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**FLORIDA GEOLOGICAL SURVEY**

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**REPORT OF INVESTIGATIONS NO. 20**

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**GROUND-WATER RESOURCES OF THE OAKLAND PARK  
AREA OF EASTERN BROWARD COUNTY, FLORIDA**

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By

C. B. Sherwood

U. S. Geological Survey

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Prepared by the

**UNITED STATES GEOLOGICAL SURVEY**

in cooperation with the

**CITY OF FORT LAUDERDALE**

and the

**FLORIDA GEOLOGICAL SURVEY**

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**TALLAHASSEE, FLORIDA**

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*Florida Geological Survey*

TALLAHASSEE

September 15, 1959

Mr. Ernest Mitts, *Director*  
Florida State Board of Conservation  
Tallahassee, Florida

Dear Mr. Mitts:

Florida Geological Survey Report of Investigations No. 20 is a paper entitled, GROUND-WATER RESOURCES OF THE OAKLAND PARK AREA OF EASTERN BROWARD COUNTY, FLORIDA, which was prepared by Mr. C. B. Sherwood, Hydraulic Engineer with the U. S. Geological Survey, in cooperation with the Florida Geological Survey and the City of Fort Lauderdale.

The Oakland Park area obtains its water from the Biscayne aquifer, composed of very permeable and porous, sandy limestones. The permeability of the aquifer increases with depth, and wells in the area generally obtain water at depths ranging from 60 to 80 feet, or between 100 and 200 feet, depending on the quantity of water desired. The data presented in this paper can be used for further development of water and wise management of resources in the area. Large quantities of ground water are still available at Oakland Park, if salt-water encroachment can be controlled. The data in this study provide the necessary information to begin an effective water management program.

Respectfully yours,

Robert O. Vernon, *Director*

Florida deposit by  
23 March 1960

Completed manuscript received

April 9, 1959

Published by the Florida Geological Survey

Rose Printing Company, Inc.

Tallahassee, Florida

September 1959

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# GROUND-WATER RESOURCES OF THE OAKLAND PARK AREA OF EASTERN BROWARD COUNTY, FLORIDA

## ABSTRACT

The Biscayne aquifer is the source of all fresh ground water in the Oakland Park area of eastern Broward County, Florida. This aquifer extends from the land surface to more than 215 feet below mean sea level and is composed chiefly of sandy marine limestone, calcareous sandstone, and beds of fine to medium quartz sand. The aquifer differs from place to place, but, in general, most of the layers of limestone and sandstone occur at depths below 60 feet. The permeability of the aquifer increases with depth.

Wells for small supplies generally obtain water at depths ranging from 60 to 80 feet, whereas wells for large supplies usually obtain water from the interval between 100 and 200 feet. Large-diameter wells obtain as much as 1,000 gpm (gallons per minute) from the lower part of the aquifer.

Chemical analyses of ground-water samples indicate a hard limestone water that is suitable, naturally or with treatment, for most ordinary uses. Periodic determinations of chloride content of the ground water show that some salt-water encroachment has occurred in areas near the coast and in the Middle River basin.

Pumping-test data for deep wells in the Prospect well field area indicate approximate aquifer coefficients of transmissibility and storage of 2,000,000 gpd per foot and 0.015, respectively. However, the data indicate also that the hydraulic characteristics of the aquifer are complicated by the presence of beds of sand, silt, and clay in the upper 100 feet of the aquifer and by recharge from surface-water sources. Quantitative data and areawide water-level and salinity data indicate that large quantities of ground water are available for future development if salt-water encroachment can be effectively controlled.

## INTRODUCTION

### PURPOSE AND SCOPE

The rapid growth of population and industries in eastern Broward County has introduced the problem of preserving existing ground-water supplies and has caused a growing need for additional supplies. As in many coastal areas, this problem involves not only finding and developing a satisfactory source of water but also protecting this source



against salt-water encroachment from the sea. Recognizing the need for data in solving their problems, officials of the city of Fort Lauderdale requested that an investigation be made of the ground-water resources of eastern Broward County, in the vicinity of Oakland Park. The investigation was made by the U. S. Geological Survey in cooperation with the Florida Geological Survey and the city of Fort Lauderdale.

The purpose of the investigation was to determine, insofar as possible, the following things:

1. The ground-water potential of the area.
2. The extent of salt-water encroachment into the Biscayne aquifer.
3. The hydraulic coefficients of the aquifer and the safe rate of withdrawal for the development of large supplies.
4. The effect of water-control works of the Central and Southern Florida Flood Control District on the ground-water resources of the area.

Field studies, begun in December 1955, consisted of the following:

1. A partial inventory of wells in the area.
2. The installation of shallow wells to be used for water-level studies and one deep test well to be used for geologic and salinity studies.
3. Pumping tests to obtain data on the water-transmitting and storing properties of the aquifer.
4. A leveling program to determine the altitudes of measuring points for water-level measurements.
5. The determination of the chloride content of water from selected wells and sampling points in streams, and comprehensive analyses of water from selected wells.
6. The installation of two automatic water-stage recorders and the areawide measurements of water level at selected times.

The investigation was made under the general supervision of A. N. Sayre, Chief, Ground Water Branch, and under the immediate supervision of Howard Klein, Geologist, and M. I. Rorabaugh, District Engineer, all of the U. S. Geological Survey.

#### PREVIOUS INVESTIGATIONS

No detailed investigation of the ground-water resources of the Oakland Park area had been made prior to this investigation. Considerable information pertinent to the area is available, however, in publications or unpublished open-file reports of the Florida Geological Survey and the U. S. Geological Survey. Data from these reports have been used freely in the preparation of this report. Frequent references to the geology of the area and the occurrence and quality of the ground water in eastern

Broward County are contained in reports by Vorhis (1948), Parker and others (1955), and Schroeder and others (1958).

### ACKNOWLEDGMENTS

Grateful acknowledgment is hereby made for the cooperation and assistance given by officials of the city of Fort Lauderdale and the engineering firm of Philpott, Ross and Saarinen. The wholehearted cooperation of the personnel of the Fort Lauderdale water-treatment plants while field work was in progress, was especially helpful. Data pertaining to flood-control works in the area were supplied by officials of the Central and Southern Florida Flood Control District.

## GEOGRAPHY

### LOCATION AND GENERAL FEATURES OF THE AREA

The Oakland Park area is on the lower east coast of Florida between the cities of Pompano Beach and Fort Lauderdale (fig. 1). It is bounded on the north by the Pompano Canal, on the east by the Intracoastal Waterway, on the south by the south fork of the Middle River, and on the west by Conservation Area No. 2.

The city of Oakland Park is north of the north fork of the Middle River, about two miles west of the Intracoastal Waterway (fig. 2). The Prospect well field, which is one source of water supply for Fort Lauderdale, lies between the upper reaches of Cypress Creek and the Middle River, about two miles northwest of Oakland Park (fig. 3).

### CLIMATE

The climate of Fort Lauderdale is subtropical and the humidity is usually high. The average monthly temperatures, as shown by U. S. Weather Bureau records, range from 68.3°F. to 82.6°F. As of the end of 1956, the mean annual temperature was 74.2°F. and the mean yearly rainfall was 59.33 inches, for 43 years of record. The heaviest rains occur during the period from June through October. Table 1 shows monthly and yearly averages of temperature and rainfall at the Fort Lauderdale station for the period 1940-56, and average rainfall at the Pompano Beach station, about seven miles north of Fort Lauderdale, for the period 1941-56.

### TOPOGRAPHY AND DRAINAGE

The Oakland Park area is on the coastal ridge that separates the Atlantic Ocean from the Everglades. The ridge in this area is about six

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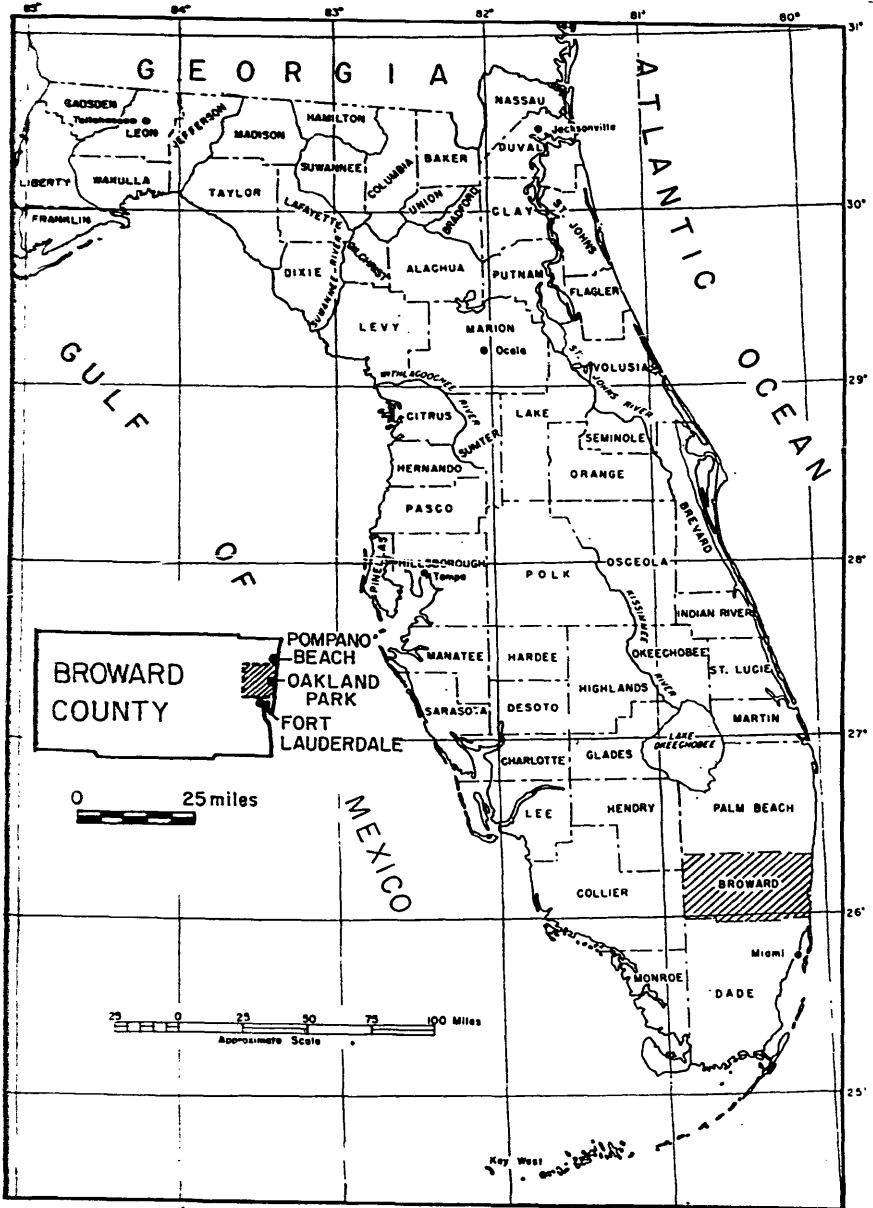


Figure 1. Map of the peninsula of Florida showing location of area investigated.

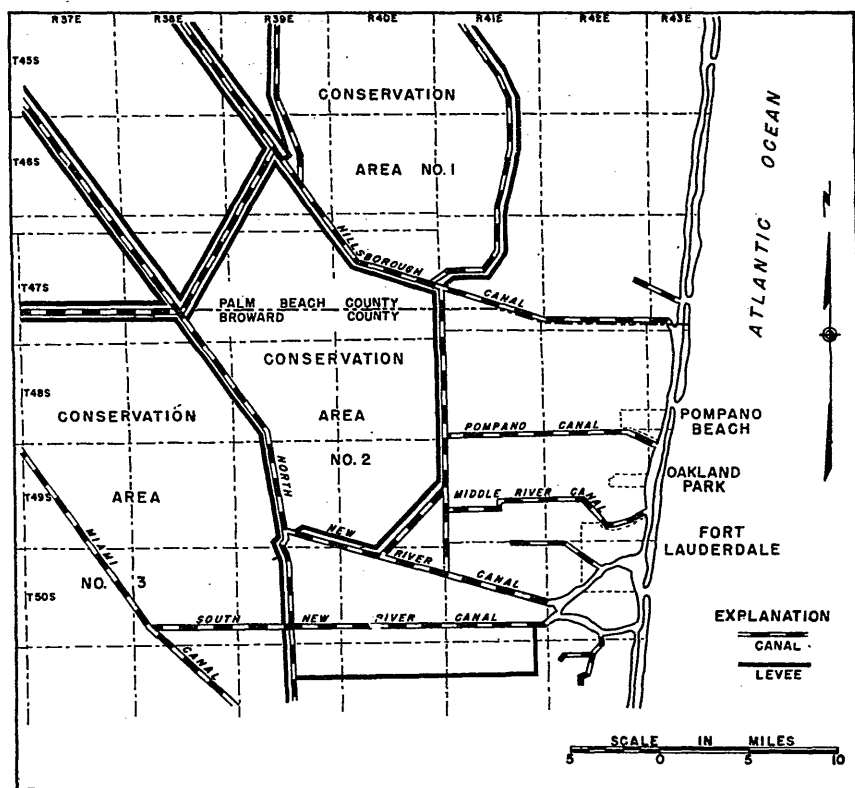


Figure 2. Map of parts of Broward and Palm Beach counties showing canals and levees of the Central and Southern Florida Flood Control District.

