

**STATE OF FLORIDA
STATE BOARD OF CONSERVATION**

J. T. Hurst, Supervisor

FLORIDA GEOLOGICAL SURVEY

Herman Gunter, Director

REPORT OF INVESTIGATION NO. 6

**GEOLOGY AND GROUND WATER OF THE
FORT LAUDERDALE AREA, FLORIDA**

By

Robert C. Vorhis

PREPARED BY THE U. S. GEOLOGICAL SURVEY
IN COOPERATION WITH THE FLORIDA GEOLOGICAL SURVEY

Tallahassee, Florida

1948

Reprint 1955

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CONTENTS

	Page
Introduction.	1
Geography	3
Location and area	3
Topography and drainage	3
Climate	5
Population and development	6
Development of municipal water supplies at Fort Lauderdale	6
Geologic formations and their water-bearing characteristics.	11
Tertiary system.	11
Miocene series.	11
Hawthorn formation.	11
Pliocene series	12
Tamiami formation.	12
Caloosahatchee marl	13
Quaternary system	14
Pleistocene and Recent series.	14
Fort Thompson formation	14
Miami oolite	14
Pamlico sand	16
Lake Flirt marl.	17
Recent organic soils	17
Present investigations	18
Test-well studies.	19
Value and uses of test wells	19
Test-well drilling	19
Results and interpretations	21
Water-level studies	23
Water-stage recorders	23
Observation well drilling program	23
The leveling program	23
Results and interpretations	25
Transmissibility	29
Salt-water encroachment.	31
Summary and conclusions	37
Bibliography.	41

ILLUSTRATIONS

Plate	Page
1 Map of southern Florida showing area of this report.	4
2 Average daily pumpage, Fort Lauderdale well field.	8
3 Geologic cross-section	10
4 A--Miami oolite north of Fort Lauderdale. B--Water-stage recorder on well G221 near Fort Lauderdale water plant.	15
5 A--Drilling well 513. B--Water-stage recorder on well S 329.	20
6 Hydrograph of well S 329.	24
7 Water-table contour map of Fort Lauderdale area for March 1, 1947	26
8 Water-table contour map of Fort Lauderdale area for May 24, 1947	27
9 Water-table contour map of Fort Lauderdale area for June 13, 1947	28
10 Time-drawdown graph for well G221	30
11 Chloride graphs	35
12 Map of Fort Lauderdale well field and adjacent areas	43

GEOLOGY AND GROUND WATER
of the
FORT LAUDERDALE AREA, FLORIDA 1/

By
ROBERT C. VORHIS

INTRODUCTION

The City of Fort Lauderdale, being faced with the problem of a greatly increased demand for water, has had need for geologic and ground-water data on which to base engineering decisions concerning the adequacy of the present well field and possible locations for an additional wellfield. In order that the data might be collected, the City of Fort Lauderdale, in October 1946, requested an investigation by the U. S. Geological Survey and the study was started immediately. Some of the work has been done as a part of the southern Florida water-resources investigations that are being made by the U. S. Geological Survey in cooperation with the Florida Geological Survey, but most of the cost has been borne by the City of Fort Lauderdale.

Little detailed work relating to ground-water conditions had been done previously in the Fort Lauderdale area. An annotated bibliography of articles with material relating specifically to geology and ground water of this area is included at the end of this report.

The investigation was directed toward assembling, organizing, and interpreting geologic and hydrologic data concerning the following:

- (1) Areal extent and vertical distribution of water-bearing formations (aquifers).

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- (2) Hydrologic and lithologic characteristics of these aquifers.
- (3) Quality of water at various depths in aquifers.
- (4) Present extent of and probable future salt-water encroachment.
- (5) Elevation and shape of the water table in the well-field area at various times of the year.
- (6) Effect on the water table of pumping from wells, as shown by the mapped cone of depression around the well field.
- (7) Effect on the water table of drainage ditches and other developments.
- (8) Average height of water table at various places in the area.

The office and field work was done under the general administration and supervision of A. N. Sayre, Geologist in Charge of the Ground Water Division, U. S. Geological Survey, Washington, D. C., and Herman Gunter, Director, Florida Geological Survey, Tallahassee, Florida. Immediate supervision of the investigation and of the writing of this report was by Garald G. Parker, District Geologist, Miami, Florida. Additional help and advice was given by Nevin D. Hoy, Geologist, M. A. Warren, Hydraulic Engineer, both of the Miami office, and H. H. Cooper, Jr., District Engineer of the Tallahassee office. Water analyses were made by Berton Law, Chemist, in the Miami laboratory of the U.S. Geological Survey and by Mrs. Patricia Sherwood, who was then City Chemist of Fort Lauderdale. The leveling was done under the direction of Kenneth L. Jackson, Engineering Aide. Illustrations were drafted by Ross A. Ellwood, Engineering Draftsman, and the typing was done by M. Marvine Melton and Laura G. Pollard.

Mr. J. H. Philpott, former City Manager of Fort Lauderdale, Mr. Charles L. Fiveash, Superintendent of the Department of Water and Sewers, Dr. A. P. Black, Consulting

Chemist, Gainesville, Florida, and Messrs. L. C. Coe and Guy Tanner, Miami, Florida, well-drilling contractors, have been especially helpful and deserve much credit for the prosecution of the studies. In addition, grateful acknowledgement is made for cooperation and assistance given by officials and many citizens of the City of Fort Lauderdale.

GEOGRAPHY

LOCATION AND AREA

Fort Lauderdale is on the Atlantic Coastal Ridge, 25 miles north of Miami. This ridge lies between the muck lands of the Everglades on the west and the narrow mangrove swamps along the Atlantic Ocean on the east.

Most of the field work in connection with this report was done in the region to the west of Fort Lauderdale as shown on plate 1. The area of intensive field work is centered about the grounds of the Fort Lauderdale Golf and Country Club, in which the city well field is located (see pl. 12).

TOPOGRAPHY AND DRAINAGE

The Atlantic Coastal Ridge near Fort Lauderdale is approximately 5 miles wide and has very little relief, averaging only 8 feet above mean sea level, the highest elevation rising to about 20 feet.

Oolitic limestone, sand, muck, and marl are the geologic materials outcropping in the Fort Lauderdale Area. The sand and oolitic sands are very permeable and permit rain water to penetrate downward rapidly. Drainage is largely underground, thus accounting for the scarcity of surficial drainage channels. The principal one is New River (see pl. 12) a shallow forked stream which leads about $6\frac{1}{2}$ miles inland and cuts through the coastal ridge to the Atlantic Ocean.

North Fork of New River is relatively unimproved and uncontrolled. Its tidal portion extends upstream to a point approximately $2\frac{1}{2}$ miles northeast of the well field, and salt water is free to advance upstream as far as the tides and

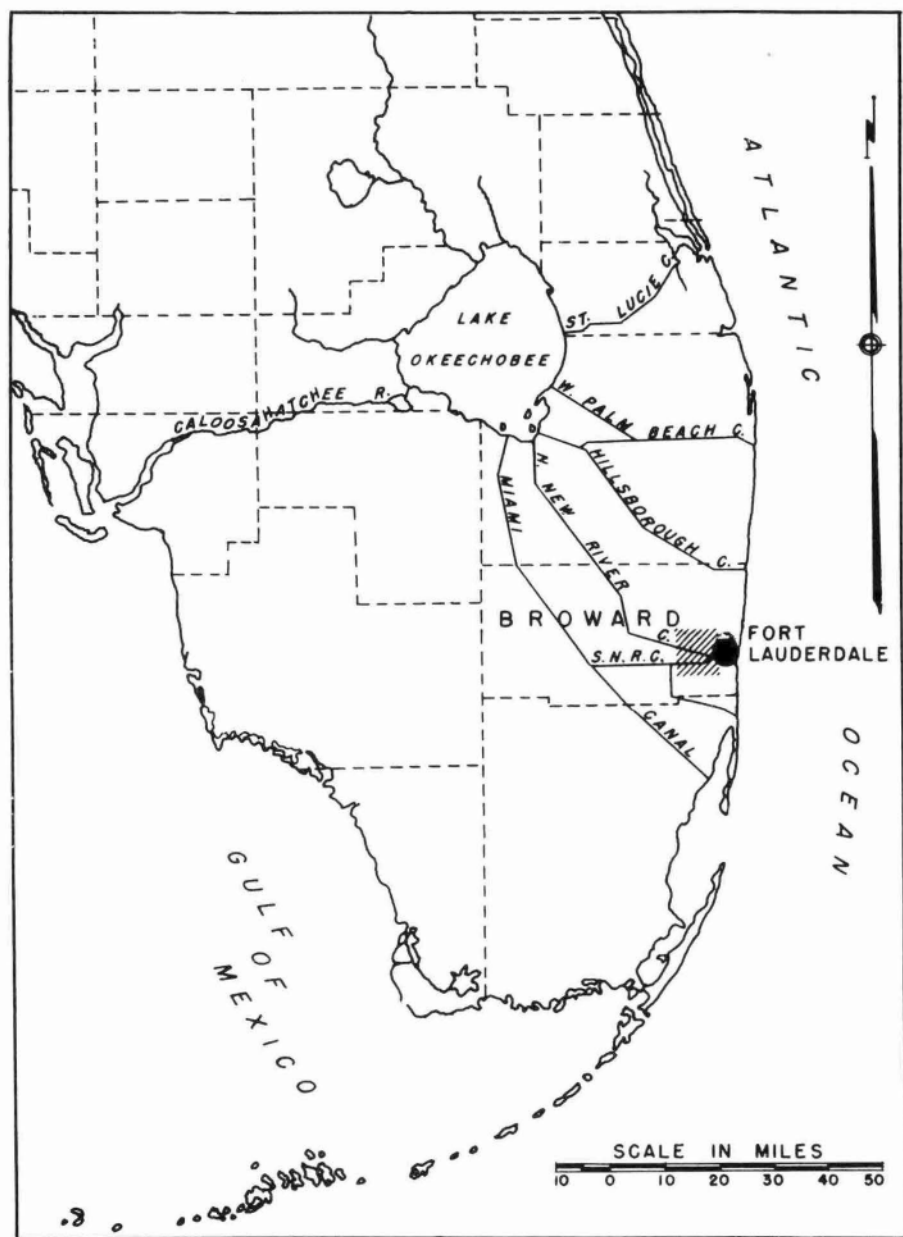


PLATE 1

MAP OF SOUTHERN FLORIDA SHOWING
AREA OF THIS REPORT

PLATE 1

the fresh-water flow in the fork permit. The bed of North Fork is rather heavily silted in its upper reaches and is therefore relatively impermeable; thus, the salt water that occasionally extends to these reaches does not greatly contaminate the surrounding ground water.

