GROUND WATER

By Garald G. Parker

OCCURRENCE

INTRODUCTION AND GENERAL PRINCIPLES

DEFINIITION OF GROUND WATER

Water that occurs beneath the surface of the earth in the zone of saturation where it fills the interstices, joints, crevices, fissures, solution holes, and any or all other voids, is called ground water (Meinzer, 1923a; 1923b, p. 5). It is the water that supplies springs and wells, and that seeps into lakes and streams to maintain their stages and flows between rains. The geologic formations whose interstices or openings are filled with water, and from which water is collectible for use, are called aquifers.

NONARTESIAN WATER AND THE WATER TABLE

The water that infiltrates the ground and fills the voids between rock particles makes a water-saturated zone whose upper surface is under atmospheric pressure; this surface is called the water table. To most laymen the term "water table" denotes a flat or plane surface; actually it seldom is that. A glance at figure 29 will show plainly what the term means.

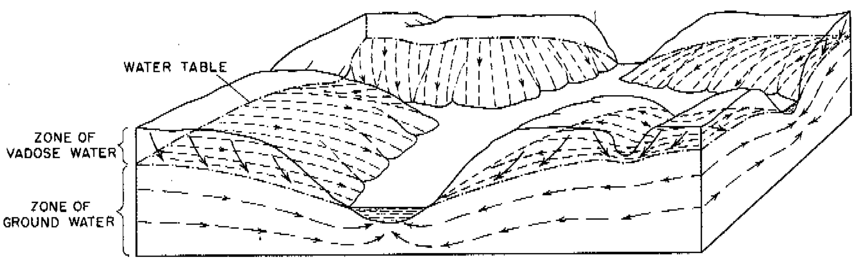

Figure 29. —Idealized block diagram showing relationship of water table to land surface.

The water table is higher beneath uplands than beneath lowlands, and in general it reflects the topography of the land in a subdued fashion. The water table is an unconfined air-water surface, acted upon mainly by gravity and atmospheric pressure; in a well that penetrates the water table, water ordinarily will not rise above the water level in the surrounding aquifer, which contrasts with the water of artesian aquifers (see following section). Where the water table intersects the land surface, seeps or springs form, and, according to topography, a marsh, lake, or stream results.

Vadose water is water held in suspension in the zone of aeration above the water table. In areas where the ground-water resources are carefully studied, maps of the water table may be prepared for selected times. Such maps show by contours the altitude of the water table with reference to a common datum plane (such as mean sea level) and indicate the direction of ground-water flow, which is normal to the contours. Such maps may indicate the source of water of a given well field, the area influenced by pumping from the well, and other valuable and pertinent data. Several water-table maps are given elsewhere in this report (see, for example, figs. 32, 42, 46, 77, and 189).

ARTESIAN WATER AND THE PIEZOMETRIC SURFACE

When water completely fills an aquifer whose upper surface is relatively impermeable, it is under pressure both from the water entering the aquifer at a higher level (where there is no confining upper surface) and from the weight of the overlying beds. A well drilled into such an artesian aquifer will relieve the pressure, thus locally allowing the water to rise in the well to a distance necessary to balance the pressure. Such a well is an artesian well regardless of whether or not it will flow. Figure 30 is a cross section of a

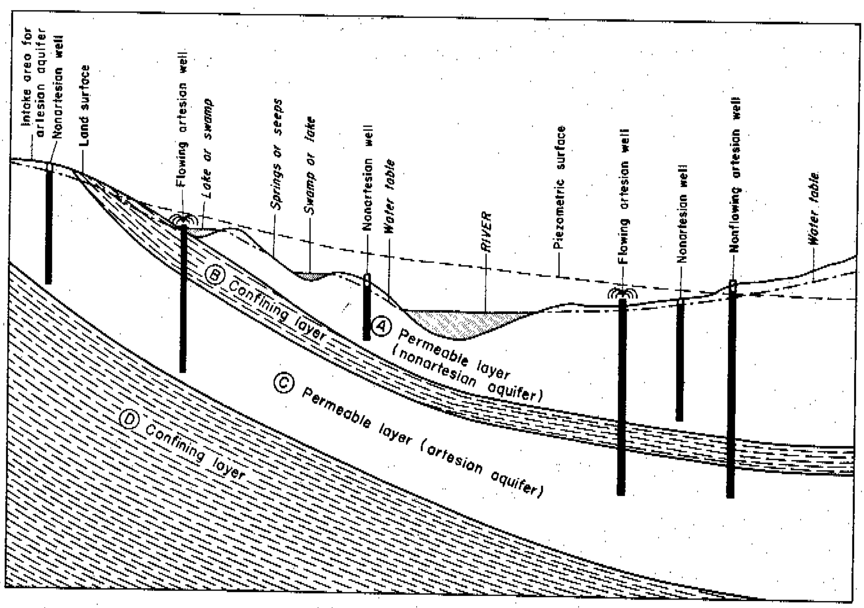

Figure 30. —Idealized cross section showing relationship between water table and piezometric surface of artesian water in an area with geologic structure similar to that of Kissimmee valley.

hypothetical area with a geologic structure similar to that of the Kissimmee River valley. Aquifer A contains only nonartesian water or water that occurs under water-table conditions. Layer B, a bed of relatively impermeable marl or clayey material, separates aquifer A from aquifer C, which, down slope from the intake area, contains water under artesian pressure.

In the highland area, where permeable beds crop out, aquifer C has a water table, and the water there is not confined. Such an area is termed a "recharge area", because it is there that the aquifer naturally receives its water. An artesian aquifer is both an underground reservoir and a conduit operating under natural pressures, and the water in it behaves in a manner similar to water in a city water-supply distribution system.

When water is withdrawn from an artesian well, no unwatering of the aquifer occurs unless the water level is drawn down below the bottom of the overlying confining beds; instead, the space formerly occupied by the removed water is taken up by a combination of both the expansion of the water remaining, and the compression of the aquifer resulting from the lowered pressure. Unwatering may eventually occur in the recharge area where the water level declines when the effect of well-discharge reaches it. On the contrary, when water is withdrawn from an aquifer under water-table conditions an actual unwatering of the aquifer occurs in the area surrounding the well.

