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FLORIDA GEOLOGICAL SURVEY
Herman Gunter, Director

REPORT OF INVESTIGATIONS

NO. 4

INTERIM REPORT ON THE INVESTIGATIONS OF WATER RESOURCES IN SOUTHEASTERN FLORIDA WITH SPECIAL REFERENCE TO THE MIAMI AREA IN DADE COUNTY

By

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United States Geological Survey

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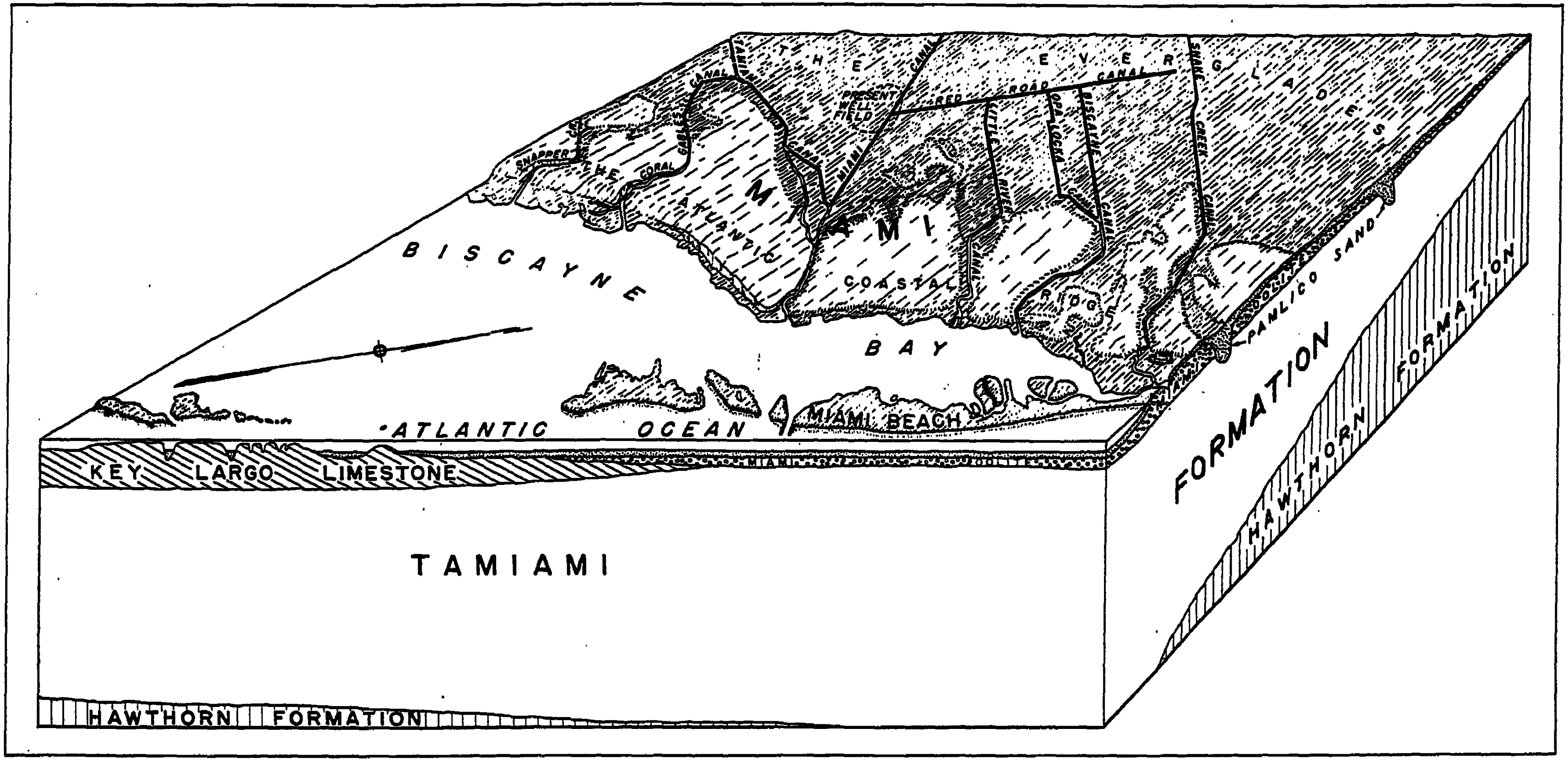


BLOCK DIAGRAM OF THE GREATER MIAMI AREA

INTRODUCTION

In 1939 the Geological Survey, U. S. Department of the Interior undertook a thorough investigation of the water resources of southeastern Florida, with special reference to the water supplies of Dade County, Miami, Miami Beach and Coral Gables. The investigation was made with the financial support of these cities and of Dade County, and was requested because of the appearance of salty water in the Miami well field, adjacent to the Miami Canal, about six and one-half miles inland from Biscayne Bay. The objectives of the study were sufficiently broad to include an evaluation of all the water resources of southeastern Florida with emphasis on those supplies practicable of development for municipal use in the Miami area.

In order to carry out the investigation effectively, it was necessary to obtain basic geologic, hydrologic, and chemical data. Specifically, it was necessary to determine the depth, thickness, and areal extent of the water-bearing rock formations; the capacity of these formations to transmit and yield water; the areas and rates of recharge and discharge, the quality and quantity of water in the different parts of the water-bearing rocks; the source and approximate rate of movement of salt water at all depths in the water-bearing rocks, factors controlling salt-water encroachment; the height of the water table and the direction of flow of the ground water at different times of the year; the stage and discharge of the canals throughout the year; the periods when the canals drained the nearby land areas and when they fed water to these areas; and the approximate quantities of water involved.

More than 60 exploratory test wells were drilled in order to obtain data on the geology and hydrology of the formations penetrated. One well was 812 feet deep, one 604 feet deep and the rest ranged between 20 and 350 feet, most of them being between 200 and 300 feet. Samples were collected of the rock cuttings and of the water encountered in the test wells, and pumping tests made at many levels as the wells were being drilled. In addition to these test wells, numerous shallow, observation wells were installed for periodic water-level measurements. Twenty-one automatic water-level recorders were placed on selected wells to determine the fluctuations of the water table.

Studies were made along several stretches of the major drainage canals to determine the amounts of gain or loss of the ground water. Several studies were made of the altitude and movement of the ground water in relation to the stage of the canals in an extensive area west of Hialeah and Miami Springs, during low, average and high water conditions, to permit effective evaluation of water-control measures to protect the present well field. These studies also have a direct bearing upon the future development of additional supplies in the area. Four intensive studies were made in the Silver Bluff area of Miami to determine the conditions governing salt-water encroachment at depth in the water-bearing formation. Thousands of samples of water from representative wells were collected, and analyzed to determine the quality of water. In a study of the problem of salt-water encroachment, samples of water from Biscayne Bay were also analyzed. Artificial mixtures of normal ground water with sea water were made in various proportions and comparisons were made between these and samples of salt-contaminated ground water. Eighteen rain gages and four evaporation stations were installed to assist in determinations of the supply of water from rainfall and of losses that are due to transpiration and evaporation.

Most of this work was done in Dade County, in the area centering around Miami, but some of the problems led to remote parts of the Everglades and Big Cypress Swamp. For example, geologic reconnaissance studies were made over most of southern Florida so that the areas of outcrop of the different formations could be determined and the geologic structure of southeastern Florida understood; the flow of arterial canals was measured in the Everglades, and analyses were made of records of stage and flow for Lake Okeechobee and its connecting channels and basins for the purpose of evaluating the more distant possible sources of surface water supplies and for defining the hydrology of the whole drainage area.

The writers wish to acknowledge gratefully the assistance given the U. S. Geological Survey by Dade County and the Cities of Miami, Miami Beach, and Coral Gables, and by the many persons, agencies, organizations, and firms who have provided information and records, and who have in any way helped make available the facilities to carry on the investigation of which this interim report is a product. So many have aided that it is impossible to list them in a brief paper of this kind, but a full statement of acknowledgments will appear in the comprehensive report to follow.

As the investigation has proceeded reports have been prepared from time to time by members of the staff. Several reports have been written that are restricted because of their military nature. The unrestricted reports are as follows:

(1) Cross, W. P., and Cooper, H. H. (1940) Water Levels and artesian pressure in Florida, 1939, U. S. Geological Survey Water Supply Paper 886, pp. 64-69.

(2) Cross, W. P., Love, S. K., Parker, G. G., and Wallace, D. S. (1940) Progress report on water resources investigations in southeastern Florida. Mimeographed in 2 volumes.

(3) Parker, G. G. (1942) Notes on the geology and ground water of the Everglades in southern Florida, Proc. Soil Science Society of Florida, volume IV-A, pp. 47-76.

(4) Ferguson G. E. (1942) Plan and progress of recent surface water studies in the Everglades, Proc. Soil Science Society of Florida, volume IV-A, pp. 77-85.

(5) Cross, W. P. (1942) Water levels and artesian pressure in southeastern Florida, 1940, U. S. Geological Survey, Water Supply Paper 907, pp. 26-34.

(6) Cross, W. P., and Love, S. K. (1942) Ground water in southeastern Florida, Journal of American Water Works Association, volume 34, No. 4, pp. 490-504.

(7) Love, S. K., and Swenson, H. A. (1942) Chemical character of public water supplies in southeastern Florida, Journal of American Water Works Association, volume 34, No. 11, pp-1624-1628.