TABLE 1. Average Monthly Temperature, in Degrees, at Fort Lauderdale, and Average Monthly Rainfall, in Inches, at Fort Lauderdale and Pompano Beach

Month	Temperature		Rainfall	
	Fort Lauderdale	Fort Lauderdale <sup>1</sup>	Pompano Beach <sup>2</sup>	
Jan.	68.3	2.18	2.22	
Feb.	68.3	1.96	1.51	
Mar.	70.9	2.81	2.17	
Apr.	74.2	4.06	3.86	
May	77.4	4.93	3.60	
June	80.3	7.55	6.01	
July	81.7	6.03	7.39	
Aug.	82.6	6.74	6.68	
Sept.	81.5	8.82	9.32	
Oct.	77.8	8.83	9.58	
Nov.	72.3	3.05	3.09	
Dec.	69.2	2.37	2.08	
Yearly average	74.2	59.33	57.51	

<sup>1</sup>Discontinuous record 1940-56, U. S. Weather Bureau.

<sup>2</sup>Discontinuous record 1941-56, U. S. Weather Bureau.

miles wide and is very low and nearly flat, except where it is cut by the main streams — Cypress Creek near Pompano Beach and the Middle River south of Oakland Park (fig. 3).

The land surface ranges in altitude from about four feet above mean sea level in areas adjacent to stream channels to about 15 feet above mean sea level in the vicinity of the Prospect Air Field and in the area which parallels U. S. Highway 1, west of the Intracoastal Waterway. Most of the area, however, is about nine feet above mean sea level.

The area is drained chiefly by underground flow toward the ocean and into the canals and streams that flow generally eastward to the Intracoastal Waterway. The permeable quartz sand and oolitic limestone that form the shallow subsurface materials allow rainwater to infiltrate rapidly to the water table, and there is very little surface runoff to the canals and streams. The underground flow pattern is considerably influenced by continuous pumping in Fort Lauderdale's Prospect well field and by water-control structures in canals.

The Pompano Canal and Cypress Creek traverse the northern part of the area from west to east, through the ridge, to the Intracoastal Waterway. Cypress Creek drains the slough area north of Prospect field, and the Pompano Canal drains the area west of Pompano Beach and is a part of the overall flood-control system in southern Florida. The tributaries of the Middle River traverse the southern part of the area and drain the low areas south of Prospect field. Local farm drainage is effected by intricate systems of shallow ditches which connect to major drainage channels. The drainage and flood-control works are part of a cooperative state and federal program designed to alleviate the effects of both flood and drought conditions in central and southern Florida.

The Oakland Park area lies east of one of a series of water conservation areas (Conservation Area No. 2) that are bounded by a levee system extending from Lake Okeechobee to southern Dade County (fig. 2). The Pompano Canal and the Middle River Canal connect with a canal on the east side of Conservation Area No. 2. The Pompano Canal is controlled by dams near its confluence with Cypress Creek, and the Middle River Canal is controlled by a dam about  $5\frac{1}{2}$  miles inland from the Intracoastal Waterway. The tidal reach of Cypress Creek extends inland about two miles, and the various branches of the Middle River are tidal as far upstream as the flood-control dam. In the tidal reaches of these streams salt water is free to advance upstream as far as tides and fresh-water flow permit.

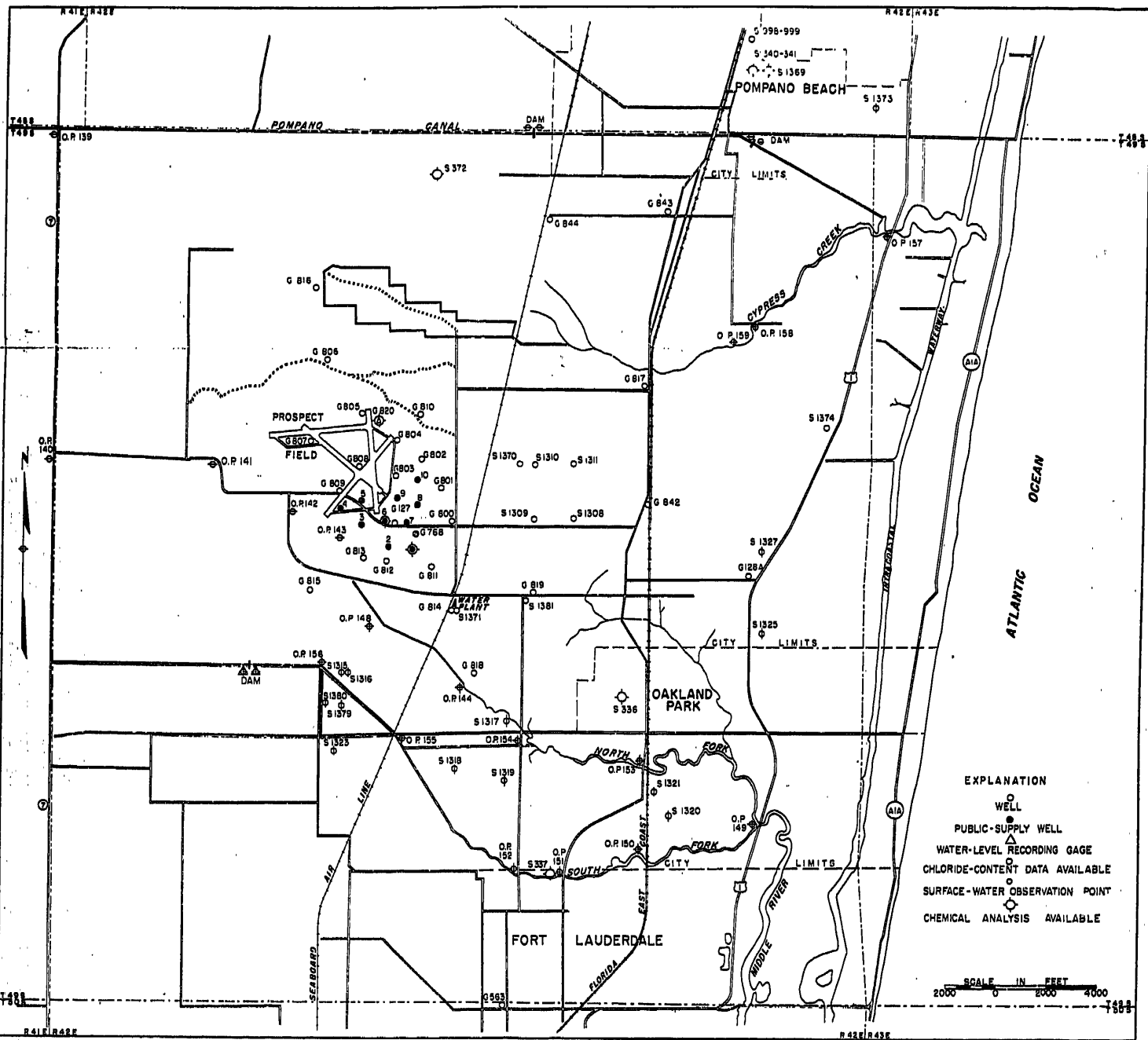


Figure 3. Map of Oakland Park area showing locations of wells.

## GEOLOGIC FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS

The name Biscayne aquifer was used by Parker (1951, p. 820-823) for the "hydrologic unit of water-bearing rocks that carries unconfined ground water in southeastern Florida." This aquifer is the only source of fresh ground water in Dade and Broward counties. Limestone strata at depths of 900 to 1,000 feet yield large quantities of water under artesian pressure, but the water is highly mineralized and unsuitable for general use. The artesian aquifer is not discussed in this report.

In the Oakland Park area the Biscayne aquifer includes marine deposits ranging in age (oldest to youngest) from late Miocene through Pleistocene, in the following sequence (Schroeder, 1958): Tamiami formation (upper part), Anastasia formation, Miami oolite, and Pamlico sand. In Dade County and southern Broward County the aquifer is underlain by a relatively impermeable greenish marl at or near the top of the Tamiami formation, but in northeastern Broward County the aquifer thickens and its base is considerably below the top of the Tamiami formation. Some of the geologic information included in this report was obtained from shallow observation wells in the Oakland Park area and some was obtained from four deep wells, namely, test well G-563 in the northern part of Fort Lauderdale, test well G-820 in the Prospect well field, and supply wells S-998 and S-999 in the Pompano Beach well field. Logs of these wells are shown in figures 4 through 7.

The log of well G-820 in the Prospect well field shows highly permeable limestone at a depth of 224 feet below the land surface, and local drillers report that similar limestones occur at greater depths. In each of the deep wells the marine deposits of the Tamiami formation of late Miocene age are overlain by very similar deposits of the Anastasia formation of the Pleistocene age. Well cuttings from both formations show that they are composed chiefly of alternating beds or lenses of sandy limestone or calcareous sandstone, sand, shells, and sandy clay or marl. Because of the lack of distinctive fossils in the samples and the absence of good stratigraphic correlation, no line of demarcation was drawn between the Tamiami and Anastasia formations. In general, the part of the aquifer underlying the Oakland Park area contains more unconsolidated sandy and clayey material than the part underlying areas south of Broward County; thus, the overall permeability of the aquifer in this area is lower than the permeability of the aquifer underlying areas to the south.

Wells developed in the limestones and sands of the Tamiami and Anastasia formations supply all the public water systems in eastern Broward

WELL G 563 4TH AVE. &amp; 10TH ST., N.W. FORT LAUDERDALE, FLA.

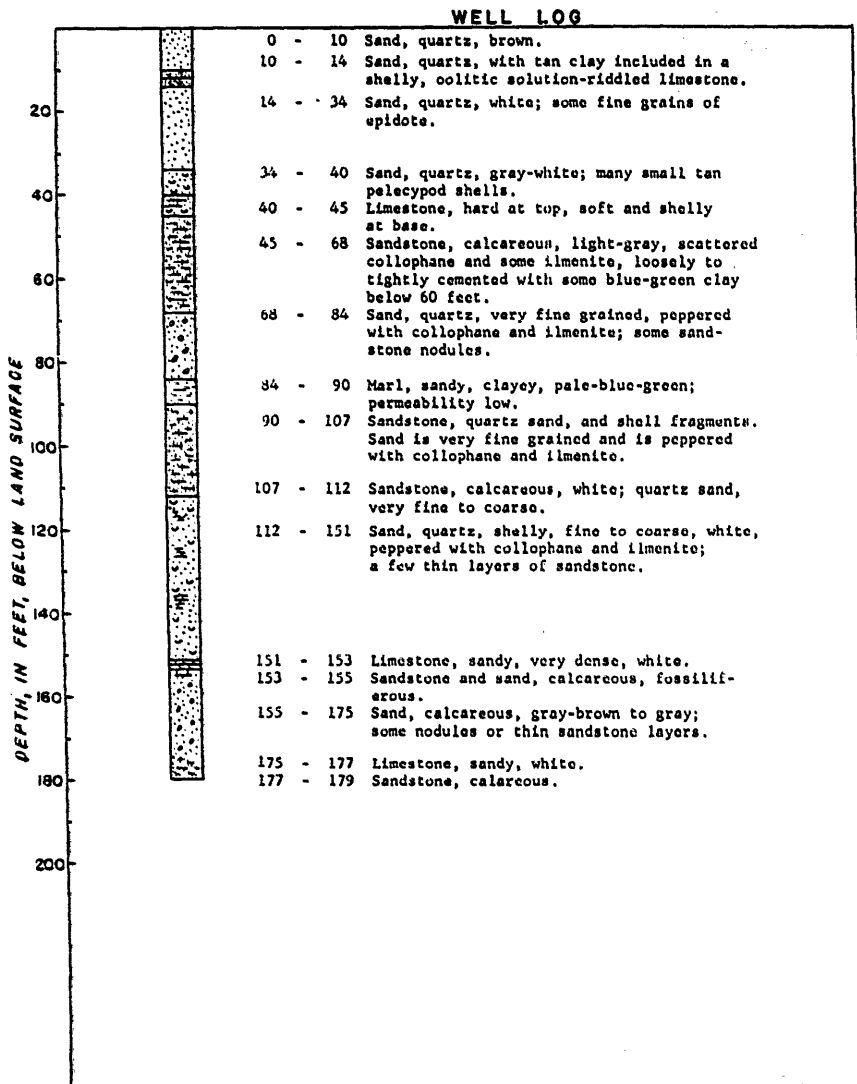


Figure 4. Log of well G-563.



WELL G 820

PROSPECT

WELL

FIELD

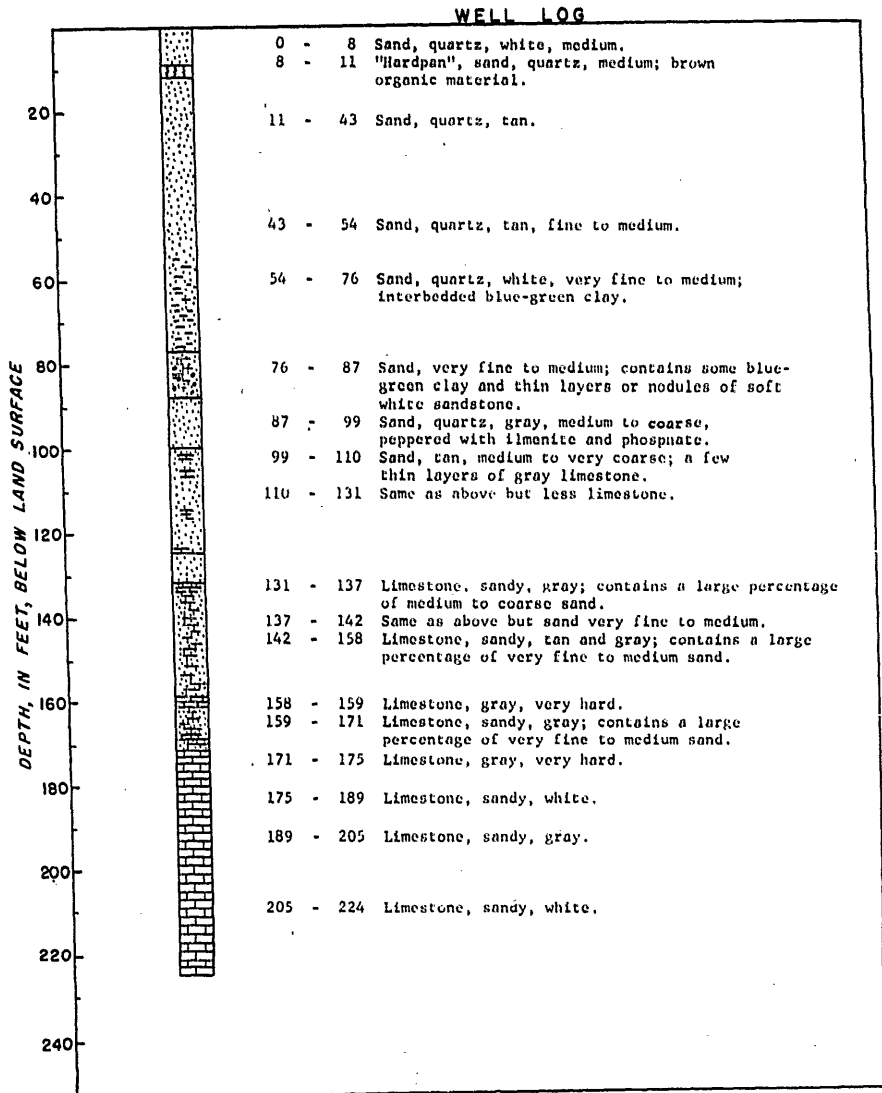


Figure 5. Log of well G-820.