The lowering of pressure in an artesian system, caused by discharge from a well, is somewhat comparable to that in a city water-supply system when a faucet is opened. In the city water-supply system the pipes are rigid and comparatively nonexpanding; thus, the pressure changes in the distribution system are readily transmitted to the elevated tank where the water level drops when faucets discharge. In artesian aquifers such rigidity is not known; most aquifers are more or less elastic and may eventually suffer some compaction and a certain amount of permanent loss of capacity through development. For further information on elasticity of artesian aquifers the reader is referred especially to two papers by Meinzer (1928, p. 263-291; 1937, p. 715).

An imaginary surface indicating the height to which water will rise in tightly cased artesian wells represents the artesian head in any given artesian aquifer; it is called the piezometric surface, and is to an artesian (confined) aquifer what the water table is to a nonartesian aquifer.

By mapping the piezometric surface much can be learned of the occurrence and behavior of water in an artesian aquifer. This was first done by Stringfield (1936, p. 134) for the Floridan aquifer, the principal artesian aquifer of the State (see fig. 35).

METHODS OF INVESTIGATION

The methods of investigating ground-water occurrence and behavior under varying conditions in southern Florida are those in general use by the U. S. Geological Survey and were, in large part, developed by this Survey (Meinzer, 1931).

Inasmuch as the occurrence and behavior of ground water is in large part dependent upon the geology of the area, many of the methods and procedures of investigation are geologic in nature. See pages 57-58, in the section on Geology.

Behavior of the water in the aquifers is studied by a variety of means and methods; these include both qualitative and quantitative approaches. The latter are described in considerable detail later under Quantitative studies in the Miami area (p. 197-290).

In addition to the problems of determining occurrence and behavior of water in the aquifers there have been other problems requiring special methods. Chief among these is the problem of salt-water encroachment. Test and observation wells were installed, water-table and isochlor maps were prepared periodically, and electrical resistivity studies were made (see the section on Salt-water encroachment, especially p. 712-725). Studies of tides, rainfall, evaporation, transpiration, wind effects, and other conditions involved special methods, most of which are described later in the Quantitative studies in the Miami area.

NONARTESIAN WATER

THE BISCAYNE AQUIFER

The Biscayne aquifer, named after Biscayne Bay, is the source of the most important water supplies developed in southeastern Florida. It is the most productive of the shallow nonartesian aquifers in the area and is one of the most permeable in the world. The aquifer extends along the eastern coast from southern Dade County into coastal Palm Beach County as a wedge-shaped underground reservoir having the thin edge to the west. It underlies the Everglades as far north as northern Broward County, though in that area it is comparatively thin, and the permeability is not as high as it is farther east and south.

The Biscayne aquifer is a hydrologic unit of water-bearing rocks ranging in age from upper Miocene through Pleistocene. The aquifer is comprised, from bottom to top, of parts or all of the following

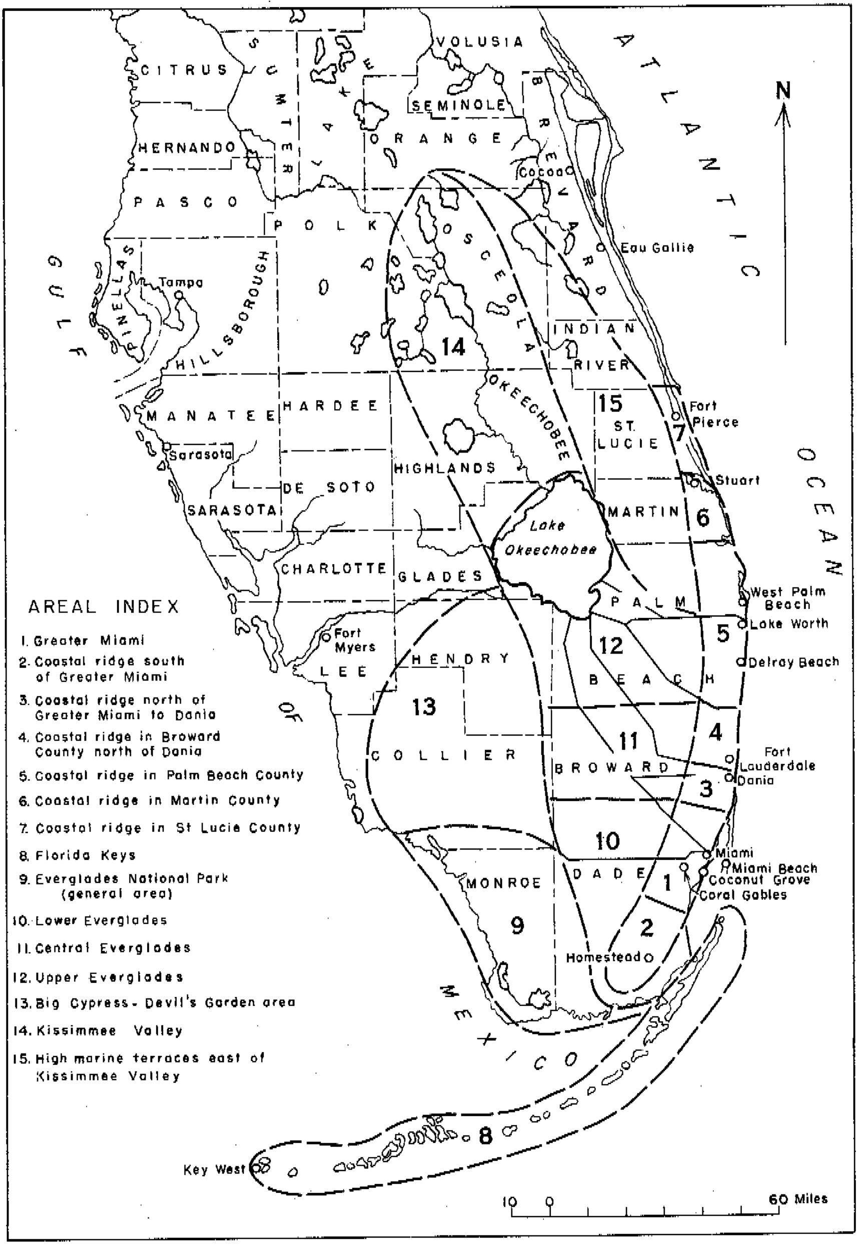

Figure 31. —Index map of southern Florida showing areas for which information on shallow nonartesian aquifers is given.

formations: (1) Tamiami formation (including only the uppermost part of the formation—a thin layer of the highly permeable Tamiami limestone of Mansfield); (2) Caloosahatchee marl (relatively insignificant erosion remnants and isolated reefs); (3) Fort Thompson formation (the southern part); (4) Anastasia formation; (5) Key Largo limestone; and (6) Pamlico sand.