South Fork of New River is maintained as a navigable stream. Portions of the channel have been dredged and numerous boat basins have been constructed, the largest of which is shown near the bend in Riverland Road on plate 12.

Middle River, a sluggish, shallow forked stream about 2 miles long, empties about 3 miles north of the mouth of New River into a salt-water lagoon in which the Intra-coastal Waterway has been developed.

Between 1907 and 1918 most of the major drainage canals of the Everglades were dredged. One of these, the North New River Canal, empties into the South Fork of New River; and another, the South New River Canal, discharges both into the South Fork of New River and into the Dania cut-off Canal.

CLIMATE

The climate of Fort Lauderdale is semitropical. The average annual rainfall during a 31-year period of record is 65.19 inches, and the heaviest rainfall occurs between May and November. The prevailing wind is from the southeast and has an approximate average velocity of 13 miles per hour. Transpiration, evaporation, and humidity are high the year around.

The average annual temperature is 75.2 degrees Fahrenheit. The average monthly minimum and maximum temperatures are 68.5 and 82.0 degrees F. and occur in January and August, respectively. The temperature of most samples of ground water collected from depths below 30 or 40 feet is very close to the mean temperature, or 76 degrees. The temperature of samples from shallower depths varies with the seasons, ranging from about 70 to 82 degrees.

POPULATION AND DEVELOPMENT

The population of Fort Lauderdale has increased markedly in recent years. The census of 1920 listed 2,065 inhabitants; in 1930 the population was 8,666; in 1940 it was 17,996; and a census in the summer of 1945 placed the total permanent population at 26,185. The population is greatly increased each winter by the influx of tourists and by many home-owners who live there only during the winter months. The Fort Lauderdale Chamber of Commerce estimates that the total of winter residents in 1946 was between 60,000 and 65,000.

The rapid growth in population that has already occurred has taxed the capacity of the present water treatment plant, and has made necessary the construction of an addition. This will more than double the original capacity of the plant and will permit greater consumption by present users as well as permitting water to be supplied to those parts of the city to which mains have not yet been extended.

DEVELOPMENT OF MUNICIPAL WATER SUPPLIES

AT FORT LAUDERDALE

For many years the water supply for Fort Lauderdale was drawn from two wells, 6 inches in diameter and approximately 60 feet deep, located to the northwest of the intersection of Andrews Avenue and 2nd Street S. W. Mr. Charles Fiveash, Superintendent of The Department of Water and Sewers, reports that these wells would yield considerably more at high tide than at low tide suggesting that river water might be able to enter the wells. Inasmuch as New River was polluted with considerable amounts of untreated sewage, it was decided to develop a new well field and locate it sufficiently far to the west to be free from the possibility of pollution. Accordingly, the two original wells were abandoned in June 1926. As an interim supply during the construction of the present water plant, two wells (S 894 and S 895 on plate 12), one 10 and the other 12 inches in diameter, were drilled to depths of 90 and 104 feet, respectively, at Broward Boulevard and 14th Avenue. These wells served as the source of supply from June 1926 until December 1927, when the present well field and plant,

to the west of Fort Lauderdale, were put in operation. The 12-inch well (S 895) is still maintained as a standby for emergency use.

The present water plant was completed late in 1927 and has been treating all water since supplied to the city. Additional treatment facilities now under construction will raise the capacity of the plant from 6 to 14 million gallons a day.

The city supply wells of Fort Lauderdale are in two different but adjacent groups and are therefore generally thought of as composing one well-field area. The first group consists of nine wells on the grounds of the Fort Lauderdale golf course. The golf course is near the western shoulder of the Atlantic Coastal Ridge, approximately 7 miles from the ocean and 1 1/4 miles north of the North New River Canal. The second group is composed of two wells at the municipal water plant on the crest of the Atlantic Coastal Ridge, approximately 1 mile southeast of the first group. Land-surface elevations in the well-field area average about 9 feet above mean sea level.

The 11 wells are gravel-packed and are pumped at a total maximum rate of approximately 6,600 gallons per minute. This is by no means the maximum capacity of the wells, a figure that has never been determined, but the present pumpage certainly is only a fraction of what these wells would yield if pumped to capacity. The City Water Department has not deemed it wise to pump these wells at greater rates for fear of causing salt-water encroachment.

Eight wells, Nos. 1, 2, 3, 4, 5, 6, 11, and 12, were drilled in 1927; Nos. 7 and 8 were drilled in 1940; and Nos. 9 and 10 were drilled in 1945. Well 1 does not contribute to the City supply but is used exclusively for watering the golf course. It was drilled and developed in the same manner as the other wells. Wells 11 and 12 are the two that are located a hundred feet east of the water plant (see pl. 12).

All except No. 11 are 12-inch wells, and all except Nos. 8, 11, and 12 were finished with casings set approximately 80 feet below land surface. All had 10 feet of open hole (unscreened) below the bottom of the casing. Well 12 was

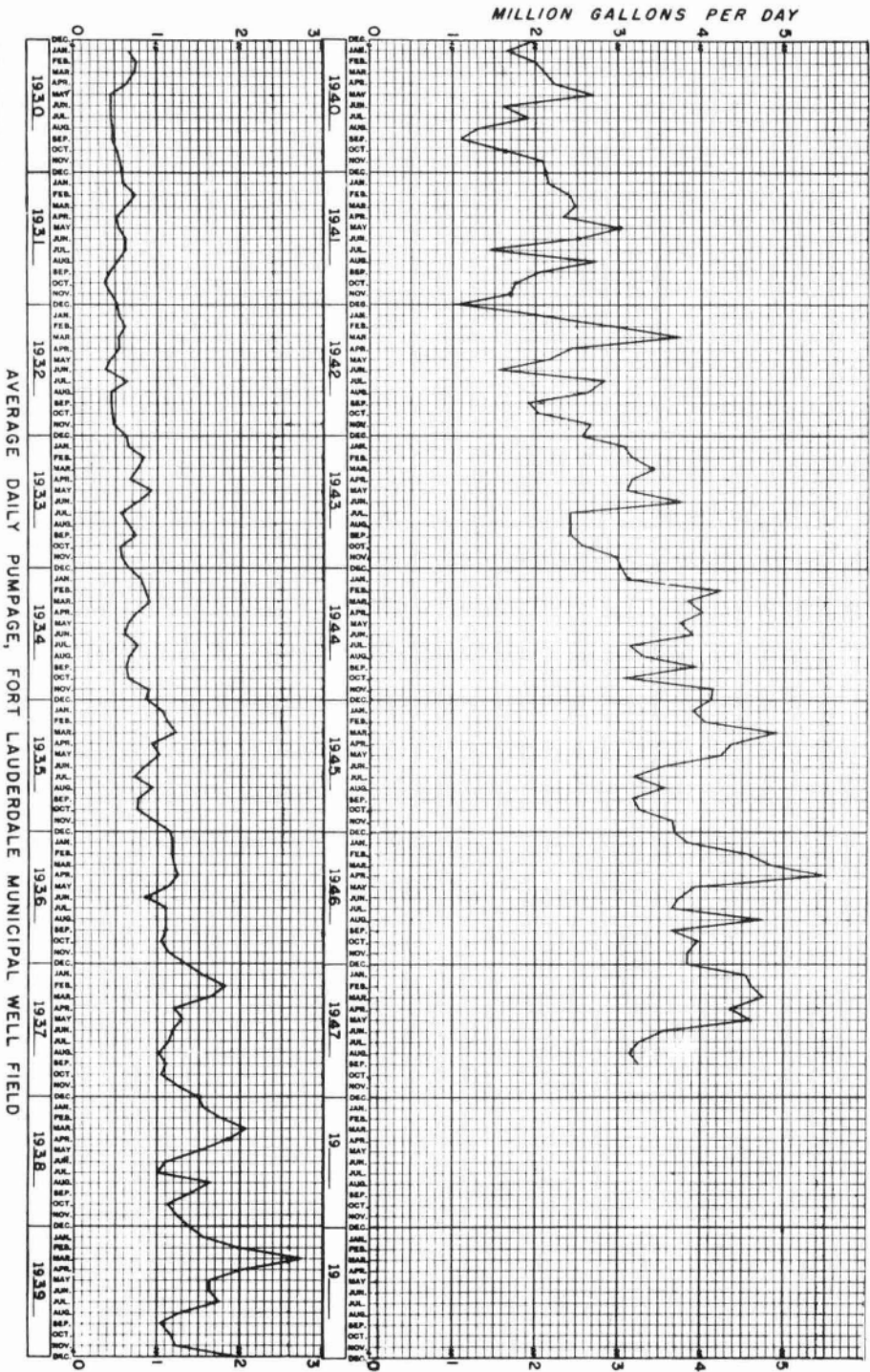


PLATE 2

cased to a depth of 92 feet below land surface. Mr. Fiveash reports that at the time the wells were completed the water table averaged about 3 feet below land surface or 6 feet above sea level.