WELL S 998

POMPANO BEACH WELL FIELD

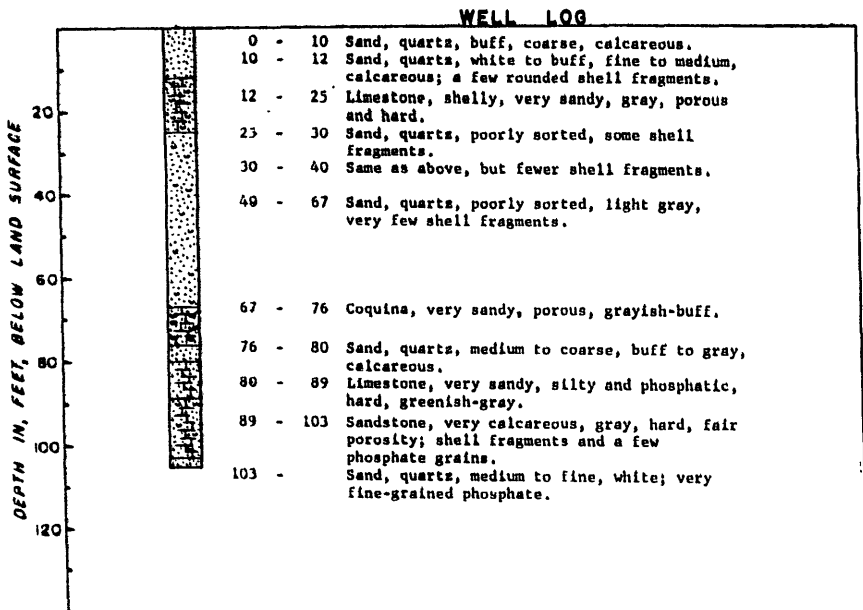


Figure 6. Log of well S-998.

County. Higher yields can be obtained from wells in the limestone parts of the aquifer than can be obtained from wells in the sandy parts. Individual 10-inch wells in the Prospect well field yield 820 gpm with approximately six feet of drawdown. These wells are screened in soft sandy limestone or calcareous sandstone, and the bottoms of the screens are set at depths ranging from 114 to 140 feet. The screens are 10 inches in diameter and average 20 feet in length. Wells for small individual supplies generally tap thin, local sandstones at depths ranging from 60 to 80 feet.

The Miami oolite of Pleistocene age, which occurs in the upper part of several test wells, is the surface rock that blankets much of southeastern Florida. In the Oakland Park area it is generally a white to yellowish thinly laminated, crossbedded oolitic limestone containing large amounts of sand and shells. The oolite is mined in shallow excavations south and west of the Prospect well field, but it is either very thin or missing in much of the Oakland Park area. The Miami oolite is very permeable, and it is tapped by domestic supply wells wherever it is thick enough to supply appreciable amounts of water.

WELL S 999

POMPANO BEACH WELL FIELD

WELL LOG

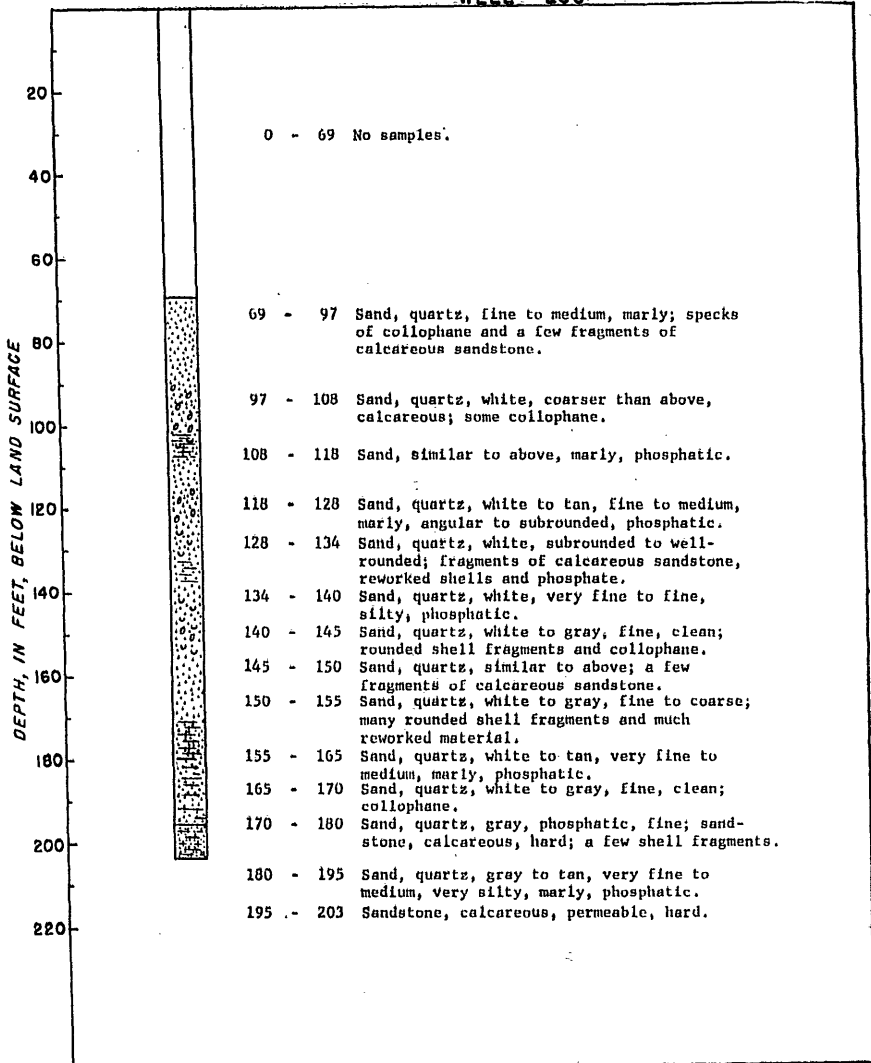


Figure 7. Log of well S-999.

The Pamlico sand, which was found near the surface in the test and observation wells, is a late Pleistocene marine terrace deposit (Parker and Cooke, 1944, p. 75). In the Oakland Park area it overlies and fills erosion channels and solution cavities in the Miami oolite and the Anastasia formation. The Pamlico sand is composed chiefly of fine to coarse quartz sand ranging in color from white to rust or gray-black, according to the amount of admixed iron oxide or carbonaceous material.

Properly developed sandpoint wells in the Pamlico sand generally yield enough fresh water for domestic purposes, but the water often has an objectionable color or odor caused by organic matter.

## GROUND WATER

Ground water is the subsurface water in the zone of saturation, the zone in which all the interstices of the soil or rocks are completely filled with water under greater than atmospheric pressure. Ground water may occur under either artesian or nonartesian conditions. Where its upper surface is free to rise or fall in a permeable stratum it is said to be under nonartesian conditions, and the surface is called the water table. Where the water is confined in a permeable bed that is overlain by a less permeable bed, its surface is not free to rise and fall. Water thus confined under pressure is said to be under artesian conditions. The height to which water will rise in tightly cased wells that penetrate an artesian aquifer defines the pressure, or piezometric, surface of the aquifer.

In the Oakland Park area the only potable ground water is the rainfall that infiltrates downward into the materials of the Biscayne aquifer. This water is said to be under nonartesian conditions, as its upper surface, the water table, is unconfined and under normal atmospheric pressure. It is recognized, however, that artesian conditions exist to some extent in parts of the aquifer. (See section on quantitative studies.)

The water table fluctuates in response to recharge or discharge, and ground water flows — under gravitational forces — from points of recharge, where water levels are high, to points of discharge, where water levels are low. The direction of flow coincides with the maximum slope of the water table. The water table may be mapped by determining the altitude of the water level in a network of wells. Systemic areawide observations of the shape, slope, and fluctuations of the water table are an important part of ground-water investigations, as they show the direction of ground-water movement and changes in the amount of ground-water storage.

### RECHARGE AND DISCHARGE

Rainfall is the source of all fresh-water recharge to the Biscayne aquifer. Not all of the rainfall infiltrates to the water table, however, as a large part is lost by evapotranspiration and a small part is lost by direct runoff into streams or the ocean. Parker (Parker and others, 1955, p. 221) estimates that about two-thirds of the annual rainfall reaches the water table in areas underlain by oolite and about half the annual rainfall reaches the water table in areas underlain by sand.

In the Oakland Park area, some surface water is introduced into the aquifer when water levels in the Middle River and Pompano canals are higher than the water table. This occurs chiefly in upstream areas, above the closed water-control structures.

Discharge from the aquifer takes place by evapotranspiration, by ground-water outflow into streams, canals, and the ocean, and by pumping. Discharge by ground-water outflow and evapotranspiration are greatest when the water table is highest, during and after periods of heavy rainfall, whereas discharge by pumping is greatest in the drier periods, which correspond with the peak tourist season. In general, the discharge by the two natural processes greatly exceeds the quantity of water withdrawn by pumping from wells. However, the operation of the Prospect well field makes pumping a significant factor. Figure 8 shows the monthly pumpage from the Prospect well field and the monthly rainfall at Fort Lauderdale during 1955 and 1956.

When water is pumped from a well in a nonartesian aquifer, the dewatering of the materials adjacent to the well causes the water table to slope downward toward the well, thus forming a cone of depression. The slope or hydraulic gradient of this cone causes ground water to flow from the surrounding area to the well. As pumping continues, the cone of depression increases in depth and areal extent until it reaches an area where ground-water discharge is salvaged and/or recharge is increased in an amount equal to the withdrawal. Studies in other areas indicate that pumping in a well field near a stream can cause large quantities of water to be drawn from the stream into the aquifer.

### WATER-LEVEL FLUCTUATIONS

Water levels in the Biscayne aquifer fluctuate considerably in response to recharge and discharge, and, to a lesser extent, they are affected by other factors such as tides (in areas adjacent to the coast and tidal canals), earthquakes, and changes in atmospheric pressure. The greatest short-term fluctuations are caused by recharge by rainfall and discharge by pumping, but gradual changes in water levels caused by evapotranspiration and normal ground-water outflow have an equally important

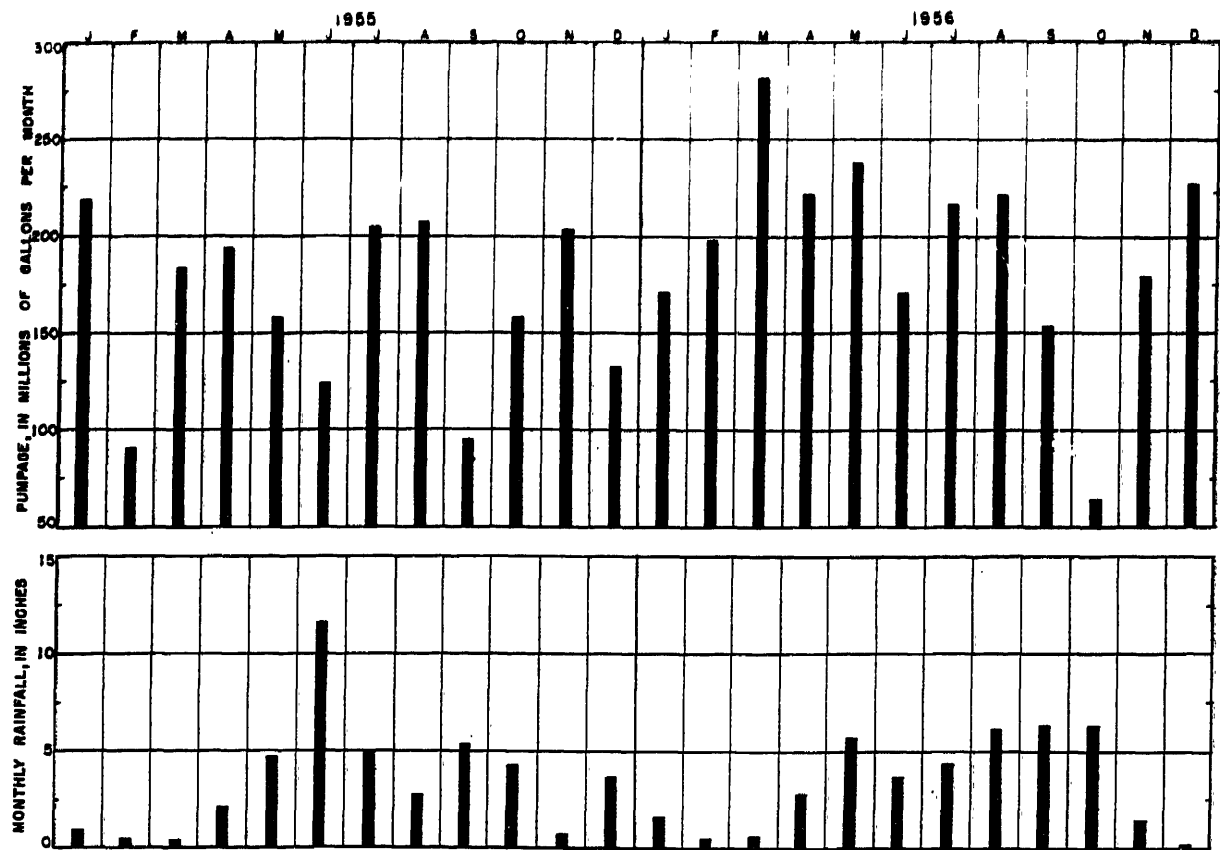


Figure 8. Monthly pumpage from the Prospect well field and monthly rainfall at Fort Lauderdale.

effect on the amount of water in storage in the aquifer. Parker and Stringfield (1950, p. 441-460) discussed the effects of earthquakes, winds, tides, and atmospheric-pressure changes on ground-water levels in southern Florida. Water-level fluctuations in the Oakland Park area are greatly influenced by pumping in the Prospect well field and by the flood-control works of the Central and Southern Florida Flood Control District.