(8) Parker, G. G., and Hoy, N. D. (1943) Additional notes on the geology and ground water of the Everglades in southern Florida, Proc. Soil Science Society of Florida, volume V-A, pp. 33-35.

(9) Cross, W. P. (1943) Water levels and artesian pressure in southeastern Florida, 1941, U. S. Geological Survey, Water Supply Paper 937, pp. 19-27.

(10) Ferguson, G. E. (1943) Summary of three years of surface water studies in the Everglades. Proc. Soil Science Society of Florida, volume V-A, pp. 18-23.

(11) Parker, G. G. and Cooke, C. W. (1944) late Cenozoic geology of southern Florida with a discussion of the ground water, Florida Geological Survey Bulletin 27.

(12) Brown, R. H. and Parker, G. G. (1944) (Abstract) Salt Water encroachment in limestone at Silver Bluff, Miami, Florida, Economic Geology, volume 39, No. 1, p. 87, Jan.-Feb., 1944.

(13) Brown, R. H. and Parker, G. G. (1944) Salt Water encroachment in limestone at Silver Bluff, Miami, Florida. Economic Geology, volume 40, No. 4, pp. 235-262.

(14-16) Parker, G. L. and Others, Surface water supplies of the United States, south Atlantic slope and eastern Gulf of Mexico basins, U. S. Geological Survey, Water Supply Papers 892, 922, and 952. These publications contain records of canal discharge in southeastern Florida for 1940, 1941, and 1942 respectively.

OCCURRENCE OF GROUND WATER IN SOUTHEASTERN FLORIDA

Ground water in southeastern Florida occurs in two principal ways: (1) under pressure, in confined and deeply buried formations and, (2) under unconfined conditions with a free upper surface (the water table) in the shallower formations.

Artesian Water.--In the first instance cited above water exists under artesian pressure. Wells drilled through the confining rocks will release this water and it will flow at the surface if the ground elevation is less than 40 feet above mean sea level. However, none of the artesian wells in southeastern Florida yield potable water, nor with the present state of knowledge can the water be used for industrial, commercial, or agricultural purposes. The water is hard, brackish to salty, sulfurous, and corrosive. Industrial plants have found it more expensive to use this artesian water that flows of its own pressure than to use municipal supply. This is because of the original high cost of the artesian well and the corrosive action of the artesian water that make it necessary frequently to replace pipes and plumbing fixtures with which the water comes in contact.

The artesian aquifers are deeply buried in southeastern Florida and require a well at least 800 feet deep to tap them sufficiently to obtain a good flow. The wells are very expensive to make and produce unusable water, so as a source of public or private supply they must be discounted.

Unconfined Ground Water.--In the second instance cited above ground water occurs in a huge underground reservoir in the pores and fissures of the rocks that overlie the confining layers which cap the artesian aquifers. The water in this reservoir is constantly being added to by the rains or by canal flow from runoff in more distant areas, and is likewise constantly being subtracted from by drainage into the canals, by transpiration, evaporation, leakage into the ocean, and by pumpage.

It is the unconfined ground water that must be depended upon for well water supplies in southeastern Florida. In the following discussion this is the water referred to, and the highly permeable water-bearing rocks that contain it are referred to as the highly permeable aquifer, or simply as "the aquifer".

UNCONFINED GROUND WATER IN THE MIAMI AREA

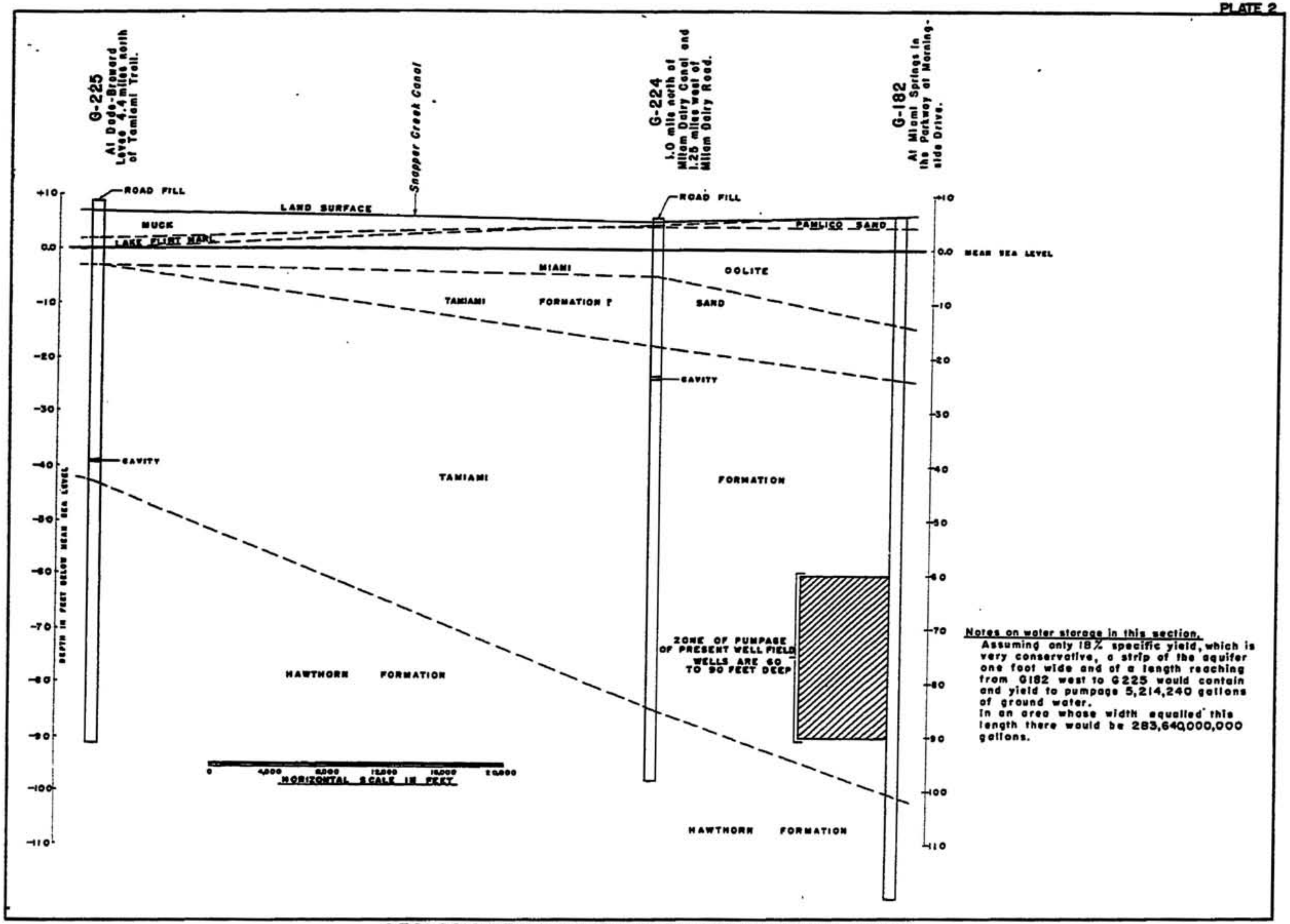
The Ground-water Reservoir.--Very large aggregate supplies of potable ground water exist in the highly permeable aquifer (Tamiami formation, chiefly) in which the present wells are developed (see Plates 1, 2). Computations based on the known depth (top to bottom) and length (east to west) of the aquifer with an estimated 18% specific yield indicate over 15 million gallons of ground water stored in each foot of width (north to south) of the aquifer.

The permeability coefficient is very high with an average value of about 35,000. This means that through a section of the formation a mile wide and a foot deep 35,000 gallons of water a day would pass through under a water table slope of one foot to the mile. In terms of transmissibility, this coefficient of 35,000 must be multiplied by the depth, in feet, of the saturated part of the aquifer. Most water-bearing materials in which wells are developed elsewhere have a coefficient of permeability that ranges from 10 to 5,000. The most permeable material ever investigated in the U. S. Geological Survey hydraulic laboratory had a coefficient of about 90,000. Field permeability tests show that in some places in the Miami area the rocks are about that permeable.

The aquifer in Dade County ranges from about 10 feet deep in the extreme west to almost 300 feet deep in limited areas along the Atlantic shore. In the vicinity of the Miami well field the formations are over 100 feet thick but of this only about 75 feet is highly permeable because of oolite and fine sand in the section (see Plate 2).