The boundaries of the Biscayne aquifer seldom follow formational boundaries, but instead, they cut across according to the geohydrologic properties. Additional information on the geographic distribution of the aquifer and on the parts of the formations comprising the unit is presented throughout in the section on geology and in following sections. The Biscayne aquifer rests upon the Floridan aquiclude (p. 189).

Several other shallow nonartesian aquifers exist in southern Florida, but they are of lesser importance. All aquifers will be discussed by areas in the sections that follow. (See fig. 31.)

GREATER MIAMI AREA

In a comprehensive report dealing with all aspects of the water-supply and related geologic factors, it is not possible to avoid some duplication of information; neither is it possible to bring together in one section all the data bearing on a particular subject. Thus, it will be noted that additional information on the early history and development of Miami's water supply will be found in the section on Salt-water encroachment.

DEVELOPMENT OF WELLS

Generally, wells are easily developed in the Biscayne aquifer. They are either of open-hole, rock-wall construction, or they are finished with a sand point. Most wells are of the former type and are from 1¼ to 18 inches in diameter. They are used for domestic, industrial, and public supply, or for drainage. A common well in this area is 6 inches in diameter and from 50 to 65 feet deep (with 3 to 10 feet of open hole in highly permeable sandy limestone below the bottom of the casing). The yield ranges from 1,000 to 1,500 gpm with a drawdown during pumping of less than 4 feet; recovery occurs almost immediately after pumping ceases. Such wells can usually be drilled in 1 or 2 days by a crew using a standard cable-tool rig.

The upper limestone of the Biscayne aquifer is ordinarily soft enough that pipe can be readily driven into it. Many people have installed their own wells for domestic or irrigation use simply by driving a piece of 1¼- to 2-inch casing into the ground with a sledge hammer, withdrawing it and emptying the included rock materials, then reinserting the casing in the same hole and driving it deeper. By repeating this process, such a well can be put down to depths of 20 to 40 feet in a day without undue hardship. Of course, this can be accomplished much more easily by machinery. Small drilling rigs using the jet-percussion method can install such a well in an hour or so.

In some parts of the Miami area, limestone is not present at shallow depths. Therefore it is necessary to use sand-point wells for development of supplies. Such wells can readily be driven either with a sledge hammer or with a light drilling rig.

EARLY SUPPLIES

Most early domestic supplies were obtained by driving casing by hand in the manner just described. As the population increased, wells of larger diameter were needed, and the first well-drilling rigs were built locally to do the work. The first drillers to operate permanently in this area were C. H. Perry, H. E. Kiser, and R. H. Magruder. These three well drillers deserve much credit for furnishing information on early water supplies in Miami. In addition, an interesting, though not entirely correct (geologically and hydrologically), account of these early developments is given by John Sewell (1933), from whose memoirs the following is quoted, with the permission of John Sewell, Jr.

"In starting Miami as a city one of the great problems was getting good water. As the city lies 6 to 18 feet above sea level, at the beginning everyone used a common pitcher pump hitched on a 2-inch pipe driven into the rock 10 or 12 feet. The rock formation being limestone naturally gave us hard water, which made a great many sick when we first began using it.

"Harry Tuttle put down the first big well, which was about 50 or 60 feet deep, with 4-inch pipe and hitched a steam pump to it to furnish water for the Miami Hotel. [The Miami Hotel of which Mr. Sewell speaks is not the present one. The first Miami Hotel was built in 1896 on Avenue D at what is now 235 South Miami Ave.] That was in the summer of 1896. Then Mr. McDonald had a similar well put down to furnish the water supply for the construction of the Royal Palm Hotel. [Built in 1896 on the north bank of Miami River where it empties into Biscayne Bay.] But both these wells gave the hard limestone water. Later Mr. Tuttle arranged with Mr. Flagler to put a pump at a big sulfur spring near the head of the Miami River, which was then known as the rapids, about 4 miles above the city, and piped the water to the city through a 6-inch pipe. The power house was built and a station established with a gasoline engine. We would carry the drums of gasoline up the Miami River on lighters, then put them on a little push car, and carry them about 200 yards north of the river to the station over a little narrow gauged railroad that we had built for the purpose. The station was located near what is now (1921) the J. W. Watson orange grove. [Exact location cannot be determined but it was not far from what is now NW. 27th Avenue and 22nd Street.] This station was run by Tom Ryan, one of our engineers of the Royal Palm construction force. This station remained for about one year, when it was decided to move the pumping station down to the city and suck the water the 4 miles instead of pushing it and the present (1921) standpipe [located at what is now the Florida Power and Light Co.'s steam-electric plant at SW. Second Avenue and the Miami River] was built to store the water supply which made conditions much better. The water supply was limited to a 6-inch supply as that was the capacity of the spring. While the water was good, we had to have a greater supply to draw from.

"Mr. Flagler sent a man here in the early part of 1898 to drill an artesian well near Avenue D and Sixth Street [now N. Miami Avenue and Sixth Street. Mr. Henry E. Kiser says that this well was abandoned at 65 feet and that he (Mr. Kiser) was the first driller ever to penetrate the artesian aquifer in this area], about where the Drake Lumber Company's office now stands. This well was put down about 800 feet. There was no flow—nothing but salt water—and this well was abandoned.