Figure 9 is a contour map of eastern Broward County, showing the approximate altitude and configuration of the water table in the Biscayne aquifer on February 15, 1941. This map was made by using some of the earliest water-level data available for the area, and it represents the water table at a time when there was no drawdown due to pumping in the Prospect well field area or to extensive water-control works. The Pompano Canal (Cypress Creek Canal) was the only major drainage canal in the immediate area. Bogart and Ferguson (Parker and others, 1955, p. 505) indicated that the canal was controlled in two pools by small dams, in much the same manner as it is at present. Parker (Parker and others, 1955, fig. 148) shows that the water level above the controls in Pompano Canal ranged from about 1.0 foot to 5.4 feet above mean sea level during the period 1940-43. The contours in figure 9 were drawn from water-stage readings in streams and canals and from water-level measurements in widely scattered wells. In the Oakland Park area, the contours show, generally, the altitude and configuration of the water table under relatively natural conditions and indicate a fairly uniform gradient toward the coast.

The graphs in figure 10 show a correlation between periodic water-level measurements made in wells G-127 and G-128 (see fig. 9 for locations) and weekly rainfall at Fort Lauderdale during 1940-41. Well G-127 was on the present site of the Prospect well field, and well G-128 was on U. S. Highway 1, 2.7 miles east of well G-127. The hydrographs indicate also the differential in head between wells G-127 and G-128 during the latter part of 1940 and all of 1941.

Ground-water levels in Broward County during 1955 and 1956 were generally below the average for the period of record, owing to a deficiency in rainfall. This condition tends to accent the effects of drainage canals, dams, and pumping on the water table.

During 1956 an areawide program of water-level observations was established and contour maps of the water table in the Biscayne aquifer were prepared. Figures 11 through 13 show contours on the water table on August 7, September 21, and October 19, during periods of low, intermediate, and high water levels, respectively. The most striking feature of

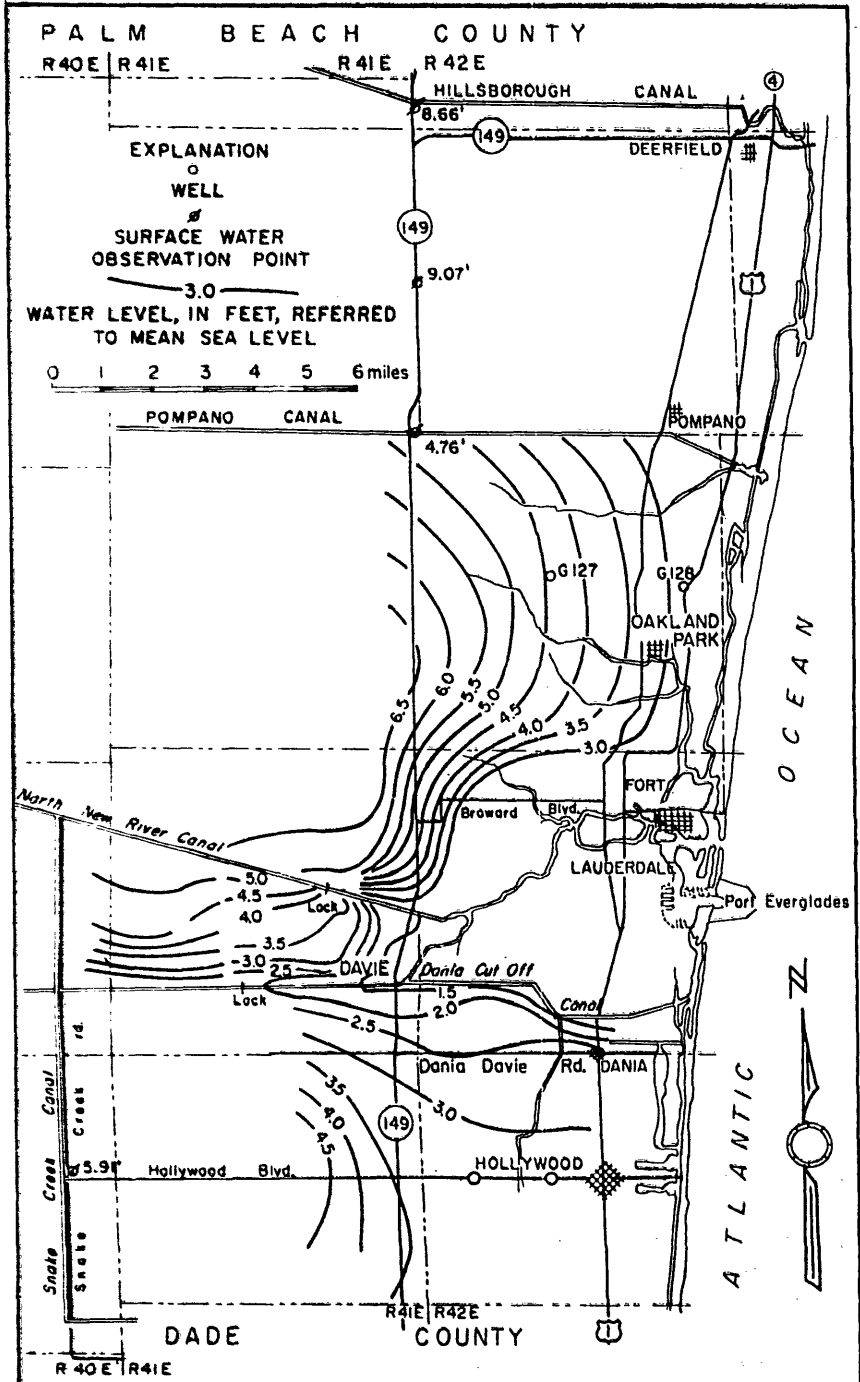


Figure 9. Map showing contours on the water table in the Biscayne aquifer, in eastern Broward County, on February 15, 1941.



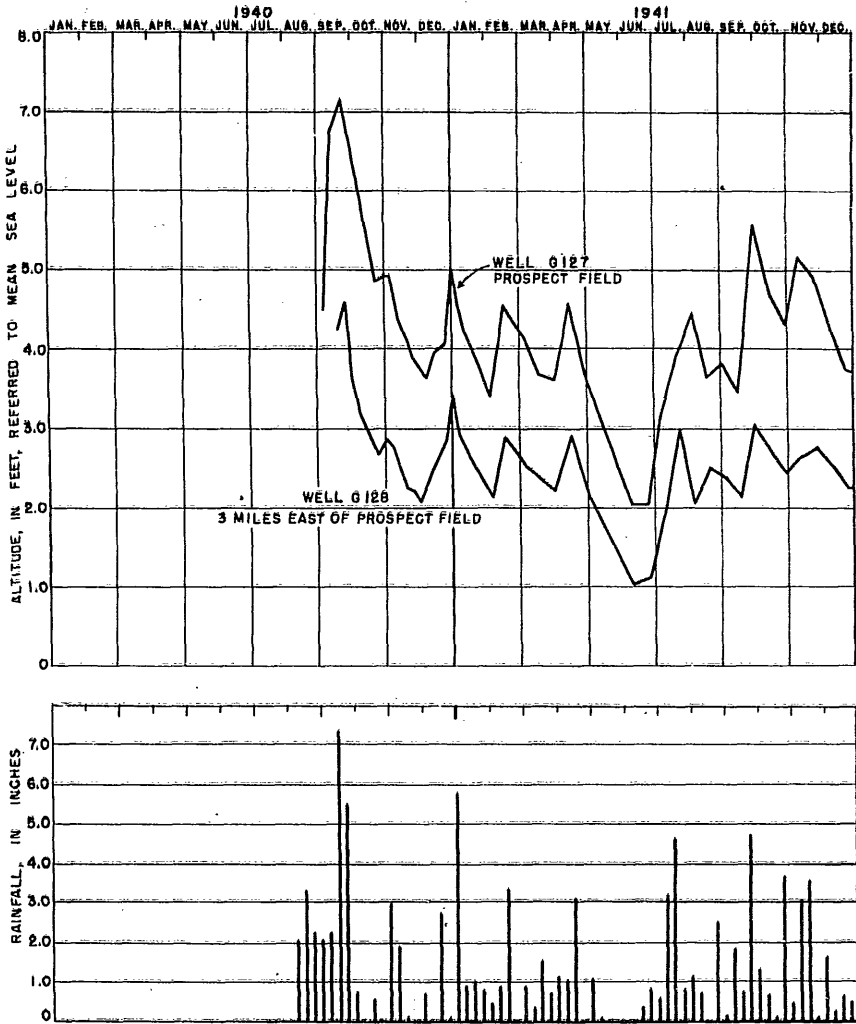


Figure 10. Hydrographs of wells G-127 and G-128 and weekly rainfall at Fort Lauderdale during 1940-41.

each contour map is the deep cone of depression caused by pumping in the Prospect well field. Significant features are the high ground-water levels and steep gradient maintained as a result of recharge by surface water in areas upstream from control structures in the Middle River and Pompano canals. The extremely low water levels and flat gradient in areas southeast of the cone of depression are caused by the large losses

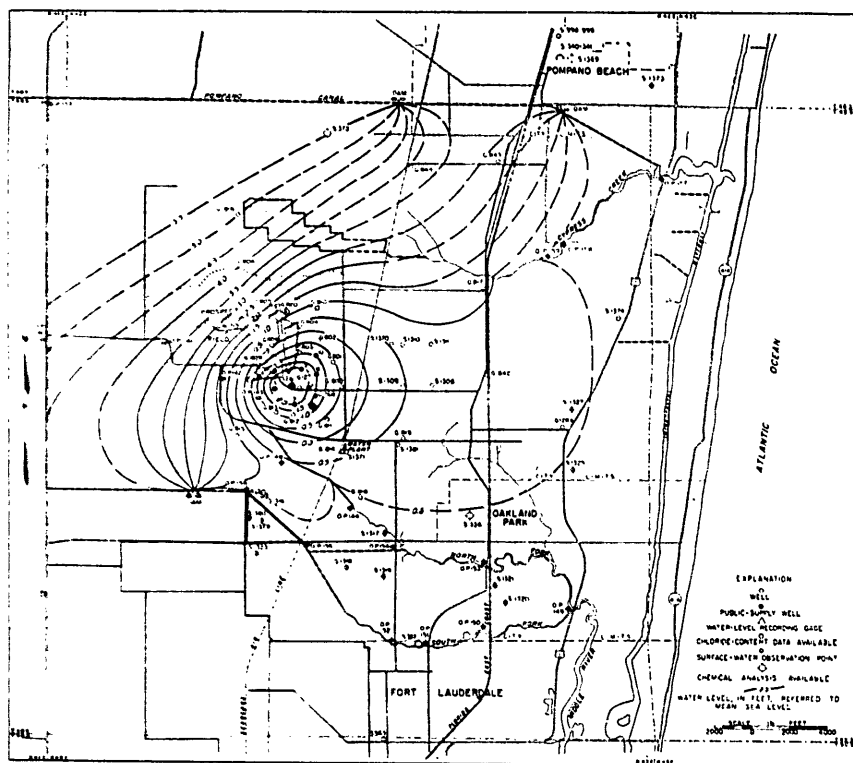


Figure 11. Map showing contours on the water table in the Biscayne aquifer in the Oakland Park area, August 7, 1956.

of ground water through drainage into the uncontrolled reaches of streams and canals and by discharge from the Prospect well field. Figure 11 shows the configuration of the water table at a time when water levels were near record lows and pumping from the well field was near maximum. The direction of ground-water flow is perpendicular to contour lines and in general it is toward the coast. The steep water-level gradient north and west of the well field indicates that most of the water pumped from the well field comes from that direction.