The highly permeable aquifer underlies the entire eastern margin of the State from the Florida Keys at least as far north as Delray, and

PLATE 2



U.S. GEOLOGICAL SURVEY

GEOLOGIC SECTION WEST FROM PRESENT WELL FIELD

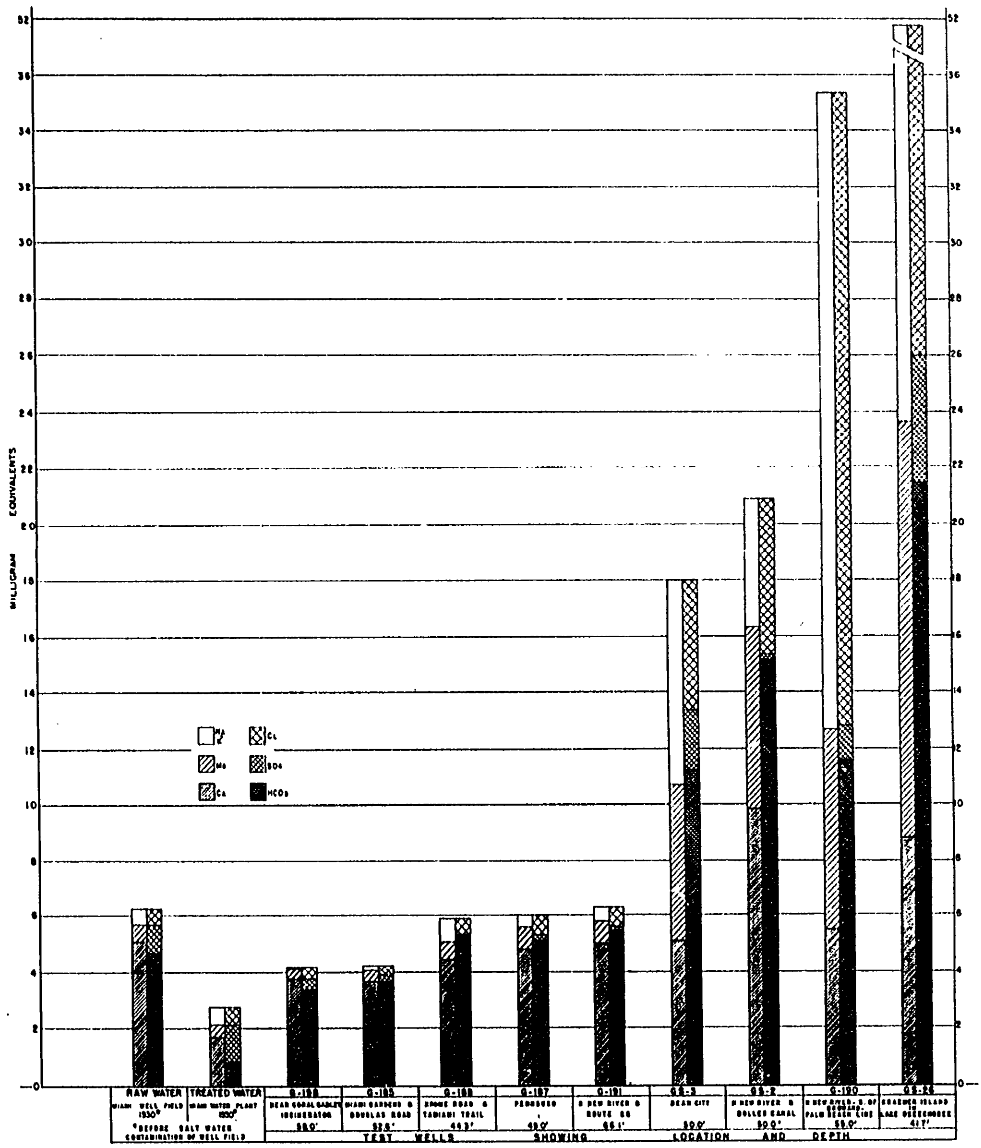
MIAMI, FLORIDA

possibly farther. Inland it thins and interfingers with the sandy, shelly Caloosahatchee marl which, in the upper part of the Everglades, contains highly mineralized water, the modified remnants of bodies of ocean water entrapped there during the high-sea levels of the Pleistocene, or Great Ice Age. The amount of water that percolates from the northern and middle part of the Everglades through the Caloosahatchee marl down gradient into the Tamiami formation is of very little consequence. The water stored in the aquifer is mostly derived from rainfall falling over the area underlain by the aquifer itself.

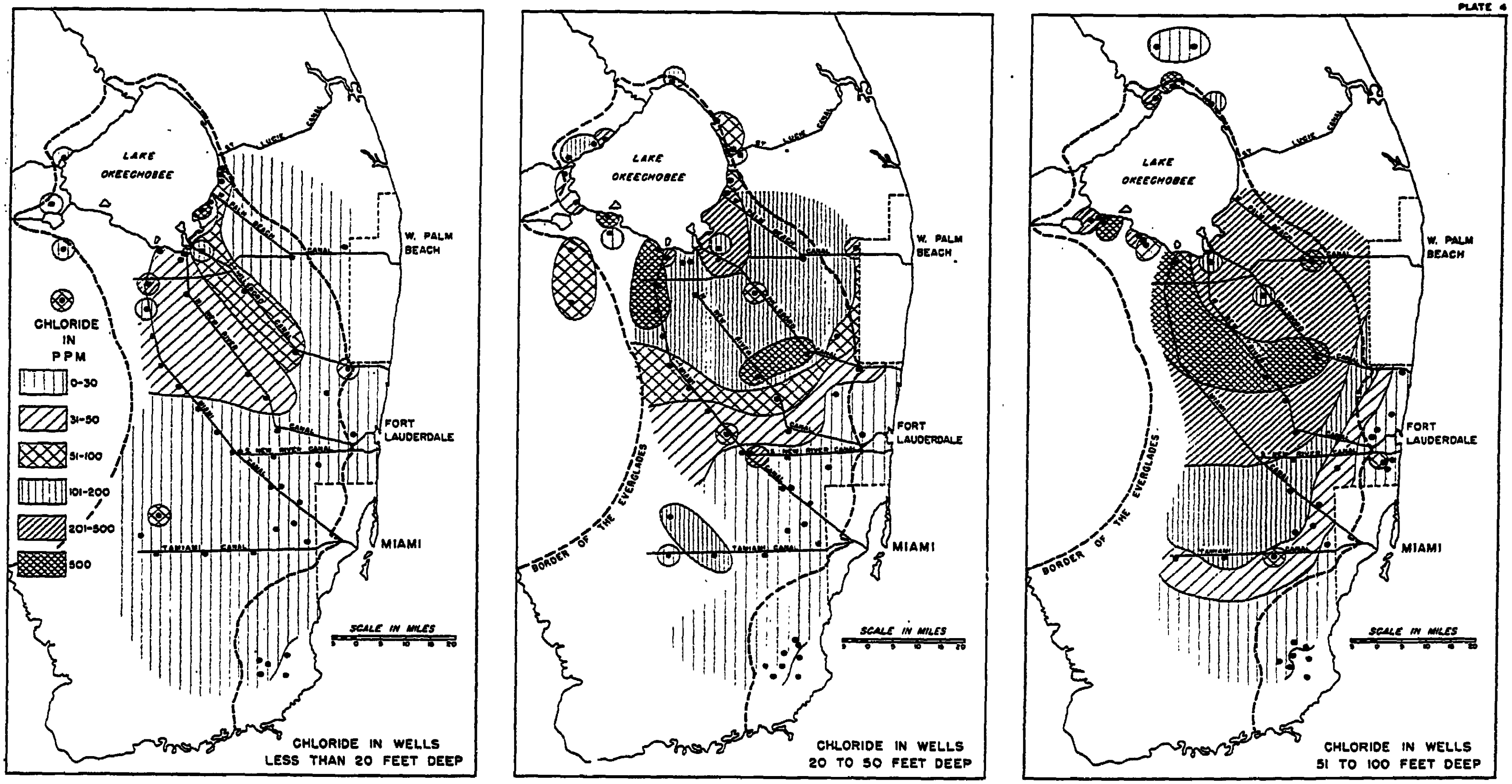
Quality of the Ground Water.--The quality of the ground water in the highly permeable aquifer is fairly uniform. The hardness ranges from about 200 to 300 parts per million and averages about 250 parts per million. The normal concentration of chloride is from about 20 to 30 parts per million. Practically all of the ground water is colored with organic matter, but in varying amounts and with little relation to depth. The color is derived from peat, muck, and other organic matter.

Ground water in the coastal ridge north and south of Miami contains somewhat less dissolved mineral matter and is a little less hard, but in other respects has about the same general character as ground water in the Miami area.

In the Everglades west and northwest of Miami the ground water is of poorer quality than in Miami. In general, the farther west and northwest that wells are developed, the poorer will be the quality of the water they yield. Hardness and concentration of dissolved mineral matter are considerably greater in the Everglades than along the Atlantic coastal ridge. See plate 3 which graphically represents the quality of water from different