In 1940, two new gravel-packed wells 12 inches in diameter, (Nos. 7 and 8), were completed, the casing being seated 80 feet below land surface in No. 7 and 62 feet below land surface in No. 8. A 6-inch diameter screen 35 feet long, was installed below the casing of each well.

During 1940 the older wells (all other than 7 and 8) were deepened 45 feet, which allowed the insertion of 35 feet of screen with 10 feet of blank pipe below the screen. All the wells were then gravel-packed.

The daily pumpage from these wells has ranged in the period from January 1930 to the present from a low of 234,000 gallons per day to a maximum of 6,615,000 gallons per day. The average daily pumpage has gradually increased over the years, as shown in plate 2, a graph of the average daily pumpage from the Fort Lauderdale municipal wells during the period 1930-1947. Records are not available for pumpage prior to 1930.

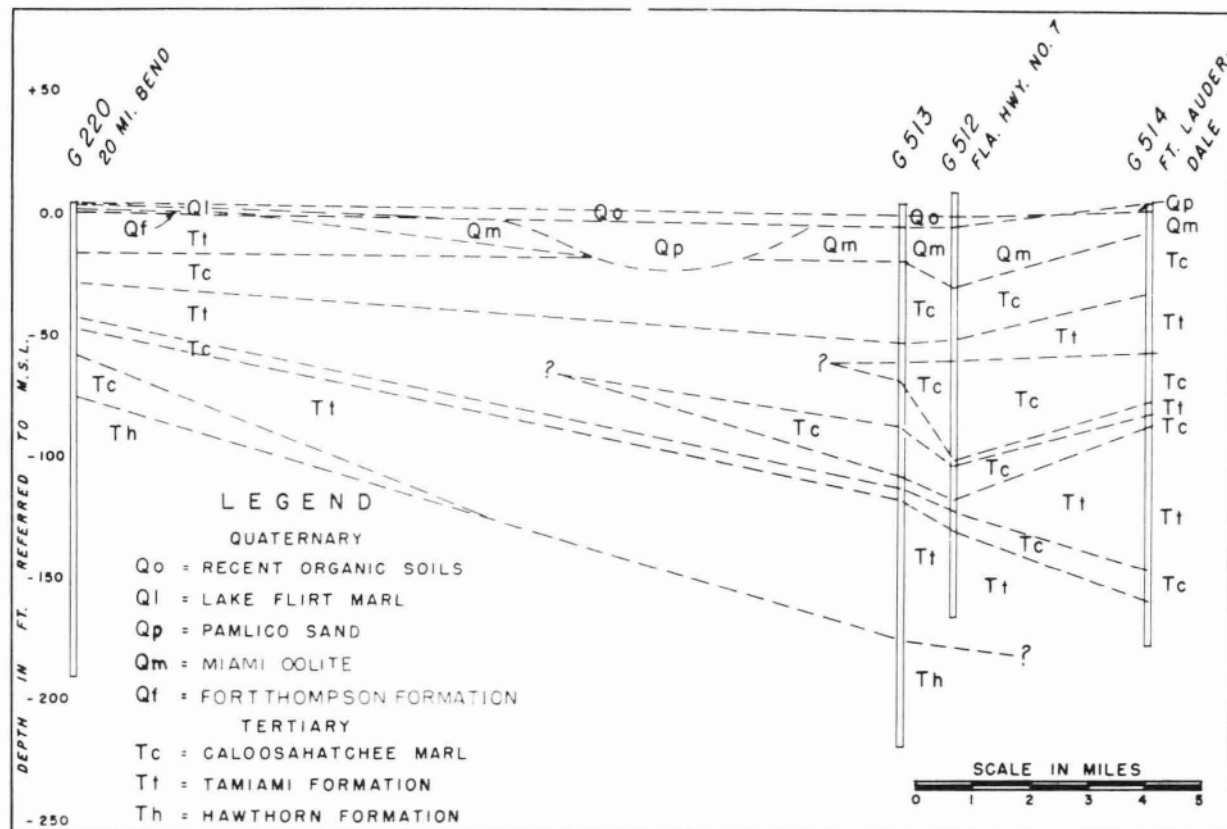


PLATE 3 EAST-WEST CROSS-SECTION ALONG NORTH NEW RIVER CANAL FROM
 20 MILE BEND TO FORT LAUDERDALE

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS

The surface materials of southeastern Broward County in the vicinity of Fort Lauderdale are formed largely by a mantle of several feet of sand (Pamlico sand) of late Pleistocene age. On the western edge of the Atlantic Coastal Ridge muck is found, especially in the vicinity of natural drainage channels. The mantling nature of these materials plus the low relief and lack of any deep cuts in the rock make it impossible to determine the geologic nature of the region from rock exposures. Examination of shallow exposures in the banks and spoil of the Everglades drainage canals and study of well-log data are the only reliable sources of geologic information. An east-west cross section along the North New River Canal from Fort Lauderdale to 20-Mile Bend is shown in plate 3.

In southeastern Florida strata older than the Hawthorn formation are of no importance as a source of potable water because the water in older strata is highly mineralized. The water is under artesian pressure but its quality is such that no use has been found for it, except for limited row-irrigation of garden vegetables and lawn sprinkling. It corrodes pipe so rapidly that it has been found to be not economically profitable to make use of the artesian pressure. All the known pre-Hawthorn strata have these same water-bearing characteristics. Inasmuch as their water is unusable for public supply these formations are not discussed in this paper.

Tertiary System

MIOCENE SERIES

HAWTHORNE FORMATION

In southern Florida the Hawthorn formation is composed predominantly of greenish-colored sediments that were laid down in a shallow, warm transgressing sea which flooded an

eroded land surface. Thus, the lower contact is unconformable. These marine deposits may be blue-green clay, gray-green marl, or varying shades of greenish sand. The change to greenish-colored sediments gives a sharp contrast with the predominantly buff to gray color of the overlying beds and makes for easy identification of the upper contact.

In the coastal area the Hawthorn formation is about 400 to 600 feet thick. Because it is composed largely of clay and marl, the formation is relatively impermeable and therefore acts as an aquiclude (non-water-bearing bed) between the highly mineralized artesian water of the underlying Eocene and related limestones and the fresh water in the overlying formations of Pliocene and Pleistocene age. Locally, wells may be developed in the Hawthorn but the water yielded is generally too highly mineralized for most purposes and occurs in rather limited quantities.

The water from the Hawthorn formation is significantly different from water of the overlying formations. It has more dissolved solids, especially of magnesium, sodium, potassium, and sulfate. The water is generally too highly mineralized to be potable but is suitable for other purposes, such as use by stock and for irrigation.

PLIOCENE SERIES

TAMIAMI FORMATION

The Tamiami formation is named for deposits "composed principally of white to cream-colored calcareous sandstone, sandy limestone, and beds and pockets of quartz sand" (Parker 1944, p. 64).

Near Fort Lauderdale the Tamiami formation interfingers with the contemporaneous Caloosahatchee marl (see description of Caloosahatchee marl below). Inasmuch as the Tamiami has no fauna distinct from faunas of the other Pliocene formations of southern Florida, it is impossible to distinguish the Tamiami except by lithologic characteristics. For this reason the cavernous sandy limestones and

calcareous sandstones of Pliocene age are considered to be Tamiami.

At Miami the Tamiami formation averages about 100 feet thick. It has been found to be one of the most productive water-bearing formations ever investigated by the U.S. Geological Survey, ranking with coarse, clean, well-sorted gravel in its capacity of transmitting water (Parker and Cooke, 1944, p. 65). In Broward County this formation is cavernous and permeable but the interfingering with the sand of the Caloosahatchee marl makes for a lower yield than in Dade County, where there is little such interfingering.

Water from this aquifer is generally very good in quality except in zones where salt-water contamination has occurred.

CALOOSAHATCHEE MARL

The Caloosahatchee marl underlies most of the Everglades and is found in the subsurface eastward under the Atlantic Coastal Ridge. According to Parker and Cooke (1944, p. 59) "The Caloosahatchee marl is a littoral (beach) and neritic (shallow, off-shore zone) deposit composed of sand, silt, clay, shells, and often enough calcareous material to make it a true marl. It contains many local beds or lenses of pure sand or clay, but the usual condition is just what one would expect of a deposit where constantly shifting currents acted upon a shallow sea bottom and shores adjacent to a low land mass that contributed only fine sediments." The large number of perfectly preserved shells is an indication that the water was deep enough to prevent breakage due to violent agitation by waves (Cooke, 1945, p. 214).

In the Fort Lauderdale area the Caloosahatchee marl occurs as gray to green marl, fine to medium-grained quartz sand, shelly sand, sandy marl, and a greenish clay. It interfingers with the contemporaneous Tamiami formation as shown in plate 3. In the logs of the test wells, the soft, relatively impermeable sandy, shelly and marly sediments of

Pliocene age are considered to be the Caloosahatchee, and the limy sandstones and sandy limestones to be the Tamiami. Separation by paleontological means is not possible, as the faunas of both are so similar.

The permeability of the Caloosahatchee marl varies with the lithology but is, for the most part, rather low. At some horizons the formation will yield no water. In the Fort Lauderdale area there are places where the Caloosahatchee marl is sufficiently permeable to yield small quantities of water suitable for domestic purposes.

