hialeah, Dade County. The structure has vertical gates to control the discharge of water from Conservation Area No. 3B to the Miami Canal.
S-32	9-15-52	The control structure is in the Levee 33 borrow canal and 15 miles northwest of Hialeah, Dade County. The structure has two bays with vertical gates to control the discharge from Levee 33 borrow canal to the Miami Canal.
S-32-A	9-15-52	The control structure is in the Levee 30 borrow canal and 15 miles northwest of Hialeah, Dade County. The structure is a gated culvert to control the flow to the north in the borrow canal and to the Miami Canal.
S-33	11-1-54	The salinity control structure is in the Plantation Road Canal (C-12), half a mile east of U.S. Highway 441 and 4 miles west of Fort Lauderdale, Broward County. The structure has two bays with vertical gates to control the flow downstream in C-12. Daily water levels collected by the C&SFFCD and daily discharge measured by the U.S.G.S. since October 1961.
S-34	9-15-52	The control structure is in the North New River Canal and Levee 35 and 18 miles west of Fort Lauderdale, Broward County. The structure has two culverts with vertical gates to discharge water from Conservation Area No. 2B to the North New River Canal. Daily water levels and discharge measured by the C&SFFCD.
S-36	11-1-54	The salinity control structure is located in the Middle River Canal (C-13) and 1.5 miles east of U.S. Highway 441 and 5 miles west of Fort Lauderdale, Broward County. The structure has two bays with vertical lift gates to control the flow in C-13. Daily water levels collected by C&SFFCD and discharge measured by the U.S.G.S. since March 1962.
S-37-A	8-9-61	The salinity control structure is located in Canal 14, east of State Highway 811 and 3 miles southwest of Pompano Beach, Broward County. The structure has four bays with vertical automatic gates to control the flow in C-14 which discharges into tide water at the Intracoastal Waterway. Daily upstream water levels and discharge measured by the U.S.G.S. since April 1962.
S-37-B	8-9-61	The control structure is in Canal 14, 2 miles south of the Pompano Canal and 4 miles southwest of Pompano Beach, Broward County. The structure is a gated control in the C-14 to discharge water downstream.

Table 7—Continued

Structure Number	Date Accepted	Remarks
S-38	7-3-61	The control structure is in Levee 36 and 12 miles west of Pompano Beach, Broward County. The structure has two culverts that have vertical lift gates to discharge water from Conservation Area No. 2A to the Pompano Canal (C-14) and the borrow canals. Daily water level collected above the structure by the Corps of Engineers and below the structure by the C&SFFCD. Daily discharge in C-14 by the U.S.G.S. since April 1962.
S-39	9-15-52	The control structure is in the Hillsboro Canal, 6.2 miles upstream from U.S. Highway 441 and 12 miles west of Deerfield Beach, Broward County. The structure has one bay with a radial gate to control the discharge from Conservation Area No. 1 to the Hillsboro Canal. Daily water levels and discharge measured by the C&SFFCD.
S-40	1-15-65	The salinity control structure is in C-15 and at Delray Beach, Palm Beach County. The structure is to control the discharge from C-15 to the Intracoastal Waterway.
S-41	9-17-65	The salinity control structure is in the Boynton Canal (C-16) downstream from U. S. Highway 1 and at Boynton Beach, Palm Beach County. The structure is controlled to discharge water from C-16 to the Intracoastal Waterway.
S-44	4-9-58	The salinity control structure is in Canal 17 north of West Palm Beach, Palm Beach County. The Structure is controlled to discharge water from C-17 to the Intracoastal Waterway.
S-46	11-1-58	The control structure in the southewest fork of the Loxahatchee River (C-18) just downstream from State Highway 706 and 3 miles west of Jupiter, Palm Beach County. The structure has three bays with fixed crest and vertical lift gates to control the flow down C-18 to the Loxahatchee River.
S-48	3-20-62	The control structure in Canal 23 dowstream from the Sunshine State Parkway and west of Stuart, Martin County. The structure controls the discharge from C-23 to St. Lucie River.
S-49	7-8-60	The control structure in Canal 24, west of the Sunshine State Parkway and 10 miles northwest of Stuart, St. Lucie County. The structure controls the flow down C-24 and to the St. Lucie River.
S-50	6-12-61	The control structure in Canal 25 at Fort Pierce, St. Lucie County. The structure controls the flow down C-25 to the Intracoastal Waterway.
S-76	11-13-53	The control structure is in Levee 8 borrow canal and northwest of Canal Point, Palm Beach County. The structure controls the flow in the L-8 Canal to and from Lake Okeechobee.
S-118	2-10-66	The salinity control structure in Canal 100, about 14 miles northeast of Homestead, Dade County. The Structure controls the flow from C-100 to Biscayne Bay.
S-121	12-15-65	The control structure is in Canal 100C and about 6 miles southwest of Miami, Dade County. The structure controls the discharge from Snapper Creek Canal (C-2) to C-100 C.