Figure 14 shows the fluctuation of water levels in wells G-768 and G-820 in the Prospect well field, monthly pumpage from the well field, and daily rainfall at Fort Lauderdale during June-December, 1956. The hydrographs show the difference between the water levels in well G-768, near the center of the cone of depression, and well G-820, near the outer edge of the cone. A comparison of the altitude of the water level of well G-768, in 1956, with that of well G-127 (same approximate loca-

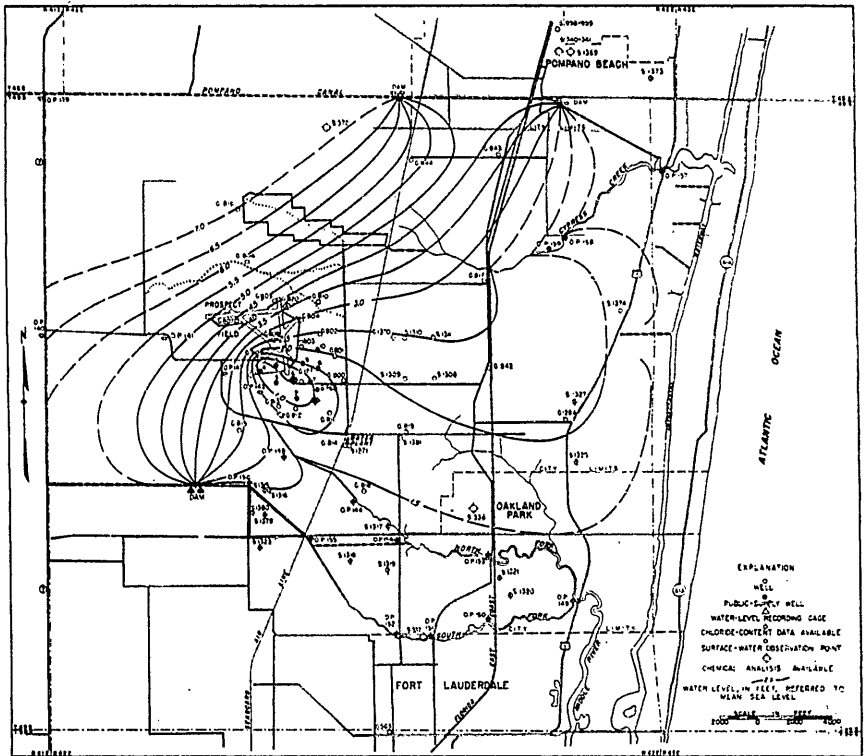


Figure 12. Map showing contours on the water table in the Biscayne aquifer in the Oakland Park area, September 21, 1956.

tion) in 1940-41 (fig. 10), shows the marked effect of heavy pumping in the area.

During extended dry periods, when there is little recharge, the rate of the natural decline in water levels decreases as the water-level gradient toward the coast diminishes. However, water levels in the well field area drop at an increased rate until the cone of depression reaches a new source of recharge or enough natural discharge is salvaged to balance the discharge due to pumping. The contours in figure 11 indicate that the water table in the area between the well field and uncontrolled reaches of the Middle River Canal was approaching the mean water level in the canal in August 1956. If the water table in the area declined to an altitude below that of the water level of the canal, some salty water would enter the aquifer from the canal. The flow of water from the canal into the aquifer would be impeded, however, by silt in the canal bed and by the relatively low permeability of the materials cut by the canal. It

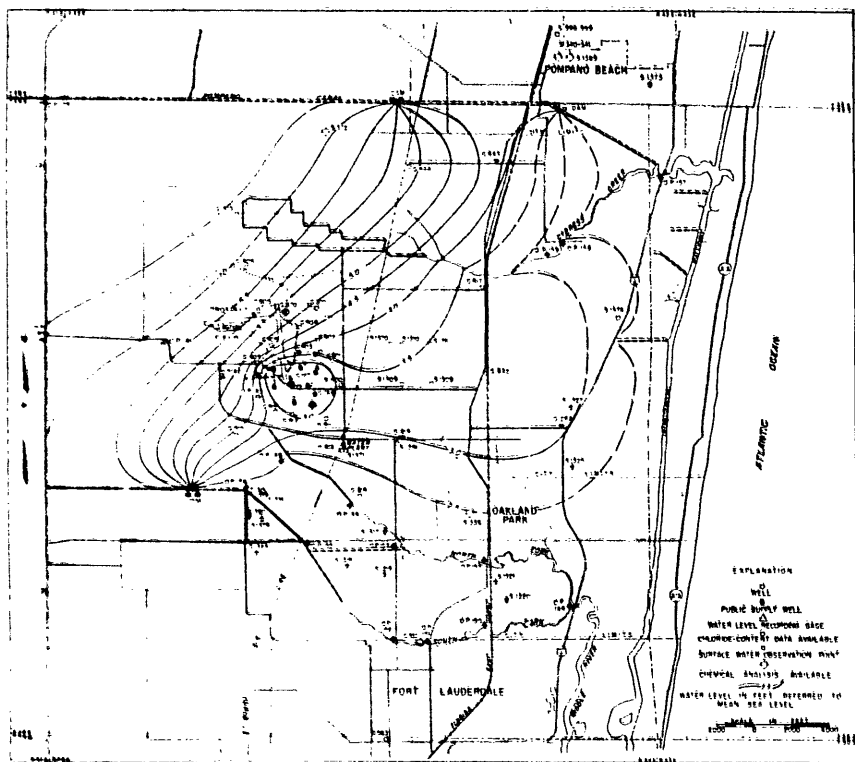


Figure 13. Map showing contours on the water table in the Biscayne aquifer in the Oakland Park area, October 19, 1956.

is possible that during a prolonged drought the cone of depression may extend outward and cause a relatively steep gradient from the salty canal to the aquifer, thus resulting in accelerated salt-water intrusion south of the well field.

Water-level recording gages are maintained above and below the dam on the Middle River Canal. Weekly readings are recorded from staff gages above and below the dams on the Pompano Canal (fig. 3). Figure 15 shows a typical water-level record obtained from gages above and below the Middle River dam on August 7-12, 1956, and figure 16 shows daily mean water levels above the dam and mean daily high and low tide levels below the dam during 1956. The 1956 average water levels above and below the dam were 4.40 and 0.60 feet above mean sea level, respectively, and the average tidal fluctuation below the dam was about 2.20 feet. Weekly water-level stages above the dam in the Pompano Canal, from April 6 to December 31, 1956, are shown in figure 17. The

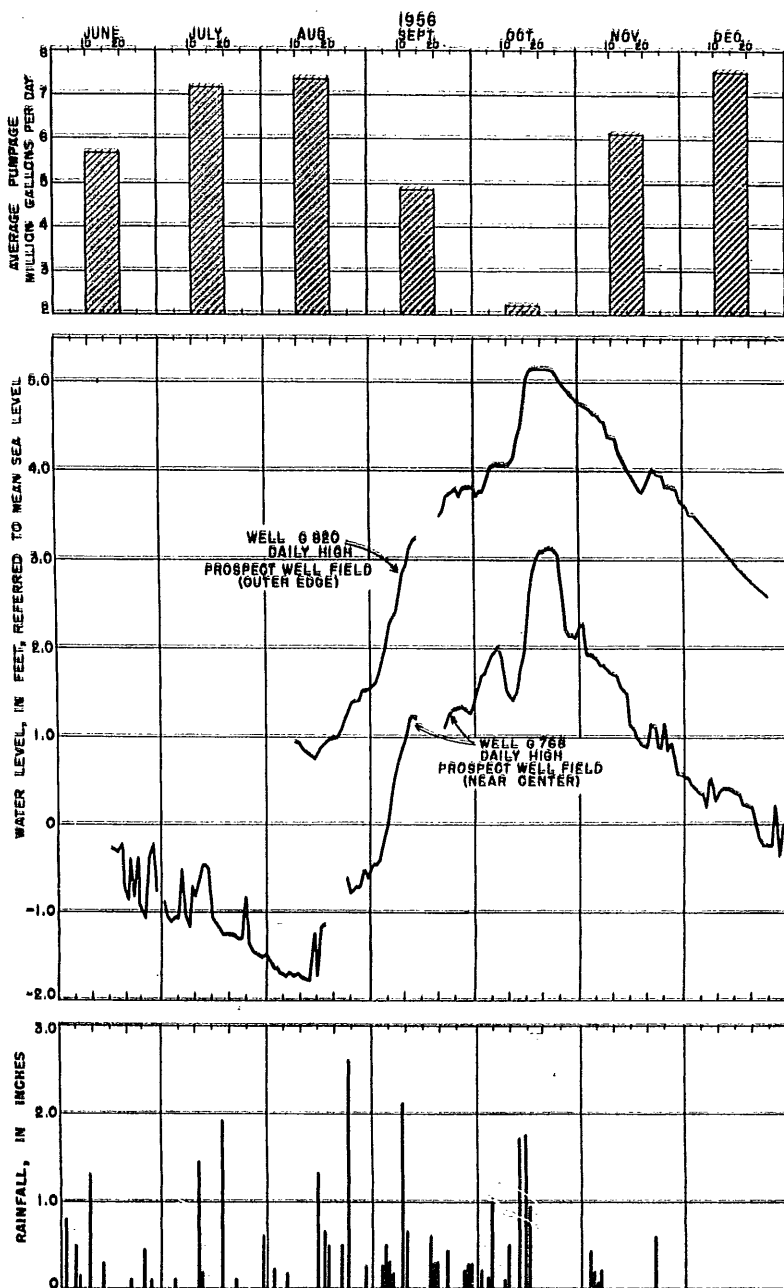


Figure 14. Hydrographs of wells G-768 and G-820, average daily pumpage from the Prospect well field, and daily rainfall at Fort Lauderdale, June-December, 1956.

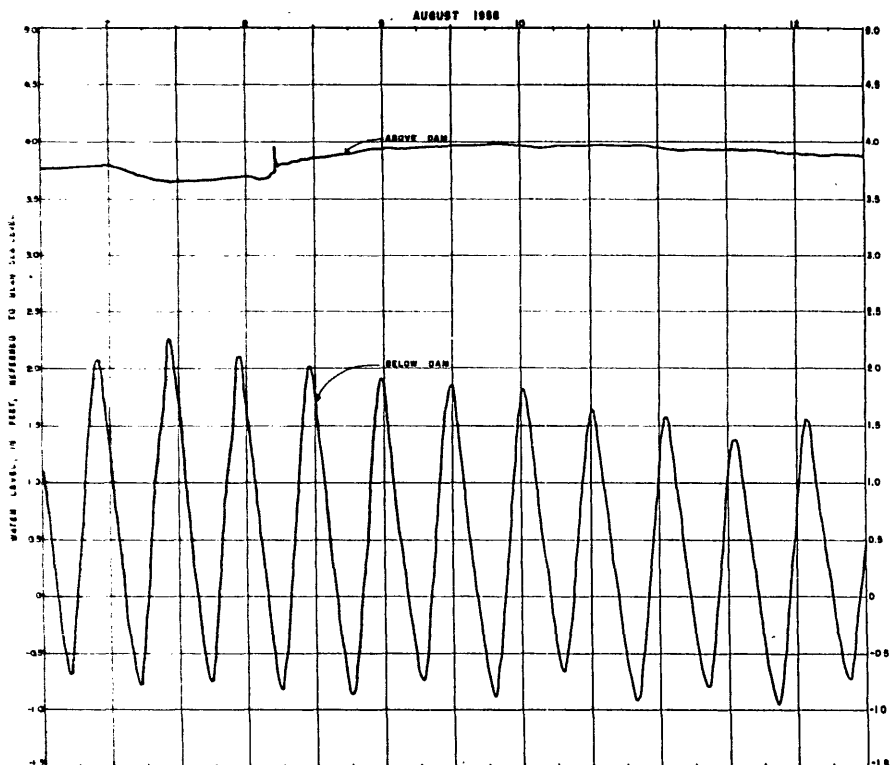


Figure 15. Hydrographs of Middle River Canal above and below dam, August 7-12, 1956.

average water levels above the east (City) and west (Market) dams during this period were 3.89 and 7.16 feet above mean sea level, respectively. No record of the tidal fluctuations in the lower reach of the canal is available, but the fluctuations are assumed to be similar to those in the Middle River Canal.

No data are available to show the beneficial effects of the flood-control works in this area during flood periods. This is unfortunate because the system was designed for both high-water and low-water conditions and its effectiveness is not fully demonstrated unless both conditions are presented.

#### SALT-WATER ENCROACHMENT

Salt-water encroachment is the chief factor limiting the use of ground water from the Biscayne aquifer. The salt water in this aquifer may come from two general sources, as follows: (1) direct movement inland from the ocean and from tidal canals and streams, and (2) sea water which

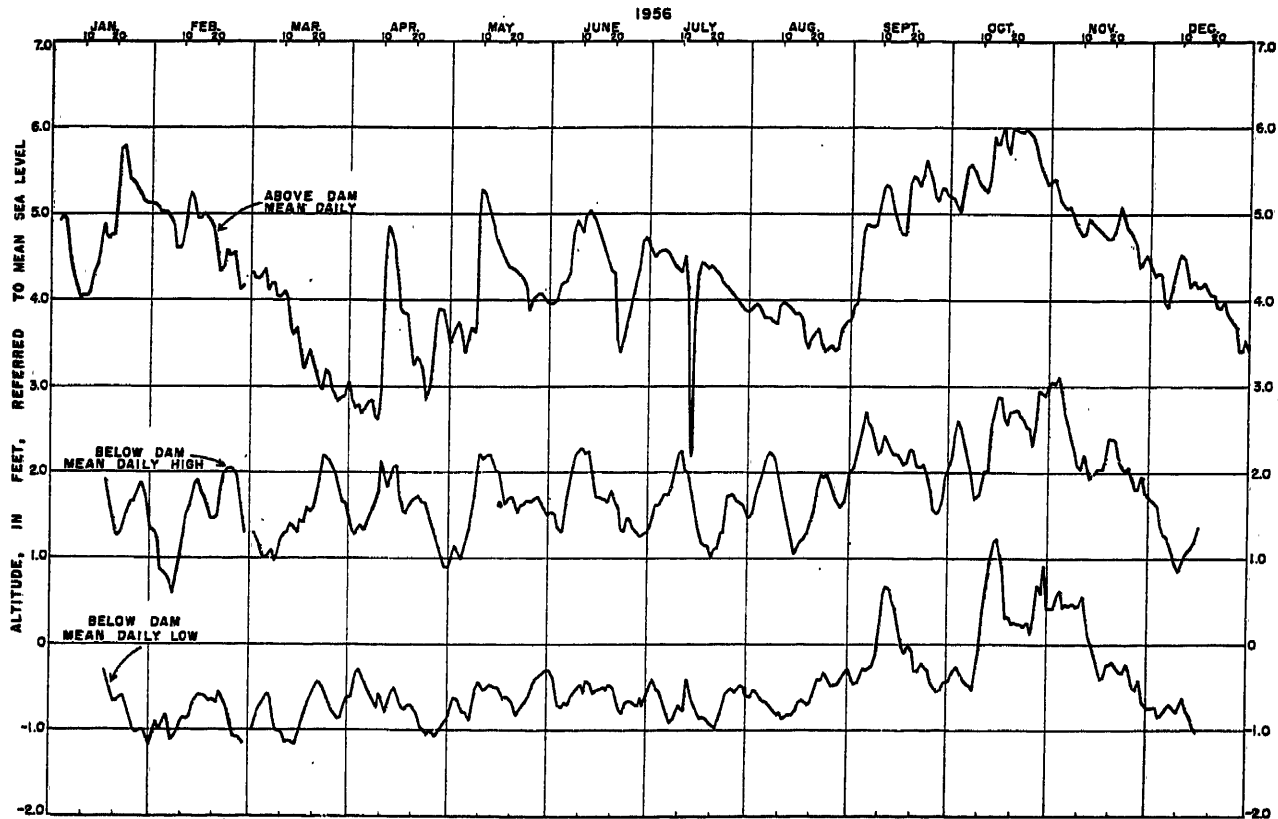


Figure 16. Hydrographs of Middle River Canal above and below dam during 1956.