Quaternary System

PLEISTOCENE AND RECENT SERIES

FORT THOMPSON FORMATION

The Fort Thompson formation consists of alternating fresh and brackish-water and marine shell marls and limestones. It underlies the Everglades soils in western Broward County (see pl. 3) but is not found in the vicinity of Fort Lauderdale. It lies unconformably upon the Tamiami formation and Caloosahatchee marl in the Everglades north of the latitude of Fort Lauderdale and is overlain unconformably by the Lake Flirt marl.

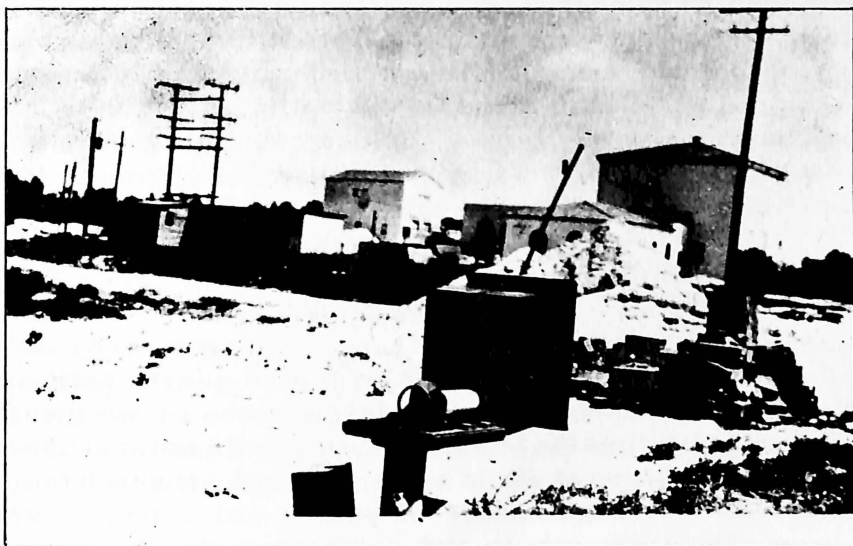
MIAMI OOLITE

The Miami oolite is named for deposits of permeable sandy, oolitic limestone in southern Florida. Weathering has perforated the oolite with vertical solution holes which have since been partially or completely filled with sand washed in from above. This causes the formation now to be sandier than it was when originally deposited (see pl. 4A).

The thickness may range up to about 30 feet. The oolite rests on a gently undulating, wave-planed platform sloping eastward; this, along with surficial inequalities, makes for variable thickness. The original deposition was in the form of a broad, slightly curving marine shoal or bar just about



A. MIAMI OOLITE EXPOSED IN A ROCK PIT NORTH OF FORT LAUDERDALE. NOTE CROSS-BEDDING AND SOLUTION HOLES IN THE OOLITE. PAMLICO SAND IS SHOWN AS CONES AT THE BASE OF THE SOLUTION HOLES AND AS A MANTLING LAYER OVER THE OOLITE. THE 6-YEAR OLD BOY GIVES SCALE.



B. WATER-STAGE RECORDER ON WELL G 221 NEAR FORT LAUDERDALE WATER PLANT.

at sea level, thickest near the Atlantic shore line and thinning to a feather edge toward the Everglades (Parker and Cooke, 1944, p. 7). It is on this bar, now called the Atlantic Coastal Ridge, that Fort Lauderdale and the other cities of southeastern Florida have been built.

The Miami oolite probably was largely deposited during the Sangamon interglacial stage. The melting of the continental glaciers formed during the preceding Illinoian stage was so extensive that the ocean level rose 100 feet above its present level. Later, as the glaciers began to reform, the sea level dropped first to 70 feet and then to 42 feet (above present sea level). At all three levels marine terraces were formed, and it was largely during these high stages of sea level that the Miami oolite and related formations were deposited. The end of deposition was brought about by a fall in ocean level caused by the advance of glacial ice during the early part of the Wisconsin stage.

The Miami oolite is a fair source of water but the formation is so thin and near the surface that comparatively few wells are developed in it. The large numbers of vertical solution holes make for greater vertical than horizontal permeability, but even so the formation is generally so permeable that water can be pumped quite easily from it in most places. Water found in the oolite is hard--a typical calcium-bicarbonate water. Unless contaminated it usually contains from 6 to 20 parts per million of chloride; locally there may be considerable color of organic origin.

PAMLICO SAND

The Pamlico sand consists largely of quartz sand and is of late Pleistocene age. Over large areas in southeastern Florida it overlies the Miami oolite and fills natural channels and solution holes in it. In color the sand ranges from dazzling white through shades of yellow and brown to red or black. The yellowish to red colors are due to iron oxide but the gray to black color is generally due to organic materials that adhere to the surfaces of the sand grains or fill the interstices between them.

The Pamlico sand was probably laid down at the time of

the latest Pleistocene high-level sea, when the shore line was 25 feet above the present one. The sand was derived from previous deposits farther north; and was washed southward by ocean currents and waves. Its principal original source is probably from the rocks of the Piedmont in Georgia and Carolinas.

The ocean level presumably stood very low during the several glacial stages that preceded the late Pleistocene 25-foot rise, because the transverse glade valleys, having depths as great as 100 feet, were then formed by streams originating in the Lake Okeechobee-Everglades area. These stream valleys indicate considerable erosion. Pamlico sand now fills these valleys and mantles the surface of the oolite.

The Pamlico sand in the transverse glades generally is a source of potable ground water. The sand is not permeable enough to yield as much water as can be obtained from the cavernous rocks of the Tamiami formation, but it is a source of adequate supplies where only small quantities are needed. The water is fresh, where not contaminated by encroaching salty water, but it may have an objectionable color due to organic materials, and locally it may have the characteristics of "swamp water," with considerable color and a smell of hydrogen sulfide.

Plate 4A shows Pamlico sand mantling the Miami oolite and filling solution holes.

LAKE FLIRT MARL

The Lake Flirt marl was deposited in the Everglades and parts of the coastal marshes of southern Florida in areas of shallow, open water. In places it overlies the Pamlico sand, the Fort Thompson formation, and the Miami oolite. It has a thickness of about 1 foot in western Broward County (see pl. 3).

RECENT ORGANIC SOILS

Peat and muck deposits accumulated in perennially

flooded areas of the Everglades in both late Pleistocene and Recent time. These deposits are comparatively thin in the Fort Lauderdale area of the Everglades, and overlap the western edge of the Atlantic Coastal Ridge.

PRESENT INVESTIGATIONS

The present investigations have continued and expanded the work previously done in the course of the southeastern Florida water-resources investigations, which were financed until 1944 by the U.S. Geological Survey in joint cooperation with Dade County and the cities of Miami, Miami Beach, and Coral Gables. Since that time the U. S. Geological Survey and the Florida Geological Survey have continued observational and research work in Broward County as a part of the joint State-wide investigation of geology and ground water.

The City of Fort Lauderdale has largely financed the additional work, which included (1) the drilling of five test wells averaging about 200 feet in depth (G 512 - G 516, incl.); (2) re-installation of the water-level recorder on well S 329, located on the northeastern edge of the Fort Lauderdale golf course; (3) installation of another such recorder on well G 221, located on the east side of State Highway 7 about 400 feet northwest of the municipal water plant; (4) drilling of 52 shallow observation wells; (5) obtaining and recording data on 90 private wells; (6) periodic measurement of water levels; (7) collecting and analyzing for chloride content water samples from 116 wells; (8) establishment of a net of levels about 27 miles long based on the U. S. Coast and Geodetic Survey mean sea level datum plane; (9) tying in all measuring points to this datum; and (10) preparation of charts, diagrams, and maps to illustrate these data. The preparation of a base map was one of the earliest and most time-consuming jobs, for it was found that no accurate large-scale map of this area existed prior to this investigation.

The above steps have been taken to obtain information about current ground-water conditions. In addition it is planned to continue, in cooperation with the City of Fort Lauderdale and the Florida Geological Survey, observations

to determine long-time trends. Thirty-six key wells located in or adjacent to zones of salt-water encroachment are to be sampled monthly for chloride content. It is also proposed that water-table maps of the well-field area be prepared at monthly intervals. Three such maps for selected times during late winter and spring of 1947 are included in this report (pls. 7-9).

TEST-WELL STUDIES

VALUE AND USES OF TEST WELLS

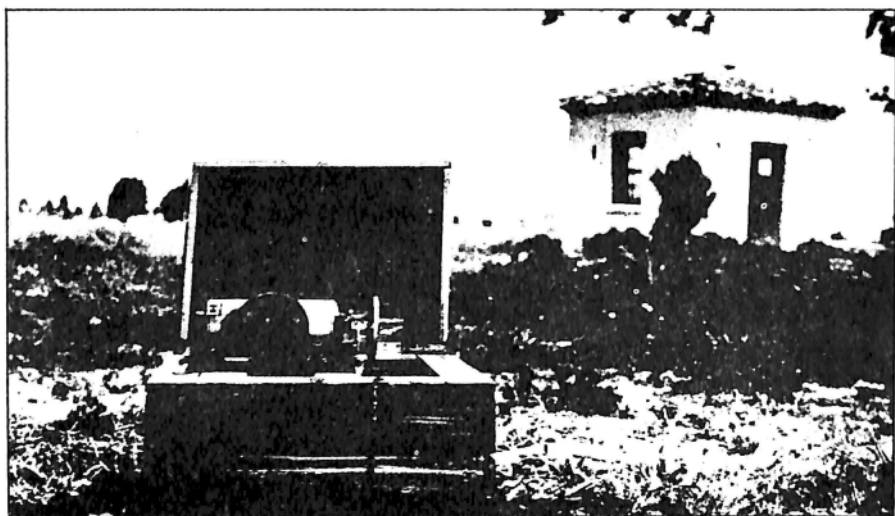
Test-well drilling has been the chief source of information on the geology and ground-water hydrology of the Fort Lauderdale area. The nature of the underlying rocks has been ascertained, and ground-water samples from numerous intervals in depth have been collected and analyzed. The usefulness of the wells was not ended as soon as their drilling was completed; measurements of water level are made periodically and samples of water are collected at monthly intervals to determine whether salt-water encroachment is occurring.