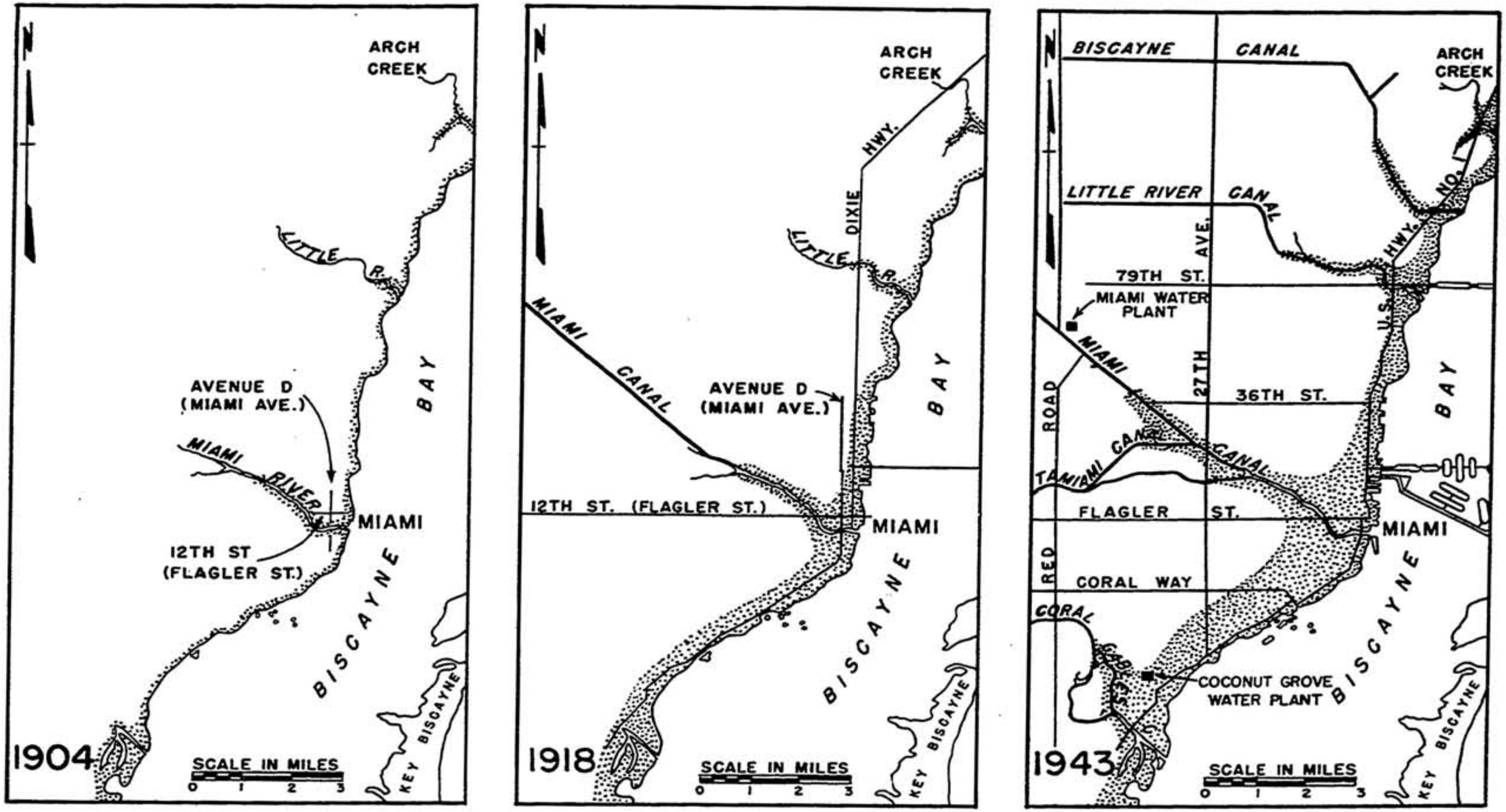
ANALYSIS OF GROUND WATER IN SOUTHEASTERN FLORIDA



—CHLORIDE CONCENTRATIONS IN GROUND WATER AT DIFFERENT DEPTHS IN THE EVERGLADES wells in the area of about the same depth, and plate 4 which indicates quality of water at different depths in the Everglades. This difference in quality is due to several factors, mainly to the very low permeability of the rocks that underlie the Everglades (the Fort Thompson formation and the Caloosahatchee marl, principally), to the very flat gradients of the water table that cannot force water to move readily in these rocks of low permeability; and to the fact that not enough time has elapsed since the ocean last covered the Everglades area to allow the rain water falling there to completely flush out the remnants of the Pleistocene (Ice Age) sea water. Actually, most of this water has been greatly modified, partly by dilution with fresh rain water and partly by chemical reactions, mainly of the base-exchange variety, with the surrounding rocks and organic matter. There are extensive areas in the Everglades where it is not possible to develop size-able supplies of suitable ground water.

Quality of the ground water may change locally along arterial canals when the canal water changes. Along the lower reaches of those canals connecting with Biscayne Bay the adjacent ground water changes with advances and retreats of the salt water from the ocean; and along these canals that drain the upper part of the Everglades, notably the North New River Canal in which the quality of water changes seasonally with discharge, there is a slight local effect when more highly mineralized canal water spreads into the nearby ground; this is especially noticeable in the area immediately upstream from each dam.

Salt Water Encroachment in the Aquifer.--With respect to the encroachment of salt water from the ocean at depth in the aquifer it is significant to note that in Miami, before the dredging of the drainage canals, perennially

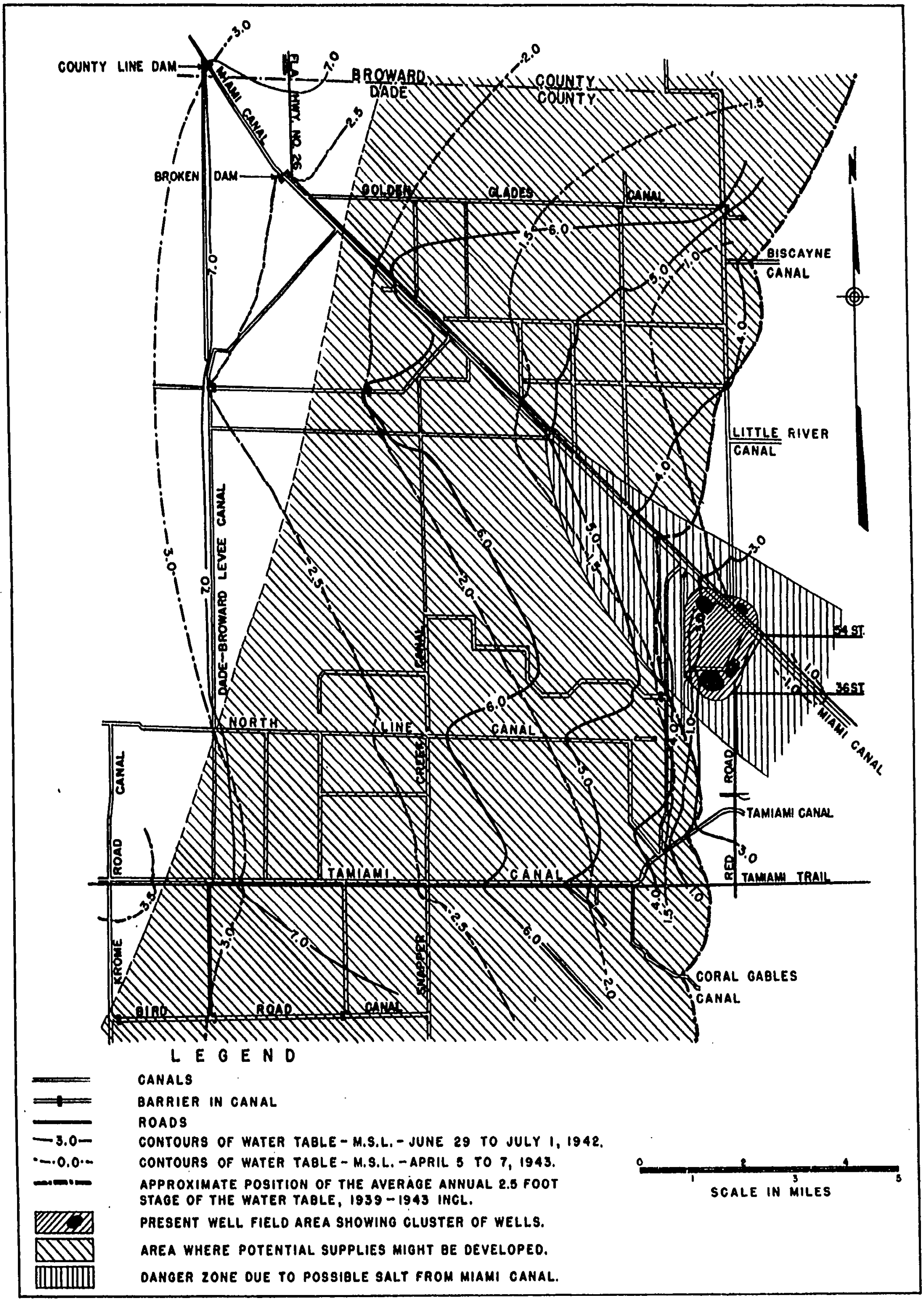


MAPS SHOWING AREAS OF SALT WATER CONCENTRATION AT MIAMI, FLORIDA IN 1904, 1918, AND 1943

NOTE: STIPPLING SHOWS EXTENT OF AREAS THAT HAVE CHLORIDE CONCENTRATION APPROXIMATING 1000 P.P.M. OR MORE, AT A DEPTH OF ABOUT 80 FEET.

flowing fresh water springs discharged along the western shore of Biscayne Bay at elevations of from 3 to 5 feet above mean sea level, thus indicating a high water table close to the shore line. These springs have long since ceased to flow, and the lowered water table no longer exerts sufficient pressure on the heavier salt water from the ocean to hold it back, so the salt water has moved inland as a blunt-nosed wedge underneath the lighter fresh water. This salt water wedge, in the Silver Bluff area, has advanced inland about 8,000 feet. Plate 5 shows maps of the Miami area indicating the zone of salt water contamination in 1904, 1918, and 1943. The maps for 1904 and 1918 are largely based on estimated and known conditions, but that for 1943 is principally based on samples from wells generally more than 60 feet deep. These maps clearly show the trend of salt water advancing inland and displacing fresh water. They show that salt water has not yet reached the Miami well field by direct infiltration from the Bay at depth in the aquifer, and likewise show why it was necessary in 1941 to abandon the ground water supply at the Coconut Grove water plant. Elsewhere along the coast the distance that the salt water has penetrated inland may be more or may be less than 8,000 feet depending upon the effectiveness of the nearby drainage canals in lowering the water table. This blunt-nosed salt water wedge encroaches haltingly, with many minor advances and retreats, and it probably will continue in this manner until eventually it will come to rest in equilibrium with fresh water where the average annual two and one-half foot contour on the water table occurs. During the short period of this investigation (4 years) the critical two and one-half foot water table contour has generally paralleled and lain slightly to the west of Red Road, and has passed <u>to the west</u> of the present well field. (see plate 6).