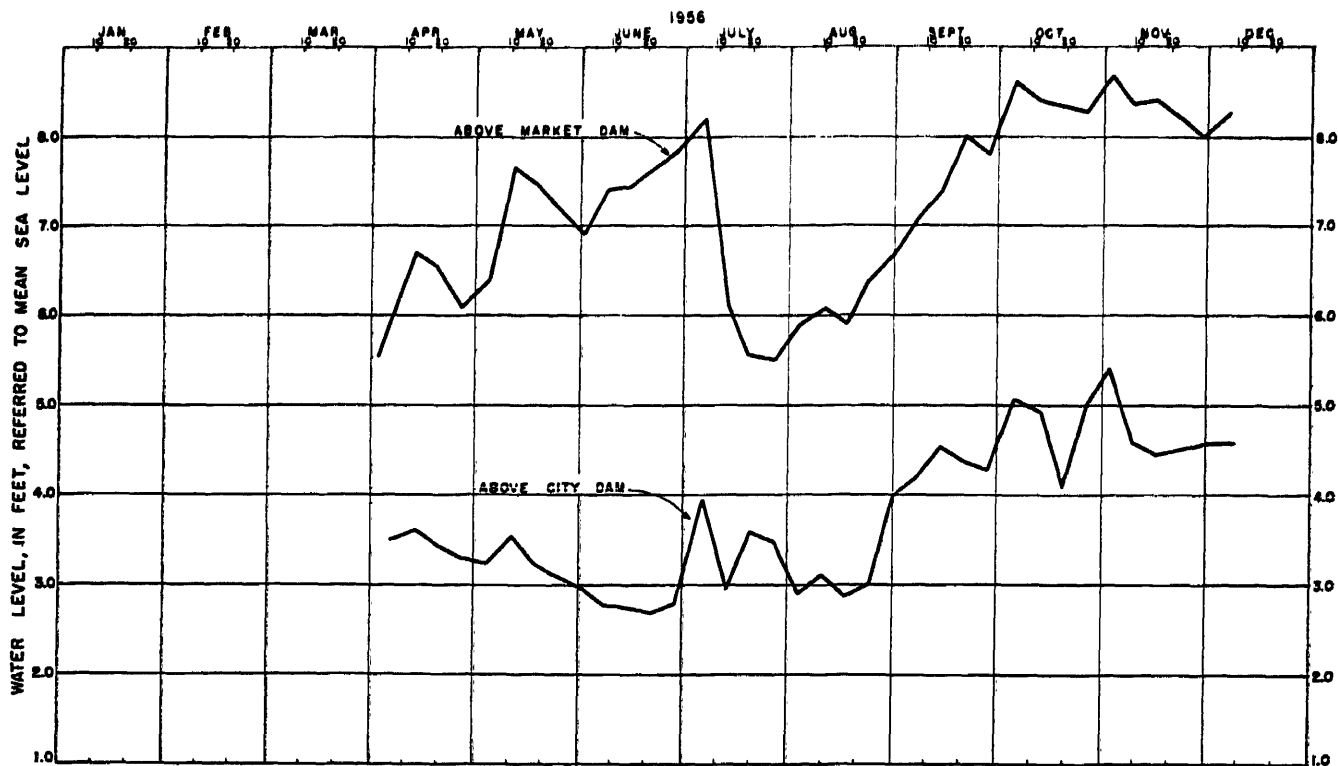


Figure 17. Hydrographs of Pompano Canal above Market and City dams, 1956.



entered the aquifer when the sea covered parts of southern Florida during various interglacial stages of the Pleistocene and is still present in parts of it. Parker (Parker and others, 1955, p. 819-821) discussed the effects of residual sea water in the Everglades area and indicated that this source of salt water caused little or no contamination of ground water in the Oakland Park area; however, ground water in the Everglades area west of Oakland Park has chloride concentrations greater than 30 ppm, the concentrations increasing in a westerly direction and with depth.

Salt-water encroachment from the ocean into the Biscayne aquifer is governed by the relationship of ground-water levels to mean sea level. In coastal areas the depth to salt water is related to the height of the fresh water above sea level. Under static conditions this relationship is that of a U-tube whose limbs contain liquids of different density, and it is expressed by the Ghyben-Herzberg principle (Brown, 1925, p. 16-17), as follows:

$$h = \frac{t}{g - 1}$$

where  $h$  is the depth of fresh water below sea level, in feet;  $t$  is the height of the fresh-water surface above sea level, in feet; and  $g$  is the specific gravity of sea water. If a specific gravity of 1.025 is assumed for sea water, then each foot of fresh water above sea level should indicate 40 feet of fresh water below sea level. In the field, this relationship is modified by mixing of fresh and salt water by dynamic hydraulic conditions, and by geologic conditions, but the relationship holds sufficiently well to be considered valid for most purposes.

Salt-water encroachment in Broward County has occurred chiefly in areas adjacent to major streams and uncontrolled parts of drainage canals that empty into the ocean. These waterways enhance the possibility of salt-water encroachment in two ways, as follows: (1) they lower ground-water levels, thereby reducing the fresh-water head that normally would oppose the inland movement of salt water, and (2) they provide a path for sea water to move inland during dry periods.

The extent of the encroachment at depth in the aquifer, in the Middle River and Cypress Creek basins, has not been determined because of the lack of deep wells in these areas. In order to determine accurately the extent of encroachment, several deep test wells would be required in the general area between U. S. Highway 1 and the Florida East Coast Railroad and in the area adjacent to the downstream parts of the Middle River. These wells would serve as outpost wells from which water

samples could be taken for periodic determinations of the chloride content of the ground water.

Considerable data are available in a similar area adjacent to the North New River in Fort Lauderdale. These data may illustrate some of the characteristics of salt-water encroachment in the area. Figure 18 shows the maximum chloride content recorded in surface-water and ground-water samples in eastern Broward County north of Dania. The ground-water samples were pumped from wells which are cased to within a few feet of their total depth; therefore, the depth of the sampling point is assumed to be approximately equal to the depth of the well. The data shown in the Oakland Park area represent samples taken during 1956-57 and those shown on the southern part of the map represent samples taken during the past 15 years (expanded from fig. 187 in Parker and others, 1955).

Along the north and south forks of the New River, salt water has migrated inland, at depth in the aquifer, as much as  $3\frac{1}{2}$  miles from the coast. The extent of salt-water encroachment at depth near the river is indicated by salinity data from well G-514 (fig. 18). The chloride content in samples taken at a depth of 177 feet in this well has ranged from 2,700 ppm to 4,900 ppm during the past 10 years. It can be seen, therefore, that salt water has encroached at depth, in this area, beyond the junction of the forks of the Middle River. Figure 19 shows the variation of chloride content in wells S-330 and S-830 caused by salt-water encroachment from the south fork of the New River during the period 1941-57 (adapted from Vorhis, 1948). These wells were sampled at depths of 35 feet and 118 feet, respectively, and are near the river, about  $5\frac{1}{2}$  miles inland from the coast. The data indicate that large and rapid changes in the chloride content of ground water are caused by salt-water encroachment from the New River.

In the Oakland Park area appreciable contamination by salt water was found in samples from wells S-1379 and S-1380, near the dam on the Middle River Canal, and in well S-1381, near the Fiveash water plant. Analyses of samples from wells S-1379 and S-1380 show chloride contents of 600 ppm and 820 ppm, respectively, and indicate contamination from the Middle River Canal during the prolonged dry period of 1955-56. A water sample collected at a depth of 240 feet in well S-1381 contained 2,640 ppm of chloride. The high chloride content in this sample indicates that salt-water encroachment has been occurring at depth in the aquifer as a result of lowered ground-water levels in the vicinity of the Middle River. These are the only data available that indicate extensive salt-water contamination in the Middle River basin. However, the high

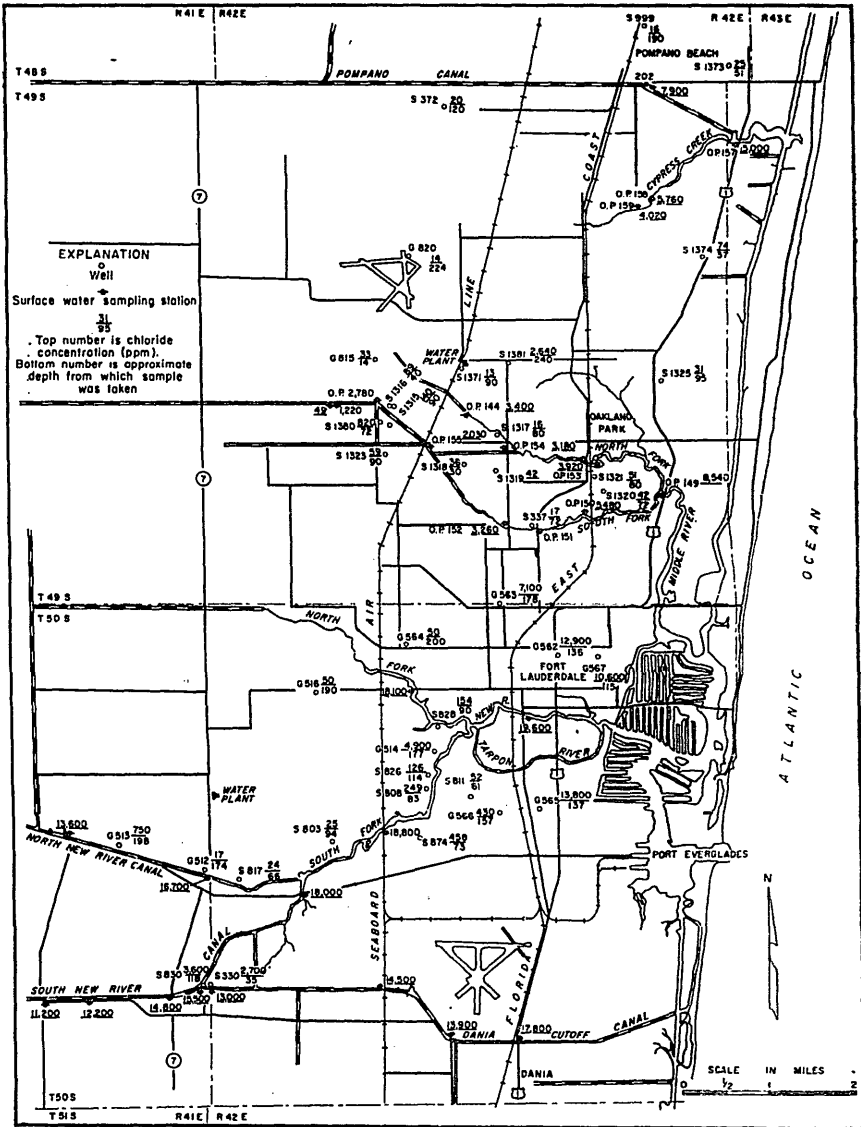


Figure 18. Map of eastern Broward County showing maximum chloride content recorded in water samples from wells and streams, 1941-57.