"Dan Cosgrove, Mr. McDonald's chief engineer, had ideas of his own about a water supply. There was a spring in Wagner's Creek near 4th Street and Avenue L [Avenue L is now NW. Seventh Avenue and Fourth Street is now NW. Eighth Street] which had a larger flow than the one in the Everglades, where we were getting our supply. He figured that there was a subterranean stream running from the spring in the Everglades and this 4th Street spring, making its way to the ocean. He never had an opportunity to experiment with his idea until 1899, when he was on construction of the Colonial House at Nassau, Bahama Islands, with Mr. McDonald. While he was constructing this hotel for Mr. Flagler, Mr. Cosgrove's health gave away and he was not able to continue the job. Mr. McDonald sent him back to Miami to let him experiment with his water investigation. I got him up a bunch of men and tools and helped him start. He got his lines and made his first experiment on what was then the golf grounds and where the present water reservoir now stands, at the east end of the Country Club Golf course [present NW. 11th Street and 10th Avenue]. He had an excavation made about 10 feet square and 5 feet deep, where he struck solid rock. Then he began drilling a 6-inch well and followed up with his iron pipe. He kept drilling until he got his pipe down between 50 and 60 feet in depth. I saw him every day and kept close track of the work. One night he came in and told me that he had struck flint rock, as he had not made an inch the whole day and had been drilling all the time, and he seemed terribly worried. But the next day before noon he came rushing in to see me and said he had struck his river. As the roof of the river caved in the water had rushed through the pipe with such a flow that it came very near drowning all of his Negroes before they could get out of the hole in the ground. He was highly elated at the flow of water, clear and pure. This proved that Cosgrove had the right theory. Cosgrove, to prove this theory was right, moved his plant down nearer the city on the same line and drilled a well between 4th and 5th Streets near Avenue L. This water tested out pure also—just as the first. Then he moved his plant still nearer the standpipe, near Avenue G and 14th Street [at what is now SW. Second Avenue and SW. Second Street], where he drilled another well. This well tested out salty, which showed that he was near the outlet of the subterranean stream. He went back to the 4th Street well and connected up his pipe with the pumping station and that was used for one year. When that well developed salt water from hard pumping it was abandoned and the permanent wells and reservoir were erected near the first well on the golf grounds and several additional wells put down, where we are still (1921) getting our water supply, only now we have a 30-inch supply line from the reservoir to the standpipe.

"In the spring of 1919 some of the wells sprung salt leaks [actually not 'leaks' at all but inland encroachment of the salt-water wedge from Biscayne Bay. See the section on Salt-water encroachment, p. 580–584], which gave the water supply some heavy criticism and caused prosecution of the water company for selling salt water, which they could not help. This case was tried in Key West, where the case was decided in favor of the water company. When these wells were originally put down they [that is, the tops of the well casing] were put below the water level where they flowed in a reservoir, as a regular artesian well, but later they had to connect pumps to these wells to get enough water for the city, and this hard pumping caused the salt water to appear, which created so much trouble with our water supply. After this trouble the water company decided not to get caught again. They started west, putting down wells about 50 feet deep and connecting them up with electric pumps, and now (1921) they have gone back $\frac{1}{2}$ mile farther west and have a number of wells with an electric pump for supply, which is, I think, the best system. Some claim the canal water filtered would be better, but in long dry spells the water gets very low in the canals and we would have to go back to our wells for a supply."

EFFECTS OF DRAINAGE

Effects of drainage will be rather thoroughly discussed in the section on Salt-water encroachment, p. 580–707, and are mentioned elsewhere in this report (see p. 9–11). The principal effect upon the water supply of the Miami area has been to set in motion a wedge of salty water encroaching inland into the fresh-water of the Biscayne aquifer, which has resulted, to date, in the loss of thousands of private supply wells along the coastline in Dade County, and the loss of two of Miami's well fields (Spring Gardens and Coconut Grove). See the section on Salt-water encroachment, p. 580 to 584.

PRESENT SUPPLIES

The Biscayne aquifer (see p. 160 and 162) is the chief source of present supplies. Most municipalities in the Greater Miami area are served by the city of Miami's supply, which at present (1946) is obtained from 20 wells, ranging in depth from about 60 to 95 feet, in the Miami Springs-Hialeah area (see the section on Salt-water encroachment, fig. 189). The field was first put into service in 1925 and has been enlarged by the drilling of additional wells from time to time as occasion demanded. The average daily pumpage from this well field in 1946 was 36,600,000 gallons.

This water is softened and the color is removed in a new and modern water-treatment plant. The water is used not only for domestic supply but also for industrial and commercial purposes, especially for industries and businesses located in areas where ground water was once fresh but is now contaminated by salty water.

Many air-conditioning units and condenser coils of industrial plants are cooled by water from wells at the site; but because of the salt-water encroachment, which has spread under most of the business, commercial, and industrial areas of Miami (see the section on Salt-water encroachment, figs. 168 and 200), treated city water that is used over and over again is generally replacing the salty and corrosive ground water from the supply wells of the salt-contaminated zone.

Some of the adjacent municipalities, such as Opa Locka, North Miami, and North Miami Beach, have their own public supplies. The wells are developed in the Biscayne aquifer and water is pumped from open-hole, rock-wall wells. Some neighboring communities, such as South Miami and Perrine, have no municipal water-supply systems. Instead, each family and building has its own private supply well.

The Miami area makes considerable use of wells for fire-fighting purposes. The Greater Miami area grew so fast that city water mains could not keep pace with the widely scattered and rapidly expanding population. In order to obtain large quantities of water to fight fires, wells have been drilled or dug at strategic locations over most of the settled areas. These wells average 6 inches in diameter and about 65 feet in depth; each will supply a pumper with at least 1,000 gpm, with a resulting drawdown that is usually less than 2 feet and rarely as great as 4 feet.

For detailed information on municipal supplies of this area, for well logs, and for other pertinent data, see the Appendix.

ATLANTIC COASTAL RIDGE SOUTH OF GREATER MIAMI IN DADE COUNTY

THE AQUIFER AND GROUND WATER

Ground water with the smallest amount of coloring matter, in Dade County, occurs in the Kendall-Florida City area. The Biscayne aquifer underlies the entire area; it ranges in thickness from 60 to 100 feet and is composed principally of highly permeable sandy limestone that is very cavernous in places (note especially cross sections *A–A'*, *B–B'*, *C–C'*, *D–D'*, and *E–E'*, in pls. 5, 6, 7, and 8). The hardness of the water is about equal to that of the Miami area, but the color of the untreated water (unless locally affected by iron oxide) compares favorably with the color of the treated water of the present (1946) Miami public supply.

The ground water in the Miami area and to the north under the Atlantic Coastal Ridge usually contains organic color ranging from 80 to 120 on the standard cobalt scale (see p. 730), but in the Kendall–Florida City area the color usually ranges from about 10 to 30. The difference in color of the raw ground water of the two areas is apparently due to the difference of materials comprising the land surface. In the Everglades, south of the latitude of South Miami, there is a deposit of gray to white marl and very little muck on the underlying rock surface, whereas north of this line the muck (decomposed organic materials) becomes progressively thicker toward Lake Okeechobee, until at the south shore of the lake it averages about 8 feet in thickness. The surficial materials of the coastal ridge in both the Miami and the Kendall–Florida City areas are almost identical, and so are the materials that comprise the Biscayne aquifer at depth; it is only on the surface, in the area west of the coastal ridge, that the materials are much different. Rainwater seeping through the black muck becomes highly stained by organic materials, whereas rainwater seeping through the white to gray marl gains only a slight amount of organic color. This is one of the proofs of the local origin of the ground water.