Table 7—Continued

Structure Number	Date Accepted	Remarks
S-122	5-17-65	The control structure in Canal 100 B, about 13 miles south of Miami, Dade County. The structure controls the discharge from C-100B to C-1.
S-124	6-21-66	The control structure in the Levee 35A borrow canal, 12 miles west of Fort Lauderdale, Broward County. The structure controls the discharge from L-35A borrow canal south to the North New River Canal.
S-125	6-21-66	The control structure in Canal 42, 9 miles west of Fort Lauderdale, Broward County. The structure controls the discharge from C-42 south to the North New River Canal.
S-151	7-27-62	The control structure in the Miami Canal about 24 miles northwest of Miami, Dade County. The structure controls the discharge from Conservation Areas No. 3A to No. 3B..

Note: Some of the more important additional structures operated by the C&SFFCD are listed below.

1. The West Palm Beach control structure located on the WPB Canal under U. S. Highway 1 discharges water from WPB Canal to the Intracoastal Waterway through five bays that are controlled by stop logs and a boat lock that has a vertical lift gate. Daily water levels and discharge measured by the U.S.G.S. since November 1939.

2. The Hillsboro Canal lock and control near Deerfield Beach, Broward County. The structure controls the flow of water down the Hillsboro Canal to the Intracoastal Waterway. Daily water levels and discharge measured by the U.S.G.S. since July 1947.

3. The lock and control on the North New River Canal near Fort Lauderdale. The structure controls the flow in the canal by the use of stop logs in the bays. The boat lock has been abandoned for several years. Daily water levels and discharge measured by U.S.G.S. since November 1939 (discharge measurements only May to September 1913).

4. The control with a boat lift in the Miami Canal at N. W. 36th Street, Miami, Dade County. The salinity structure controls the rate of flow down the Miami Canal by removing sheet steel pilings called needles. Daily water levels and discharge measured by U.S.G.S. since February 1959. Daily water levels and discharge measured at site upstream (near Hialeah Water Plant) from January 1940 through February 1959.

5. Hurricane Gate Structure No. 5 located at Canal Point, Palm Beach County. This structure controls flow between Lake Okeechobee and the West Palm Beach Canal which at times can flow in either direction. Daily water levels and discharge measured by U.S.G.S. since November 1939.

Table 8. Discharge through the Tamiami Canal outlets east of Levee 30, in acre-feet [1]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1939	—	—	—	—	—	—	—	—	—	—	4710	4630	—
1940	3660	3600	4490	2870	1430	2350	2400	3040	5260	4920	5900	6050	45970
1941	1050	5660	6890	5950	2770	1190	1050	2280	3210	5840	5470	4300	45660
1942	3810	4000	4060	1190	738	2620	6460	4180	5590	3500	1730	1910	39790
1943	1290	666	492	595	369	1010	2710	2210	4460	5410	4280	4180	27670
1944	4300	1280	861	298	1290	774	1110	1290	595	1230	2080	1110	16220
1945	1350	222	0	0	0	0	369	615	1550	6030	5770	3750	19660
1946	3070	1890	1110	536	492	60	0	1720	2620	2890	2020	2830	19240
1947	1840	1560	1720	1550	738	1840	-1350	9160	17730	31670	13920	10450	90830
1948	6390	3110	369	60	61	0	0	-61	0	15430	10830	7750	43940
1949	2830	722	246	60	-61	298	0	492	893	2580	714	1050	9820
1950	246	0	0	0	0	0	246	123	417	184	893	369	2480
1951	533	167	0	0	0	0	0	123	595	1480	1790	2520	7210
1952	1050	778	123	0	0	357	(Discontinued)	—	—	—	—	—	—
Avg	2420	1820	1570	1010	600	810	1080	2100	3580	6760	4620	3920	30290
High	6390	5660	6890	5950	2770	2620	6460	9160	17730	31670	13920	10450	119670
Low	246	0	0	0	-61	0	-1350	-61	0	184	714	369	41

[1] Includes all the flow to the south through bridges 60-62, from November 1939 through June 1952 when the station was discontinued; also the eastward flow in the Tamiami Canal through the control structure in Dade-Broward Levee from November 1939 to October 1949.