PLATE 6



MAP OF AREA WEST OF MIAMI WELL FIELD SHOWING WATER TABLE CONTOURS AND AREA SUITABLE FOR DEVELOPMENT OF LARGE GROUND WATER SUPPLIES

U.S. GEOLOGICAL SURVEY MIAMI, FLORIDA

The salt wedge moves slowly. In 34 years (1910 to 1944) it has moved about 8,000 feet inland at Silver Bluff, and possibly more depending upon its original position, which is here assumed to have been about at the shore line. Old residents of this area, however, tell of a well that formerly was sunk in Biscayne Bay to an unknown but fairly shallow depth (30 to 50 feet, possibly) and that potable water was pumped from it by boatmen. If the water obtained was fresh, then the fresh water-salt water boundary must have lain somewhat east of the shore line, out under the Bay, and the total movement of salt water inland may be nearer 10,000 than 8,000 feet. Using 8,000 feet as a base figure the average rate of movement inland has been 235 feet per year, and at this rate, if conditions remain about as they now are, it would be many more years before the salt wedge moved in as far as the present well field. But the salt wedge does not present an even front. Tongues of salty water from the Bay follow under and along the drainage canals and extend from the top of the aquifer to the very bottom. In cross section these tongues have a trapozoidal shape, narrow at the top and wide at the base.

The most threatening of these tongues is that of the Miami Canal with its spearhead now almost dormant about one-half mile west of N. W. 36th Street Bridge. This tongue may be moving at the same or a similar rate as the salt wedge along the shore. If it is, then it will be only a matter of about 43 years before the well field is reached inasmuch as the distance to be traveled is about 2 miles. Only observations carried out over a much longer period of time will definitely establish this rate of movement.

The above considerations are based on conditions as they have existed in the past. Should changes be made in the water levels, or the canals be dredged wider and/or deeper, the rate of movement of the wedge and tongues of salty encroaching water would be changed. For instance, should the Miami Canal be dredged to a depth of 25 feet as far as N. W. 36th Street Bridge as has been proposed recently highly saline water from Biscayne Bay would probably immediately penetrate inland the whole length of the deeply dredged section. It is probable that the natural fresh water flow in the canal would be insufficient to keep the salty water below the head of the 25-foot dredged section except possibly during periods of very heavy rainfall. It is entirely possible, moreover, that pockets of salty water would remain in portions of the deeply dredged section most if not all of the time. These pockets of salty water would be a constant source of contamination of the nearby shallow ground water particularly during dry periods when the water table is low. This would, in effect, rejuvenate the movement of the Miami Canal salt tongue, both laterally and upstream. However, the inland advance of the salt tongue could be held in check by maintaining an average yearly water table height of two and one-half feet above mean sea level at the head of the deeply dredged channel.

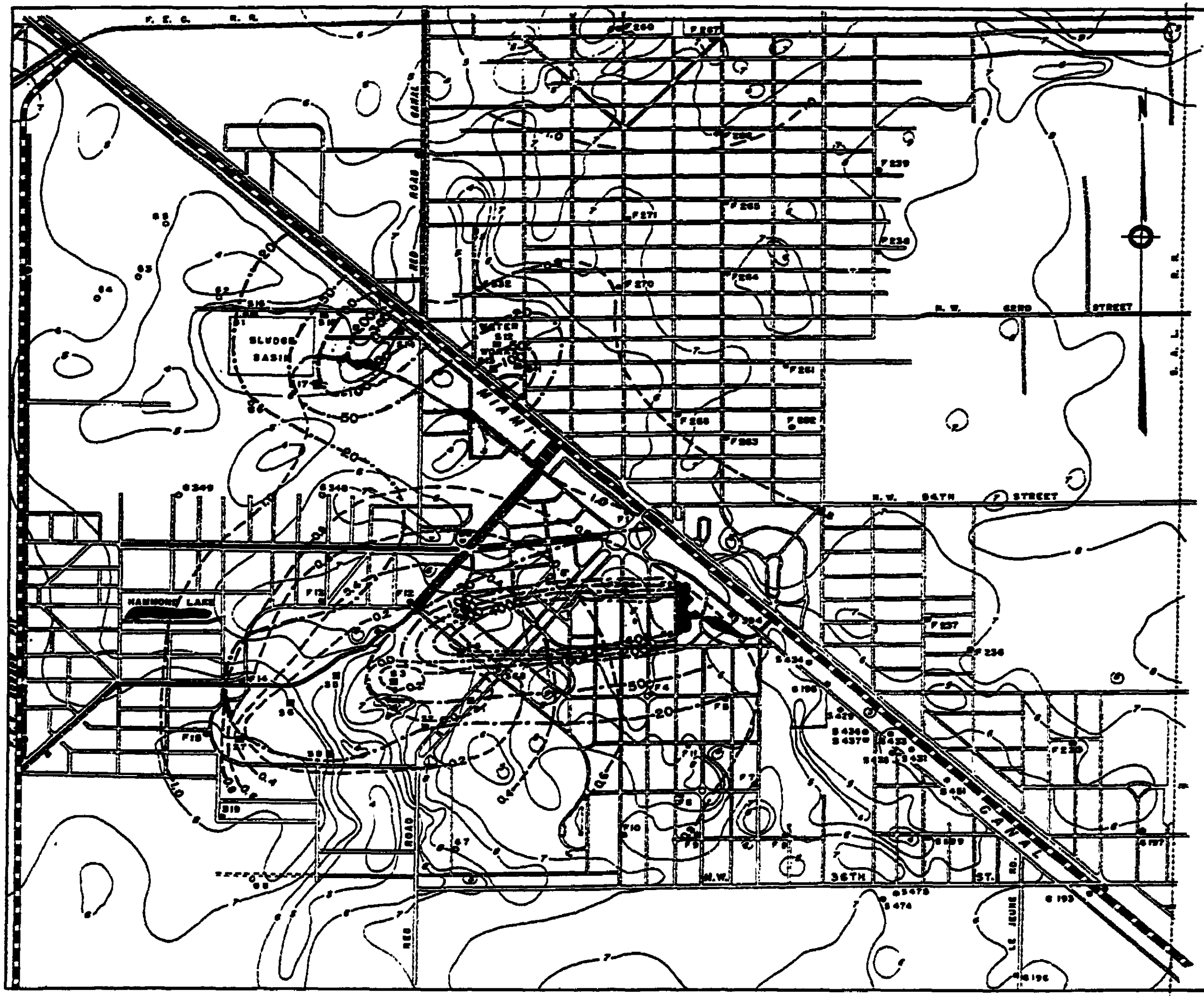
From the foregoing discussion of salt water encroachment, the fact that the present well field is ultimately threatened with permanent salt contamination is apparent. The danger is not imminent, however, nor in the near future if conditions remain as they now are. But to insure the perpetual use of the present well field the two and one-half foot average annual contour on the water table must pass to the <u>east</u> of the well field, and this will require the establishment of controls in the canals to raise the water level behind the controls to that height. Under the present regulations the tidal dam in the Miami Canal cannot be raised until the canal stage has receded to 2.2 feet above U. S. C. & G. S. mean sea level at Pennsuco, about 7.2 miles northwest of the present well field.

Salt Water in the Miami Well Field.--Contamination of the Miami well field in 1939 was not brought about by movement of salt water at depth in the aquifer, but was occasioned by a salt incursion in the Miami Canal at a time when low flow in the canal was insufficient to hold sea water at a relatively safe distance downstream from the well field.

A shallow cone of depression surrounds the Miami well field and reaches the Miami Canal much of the time. Water seeks to reach a level, so moves in laterally from the area surrounding the cone of depression, and the movement is always at right angles to the contours on the water table. Thus, when salty water occupied this reach of the Miami Canal, it came under the influence of the cone of depression around the well field and moved inward to the well field. It was inevitable that the water served the consumers became somewhat salty under the circumstances. Fortunately, the time that the salt water remained in the canal was not great so that the amount that reached the well field was not ruinous. Certain wells, for a while, contained water of over 1,000 parts per million of chloride, but the large area of salty water in the well field reached a concentration of about 400 parts per million. Thus, the damage was nominal (see plate 7).

Since then, judicious pumping of the several supply wells, effective placement of barriers in the canals and timely rainfall has prevented a recurrence of the 1939 experience.