DEVELOPMENT OF WELLS

Homestead is the only incorporated municipality in the Kendall–Florida City area that has a public water-supply system. The other communities (all small) and unincorporated areas are served by individually owned, private supplies. Most of the supply wells in this area are $1\frac{1}{4}$ to $2\frac{1}{2}$ inches in diameter, and the majority of these were hand-driven. They do not exceed 15 to 20 feet in depth because throughout much of the southern part of the area very hard layers of limestone are encountered at these depths (see cross sections *A–A'*, *B–B'*, *C–C'*, and *D–D'*, pls. 5–8).

Most grove-irrigation and fire wells of the Kendall—Florida City area are 4 to 8 inches in diameter, but some are dug wells, and many are entirely uncased. Most of those put down prior to World War II were manually constructed and were only shallow wells because of the very hard limestone layers mentioned above. However, during the War labor became scarce and costly, a pair of drought years (1944-1945) reduced the water table in some parts of the area to sea level or below (figure 45, water-table map), and many of these shallow wells thus became dry. Inability to obtain manual laborers, inability to dig through the hard limestone layers, and a shortage of qualified well drillers necessary to drill the deeper wells so urgently needed, forced many of the grove owners to look helplessly on while groves, gardens, and field crops wilted and died, or were seriously damaged.

For detailed information on well logs, pumpage, and other data from the Homestead public supply, the U. S. Navy supply for Key West and for other places in the area, see the Appendix.

ATLANTIC COASTAL RIDGE NORTH OF GREATER MIAMI TO, AND INCLUDING, DANIA IN BROWARD COUNTY

THE AQUIFER AND GROUND WATER

The Biscayne aquifer is much sandier north of Miami than it is to the south, and in several places deep sand-filled channels cut entirely through the Miami oolite into the underlying Fort Thompson formation. These sand-filled cuts are called "transverse glades" because of their characteristic glades-type vegetation. They served as discharge channels for waters from the flooded Everglades prior to man-made drainage, and even yet, in times of heavy and long-continued rains, they become occupied by shallow sluggish streams.

The ground water of this area is chemically comparable to that in the Miami well-field area, with organic color ordinarily ranging from about 80 to 120 on the standard cobalt scale, but in some cases reaching as high as 220. In some parts of the area it is difficult to develop raw water that is free from iron oxide, which occurs erratically both horizontally and vertically in the aquifer. Often, changing the depth of a well by about 10 feet, or moving its location from one side of a building to the other, may be all that is needed to obtain water of low iron content.

Prior to drainage, the entire aquifer contained only fresh, potable ground water. Now, along the coastline, and in tongues extending inland varying distances along the tidal canals and streams, salt-water encroachment has taken place. This encroachment is not generally so extensive as in the Greater Miami area and southern

Dade County, where there are more drainage canals and where the water table has lowered to a greater depth (see the section on Salt-water encroachment, fig. 200, which maps the area of encroachment in Dade County). See also the section on Characteristics of drainage basins and summaries of gaging-station records for seepage studies along North New River Canal.

DEVELOPMENT OF WELLS

Most of the private supplies in this area are obtained from the Biscayne aquifer through shallow driven wells, $1\frac{1}{4}$ to $2\frac{1}{2}$ inches in diameter, equipped with sand points. Most of these wells end in sandy oolitic limestone or quartz sand at depths of only 15 to 30 feet—most of these wells furnish copious supplies of water.

Wells for larger supplies are usually of open-hole, rock-wall construction, with as much as 15 feet of uncased hole below the end of the casing. These wells are finished in sandy limestone or calcareous sandstone and are bailed, surged, and pumped to free them of sand; then, as in the rest of southeastern Florida, they are usually equipped with centrifugal pumps. Depths of these wells range from about 45 to more than 200 feet (the deeper wells are in the northern part of the area). Data on well logs, public supplies, and other pertinent information are given in the Appendix. For data on water analyses, see also the section on Quality of ground and surface waters.

ATLANTIC COASTAL RIDGE IN BROWARD COUNTY NORTH OF DANIA

In this area, the coastal ridge averages about 7 miles in width. It is composed chiefly of sandy oolitic limestone (Miami oolite) riddled with vertical solution holes (see the section on Geology, figs. 22 and 26), and is mantled with white quartz sand of the Pamlico sand. In places the sand is heaped into low, broad dunes probably formed in latest Pleistocene and Recent time.

The New River valley cuts through the coastal ridge between Dania and Fort Lauderdale. It is the widest and deepest of all the sand-filled Pleistocene cuts in southeastern Florida. The maximum depth to hard rock is about 100 feet.

THE AQUIFER AND GROUND WATER

The Biscayne aquifer in this area is composed chiefly of sandy limestone; beds of marly or clayey sand are common in the western part, and shelly sand or shell marl lenses are common throughout the area. Cementation of the sediments is very irregular, thus leading to the occurrence of considerable rock at the site of one well whereas no consolidated materials may be found at corresponding depths at an adjacent site.

The Fort Thompson formation grades into the Anastasia formation in this area (see section on Geology, p. 90—102, and figure 10.)

Because of the greater amount of unconsolidated materials (sand, silt, clay, marl, shells, etc.) in the Biscayne aquifer of this area than in the coastal ridge to the south, wells are not so easily constructed, and yields ordinarily are lower and drawdowns are greater. In the Miami area the coefficient of transmissibility, (T), ranges from about 2 to 20 million gpd per ft, and averages about 5 million gpd per ft [see the section on Ground water (Quantitative studies), p. 270], whereas calculations of T for the Fort Lauderdale well-field area indicate a value of about 1.2 million gpd per ft (Vorhis, 1948, p. 20-21). This value may not be valid for parts of this area nearer the ocean where the Biscayne aquifer is composed of a greater amount of permeable limestone and of a lesser amount of unconsolidated materials; values of T approaching 3 million gpd per ft may be more nearly correct there.

See pages 373-374 in the section on Surface water for a study of ground-water inflow in Hillsboro Canal near Deerfield Beach. Water in the aquifer is generally similar in chemical characteristics to that in the coastal ridge from Palm Beach southward—that is, it is typical of limestone areas in southeastern Florida. In some parts of the area highly colored water is found. This color, which may exceed 200 on the standard cobalt scale, is caused by organic stain and is associated with the extensive muck and peat deposits of the vast Everglades. These organic soils lap upon the western shoulder of the coastal ridge and floor the transverse glades that cut into or through the coastal ridge in several places. The water from shallow depths and close to the muck deposits is usually more highly colored than the water from deeper parts of the aquifer and closer to the ocean. Iron oxide, which causes "red water," occurs erratically in the aquifer, and, as explained earlier (p. 168), may sometimes be avoided either by changing the depth of the well or by putting a well down on a different part of the property.