TEST-WELL DRILLING

The five test wells (G 512 through G 516) drilled during the course of the current investigations were put down by the jet-percussion method. Plate 5A shows the rig used in drilling these wells. At the start of the drilling a 20-foot length of 2-inch casing was driven down. The material forced into the casing was then jetted out, using a 1-inch jetting line, and the jetting was continued to a depth approximately 10 feet below the end of the casing. The jetting line was then removed, a pump was connected and, if possible, a water sample was obtained. Pumping continued for a long enough period to make certain that the sample would not be contaminated or diluted by water introduced into the bed during the jetting. After the sample had been collected, a section of casing 10 feet long was added and driven down to land surface; then jetting was resumed. Occasionally no water samples could be collected, owing either to low permeability or to very fine sand "heaving" in the casing and making pumping impossible. This type of "running sand,"



A. DRILLING WELL G 513



B. WATER-STAGE RECORDER ON WELL S329 NEAR CITY
WELL 3 ON FORT LAUDERDALE GOLF COURSE.

more properly termed quicksand, is rather common in some parts of the area. In many instances it was necessary to drive a sand-point into the sandy materials below the bottom of the casing in order to obtain water samples. Every effort was made to obtain representative water samples at regular intervals as the test wells were deepened.

Results and Interpretations

Interpretations of the well logs show that during Pliocene time deposits of fine-grained quartz sand were laid down alternately with deposits of calcareous sediments ranging from sandy limestone to rather pure marl. The sand is typical of littoral (beach) and neritic (near-shore) deposits derived from a nearby low-lying land mass composed largely of sandy materials. It is considered to be an eastward extension of the Caloosahatchee marl. The limy sediments are typical of shallow-water deposits of the open ocean, laid down far enough from land to have included little detrital material. These limestones are considered a northern and eastern extension of the Tamiami formation, which is typically developed in Dade and Collier counties. Using these lithologic characteristics as a basis of formation identification, it is apparent that there is considerable interfingering between the two formations. This interfingering is probably a product of alternating landward and seaward migration of the shore line due to minor changes in sea level during the Pliocene.

Until the five test wells were drilled it was believed that limestone of the Tamiami formation would be found to be the principal component of the aquifer in the area, and that the permeability would be somewhat lower than that found in Miami. However, results of test drilling and pumping show that the sand and silt of the Caloosahatchee marl are abundant and, with minor quantities of admixed clay, markedly reduce the transmissibility and yield of the aquifer as a whole.

A bed of fine white quartz sand, possibly of Caloosahatchee age, is found to underlie the Miami oolite in nearly all the wells of the Fort Lauderdale area. It is uncertain

whether the individual beds or layers underlying this sand layer have any considerable horizontal continuity. The geologic section included herewith (pl. 3) shows the various beds correlated by means of lithology, but because of lack of sufficient test wells it may be somewhat in error. Many of the beds were deposited as shallow marine and littoral sediments in an environment where currents and waves sharply limited the area in which any one type of sediment could be deposited; therefore, exact correlation of such beds is well-nigh impossible.

WATER-LEVEL STUDIES

WATER-STAGE RECORDERS

Two continuous automatic water-stage recorders are installed on observation wells in the Fort Lauderdale area. These provide the basis for a record, called a hydrograph, which shows the rise and fall of water levels plotted against time. These two recorders are shown in plates 4B and 5B and a hydrograph for well S 329 is shown in plate 6.

OBSERVATION WELL DRILLING PROGRAM

In order to prepare a water-table map it is necessary to have a number of wells in which depth-to-water measurements can be taken. At the start of the investigation only 15 wells suitable for this purpose were available; therefore it was found necessary to drill an additional 52 shallow observation wells to furnish needed control.

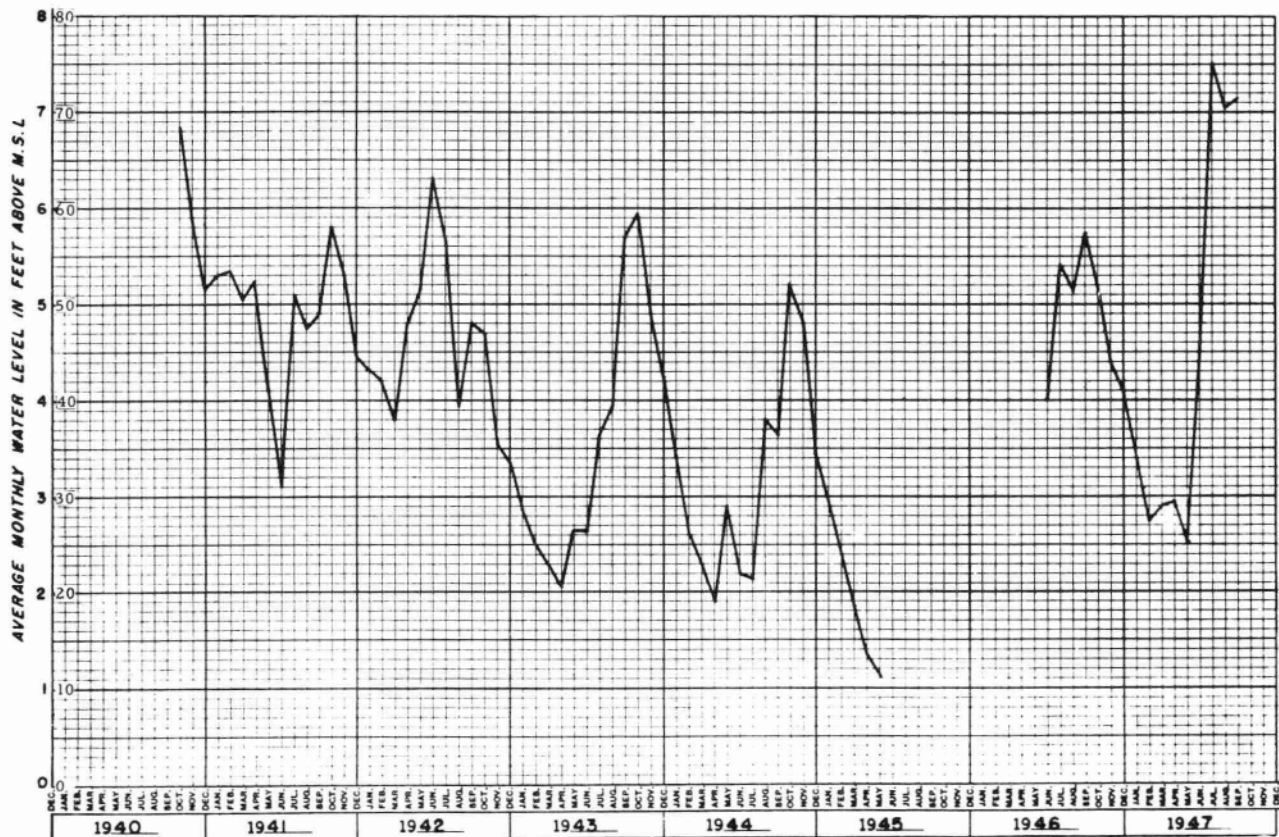
The locations were chosen in several ways. In order to determine the effect of the pumping of the city wells, observation wells were installed 10 feet from each city supply well, although in some places this distance ranged up to 100 feet. Shallow wells were also drilled approximately 1,000 feet from each two adjacent city supply wells, and additional shallow wells were drilled at approximately half-mile intervals eastward into Fort Lauderdale, northward to Plantation Road, and westward to Peter's Canal (see pl. 12).

The observation wells range in depth from 11 to 28 feet and are nearly all equipped with sand points. After being drilled each well was pumped sufficiently to be certain that it would respond quickly to water-table fluctuations.

In addition to the above wells, 10 observation points were established for water-level measurements on streams, canals, and drainage ditches. These give additional information and control for preparing water-table maps.

THE LEVELING PROGRAM

The datum plane used by the U. S. Geological Survey in preparing water-table maps in southern Florida is U. S.



HYDROGRAPH OF WELL S-329

PLATE 6

Coast and Geodetic Survey mean sea level (1929 adjustment). This datum plane is used by the Everglades Drainage District, by many municipalities, and is the most satisfactory datum plane for use in ground and surface-water studies.

In order to determine accurately the water-table height with respect to mean sea level, it is necessary to know the elevation of the measuring point on each observation well. This was obtained by running a net of levels from a second-order level line established by the U. S. Coast and Geodetic Survey. The line runs along State Highway 7 through the area of this report. The U. S. Geological Survey level net in the well-field area includes more than 27 miles of lines that were run and tied in to the above-mentioned U. S. Coast and Geodetic Survey line.

The points from which measurements are made and to which elevations are accurately established are usually the tops of the well casing. Inasmuch as the depth to water can be determined to a hundredth of a foot (the limit of accuracy to which a wetted steel tape can be read easily), it was necessary that the elevations be established to a corresponding accuracy and 27 miles of closed level lines were run to accord with such a standard.

The well elevations are shown on plate 12 in italics. The measuring point in each case is the top of the well casing, the well cap being removed.