Table 9 Discharge through the Tamiami Canal outlets between Levee 30 and Levee 67A, in acre-feet[1]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1939	—	—	—	—	—	—	—	—	—	—	27970	5660	—
1940	3690	1730	61	0	61	0	615	1040	11310	12360	9520	6030	46420
1941	7440	15328	7440	11840	2830	357	6210	6330	6550	9100	6600	3630	83660
1942	1840	222	61	238	0	11130	9280	6400	7620	3630	0	0	40420
1943	0	0	0	0	307	0	184	1290	6550	6330	4400	3870	22930
1944	1840	0	0	0	246	0	369	1840	476	799	833	0	6400
1945	0	0	0	0	0	0	0	184	22790	23860	21720	8480	77030
1946	3200	0	0	0	123	119	123	615	8390	3810	3750	1840	21970
1947	1050	56	0	0	61	3810	13400	32710	45640	222800	143800	33630	496960
1948	57060	19440	1720	0	61	0	184	0	8690	148400	91760	46300	373620
1949	11680	3110	0	0	0	60	369	1660	14220	31850	26480	9350	98780
1950	5350	1000	307	0	0	0	61	61	1550	8420	9460	2400	28610
1951	799	555	0	0	0	0	0	61	3450	13100	16900	13340	48200
1952	2640	1500	0	0	0	0	3070	2210	5590	33940	46950	27980	123880
1953	20110	21220	5960	119	61	60	307	6890	1480	115500	147300	115200	319010
1954	75940	25660	11930	1670	2340	22430	38310	55770	76110	95550	74880	66650	547160
1955	39230	16440	2090	0	0	1070	2090	11740	37840	35110	19760	9100	174470
1956	2090	288	0	0	0	0	0	430	1070	21520	15290	3500	44180
1957	184	56	123	0	5900	238	1540	7320	39750	140600	101700	62230	359640
1958	83750	108700	93580	88420	59580	74260	74150	36580	37840	37140	26000	20780	740780
1959	16230	6110	4610	1490	615	19760	99060	123300	112000	111000	131300	131600	757080
1960	99240	58960	34800	11310	4180	4880	5230	11190	80090	186500	177800	132900	807080
1961	74220	39430	12910	595	0	357	738	1780	1430	492	0	0	131950
1962	0	0	0	0	0	1250	2400	4120	8210	12240	6780	5840	40840
1963	3570	1610	1350	0	0	0	1350	4920	15650	4540	3570	2490	39050
1964	3330	1250	373	-46	-161	2540	1800	3500	4650	6840	8070	10490	42640
1965	7680	5150	4480	1240	113	-22	-34	97	2060	7240	10390	9200	47590
1966	9280	6570	4450	2730	1450	8720	15580	13460	8770	9540	7080	4390	92020
1967	3420	2760	1180	499	0	742	1130	1930	2550	14030	13550	11450	53240
1968	8180	4840	2680	739	2960	15210	16920	16500	13310	19920	15440	10280	126980
1969	9440	6110	5160	3600	6130	10520	7460	12280	10360	—	—	—	—
Avg	18420	11630	6510	4150	2900	5920	10060	12210	19870	46110	38970	25290	199740
High	99240	108700	93580	88420	59580	74260	99060	123300	112000	222800	177800	132900	1391640
Low	0	0	0	-46	-161	-22	-34	0	476	492	0	0	705

[1] Includes all the flow southward beneath 19 bridges from bridge 41 to 59. The flow in this section has been limited to seepage through Levee 29 immediately north of the Tamiami Canal since 1963.