In some places, such as the Fort Lauderdale well-field area, salty ground-water residual from the Pleistocene high-level seas (p. 112-125) occurs at depths as shallow as 165 feet below land surface. There, the salinity increases with depth and is a serious hazard to water supplies because the saline water might be drawn upward into the well field by long-continued and large-scale pumping. (See the Appendix for well logs and other data on supplies of this area; see also the section on Quality of ground and surface waters for information on the chemical quality of the ground water.)

EFFECTS OF DRAINAGE

The only part of the coastal ridge between Dania and the northern border of Broward County where effects of drainage on the ground water are noticeable is in the Fort Lauderdale area. There, the dredging of the North New River, South New River, and Dania Cut-off Canals, as well as numerous smaller channels in the metropolitan area, has effectively lowered the average height of the water table and has, through changing the natural balance between fresh and salt water, caused sea water to migrate inland on a broad front all along the coastal zone from Dania to and slightly beyond Fort Lauderdale.

Also, during times of drought when flow in the canals is reduced, sea water is free to advance inland as far as the control dams in the North New River and South New River Canals. Respectively, these dams are located approximately 7½ and 9 miles inland from the ocean.

When sea water flows inland in these canals, it seeps out through their sides and bottoms. This action has resulted in the formation of an irregular tongue of salty ground water extending inland from the ocean for a distance of more than 6 miles. This is a different type of encroachment from that mentioned above, although both types are a direct result of the effects of drainage canals and reclamation work in the Everglades.

This tongue of salty ground water is irregular with respect both to time and to place. It is caused by several factors, chief among them being: 1. Changes in salinity of the canal water itself, which may range from concentrations of sea-water during time of drought to almost no salinity during rainy seasons. 2. Unequal opportunities for salty water to escape from the canals. (This inequality is caused by variable sedimentation of the canal bottoms and sides with respect to both time and place; seepage is small in a section of a canal that has a heavy deposit of sediment.) 3. Variations in permeability of the geologic materials through which the canals are dredged. (In a canal free of sediment, seepage of salty water outward into the aquifer will proceed rapidly in highly permeable materials, slowly in materials of low permeability, and essentially not at all in impermeable materials. Although there are no truly impermeable beds in the upper part of the Biscayne aquifer in New River basin, there are, in places, lenses or layers of fine sand, silty or clayey sand of low permeability, and limestones and sands of high permeability. Thus, the geologic conditions in the aquifer are a controlling factor in the rate of movement of salty water into or out of the aquifer.)

These several factors are involved in the explanation of irregular occurrence of saline water in the aquifer of New River basin.

DEVELOPMENT OF WELLS

For general household purposes, or for lawn and garden irrigation, driven sand-point wells, $1\frac{1}{4}$ to $2\frac{1}{2}$ inches in diameter and ranging in depth from about 15 to 40 feet, are the most common. Where rock occurs at these shallow depths, sand points are not needed and open-hole, rock-wall wells are constructed. The rock is generally soft enough for well casings to be driven by hand.

For larger supplies, such as for citrus grove or farm irrigation, air conditioning, and fire fighting, most wells are drilled by the standard cable-tool method. Such wells range in diameter from 4 inches to as much as 18 inches and are usually 6 to 8 inches; the depth of the wells depends upon the depth to rock, because most of these wells are of open-hole, rock-wall construction and have 1 to 15 feet of uncased hole below the bottom of the casing. Yields in such wells compare favorably with those from similarly constructed wells in the Miami area—it is not unusual for a 6-inch diameter well to yield 1,000 gpm. Drawdowns, however, are usually greater than in the Miami area, ranging from 2 to about 10 feet.

Public-supply wells of Fort Lauderdale and the new municipal-supply well at Dania are of gravel-pack construction and have an average of about 40 feet of shutter-type screen placed in an enveloping wall of gravel. For detailed data on these and other wells in the area see the Appendix. Details on the quality of water may be found in the section on Quality of ground and surface waters.

ATLANTIC COASTAL RIDGE IN PALM BEACH COUNTY

THE AQUIFER AND GROUND WATER

The Fort Thompson formation, which is a major unit of the Biscayne aquifer in Dade and Broward Counties, grades into the Anastasia formation in the area between Delray Beach and West Palm Beach. The northernmost important occurrence of the Fort Thompson formation has been noted in well cuttings from the Delray Beach well field.

The areal and vertical distribution of limestone in this area is not uniform. Well logs for sites within 100 feet of each other may show entirely different figures for depth to rock and for thickness of rock—in fact, some wells may penetrate little or no rock at all. The absence of rock in some of the areas may be a result of original lithologic differences, but generally this situation is caused by solution or erosion of the original limestone, and subsequent filling by sand.

The rock ranges from coquina to dense, hard calcareous sandstone, but ordinarily, it is sandy limestone. Generally, it is riddled with solution holes of varying size and extent, but many of the holes are definitely aligned. Core samples of the limestone from a test well (S 394) at Delray Beach are illustrated in figure 15.

The sand that overlies the rock and fills solution holes in it, or that occurs in beus and pockets beneath the top layer of rock, is composed principally of quartz grains with some worn shell fragments. The grain size ranges from very fine to coarse and averages in most places fine to medium; the degree of sorting in different places ranges from good to poor. Generally the sand is permeable.

In that part of the coastal ridge north of West Palm Beach the Fort Thompson formation disappears entirely, and materials of the Anastasia formation and the Caloosahatchee marl compose the deeper part of the aquifer. These materials range from sand to shell marl and in some places, where cementation has taken place, to irregular local lenses of sandy or shelly limestone.

Water in the aquifer of this part of the coastal ridge is a typical calcium bicarbonate type water, and is very similar to that described for the area immediately to the south. "Iron water" is not uncommon, but generally it can be avoided if care is taken in selecting the depth and location of the well, because it is not uniformly present in the aquifer. Color, other than iron, is of organic origin and usually ranges from about 20 to 110 and averages about 35 (standard cobalt scale).