RESULTS AND INTERPRETATIONS

Three maps of the water table in the Fort Lauderdale area are included with this report. Plate 7 shows the water table as of March 1, 1947, and is typical of the conditions found in late winter of 1947. Plate 8 shows the water table on May 24, 1947, very close to the end of a dry spring period. Plate 9, depicts the water table as of June 13, 1947, after a week in which there were a number of very heavy rains.

The contours, which are drawn with an interval of 0.25 of a foot, show that pumpage from the well-field area has only a slight effect on the water table. No deep cone of

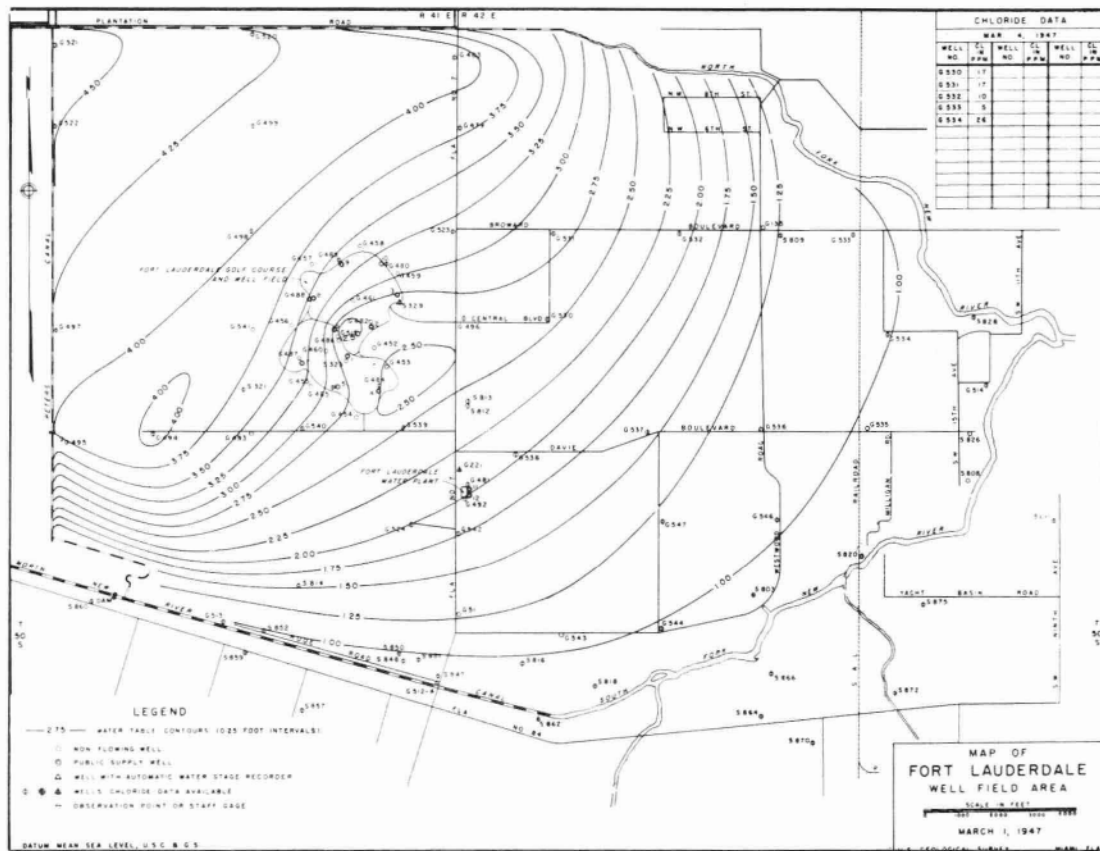


PLATE 7

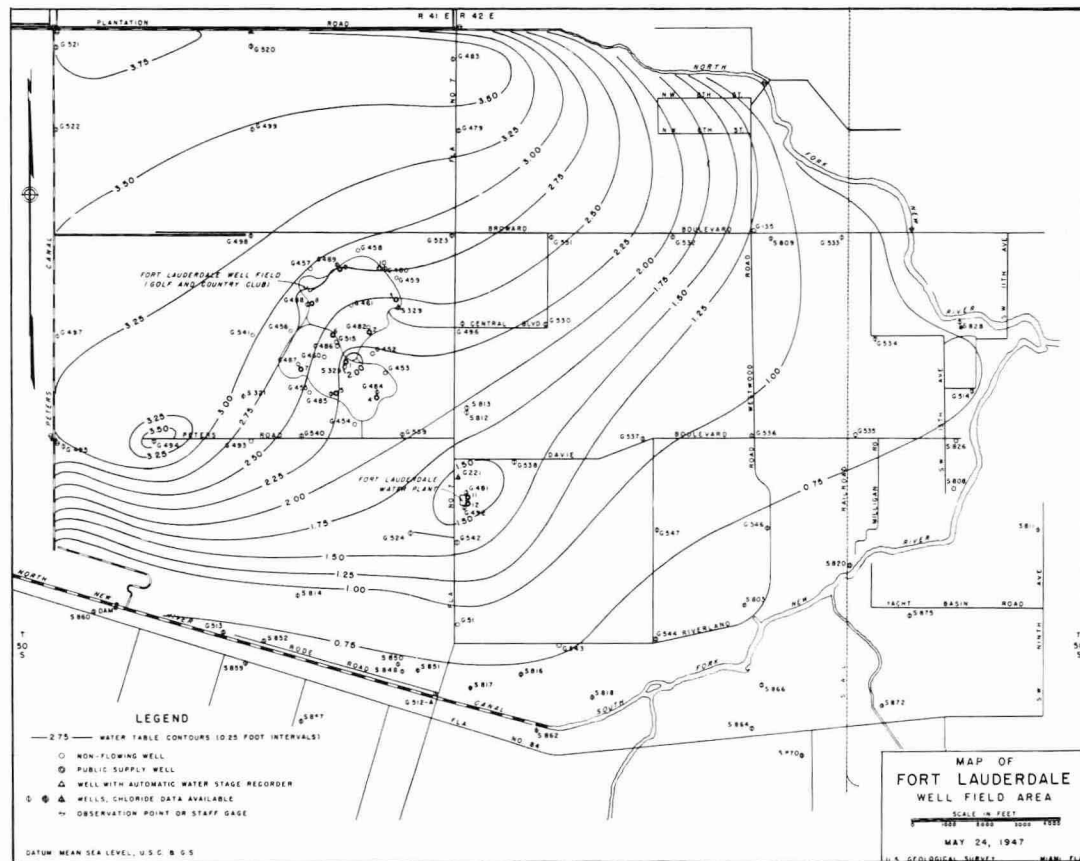


PLATE 8

depression is ever apparent, and the usual situation found is that the contours, instead of being smoothly curved lines on the map (as they would be if no pumpage occurred), are slightly deflected in the area of pumpage. Greatest effect of pumpage on the shape of the water table is shown on Plate 8 where a closed contour (1.50 feet) occurs at the water plant with slight bending of adjacent contours, and a small area is similarly affected on the golf grounds. Note on this same plate the ground-water mound built up by irrigation at the west end of Peters Road.

The contours indicate that ground-water flow is generally from northwest to southeast, on a very gentle gradient averaging approximately 1 foot to the mile. By drawing flow lines normal to the contour lines on the water table, the area contributing water to the well field can be delineated. The ground water contributing to the wells originates from rainfall on the well field itself and immediately to the northwest; it is not derived from areas far out in the Everglades, as many people have believed.

The water table maps indicate that no over-development of ground-water supplies in the well-field area has taken place.

TRANSMISSABILITY

The capacity of a formation to transmit water may be expressed by the coefficient of transmissibility, which is the number of gallons of water that will move in 1 day under a unit hydraulic gradient (1 foot per mile) through a vertical strip of the aquifer 1 mile wide and having the full depth (or thickness) of the aquifer.

The coefficient of transmissibility for the aquifer in the Fort Lauderdale well-field area is approximately 1,200,000. This means that 1,200,000 gallons of water will flow in 1 day through a vertical strip of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile. The graphical method (Cooper and Jacob) used in arriving at this value is shown in plate 10. Drawdown and time data were taken from water-stage recorder charts; rate of pumping is the quantity