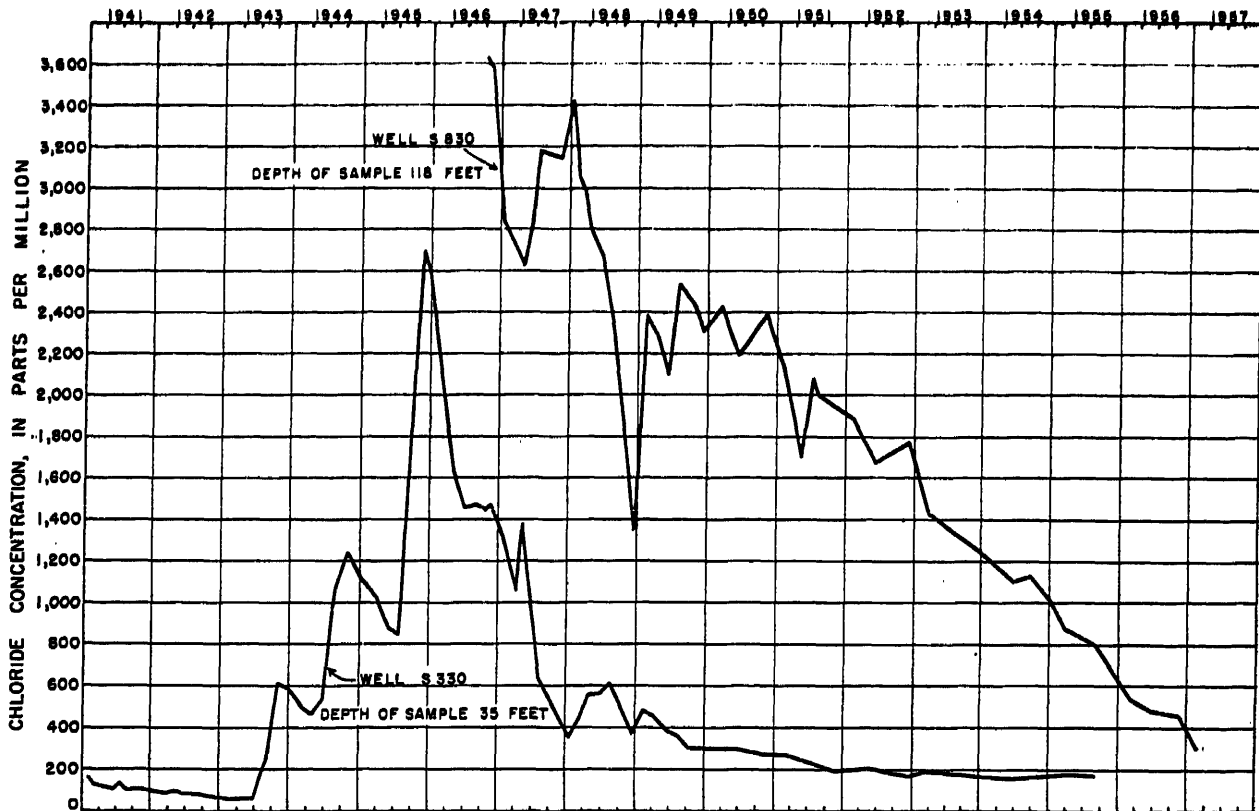


Figure 19. Chloride content of water from wells S-330 and S-830, at junction of South New River and Dania cutoff canals, 1941-57.

chloride content of the canal water (fig. 18) and the low ground-water levels shown on the contour map for August 7 (fig. 11) indicate that there might be considerable salt-water encroachment in this area.

In the area north of the Middle River basin, the available data indicate that salt-water encroachment has been limited to areas close to the Intracoastal Waterway or Cypress Creek. This limitation is partially due to the high ground-water levels maintained by the control near the mouth of Pompano Canal and to the fact that Cypress Creek is not an improved drainage channel such as the Middle River and the south fork of the New River.

### QUALITY OF WATER

The suitability of ground water for general use depends largely on the degree to which it fulfills the following requirements: (1) it must be safe to drink — that is, free from disease-causing bacteria and from excessive quantities of harmful minerals; (2) it should be clear and free from unpleasant taste or odor; (3) it should be relatively soft; and (4) it should not be corrosive or excessively damaging to metal surfaces. The first two requirements are most important for domestic or public supplies and the last two are most important for industrial supplies.

As ground water must seep through more than 100 feet of sand and rock to reach the producing zone of the Biscayne aquifer, it is generally free of dangerous bacteria and suspended material. However, it is affected by the composition and solubility of the rocks and sediments with which it has been in contact. As rainwater infiltrates into the aquifer it exerts a solvent action upon the rocks through which it passes. This action is aided by the presence of carbon dioxide, absorbed from the atmosphere and from organic material in the soil.

To determine the mineral constituents of ground water at different depths and locations in the area, chemical analyses were made of water samples from selected wells. The results of these analyses are shown in table 2. (See fig. 3 for well locations.)

The analyses of the water from these wells show the characteristics of a hard to very hard limestone water, suitable (naturally or with fairly simple treatment) for all ordinary uses. Using the amount of dissolved solids as an indication of the mineralization of the water, the samples from wells S-340, S-341 and S-1369 in the Pompano Beach area showed less mineralization than the samples from well G-820 in the Prospect well field and wells S-336 and S-337 in the Middle River basin. The test-well logs (figs. 4-7) show that the amount of limestone penetrated in wells S-998 and S-999 in Pompano Beach was much less than that

Table 2. Chemical Analyses of Water from Selected Wells  
(Chemical constituents in parts per million)

	City Well No. 1	City Well No. 6	Well G 820	Well S 1369 <sup>1</sup>	Well S 336 <sup>2</sup>	Well S 337 <sup>2</sup>	Well S 340 <sup>2</sup>	Well S 341 <sup>2</sup>	Well S 372 <sup>2</sup>
Silica (SiO <sub>2</sub> )	9.4	9.3	42	18					
Iron (Fe) <sup>3</sup>	.24	.02	.04	.01					
Calcium (Ca)	70	75	68	47	89	113	47	56	74
Magnesium (Mg)	1.8	1.2	9.8	1.1	3.1	3.1	2.3	2.5	2.7
Sodium and potassium (Na+K)	7.5	6.9	10.0	10.6	7.6	18	8.5	5.8	5.4
Bicarbonate (HCO <sub>3</sub> )	217	204	258	140	265	297	136	173	226
Sulfate (SO <sub>4</sub> )	1.0	6.0	1.8	14	5.8	1	1	1	1
Chloride (Cl)	14	12	14	16	20	64	15	14	15
Fluoride (F)	.3	.2	.2	.1					
Nitrate (NO <sub>3</sub> )	.1	.2	.5	.4					
Dissolved solids									
Residue on evaporation at 180°C.	221	234	287	182	256 <sup>4</sup>	345 <sup>4</sup>	165 <sup>4</sup>	164 <sup>4</sup>	209 <sup>4</sup>
Total hardness as CaCO <sub>3</sub>	182	192	210	122	235	295	127	150	196
Noncarbonate	4	25	0	8					
Color	15	10	5	5	130	50	20	20	40
Temperature (°F.)					77		76		
pH	7.5	7.9	7.9	7.8					
Specific conductance (micromhos at 25°C.)	372	378	420	291	468	643	268	307	389
Date of collection	Mar. 29 1957	Nov. 11 1956	July 9 1956	Sept. 10 1956	Nov. 19 1940	Oct. 18 1940	Nov. 29 1941	Oct. 18 1941	Oct. 18 1941
Depth of sample (feet below land surface)	130	130	224	190	60.9	72	170	189	120
Aquifer	Biscayne	Biscayne	Biscayne	Biscayne	Biscayne	Biscayne	Biscayne	Biscayne	Biscayne

<sup>1</sup> City of Pompano Beach supply well 3.

<sup>2</sup> Iron in solution at time of analysis.

<sup>3</sup> Parker and others (1955, p. 798).

<sup>4</sup> Sum of determined constituents.

in well G-820 in the Prospect well field and well G-563 near the south fork of the Middle River. Thus, the difference in the mineralization of the samples is probably related to the amount of limestone contacted by the water as it infiltrated down from the surface.

Hardness of water is generally recognized because it increases the consumption of soap. Also, hard water causes the formation of scale in steam boilers or other vessels in which the water is heated. Water having a hardness of less than 60 ppm is considered soft; 60 to 120 ppm, moderately hard; 121 to 200 ppm, hard; and more than 200 ppm, very hard and unsatisfactory for most uses unless treated. Generally, the ground water in the Oakland Park area ranges in hardness from about 120 to 200 ppm and may be used with or without treatment, according to the use.

Iron is one of the most noticeable constituents found in ground water in the Oakland Park area. In quantities of more than 0.5 to 1.0 ppm it will give the water a disagreeable taste, and in concentrations greater than 0.3 ppm will cause reddish-brown stain on clothing and fixtures. The iron content of the water differs from place to place and with depth, but it is not predictable. Iron may be removed easily by aeration and filtration from water that is to be used for large public supplies or industries, but it is more difficult to remove economically from water that is to be used for small domestic supplies. The analyses show iron in solution and do not include iron that may have precipitated between the time the sample was collected and the time of analysis.

Color in water is caused almost entirely by organic matter extracted from peat, vegetation, and similar organic materials and is often accompanied by tastes and odors from the same sources. These characteristics may not be harmful to persons using the water, but their psychological effects on the consumer make them undesirable in drinking water. The analyses showing a color higher than 20 (the concentration at which color is considered to become objectionable) were of water from relatively shallow wells or wells near to streams.

The pH indicates the degree of acidity or alkalinity of a water and is an important indication of its corrosive tendencies. A pH of 7.0 indicates neutrality, which means that the water is neither acid nor alkaline. Values below 7.0 denote increasing acidity; values above 7.0 indicate increasing alkalinity. The corrosiveness of water usually increases as the pH decreases. The pH of the samples ranged from 7.5 to 7.9, indicating that ground water in the area is moderately alkaline and should not be corrosive.

As the amount of chloride in ground water is used to indicate the

extent of salt-water encroachment from the ocean, samples were collected from several wells in the Oakland Park area and analyzed for chloride content. The data from the analysis of these samples are shown in figure 18.

### QUANTITATIVE STUDIES

Knowledge of the hydraulic properties of the aquifers of an area is essential to the evaluation of the ground-water resources. The principal hydraulic properties of an aquifer are its capacities to transmit and store water. These properties are generally expressed as the coefficients of transmissibility and storage.

The coefficient of transmissibility is a measure of the capacity of an aquifer to transmit water. In customary units it is the quantity of water, in gallons per day (gpd), that will flow through a vertical section of the aquifer 1 foot wide and extending the full saturated height, under a unit hydraulic gradient, at the prevailing temperature of the water (Theis,

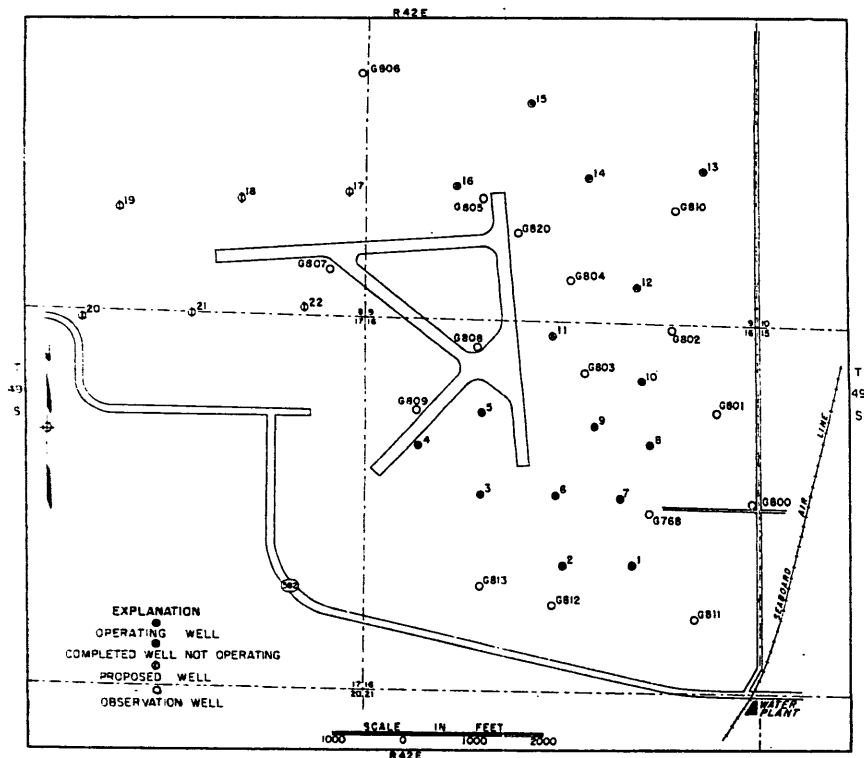


Figure 20. Map of Prospect well field showing layout of municipal supply wells and observation wells.



1938, p. 892). The coefficient of storage is a measure of the capacity of an aquifer to store water and is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

In this area, the best opportunity for making pumping tests to obtain these aquifer coefficients was through the use of municipal supply wells in the Prospect well field. Figure 20 shows the layout of the municipal supply wells and observation wells in this well field. Two tests were run in this field by observing the effects on water levels of changes in the rate of pumping. A 12-hour pumping test was made on August 8, 1956, using 10 city supply wells, each being pumped at the rate of 820 gpm. City supply wells 3, 4, and 5 were operated for eight hours prior to the start of the test, and then pumping was begun in the remaining seven wells in the field at the beginning of the test. Water-level recorders were operated on wells G-768 and G-820 beginning June 15, 1956, and August 6, 1956, respectively, and tape measurements of the changes in water level were made in well G-803 during the test. Well G-820 is a 4-inch well, drilled to a depth of 224 feet, and the casing was dynamited at a depth of 215 feet to open it to the aquifer. Well G-768 is a 6-inch well, 91 feet deep, cased to an approximate depth of 80 feet; and well G-803 is a 1½-inch sandpoint well 16 feet deep, cased to 14 feet below the land surface and screened from 14 to 16 feet below the land surface. A drawdown of 1.0 foot was recorded in well G-768, whereas no measurable drawdown occurred in well G-803 during the test. If drawdown affected the water level in well G-820 it was apparently overshadowed by the natural decline of the water table and fluctuations caused by changes in barometric pressure. Figure 21 shows the fluctuation of the water level in well G-768 before and during the test.

On March 27, 1957, a 36-hour test was made using city wells 11, 12, and 14 (fig. 20) as observation wells. Supply wells 1, 2, and 3 were operated for 20 hours preceding this test and then pumping was started in wells 8, 9, and 10. Each of these wells is pumped at approximately 820 gpm. A water-level recorder was in operation on well G-820 during the 20-hour period before the test, and recorders were operated on city wells 11, 12, and 14 during the test. Drawdowns of approximately 0.2 foot and 0.4 foot were recorded in city wells 11 and 12, respectively, whereas city well 14 and well G-820 showed no appreciable drawdown. All the city supply wells are finished with well screens 20 feet long which extend to a depth of approximately 130 feet. The water pumped in both tests was discharged into the city mains so that no complication was caused by infiltration of the pumped water near the wells.