Further, pumping an average of about 28 million gallons per day from the well field has removed much of this body of salty water from the



PUMPING RECORD							
WELL NO.	HOURS PUMPED PER DAY DECEMBER 1939						
	23	24	25	26	27	28	29
S1	12.25	12.10	12.58	13.83	14.50	15.67	12.08
S2	9.58	11.83	11.75	11.67	14.58	16.17	12.33
S3	12.00	12.17	12.17	12.00	14.58	16.25	12.58
S4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S5	11.67	11.67	11.67	11.67	9.33	7.92	11.75
S6	11.67	11.83	11.83	12.33	17.33	7.83	11.67
S7	11.67	12.17	12.00	12.33	9.58	12.58	13.00
S8	5.58	3.67	9.50	2.50	19.67	15.25	13.42
S11	24.00	20.50	16.00	22.33	20.00	24.00	24.00
S12	16.25	22.00	16.58	13.58	16.00	12.50	9.50
S13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S16	11.83	12.08	11.08	10.83	11.00	11.08	12.33
S17	12.17	11.92	13.08	13.17	13.17	13.08	11.83
TOTAL PUMPAGE M. G. D.	23.38	23.80	22.67	23.00	25.97	26.78	25.04
RAINFALL IN IN. AT WATER WORKS	0.00	0.00	0.00	0.00	0.00	0.00	0.85

● DEEP WELL
○ SHALLOW OBSERVATION WELL
■ ACTIVE SUPPLY WELL
⊙ STAFF GAGE
— 50 — PARTS PER MILLION CHLORIDE
– – 0.2 – – WATER TABLE CONTOURS
— 7 — CONTOURS OF GROUND SURFACE

NOTE -
AT THE TIME THESE DATA WERE GATHERED, NOT ENOUGH CONTROL POINTS WERE ESTABLISHED TO MAP THE AREA COMPLETELY.

DATUM: MEAN SEA LEVEL U.S.C. & G.S.

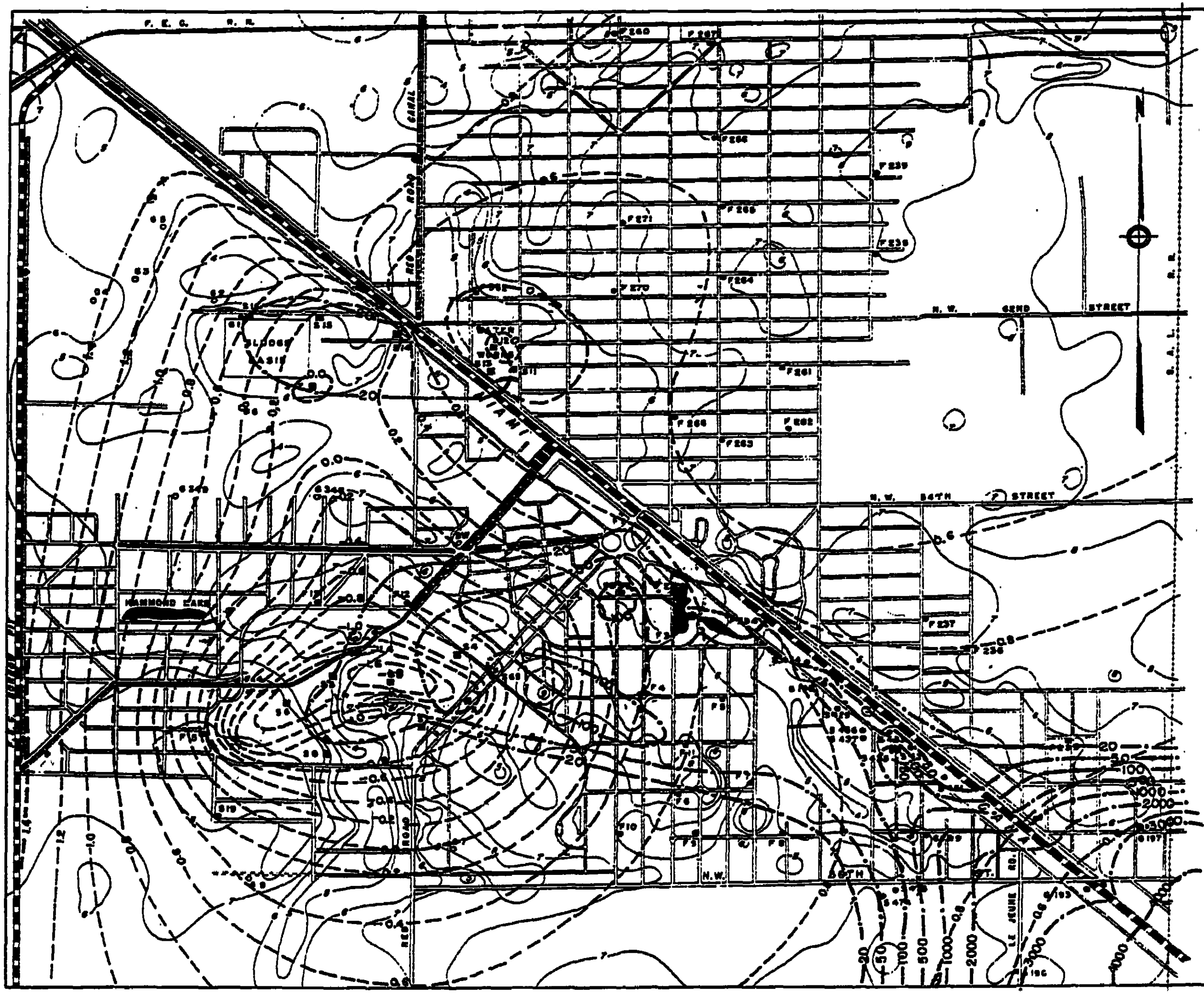
MAP OF
MIAMI WELL FIELD AREA

SCALE IN FEET
0 1000 2000 3000
0.0 0.1 0.2 0.3 0.4 0.5
ONE HALF MILE

DECEMBER 26, 1939.

U. S. GEOLOGICAL SURVEY MIAMI, FLA.

PLATE 8



WELL NO.	HOURS PUMPED PER DAY FEBRUARY 23	24	25	26	27	28	29
S1	0.00	0.00	0.00	0.00	14.00	24.00	24.00
S2	24.00	24.00	24.00	24.00	9.50	0.00	0.00
S3	20.30	24.00	24.00	24.00	24.00	24.00	24.00
S4	24.00	24.00	24.00	24.00	10.05	0.00	0.00
S5	20.30	24.00	24.00	24.00	24.00	24.00	24.00
S6	24.00	24.00	24.00	24.00	24.00	24.00	24.00
S7	0.00	0.00	0.00	0.00	14.25	24.00	24.00
S8	24.00	24.00	24.00	24.00	9.30	0.00	0.00
S11	14.30	18.00	17.30	18.25	24.00	0.30	0.00
S12	12.45	12.15	16.30	15.30	9.15	13.35	24.00
S13	3.00	4.00	2.30	16.30	15.20	20.30	16.50
S14	24.00	24.00	24.00	24.00	9.00	18.15	24.00
S15	0.00	0.00	0.00	0.00	14.45	22.00	24.00
S16	24.00	24.00	24.00	24.00	9.10	2.00	0.00
S17	24.00	20.50	18.35	4.45	14.35	13.45	24.00
TOTAL PUMPAGE M. G. D.	35.23	36.39	36.17	36.76	36.72	34.39	36.27
RAINFALL IN IN. AT WATER WORKS	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PUMPING RECORD

● DEEP WELL
○ SHALLOW OBSERVATION WELL
■ ACTIVE SUPPLY WELL
⊙ STAFF GAGE
—50— PARTS PER MILLION CHLORIDE
—0.2— WATER TABLE CONTOURS
—7— CONTOURS OF GROUND SURFACE

NOTE..
TIDAL DAM AT N. W. 36TH. ST. IN IN CONTINUOUS OPERATION SINCE FEB. 14, 1944.
DATUM: MEAN SEA LEVEL U.S.C. & G.S.

MAP OF
MIAMI WELL FIELD AREA
SCALE IN FEET
0 1000 2000 3000
0.0 0.1 0.2 0.3 0.4 0.5
ONE HALF MILE
FEBRUARY. 29, 1944.
U. S. GEOLOGICAL SURVEY MIAMI, FLA.

well field and the remainder has been greatly diluted with inflowing fresh water so that the field now contains a relatively small amount of chloride--about 100 parts per million (see plate 8).

The salting of the present well field clearly points out the danger of developing a new supply near enough to a canal that may, at times, contain salt water. Under the influence of the cone of depression surrounding the field this salt water could move into the field and contaminate it.

Development of Additional Ground Water Supplies.--In choosing the site of additional well supplies several important factors should be considered. Among these, without any attempt being made to arrange them in order of importance, are the following:

(1) Sufficient thickness of permeable aquifer

(2) Satisfactory quality of ground water.

(3) Safety from possible encroachment of salt water at depth in the aquifer and from canals carrying, at times, sea water.

(4) Location far enough removed from possible future developments and activities of other interests that might interfere with safe and continuous operations.

(5) Location consistent with shortest pumping distance to water treatment plant and to distribution system.

(6) Location consistent with accessibility to well field area.