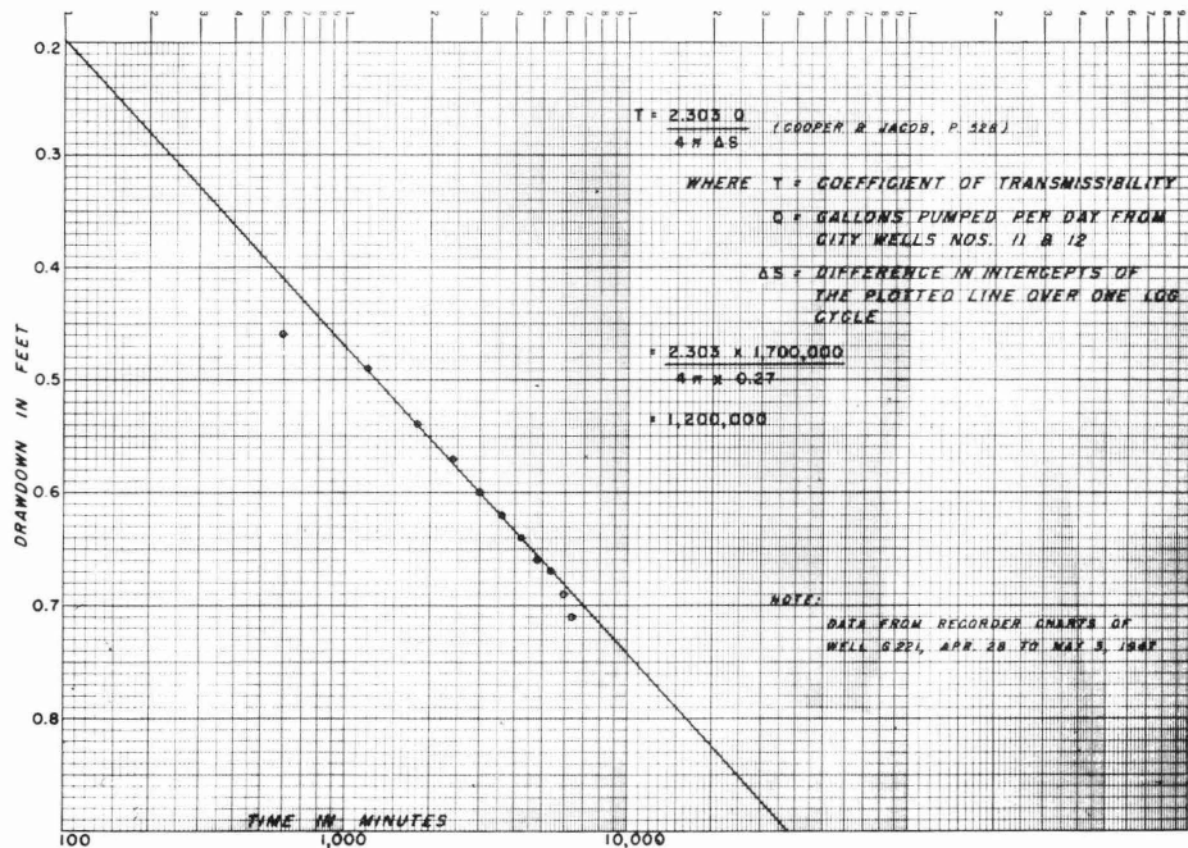


PLATE 10

TIME-DRAWDOWN GRAPH FOR WELL G 221

reported for city supply wells 11 and 12. The falling off of the last two points on the graph indicates a boundary effect, or reduced transmissibility as water levels decline, or both. The value given for the coefficient of transmissibility is tentative and indicates only the order of magnitude for the coefficient. In order to obtain a value on which important engineering decisions may be based, a carefully controlled pumping test would be necessary.

SALT-WATER ENCROACHMENT

Samples of ground water were collected from all test wells at frequent intervals during the drilling. In addition to the test-well samples, a large number of water samples were collected from wells in areas of possible salt-water encroachment, and from most of the observation wells.

Samples from wells not equipped with pumps were collected by means of a portable power pump or a common pitcher pump. In collecting samples from wells in which the water had been standing unpumped for a relatively long period of time, sufficient pumping was done to clear the well and obtain a representative sample of water from the aquifer.

All analyses of these samples for chloride content were made in accordance with the standards of the U. S. Geological Survey. The error is less than 1 percent, regardless of the salt concentration.

In addition to using chemical analyses for chloride determination, the electrical-resistivity method of geophysical prospecting was used to test for the presence of salt water at depth. The locations of the test sites are shown on plate 12. The final results obtained from these tests are not available as yet. However, field computations indicate that the method is successful and that mineralized water underlies the entire area at differing depths. A subsequent report will give the detailed results.

Chloride encroachment in the Fort Lauderdale area may be from any of four sources: (1) from the ocean; (2) from

ocean-water tongues in canals; (3) from Everglades Drainage District canals into which salty Everglades ground water has seeped; (4) from the salty connate or residual water which underlies the area at a depth of from 150 to 300 feet and more.

In the Fort Lauderdale area encroachment from the ocean directly into the aquifer is believed to occur only within a mile or so of the shore. Owing to a number of factors, the rate and extent of ocean-water encroachment at Fort Lauderdale has not been as fast nor as extensive as in Dade County near Miami. These factors include (1) lower transmissibility; (2) layers or beds of sediments that are relatively impermeable; (3) less pumpage; (4) higher water table.

In part of the Miami area encroachment from the ocean at depth in the aquifer has been computed to be as great as 890 feet per year and to have averaged about 235 feet per year (Parker, 1945 b, p. 539). The rate of encroachment in the Fort Lauderdale area has not been computed but it is probably much less, owing to the above-mentioned factors. This type of encroachment is not found in any of the area shown on plate 12.

The most serious threat of well-field contamination from ocean water exists in the lateral movement of salt water from North New River Canal. Plate 11 indicates the high chloride content found from time to time in this canal as far inland as the control lock and dam. Test well G 514, located at 9th Street and 12th Avenue Southwest in Fort Lauderdale, shows marked contamination from this source. At a depth of 116 feet below land surface the chloride content was 178 parts per million, but only 10 feet deeper, at 126 feet, it was 2,690 parts per million. This chloride content is far too large to have been derived from the connate salt water which underlies all of south Florida, for connate water at this elevation has been flushed out in areas much farther to the west. Further, the chloride concentration is too great to be explained by seepage of salty Everglades water into the canal. The profiles of ocean-water encroachment published by Brown and Parker (1945, figs. 11-13) indicate that, where there is direct encroachment of ocean

water, the chloride content increases with depth more rapidly than is the case in well G 514. Thus, by a process of elimination, the source of the contamination is concluded to be ocean-water tongues that have intruded along the bed of North New River.

Other wells along New River show contamination from this source. These include wells S 827 and 828 on the North Fork of New River and wells S 808 and S 820 on the left bank of the South Fork of New River. Pumping the above wells has drawn in salty water from the canal. On the right bank of the river (see pl. 12) wells S 862, S 866, S 864, S 868, S 870, S 872, and S 874 all show even greater contamination. This is due to slow, sustained movement of the ground water from northwest to southeast, carrying contaminated water with it - contamination that seeped both downward and laterally and was carried farthest in the most permeable parts of the aquifer.

Chloride tests on water from test wells G 512 and G 513 illustrate this type of encroachment. In well G 512 a zone of contamination in which the water contained 180 parts per million was found at 42 feet. This was the highest salt content for any horizon in the entire 175-foot depth of the well. In well G 513 zones of lateral intrusion were found 10 and 52 feet below land surface. In these two zones the chloride content was 59 and 52 parts per million, respectively. The beds enclosing these zones contained water of only 28 parts per million or less. The encroachment was selective, occurring only in the more permeable zones.

This selective type of encroachment occurs especially during dry periods when there is little or no seaward flow in the canals and rivers; instead, there is an inland flow of ocean water. In dry weather wells are pumped most heavily and this serves to accelerate the rate and amount of encroachment. This type of intrusion can be prevented only by (1) continuous fresh-water flow sufficient to keep the salt water swept out of the canals; or (2) installation of locks at some downstream site.

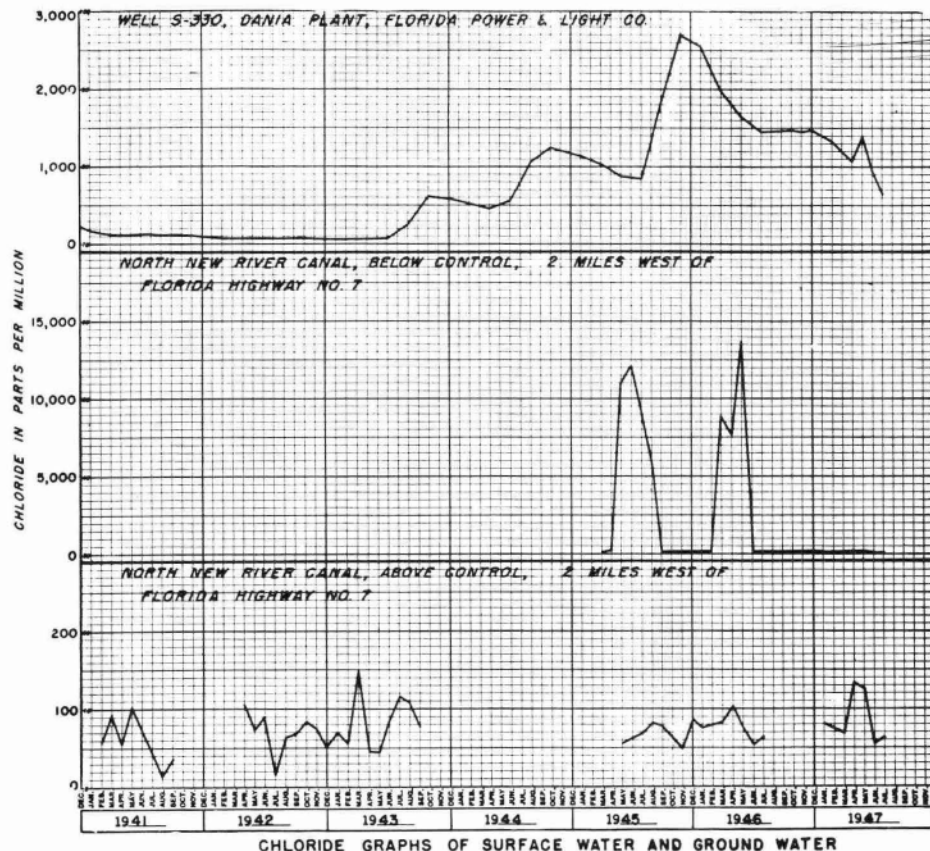
Another area in which lateral encroachment has occurred is in the vicinity of the Dania plant of the Florida Power

and Light Company. The water in well S 330 at this plant contained 213 parts per million of chloride when first sampled by the U. S. Geological Survey in November 1940 (see pl. 11). This indicates salt-water intrusion because in this area the normal chloride content of ground water is only about 20 parts per million, and canal water from the Everglades has not been observed to exceed 148 parts per million in the North New River Canal. In subsequent samplings the amount of chloride in well S 330 decreased gradually to 53 parts per million, with but few slight variations. Then the effects of drought became noticeable and the chloride content rose to 615 parts per million in October 1943. Fall rains of that year pushed the encroaching salty ground water oceanward and gradually reduced the concentration to 458 parts per million by April 1944. Since then, reduced flow in the South New River Canal and a lowered water table have permitted several salt-water advances such as are shown for the North New River Canal in plate 9. A maximum chloride content of 2,700 parts per million was reached in November 1945, and it has since declined to 640 parts per million (in July 1947).