Table 10. Discharge through the Tamiami Canal outlets between Levee 67A and 40-Mile Bend, in acre-feet [1]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1939	—	—	—	—	—	—	—	—	—	—	11900	5660	—
1940	4610	1780	123	179	123	60	0	6330	22610	14700	5710	4240	60460
1941	4300	12140	5600	10290	3070	2140	12240	9350	6130	8240	8450	5230	87180
1942	2830	666	615	298	984	14820	6400	1350	1250	799	0	0	30010
1943	0	0	0	0	0	119	2890	3380	15350	11500	4400	3500	41220
1944	1780	403	0	0	0	0	615	3810	417	2090	2260	246	11620
1945	123	0	0	0	0	0	676	7320	24810	27920	17910	7500	86260
1946	3010	111	0	0	123	357	1230	3870	11130	12850	6310	6270	45260
1947	2090	1670	553	60	0	6190	32830	39480	41770	125600	64090	30560	344890
1948	16420	3970	61	0	0	0	0	861	15830	109100	43320	15500	205060
1949	11680	0	0	0	0	2080	6270	10640	21240	38370	18680	7690	116650
1950	5160	0	0	0	0	0	1660	861	8390	29640	10650	3870	60230
1951	3320	1330	0	0	0	0	676	3380	5830	12850	12910	6460	46760
1952	1480	1040	0	0	0	238	5600	8240	11360	31910	22550	11810	94230
1953	8420	6000	1110	0	0	0	2090	8610	30470	51530	50280	32340	190850
1954	17890	4610	1600	60	1230	20710	21890	21950	33320	31050	22490	14140	190940
1955	6700	1220	0	0	0	179	1600	4490	13630	8060	4220	799	40900
1956	0	0	0	0	0	0	0	246	4820	18820	7080	123	31090
1957	0	0	0	0	369	0	1720	5900	20940	47650	27730	14390	118700
1958	25580	32660	30130	19700	23980	29040	32340	14630	9760	9350	2800	2640	232610
1959	1910	555	184	0	799	15000	38610	40890	44210	49930	60520	55030	307640
1960	32040	18520	7440	3210	123	4460	2950	12670	70450	107400	84200	36280	379740
1961	25020	11050	799	0	0	0	922	3870	1670	861	0	0	44190
1962	0	0	0	0	0	1190	3260	2770	6720	9410	1070	0	24420
1963	0	0	0	0	0	0	0	0	0	0	0	0	0
1964	0	0	0	56	811	2530	1570	0	0	0	0	0	4970
1965	2260	0	0	93	0	0	0	728	3460	5720	21700	2980	36940
1966	1320	5780	43490	41750	42360	67770	200300	242500	165600	159900	35690	0	1006460
1967	9130	7760	16310	10640	6380	7750	17720	33440	29520	18490	16380	7860	181380
1968	9350	7630	6240	4830	5430	91520	248000	269100	179700	113500	59330	16370	1011000
1969	15850	26620	85450	91850	97230	178400	214000	197400	182400	—	—	—	—
Avg	7080	4850	6660	6100	6100	14820	28600	31940	32760	36460	20750	9720	205840
High	32040	32660	85450	91850	97230	178400	214000	269100	182400	159900	84200	55030	1482260
Low	0	0	0	0	0	0	0	0	0	0	0	0	0

[1] Includes all the flow southward through 12 bridges from bridge 29 to 40. The flow in the section has been regulated by and measured at S-12 structures A, B, C, and D since 1963.