EFFECTS OF DRAINAGE

Whereas in Dade and Broward Counties the program of draining the Everglades has had a serious effect on the coastal ground water in the Biscayne aquifer, it has had little effect in Palm Beach County. This is largely because of the maintenance of a higher water table in Palm Beach County through a system of carefully operated water-control districts, such as the Lake Worth Drainage District. Also, the geologic materials composing the aquifer in Palm Beach County are generally of much lower permeability than in the Miami area, and salt-water encroachment would not be as rapid even if the water table were lowered enough to induce it.

Thus, salt-water encroachment in Palm Beach County to date is not of major importance; wells 80 to 100 feet deep near the shoreline of Lake Worth (a salt-water lagoon) can still obtain potable water, as similar wells once did in Dade and Broward Counties, prior to drainage.

DEVELOPMENT OF WELLS

In the area from Delray Beach southward, wells 4 to 18 inches in diameter are commonly of open-hole, rock-wall construction, with 1 foot or more of open hole in the rock below the bottom of the casing. However, in some places the solution-riddled character of this rock is a serious hazard to the development of such wells. Even though the casing is set and firmly seated in the rock, solution holes connecting (either directly or tortuously) with the overlying sand can funnel sand into the well. This will cause land-surface subsidence if the driller bails or pumps too much sand out of the well he is attempting to develop. This occurred in 1947 at the site of an 18-inch well being drilled for the city of Delray Beach by J. P. Carroll. The situation was remedied by installing a screen in the well, thus preventing the sand from entering.

North of West Palm Beach most of the larger wells in the Biscayne aquifer are developed with screens and yield large quantities of water with relatively small drawdowns. Gravel-packed wells, which are really screened wells in an enveloping pocket of artificially placed gravel, have been developed in some places and produce excellent yields. Large-diameter, open-hole, rock-wall wells north of West Palm Beach are rare, but many smaller-diameter wells (45 to 100 feet deep) are in service and yield copious supplies of potable water.

Shallow, driven or jetted wells, $1\frac{1}{4}$ to $2\frac{1}{2}$ inches in diameter, furnish most rural family supplies and are commonly used in the urban areas for garden and lawn irrigation. These wells are generally less than 30 feet deep and can be put down manually, or by light drilling rigs, in a very short time.

ATLANTIC COASTAL RIDGE IN MARTIN COUNTY

THE AQUIFER AND GROUND WATER

The aquifer of the coastal ridge area of Martin County is generally not so sandy as in the northern part of Palm Beach County. This is shown by the selected well logs for these areas, given in the Appendix.

In some parts of the area Pamilico sand is heaped in Pleistocene dunes and beach ridges to heights of as much as 50 feet above sea level. Materials of the Anastasia formation underlie these sands and range from coquina and shelly limestone to shell and quartz sands. Beneath the Anastasia formation are irregularly cemented sands and shell marls or clayey marls, sand, and silt of the Caloosahatchee marl. Generally, these materials act as one water-bearing unit (aquifer), but locally, layers of hardpan (such as that at Indian Town, see p. 193) or dense marly material (such as that at Fort Pierce, see p. 195-196), separate the uppermost part of the aquifer and create local low-pressure artesian aquifers. Where these low-pressure artesian aquifers extend seaward beneath Indian River or the Atlantic Ocean it is possible to develop shallow (35 to 100 feet) wells that furnish potable water, even though the water in the overlying materials may be as salty as sea water. Such areas are exemplified at Jensen Beach, Sewell's Point, and Salerno.

The beach ridge and dune sands contain soft, slightly acidic water, as contrasted to the typically hard, alkaline, calcium bicarbonate water in the calcareous rocks of the lower part of the aquifer. The color of the ground water is usually low, ranging from about 10 to 50 (cobalt scale). (See the section on Quality of ground and surface waters, for analyses of typical waters.)

EFFECTS OF DRAINAGE

Drainage of the Everglades has had no noticeable effect on the ground water of the coastal area of Martin County.

DEVELOPMENT OF WELLS

Most supplies for homes and for small business or commercial houses are usually obtained through $1\frac{1}{4}$- to $2\frac{1}{2}$-inch driven wells finished with sand points at depths of 15 to 40 feet below land surface. Such wells are easily constructed, either manually or by light drilling rigs, and furnish plentiful supplies of potable water. Some of these small private wells are of open-hole, rock-wall construction, finished with 1 foot or more of uncased hole below the bottom of the casing in the permeable rock.

Larger supplies require bigger wells. Examples of these are the Hobe Sound public-supply wells, which are 12 inches in diameter and range in depth from 78 to 117 feet. They are of open-hole, rock-wall construction. The wells at nearby Camp Murphy are also 12 inches in diameter and average about 100 feet in depth. These wells, however, are of gravel-pack construction. All are capable of yielding large supplies (in excess of 1,500 gpm). At Stuart, numerous open-hole, rock-wall wells, 4 to 6 inches in diameter, ranging in depth from 47 to 88 feet and averaging about 65 feet, are in use. There are three municipal public-supply wells at Stuart, ranging from 75 to 85 feet in depth. (See Appendix.)

ATLANTIC COASTAL RIDGE IN ST. LUCIE COUNTY

THE AQUIFER, GROUND WATER, AND DEVELOPMENT OF WELLS

The coastal ridge south of Fort Pierce is generally much flatter, wider, and of lower altitude than the area of high sand dunes and parallel beach ridges north of the city. In this lower southern part a long, shallow, swampy, muck-bottomed swale, called the Savanna, parallels and lies west of the high, narrow beach ridge that borders Indian River. The Savanna is about 13 miles long, averages about $\frac{1}{4}$ to $\frac{1}{2}$ mile wide, and terminates to the north at the southern limits of Fort Pierce. There, the municipal water-supply plant has been built, and the well field has been developed.

A shallow hardpan underlies much of the coastal ridge in St. Lucie County and prevents or retards free movement of water from the land surface to the shallow aquifer. The uppermost part of the shallow aquifer at Fort Pierce is separated from the lower part by a relatively impermeable marly layer about 10 feet thick. This, together with the east-sloping structure of the geologic formations, gives rise to the development of a shallow, low-pressure artesian system (see p. 194-195 and figs. 36 and 37). A similar occurrence was described previously for the coastal area of Martin County (see p. 174-175).