Contamination from mineralized canal water where the saltiness is picked up by inflow of salty ground water in the middle and upper Everglades operates in the same fashion as the type described immediately above. The results, however, are far less serious. The chloride content of the North New River Canal at the upstream side of the coastal lock and dam during the period from February 1941 through April 1947 has been observed to vary from a low of 49 parts per million to a maximum of 148 parts per million (see pl. 11).

These amounts are not sufficient to render water unfit for drinking, but it is important to recognize this type of intrusion for what it is and not confuse it with intrusion by way of ocean-water tongues. Once this canal water seeps into the ground there is little likelihood that its chloride content will be further concentrated. Instead, its chloride content will be diluted by mixing with fresh ground water.

The chloride content of uncontaminated ground water may range from approximately 4 to 30 parts per million.



CHLORIDE GRAPHS OF SURFACE WATER AND GROUND WATER

In areas adjacent to canals or rivers any content in excess of 30 parts per million but less than 150 parts per million, may represent encroachment by contaminated canal water from the Everglades. Any content higher than approximately 150 parts per million is evidence that the contamination originated from ocean water.

Salty water underlies all of southern Florida and is found in all areas if drilling is carried deep enough. The observed range in depths to salty water in the Fort Lauderdale well-field area is 150 to 225 feet. One test well in the area (G 516, 200 feet deep) failed to show salt water, but it is probable that salt water can be found even under this well, probably within the next 25 to 50 feet of depth. This salty ground water, especially at great depth, may be of connate origin (water deposited with the sediments in which it is found), but it is more likely that it is modified sea water that penetrated downward during the late Pleistocene when this area was submerged beneath the high-level seas of an interglacial stage. Since then the ocean level has not declined enough or sufficient time has not elapsed for this water to be completely drained or flushed out and replaced by fresh water, but it has been altered by cation exchange and dilution.

In well G 515, near the center of the Fort Lauderdale golf course, a chloride content of 300 parts per million was found at a depth of 165 feet below land surface and this increased to 600 parts per million at 183 feet. It is possible that heavy pumping would cause this salt water to be drawn upward, thus acting as another source of contamination. In fact, this salty ground water probably is the source of the higher chloride contents now found in the raw water of the municipal supply. Records kept by Mr. Charles Fiveash, Superintendent of the Department of Water and Sewers, indicate that the chloride content of raw water from the Fort Lauderdale well field has increased gradually since the well field was put in operation. These records show that the average chloride content of the water in the well field when pumping first started in 1927 was about 10 parts per million. Records are available for average chloride content during 6-month periods from 1932 to the present. The average for the first 6 months in 1932 was 13 parts per million. During the last 6 months of 1932 the average was 12 parts per million.

The content has gradually increased, with some fluctuations, and for the first 4-months of 1947 was 20 parts per million. The highest 6-month average was 24 parts per million for January-June 1944. The lowest 6-month average was for the last half of 1933, only 10 parts per million.

SUMMARY AND CONCLUSIONS

The lithology of the well-field area has been determined from study of the cuttings obtained from six test wells, among which is G 515 in the grounds of the Fort Lauderdale golf course. A large part of the upper section of the aquifer has a low permeability, being composed of very fine-grained quartz sand mixed with clay and marl. The most permeable zone at well G 515 is found between 104 and 123 feet below the land surface, and it is in this zone that future wells can best be developed. This permeable zone is characterized by discontinuous layers of sandy limestone or calcareous sandstone up to 6 feet thick, associated with permeable shelly sands. The water from this horizon is in a semi-confined state, owing to the relatively low permeability of the overlying beds. The water is under no artesian pressure as such - that is, it does not rise in wells above the level at which it is struck - but when water is removed by pumping the inflowing water finds it easiest to travel in a more or less horizontal rather than a vertical direction.

Lenses of permeable sand, which in some places have considerable horizontal extent, interfinger with the beds having relatively low permeability in the upper section of the aquifer, and it is in these permeable lenses that salty water moves out of the tidal canals most easily.

Hydrologic studies indicate that ground-water flow is generally from northwest to southeast, and that the source of the ground water is not far distant, most of it being derived from rain which has fallen on the Atlantic Coastal Ridge; not from far in the Everglades. The floor of the middle and northern Everglades is quite impermeable and the ground water is relatively highly mineralized even near the surface. If there were any considerable ground-water flow through the rocks underlying the Everglades, fresh water should long since have flushed out the salty water.

The water-table contours indicate that the present drainage canals and ditches in the well-field area do not draw off excessive quantities of ground water. In fact, there is evidence that during dry seasons Peters Canal helps considerably to maintain higher water levels closer to the North New River Canal than would be found if Peters Canal were not in existence. Furthermore, irrigation with pumped ground water around the farm buildings of the Peters' ranch has created a ground-water mound to the west and southwest of the Fort Lauderdale well field, and helps maintain the ground-water level of the well field during dry periods (see pls. 7 and 8).

The quantity of water available for pumping is not known. No city supply well in the area has ever been pumped to its maximum capacity, nor has a pumping test been run to determine the hydrologic coefficients of the aquifer. However, it is obvious that the present well field is not over developed.

The average water levels seem to be adequate to protect the present wells from salt-water encroachment, provided present rates of withdrawal are not exceeded. During dry seasons the well-field water levels average about 2.5 feet above mean sea level, but rainfall raises the water level rapidly and the annual average water level of approximately 4 feet is adequate to protect the wells from any further ocean-water encroachment to a depth of approximately 160 feet.

With the establishment of the Broward Conservation District's new water preserve it should be possible, during droughts, to divert water to the well-field area by means of ditches, dikes, and pumps. A higher water table, averaging 5 or 6 feet above mean sea level, could then be maintained in the well-field area to give adequate safety against salt-water encroachment. This highly colored surface water might cause a slight rise in the color of the City's raw-water supply but it probably would not be excessive.

The years 1940 - 46 during which water-level measurements have been recorded include only one year, 1940, in which the rainfall exceeded the average annual rainfall.

From 1941-44 it ranged from 10 to 24 inches below normal. Weather Bureau records for Fort Lauderdale are incomplete for the years 1944-46 but the years 1944 and 1945 are among the driest years on record for southern Florida.

A slight increase in the chloride content of the City water supply has occurred over the years, probably as a result of upward movement of the mineralized water underlying the well field. The water from the city wells during the first year of pumping averaged about 10 or 11 parts per million of chloride. This has risen gradually, with slight fluctuations, to the present average of 21 parts per million. The increase was probably caused to some extent by deepening the wells in 1940. There is no immediate danger from this source, but pumping rates should not be increased without further studies to determine the probable effects.

As for private supplies, many wells in the North New River Basin have been factors in inducing chloride contamination of the aquifer by drawing salty ocean water in from the canals. These contaminated zones are irregular in shape and areal distribution. The chloride has come from ocean-water tongues which have intruded North New River, its tributaries, and the lower reaches of its tributary canals. This source of contamination can be checked only in two ways: (1) by providing sufficient flow in the canals to keep ocean-water tongues washed out of the rivers and canals, and (2) by building a dam or control works as far downstream as possible to prevent salt-water tongues from advancing into critical areas.

On the basis of present information a number of conclusions can be drawn relative to the well field. The present wells probably are adequate to supply the quantities needed but without pumping test data the present pumping rates cannot be materially increased without the danger of inducing chloride encroachment from the underlying salt water. The present pumping does not intercept a very large portion of the natural ground-water flow, most of which is wasted by flow to the North New River Canal and thus to the ocean. This will always be the case to some extent, but much of this wasted flow could be captured by extending the well field to the northwest and increasing the pumpage.

Sufficient work has not been done during the present investigation to determine accurately the hydrologic coefficients of the aquifer and to obtain this information it is recommended that as soon as possible a pumping test be made in accordance with the methods used by the U.S. Geological Survey. During this test a well discharging at least 1,000 gallons per minute should be used. Such a test can determine whether an increased rate of pumping will promote encroachment from the salty connate water underlying the well field. It can also furnish quantitative information as to the coefficients of storage and transmissibility of the aquifer and these data could then be used to determine the proper well spacing for maximum production of water with minimum drawdown of the water table. Drawdowns in observation wells near the present city supply wells indicate a coefficient of transmissibility of approximately 1,200,000 gallons per day per foot but this should be verified by a comprehensive pumping test before being used in well-spacing calculations or in predicting future drawdowns and extent of cones of depression.

On account of continually changing conditions of weather, drainage, pumpage, cultural developments, etc., it is believed that the following investigative ground-water program should be carried out in the future: (1) chloride determinations should be made regularly until such time as definite trends can be established; this can be accomplished if the sampling of the 36 wells now being done monthly is continued and analyses are made regularly for a period of several years; (2) monthly observations should be made of the water table in the well-field area; and (3) at least two more water-stage recorders should be installed, one to the northwest and the other to the north of the present well field, so that information may be had for these source areas of the present Fort Lauderdale water supply.

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