Table 11. Discharge through the Tamiami Canal outlets between 40-Mile Bend and Monroe, Florida, in acre-feet.[1]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1939	—	—	—	—	—	—	—	—	—	—	6010	3260	—
1940	1720	944	123	60	184	3510	7750	19060	41360	18820	2920	861	97310
1941	6890	13800	11250	10350	3690	5770	35290	27120	25170	20540	21480	7560	188910
1942	4430	833	984	298	492	51650	8920	2830	16600	3690	298	0	91020
1943	123	0	0	179	984	1070	4180	17710	43260	23800	5530	3010	99850
1944	1170	863	184	0	0	893	3630	11870	9340	11250	5890	799	45890
1945	676	666	246	0	0	238	10020	17950	43380	36460	12730	3140	125510
1946	799	0	0	0	0	2380	4490	6030	25050	24600	11840	3750	78940
1947	861	278	3440	893	184	18030	40950	56200	72300	147900	67890	95370	504300
1948	13840	2700	738	357	61	595	3630	8920	45340	164600	24100	5530	270410
1949	2890	389	0	0	0	2020	20110	26190	35640	68010	26960	3810	186020
1950	1600	444	123	60	61	417	4920	7010	34570	75880	12910	4430	142420
1951	2090	500	246	298	0	0	10270	22750	18330	32100	22970	5600	115150
1952	369	2590	246	60	0	476	11680	21400	33740	67940	36890	9960	185350
1953	6030	4830	615	536	184	2020	20480	30380	64620	75630	37430	21150	263900
1954	8360	1610	1170	1130	7750	50400	48580	33260	47360	40090	13210	5780	258700
1955	1660	0	0	0	0	7560	10390	6460	21060	3140	655	430	51360
1956	1230	460	0	0	0	60	6150	15370	26420	46120	5180	246	101240
1957	0	56	492	119	4860	11730	25760	35110	43910	58900	19220	8240	208400
1958	36090	23820	31600	14940	44390	46240	47040	34860	23440	7190	2080	1600	313290
1959	2150	1560	1600	714	6330	61350	49800	39540	62720	84610	79500	43350	433220
1960	13710	4140	1230	6310	369	10590	24720	41010	141700	153000	77950	20840	495570
1961	5720	1780	246	0	61	1250	16850	23550	10410	2090	298	0	62260
1962	0	0	0	0	0	22020	16110	16290	42840	44460	19930	4670	166320
1963	430	2000	430	0	369	4050	3320	3690	17850	51130	4340	1290	88900
1964	11760	2700	944	631	198	8880	10920	28280	15800	21930	20670	7350	130060
1965	3470	2100	1080	210	131	1120	15760	20890	30420	35140	24330	4900	139550
1966	3180	3940	1260	351	131	25590	124300	92190	62580	37490	7510	1820	360340
1967	1560	885	194	20	0	24370	30400	17810	8010	36690	8320	4110	132370
1968	2640	1390	975	193	6880	80130	62450	37200	30290	30410	18340	5200	276100
1969	4920	2440	2900	7170	35840	89890	80030	53470	41810	—	—	—	—
Avg	4680	2590	2080	1500	3770	17810	25300	25810	37840	49090	19910	9270	193540
High	36090	23820	31600	14940	44390	89890	124300	92190	141700	153000	77950	95370	925240
Low	0	0	0	0	0	0	3320	2830	8010	2090	298	0	16550

[1] Includes the flow southward through 29 bridges from bridge 96 to 117 and bridge 22 to 28. The flow from this section of the Tamiami Canal outlets has been the least affected by regulation and remains almost in a natural state. Flow in the regulated sections of the Tamiami Canal outlets has been compared with the flow in the 40-Mile Bend to Monroe segment to determine the effects of regulation.

TABLE 12. Tamiami Canal outlet bridges numbering system and mileage from Monroe, Florida east to Dade-Broward Levee. [1]

Bridge Numbers		Mile-
Old	New	age
Monroe, Fla.		0
124	96	0
125	97	0.8
126	98	1.8
127	99	3.3
128	100	4.3
129	101	5.4
130	102	5.8
131	103	6.4
132	104	6.9
133	105	7.2
134	106	7.7
135	107	8.7
136	108	9.2
137	109	9.7
138	110	10.4
139	111	10.9
140	112	11.5
141	113	12.0
142	114	12.8
143	115	13.5

Bridge Numbers		Mile-
Old	New	age
144	116	14.0
145	117	14.9
146	22	15.9
147	23	17.0
148	24	17.9
149	25	18.5
150	26	18.7
151	27	19.2
152	28	19.9
40 mi-bend		20.1
153	29	20.4
154	30	21.2
155	31	22.2
156	32	22.9
157	33	23.3
158	34	23.8
159	35	24.7
160	36	25.7
161	37	26.7
162	38	27.7
163	39	28.7

Bridge Numbers		Mile-
Old	New	age
164	40	29.7
Levee - 67A		29.9
165	41	30.0
166	42	30.8
167	43	31.6
168	44	32.2
169	45	32.7
170	46	33.4
171	47	33.8
172	48	34.5
173	49	35.2
174	50	35.5
175	51	36.0
176	52	36.6
177	53	36.7
178	54	37.2
179	55	37.7
180	56	38.2
181	57	39.0
182	58	39.6
183	59	40.1
Levee - 30		40.9
184	60	41.0
185	61	41.8
186	62	43.8
D-B Levee		43.9

[1] The Tamiami Canal outlet bridges were renumbered as indicated above in August 1942. All the old wooden bridges (40 to 62) were replaced by smooth concrete culverts between August 1952 and January 1953, and on all the remaining bridges, 96 to 117 and 22 to 39, the wooden decking was replaced by concrete in 1963. The distance between any two bridges may be computed from the difference in mileage figures as indicated. Monroe, Florida used as a starting point from west to east for all mileage.