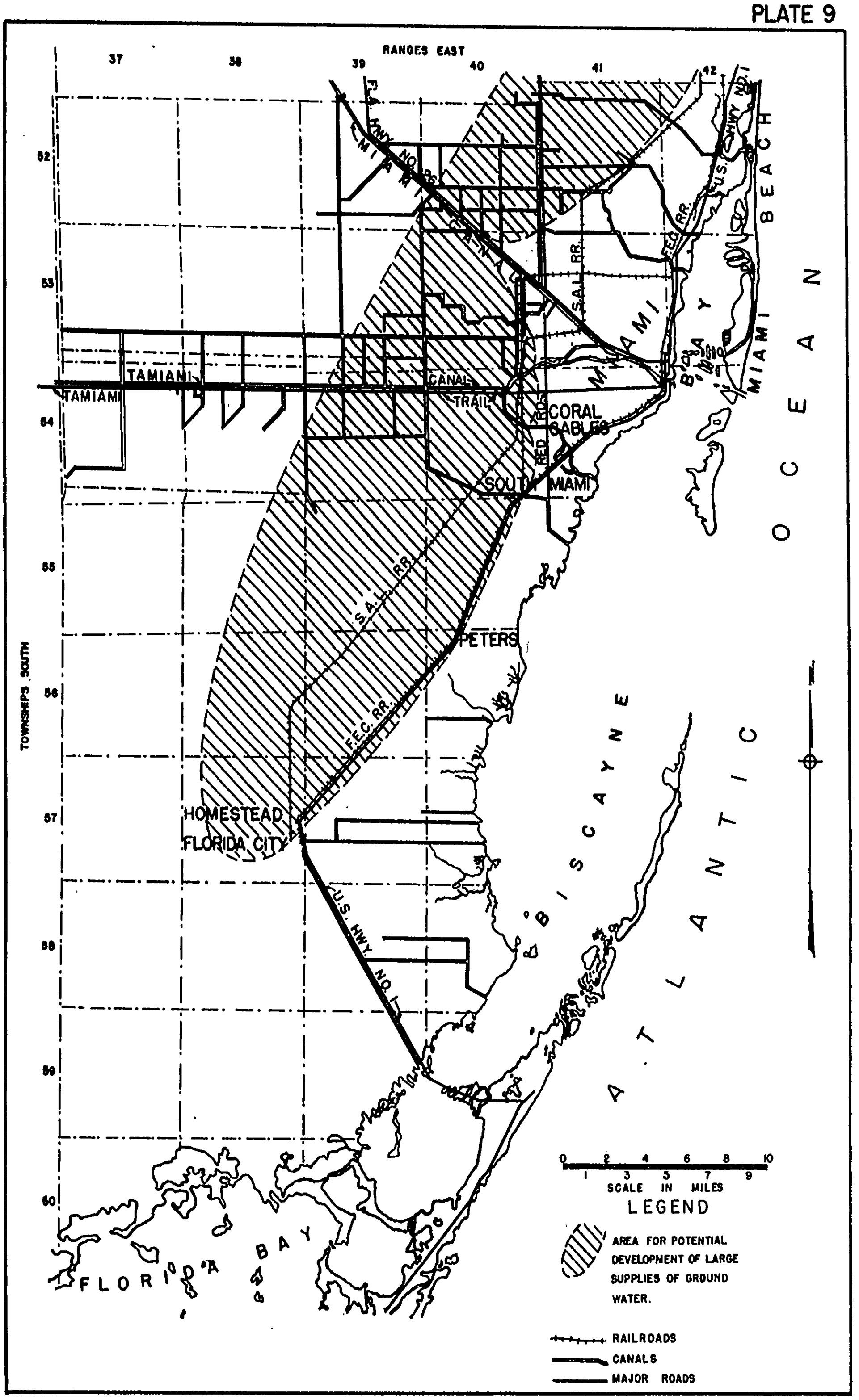
(7) Proper spacing of wells so that a minimum cone of depression will develop.

Earlier in this report factors (1), (2), and (3) have been generally discussed. At this point it would be pertinent to point out, that in an area about seven miles wide (see plate 6), measured west from the present well field, and extending northeast and southwest roughly paralleling the shore line, a well field might be developed almost any place. In a zone along the Miami Canal where salt water might sometime penetrate if regulation of the canal is not practiced it probably would be unsafe to develop a field. In this seven mile wide area there is sufficient depth of permeable aquifer and satisfactory quality and quantity of water to supply any foreseen population growth of the Miami area.

North and south of metropolitan Miami the coastal ridge is underlain by about 100 feet of highly permeable rock similar to that in which the present wells of the municipal supply are developed. The ground water, except that in a zone about 8,000 feet inland from the Bay and in tongues following under and along the drainage canals which at times carry salty water, is of excellent quality, can be obtained in large quantities, and is usually lower in color and hardness than the ground waters of the Everglades.

To the south of Miami along the Coastal Ridge, very large supplies (thirty millions of gallons per day or more) could be developed, but to be safe from salt water encroachment should be located a mile or more away from the larger drainage canals, and in no case should be nearer than 3 miles to the Bay. (see plate 9). In general, such large supplies could be developed almost anywhere west of Red Road and southward along U. S. Highway 1, on the western side, at least to Peters. Beyond Peters the area between the Bay and U. S. Highway 1 is much wider than to the north and becomes wider with greater distance to the south. Supplies can be developed east of Homestead for a distance of several miles, but the presence of drainage canals in this area must always be borne in mind and locations made accordingly. However, if a large supply were to be developed south of Peters it would be better to choose a site along or west of U. S. Highway 1, not east of it.

PLATE 9



MAP OF EASTERN PART OF DADE COUNTY, FLA., SHOWING AREA FOR POTENTIAL DEVELOPMENT OF LARGE SUPPLIES OF GROUND WATER

To the north of Miami the formations contain greater amounts of sand than to the south, therefore, wells are more difficult to develop, the yield is not so large, and drawdown is greater. The same salt water encroachment safety factors apply here as mentioned above.

In Dade County, generally speaking, it would be unsafe to attempt the development of a large supply east of the S. A. L. Railroad as far south as South Miami, and beyond this point U. S. Highway 1 would be the dividing line.

Under factor (4) agricultural, commercial, industrial, and sanitary aspects should be considered. For instance, should unrestricted development ever take place adjacent to or surrounding the area chosen for development of a well field, drainage might be demanded that would result in salt water gaining access to the site either through new canals or eventually by a further lowering of the water table and consequent farther movement to the west of the average annual two and one-half foot contour on the water table.

The development of such commercial and industrial or sanitary interests as the Miami Intransit Air Depot, the proposed City of Miami sewage disposal plant, and a proposed airfield for privately owned airplanes and "dusters" have to be considered. The Miami Intransit Air Depot is soon to start pumping one and one-half to two million gallons per day of ground water and will develop a small cone of depression around its well field. There is no estimate of what the total pumpage may be in the future, but should a well field be located nearby, the two cones of depression would merge into one large one. The sewage plant would have large quantities of waste to dispose of daily, possibly by emptying the treated effluent into the Tamiami Canal. The establishment of the proposed airfield would be another interest demanding lowered water tables.

Factors (5) and (6) are engineering economics problems that need not be discussed here.

Factor (7) may be enlarged upon somewhat. In planning a well field, the manner of spacing the wells and their distance apart must be considered. Elsewhere it probably would be the best plan to align the wells at right angles to the direction of flow of the ground water, in other words, parallel to the contours on the water table (see plate 5). In the Miami area, however, the water table gradients are so flat that it would make little difference how the wells are patterned or laid out. From a study of the characteristics of the cone of depression surrounding the present well field it is believed that, were wells of similar capacity constructed in the new field, they should not be closer together than 750 feet, and 1,000 feet apart would be better. Whether the wells be laid out in the form of one or more long parallel rows, or in the form of a "y", and "x", a "v", or any other pattern, is a matter of engineering economics.

PROTECTION OF GROUND WATER SUPPLIES IN THE MIAMI AREA

The protection of ground water supplies in the Miami area embraces two problems: one is the protection of the present well field from salt water encroachment by way of the Miami Canal and the other is the protection of both the present well field and all other sources of ground water supply from salt water encroachment at depth in the aquifer. The characteristics of both movements are described in an earlier section of this report. The successful solution of these problems is through control of ground water levels by means of regulation of the drainage canals.

Protection from Salt Water Encroachment by Way of the Miami Canal.--The more immediate problem is the protection of the present well field from sea water which passes upstream in the Miami Canal during periods when the fresh water flows are insufficient to hold the sea water back. This problem might be attacked in three ways. First, the discharge in the unregulated lower reaches of the Miami Canal might be augmented so that the larger discharges obtained would hold sea water sufficiently far downstream, without the use of dams, to prevent its encroachment into the well field. Second, a system of barriers might be maintained in the Miami Canal to prevent wastage of fresh water and the incursion of salt water far up the Canal and thus achieve a similar effect. Third, canal flow regulation and/or augmentation might be combined with the operation of a salt water barrier.

The first method does not appear practicable because of the difficulties of providing the relatively high rates of flow needed during periods of drought. A minimum discharge of about 250 million gallons per day should be maintained at the Miami water plant for effective sea water flushing action without the use of barriers.

The second method involves operations very much the same as those employed by the City during the past two low water periods when a pneumatic type of tidal gate at 36th Street effectively prevented free upstream movement of salt water. It is evident, however, that the successful continued use of such a barrier will require larger discharges during low water periods than can be provided under the present state of development of the canal basin upstream.

The third method, which is a combination of the first two, appears to be the most practicable. A somewhat higher low water flow in the Canal could be achieved by relatively minor improvements which would increase the capacity and decrease the rate of loss from the storage area above the County Line dam. This includes the placing of additional barriers at strategic locations on the canals bordering and leading from the storage area. These canals collect and drain off the stored water at a more rapid rate than desirable. With the degree of regulation of flows thus established and proper regulation of the present tidal dam sea water would be effectively held below such a barrier except perhaps during times of high wind or hurricane tides.