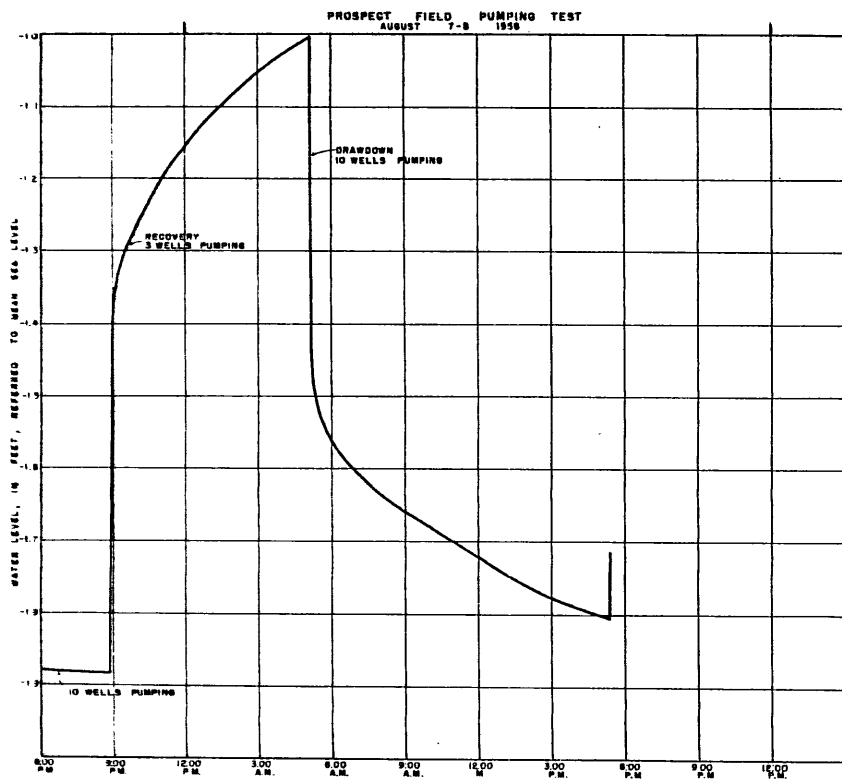


Figure 21. Hydrograph of well G-768, in the Prospect well field, during pumping test, August 7-8, 1956.

Water-level and pumping-test data indicate that under static (non-pumping) conditions the Biscayne aquifer exhibits different characteristics than it does under pumping conditions. Under static conditions, the water level in a shallow well will stand at the same altitude as the water level in an adjacent deep well, suggesting that the aquifer is under non-artesian conditions. However, when the deep, highly permeable zones of the aquifer were pumped, water levels in deep wells as much as 1,000 feet away showed an immediate rapid decline. Water levels in shallow wells much closer to the pumping wells showed no immediate change during the test, but they do show a long-term drawdown of several feet. (See contour maps, figs. 11, 12 and 13.) Thus, in pumping tests of short duration the zone in which the supply wells are developed reacts as an artesian aquifer overlain and partly confined by a leaky roof of less permeable beds (fig. 5). The fact that the water levels of deep wells

respond readily to changes in barometric pressure is further evidence of artesian conditions.

Data from the aquifer tests were first analyzed by the Theis non-equilibrium method (Theis, 1935), which assumes the following conditions: (1) the aquifer is without limit in a lateral direction; (2) the aquifer is homogeneous throughout and transmits water equally readily in all directions at all times; (3) the pumped well completely penetrates the aquifer; (4) the pumped well has an infinitesimal diameter; and (5) water taken from storage in the aquifer is discharged instantaneously with the decline in head. Although not all these assumptions were fulfilled, this method was useful in that it indicated that the pumped zone was receiving recharge during the test.

Further analysis was made by means of a leaky-aquifer type curve developed by H. H. Cooper, Jr., of the U. S. Geological Survey, Tallahassee, Florida, (personal communication) and by a method outlined by Hantush (1956) which is based on the theory of ground-water flow in a leaky artesian aquifer (Hantush and Jacob, 1955). Figure 22 shows radial flow in and leakage to an ideal leaky artesian aquifer (Jacob, 1946). These methods involve the same assumptions of the Theis method, but, in addition, they assume leakage into the aquifer through a semiconfining bed and a constant head in the bed supplying the leakage. In treating

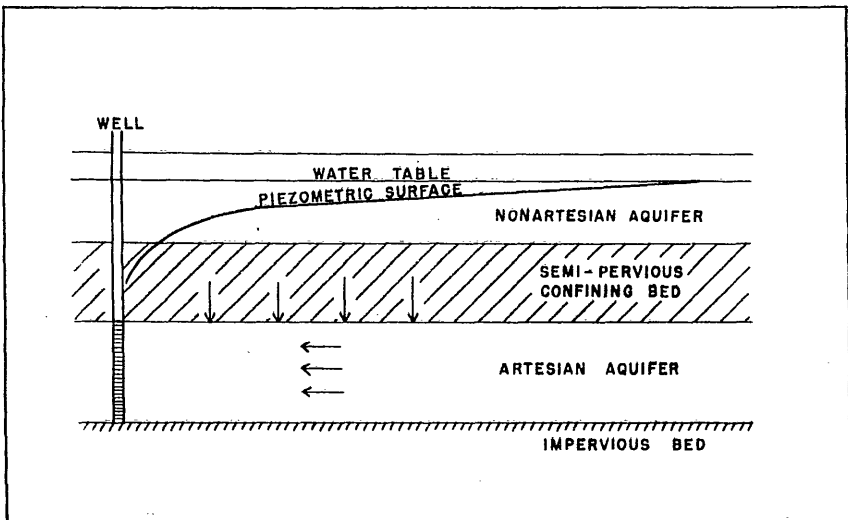


Figure 22. Idealized sketch showing flow in a leaky aquifer (modified from Jacob, 1946, p. 199).

problems in leaky systems these methods add a third aquifer coefficient, called the leakage coefficient, which indicates the ability of the semi-confining bed to transmit water upward from or downward into the aquifer being tested. This coefficient may be defined as the quantity of flow that crosses a unit area of the interface between the main aquifer and its semiconfining bed if the difference between the head in the main aquifer and the bed supplying the leakage is unity. It is obvious that the head in the bed supplying the leakage in the well field area is not constant during long periods, but water levels in shallow wells in the well field were very nearly constant during the pumping tests. The water level in well G-803 rose 0.02 foot during the 16 hours preceding the first pumping test and declined 0.03 foot during the first five hours of the test.

Computation of the aquifer coefficients is complicated not only by vertical leakage in the stratified material but also by the possibility of inducing recharge from canals and quarries and the limitations on the accurate measurement of the small drawdowns.

The coefficients of transmissibility obtained ranged from 2,000,000 to 3,000,000 gpd per foot. The storage coefficient was approximately 0.015, and the leakage coefficient was about one gpd per square foot per foot of vertical head.

It is apparent from the large cone of depression shown in figures 11, 12, and 13 that long-term pumping has caused considerable unwatering of the beds overlying the pumped zone in the aquifer. Thus, the drawdown caused by large-scale pumping from the deep zone is reflected at the water table, and it is controlled by the coefficients of transmissibility and storage of both the pumped zone and the overlying beds.

An approximate value for the coefficient of transmissibility, under equilibrium conditions, may be calculated by substituting the average hydraulic gradient at points around the cone of depression and the average pumpage from the well field in the formula  $Q = TIW$  (a modified expression of Darcy's law for ground-water flow) where:

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

The record of water-level fluctuations in well G-768 during the period July 12-24 (fig. 23) indicates that water levels in the well field area had reached approximate equilibrium for the rate of pumping at that time. A coefficient of transmissibility of about 1,000,000 gpd per foot was

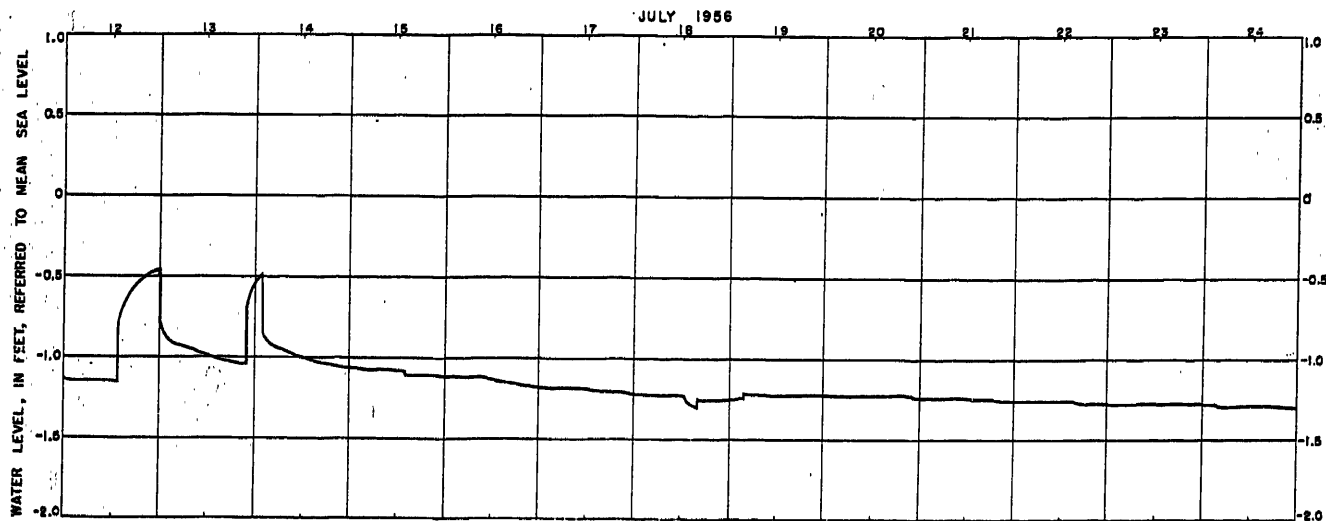


Figure 23. Hydrograph of well G-768, in the Prospect well field, showing effect of pumping in the well field.

obtained from the above formula by using the water-level data from the contour map of August 7, 1956, and the average pumping rate for the period July 25-August 7, 1956 (10.0 mgd). This figure is on the low side because evapotranspiration was not considered. The area within the contour used (sea level) is about 34,000,000 square feet. Evapotranspiration of ground water is estimated at 6 inches per month or 0.2 inch per day. Natural water loss for the area is then about 4.2 mgd. By use of the combined discharge of 10.0 mgd by pumping and 4.2 mgd by evapotranspiration, the coefficient of transmissibility is computed to be about 1,500,000 gpd per foot.

#### GROUND-WATER USE

Wells supply most of the water for public, domestic, irrigation, and industrial use in the Oakland Park area. Until recent years the area was relatively undeveloped and ground-water withdrawals were small. Since about 1950, however, the growth of population and industry in the area has been extremely rapid, and ground-water use has increased correspondingly.

The largest pumpage is that from the Prospect well field, which yielded about 10.0 mgd in 1956. When all proposed wells are in operation, the pumpage from the field will be about 20 mgd. Separate water-supply systems have been developed for several large housing developments in the area, and many residents have private wells for domestic use and lawn sprinkling. In the area west of Oakland Park, several large farms use ground water for irrigation. Generally, the peak pumping for municipal supplies and irrigation occurs during December through June, as these months include both the tourist season and the dry season. The use of ground water by industries is growing rapidly, especially in areas adjacent to the two railroads.

#### CONCLUSIONS

The Biscayne aquifer is the source of all fresh ground water in the Oakland Park area. The water in the aquifer comes from local rainfall or from surface water brought into the area by canals. It is generally of good quality except for hardness and color. The Biscayne aquifer is composed of permeable marine deposits — chiefly sandy limestone, calcareous sandstone, and quartz sand — which extend from the land surface to a depth of more than 215 feet below mean sea level. The components of the aquifer differ from place to place, but, in general, the amount of sand decreases with depth and most of the consolidated rocks occur at depths greater than 60 feet.

Wells used for small water supplies generally tap thin beds of limestone at depths ranging from 60 to 80 feet, whereas most wells used for large supplies are developed in highly permeable limestones and sandstones of the Anastasia and Tamiami formations, at depths greater than 100 feet.

There is a natural seaward water-level gradient in the Oakland Park area, but it is greatly influenced by pumping in the Prospect well field and by water-control structures in the Middle River and Pompano canals. Ground-water levels in areas downgradient (east) from these canal controls are lowered by pumping and by ground-water drainage into the canals, whereas water levels in areas upgradient (west) from the controls remain high owing to ground-water recharge from the canals.

Salt-water encroachment from the ocean is the chief factor affecting the use of ground water in the Oakland Park area. This encroachment is governed by the relationship of ground-water levels to mean sea level and may occur in two ways: (1) direct inland movement of salt water at depth in the aquifer, and (2) the movement of salt water from tidal reaches of canals into the aquifer during low-water periods. Determinations of the chloride content of water from the deep wells in the area indicate that under the conditions in 1956 there is little danger of salt-water encroachment except in areas adjacent to Cypress Creek and the Intracoastal Waterway and in the Middle River basin. Direct contamination from the Middle River Canal has occurred in wells only a mile east of the dam. Further encroachment could be retarded by placing and operating controls downstream from the present location of the control in the Middle River Canal and by reducing drawdowns in the Prospect well field and vicinity.

Pumping tests in the Prospect well field and areawide water-level data indicate that large quantities of ground water are available for future development, especially in areas west of the controls on the two major canals.

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