<u>Protection from Salt Water Encroachment at Depth in the Aquifer</u>.--Although the advance of the salt water front does not immediately endanger the Miami well field nor the potentially important supply areas to the west, north, and south, the problem as described in earlier sections is nevertheless sufficiently acute to demand early attention. In the light of scientific data now available the salt water encroachment is shown to be the result of overdrainage, not only of the Everglades but also of the Coastal

Ridge. The problem covers more than the protection of the Miami well field; it involves the preservation of as much as possible of the still uncontaminated parts of the aquifer in the coastal areas so that existing and future water supplies in these areas may be safeguarded, it is a county-wide problem involving the investments of home-owners and property-holders outside the boundaries of the municipalities.

The maintenance of ground water levels at an average yearly stage of two and one-half feet or more above mean sea level can be affected only by control of the canals which drain Dade County. Because of development subsequent to, and made possible by drainage operations, it is not to be expected that original water levels can be restored, that parts of the aquifer now salted will be reclaimed, or that springs will again issue along the western shore of Biscayne Bay. The greatest degree of water control that can be effected through the regulation of the canals without endangering developed activities probably will not prevent some further inland movement of the salt water front but will preserve a substantially large area that otherwise would be lost to encroaching salt water.

In a control program the Miami and Tamiami Canals will be of greatest importance, to the City of Miami principally because of location of the Miami well field between their converging reaches. The Coral Gables Canal will be important, too, because of its strategic location immediately south of the well field area, and also because it is one of the larger and deeper waterways that allows salt water access to an ever-widening and lengthening zone along its course. To Dade County and the rest of the municipalities within it, the other unregulated canals are very important, especially Little River, Biscayne, Snake, and Snapper Creek Canals.

The farther downstream control structures could be placed and operated in these and connecting canals which discharge into salt water, the more effective water control would become, and the closer to the Bay the encroaching salt water would be held.

SURFACE WATER SUPPLIES IN SOUTHEASTERN FLORIDA

There are briefly described below, from the standpoint of quantity and quality, the several surface water sources in southeastern Florida that might be considered as possible future supplies for the Miami area. The brief evaluation of these sources does not include the economics of development other than reference to their distances from the point of utilization. A certain potential source of supply may, because of its remoteness, be considered impracticable for early development but may, owing to greatly increased population and water consumption, be an entirely feasible supply in the distant future.

KISSIMMEE RIVER

This is the most distant of all sources covered in this report, the mouth of the Kissimmee River being nearly 100 airline miles from Miami and a considerably longer distance by any practicable water-conduit route. The quantity of water available from the Kissimmee River is best determined from the discharge as measured since 1928 at a gaging station near the point of discharge of the river into Lake Okeechobee. During this period the minimum daily discharge was over 130 millions of gallons or over 3 times the greatest daily rate of production of treated water at the Miami plant. Factors to be considered in the selection of this supply include the effect of possible upstream development upon existing drouth or base flow, and the effect of possible large future diversions from the Kissimmee River upon the storage requirements in Lake Okeechobee which are principally for navigation and agricultural activities. The Kissimmee River is designated by law a navigable waterway.

The quality of water in the Kissimmee River is, from many points of view, the best to be found in southeastern Florida. Its average hardness of about 20 parts per million classifies it as the largest, single source of very soft water in this part of the State. The total mineral content of about 70 parts per million is also lower than that of any other major source of water in the area included in the investigation. The color of the Kissimmee River is high and objectionable but could be removed with proper treatment. Although soft waters tend to be corrosive it is a rather simple matter to correct this condition.

LAKE OKEECHOBEE

This large body of water, the nearest shore of which lies about 65 air line miles northwest of Miami has long been considered by many persons as a possible future source of water supply for the municipalities along the Florida lower east coast. Certain groups have favored carrying the water to the coastal strip by closed conduit or pipe line; others by use of the existing open canals. Studies dealing with the adequacy of water in Lake

Okeechobee are complex for they involve problems of Lake regulation for flood control, navigation, and agriculture. The changes which further development of the Kissimmee River basin and the Everglades would bring about must also be considered.

The amount of water to be diverted from Lake Okeechobee for municipal use in the Miami area would vary greatly with the type of conduit provided to carry the water to the coast. This amount would be essentially that required for treatment, if a pipe line or other water-tight channel were used, but would necessarily be many times greater if an unlined open channel were utilized. In the former case the amount diverted would be only a small percentage of the loss from the Lake by evaporation and transpiration (about 4 feet per year) and seemingly would have little effect upon the stage. For example a diversion equal in amount to the present maximum output of treated water at the Miami water plant would reduce the stage only about a hundredth of a foot in one month over the 500 square mile low-water area of the Lake.

The water in Lake Okeechobee is intermediate in hardness and in total dissolved mineral matter between that of the Kissimmee River and the surface and ground water in the Miami area. It is suitable for most purposes, and is currently the source of the public water supplies for most cities and towns near Lake Okeechobee.

If diversion from the Lake were through unlined channels, such as arterial canals, cut through the muck and rock of the Everglades, the water delivered for municipal use at the lower end would differ in both quantity and quality from that diverted from the Lake. Due to the highly permeable character of the rock formations along the lower reaches of such canals water would pass freely between the channel and adjacent banks. During low water periods adjacent ground water would be readily recharged from the canal with large accompanying losses to the conveyed supply. It is apparent that such an operation would have a direct relation to water control activities in the area adjacent to the channel. During other periods it is likely that considerable quantities of the highly mineralized water from the formations cut through would enter the channel giving the resulting mixture a quality poorer than the Lake water.

NORTH NEW RIVER CANAL

The North New River Canal has long been considered as a channel through which to carry water, the greater part of the distance, from the Lake to the Miami area. The water carrying conditions of unlined channels described in the preceding section are applicable to this canal and to connecting canals south towards Miami.

The composition of water in the North New River Canal, under existing limited diversion from the Lake, varies between rather wide limits. Analyses show that during a period of one year the concentration of dissolved mineral matter ranged between 205 and 813 parts per million and that the hardness ranged between 126 and 456 parts per million with the higher concentrations occurring at times of low flow. Water in this canal is more difficult to treat during a greater part of the year than water currently pumped from the present Miami well field. Water having the composition of the average found in the North New River Canal would be of poorer quality than water in Lake Okeechobee or water now being used for the public supply of Miami. Increased diversion from the Lake through the canal might improve the quality of the canal water slightly during dry periods.

MIAMI CANAL

The Miami Canal is, along its middle course, only partially excavated, and water does not pass through that muck and weed choked part of its channel during normal and drought periods. In fact, the flow in the upper reaches of the Miami Canal is toward the Lake at frequent intervals throughout the year. If this canal were deepened to accomodate diversions from Lake Okeechobee, mineralized ground water would be encountered in its middle and upper reaches similar to that found in the North New River Canal.

Flow in the lower Miami Canal serves during normal periods to help protect the Miami well field from salt contamination, and is in itself a possible source of municipal supply. The minimum discharge (approximately 250 millions of gallons per day) considered sufficient to effectively hold sea water downstream without the use of the recently constructed pneumatic tidal dam is several times the present output of treated water. The minimum unregulated discharge in the Miami Canal during severe drought is not accurately known since retention structures have been in use during these periods as a protection against upstream migration of sea water. The location of the intake for any possible municipal use of canal water would determine the necessity for and location of a tidal gate or barrier to be used during drought flows. Without a barrier the intake would necessarily be placed at or above the farthest migration of salt water which, within the past few years, has been several miles upstream from the water plant.

The composition of water in the lower reaches of the Miami Canal changes somewhat with discharge, but is generally similar to the composition of ground water withdrawn from the Miami well field for the municipal supply.

A direct diversion by pipe line or lined conduit from a point in the Miami Canal above the County Line dam would draw water directly from the headwaters storage area. Measurements made during the release of water from this area through the gates in County Line dam indicate that considerable storage is available there. During a period of 10 days (March 28 - April 6, 1942) a total of over 1.5 billions of gallons was withdrawn with an accompanying average lowering of water elevation in the backwater of Miami and South New River Canals of less than one foot. Such a withdrawal would be equivalent to a diversion of 50 million gallons a day for a period of one month. It is estimated, however, that there are several times that amount of water available by pumpage from or release through the dams in the Miami and South New River Canals during the normally dry winter and spring months in the present state of development of this storage area.

Prior to any steps toward the development of this source the hydrologic and hydraulic characteristics of the area should be more completely studied. During the comparatively dry winter and spring months the total evaporation and transpiration over this reservoir area, together with leakage, at times removes water at rates in excess of one tenth of a foot decline in water levels each week. However, the lower the water levels in the area fall the less is the loss by total evaporation and transpiration. The open water storage in the canal is only a small part of the total ground water storage in the shallow but relatively permeable formations of the area. There would apparently be little advantage in increasing by excavation the open water storage volume because such areas have greater evaporation losses during low levels in the reservoir than the land areas beneath which water is stored naturally in the porous rock.

Future development in, or future water policies relating to, this storage area may dictate its value as a source of supply or even as an equalizing basin for the flow of the Miami Canal. As a reservoir it could be improved with respect to capacity and storage characteristic by the placing of additional retention structures in existing canals, or it could be largely nullified by the opening or removal of the dams in the Miami and the South New River Canals.

Analyses indicate that water in the Miami Canal north of Dade-Broward County line dam is somewhat softer and contains less dissolved mineral matter than the Miami Canal at the water plant in Hialeah. However, as large withdrawals made from this section of the Miami Canal are replaced by water withdrawn from the ground water reservoir in the adjacent area, the water will probably increase in hardness and in dissolved mineral matter. Such increase is indicated by the analyses of samples of shallow ground water collected from observation wells in the area.