Above this shallow, low-pressure artesian aquifer the ground water occurs under water-table conditions in the pores and interstices between the sand grains, and it can be recovered through shallow, driven, screened wells. In that part of the area lying south of Fort Pierce and west of the Savanna, the water is soft but usually has an objectionably high color (around 200 on the standard platinum-cobalt scale). North of Fort Pierce in the high dune area, and south along the narrow beach ridge that lies between the Savanna and Indian River, similar ground water, with organic color ranging from 10 to 50, can commonly be obtained. To obtain this water, screened wells are usually driven to depths of about 15 to 50 feet, depending upon the elevation at the well site.

THE FLORIDA KEYS

THE AQUIFER, GROUND WATER, AND DEVELOPMENT OF WELLS

The only fresh water that occurs in the rocks of the Florida Keys floats as a thin lens of varying thickness on the underlying salt water of each of the larger keys—the smaller keys usually lack this fresh-water lens. During the rainy season the fresh-water lenses increase somewhat in thickness, but during the dry season, even with no pumping, the fresh water tends to disappear rapidly through seepage to the sea and by evapotranspirative processes. The rocks are very permeable and the water table of each key undulates with the tides. Thus, rainwater escapes readily to the sea, and salt water finds free access to the permeable rocks.

In order to obtain information about the effect of tides on the ground water of the larger keys, an automatic water-stage recorder was placed in operation during the last week of May 1941 on a fire well (F 628) located near the center and on one of the highest parts, of Key West, where the land is about 10.5 feet above mean sea level. In this well, the maximum tidal fluctuation was 0.79 foot, whereas in the nearby ocean the maximum fluctuation during the same tide was 1.9 feet. During low tides, water in the well stood an average of 0.69 foot above ocean level, but during high tides, the ocean level stood an average of 0.04 foot above water level in the well. There was a lag of only a few minutes between the time that the maximum high or maximum low occurred in the well and the corresponding high or low occurred in the ocean. Similar results were obtained when a recorder was mounted on the CCC Camp well (S 701), on Big Pine Key.

Samples of water from most wells in the Florida Keys were obtained and brought to the laboratory for analysis. This study showed that even though the sampling period closely followed a period of heavy rains, no supply (even the shallowest) was entirely free of sea-water contamination and some were heavily contaminated.

Key West and Big Pine Key contain the largest quantities of fresh water; they have the greatest potential supplies of any of the Keys. However, these supplies are strictly limited, and pumpage of several thousands of gallons per day, even during the rainy season, would soon exhaust the fresh water.

Deeper wells, including one more than 15,000 feet deep (see section on Geology, p. 61) have not encountered fresh water, nor should any be expected because the piezometric map of the Floridan aquifer (fig. 35) indicates that the artesian pressure in the area of the Florida Keys is too low to hold sea water out; or to state it another way, the artesian pressure is too low to force fresh water into the aquifer in this area.

Fire wells can be easily and quickly made anywhere in the Florida Keys at depths ranging from a few feet to more than a hundred feet. Most fire wells on Key West are entirely uncased and are of open-hole, rock-wall construction. These wells range in diameter from 8 to 18 inches and are about 52 to 85 feet deep. Each well will supply several thousand gallons per minute of sea water.

THE EVERGLADES NATIONAL PARK AREA

AREA DEFINED

The area included is approximately that now within the Everglades National Park. It is shown as Area 9 on the index map (fig. 31) and includes the southwestern part of the lower Everglades and Big Cypress Swamp (see the section on Geomorphology, p. 144-145 and 147-151) and parts of the Mangrove Swamps and coastal marshes (see section on Geomorphology, p. 154). It is one of the last remaining areas of primitive tropical wilderness on the North American continent.

THE AQUIFER AND GROUND WATER

Information on the artesian aquifers of this area is given on pages 188-197. The Biscayne aquifer in which nonartesian water occurs is composed chiefly of rocks of the Miami oolite and Fort Thompson formation. These rocks are riddled with solution holes and are highly permeable. It is believed that a coefficient of permeability of about 50,000 (see section on Quantitative ground-water studies, p. 236-237) would be proper for these rocks. The aquifer is not thick, however; at the Tamiami Trail it is only about 20 feet thick, and to the south, at the site of test well GS 30, 13 miles southwest of Royal Palm State Park (see Appendix) it is about 30 feet thick. No tests have been made to determine its thickness at Cape Sable, but it is believed to be about the same thickness as at well GS 30.

The quality of the water in the area several miles inland from the Bay of Florida or the Gulf of Mexico, or from tidal canals and ditches connecting with salt water, is good; it is a typical calcium bicarbonate type water. But salt water occurs in the coastal area and in an indefinitely defined zone extending inland along the tidal canals or ditches (such as that along Florida Route 27, the Florida City—Cape Sable Road). Samples from GS 30, taken in September 1943, indicate that, even this far inland, salt-water encroachment has taken place. At 16.3 feet below land surface, the chloride content was 490 ppm; at 28 feet below land surface, it was 2,920 ppm; and at 34 feet, it was 3,750 ppm.

DEVELOPMENT OF WELLS

Satisfactory fire wells could be made anywhere in this area at depths of about 10 to 30 feet, and excellent wells for potable water could be developed at similar depths several miles inland from sources of sea water. These wells could be dug, drilled, or driven and finished as open-hole, rock-wall wells capable of yielding as much as several thousand gallons per minute. However, if permanent supplies of this magnitude were developed it would be essential to stay as far away from salt-water sources as possible to prevent contamination by encroachment of sea water.

THE LOWER EVERGLADES

AREA DEFINED

The area included extends from the arbitrarily chosen southern line of Broward County on the north to the Everglades National Park area and the Bay of Florida on the west and south and to the Greater Miami area on the east. Its boundaries are approximately those shown in Area 10, figure 31.

THE AQUIFER AND GROUND WATER

Principal components of the Biscayne aquifer in this area are the Fort Thompson formation and the Miami oolite. Their relations to each other and to the "basement" or relatively impermeable floor of the aquifer are shown in the geologic cross sections of Dade County, especially on plates 8 and 9, sections *F–F'*, *G–G'*, and *J–J'*. In general, the aquifer is wedge-shaped and is thinnest toward the west. At the western boundary of Dade County the aquifer is about 15 feet thick; in the vicinity of the Dade–Broward levee it is nearly 50 feet thick; and in the area just west of Miami Springs it is about 90 feet thick.

In approximately the eastern third of this area the aquifer is generally highly permeable. The data obtained from a pumping test made on well G 218 (see the section on Ground water, Quantitative studies, p. 272–274) indicates a coefficient of transmissibility of about 4 million gpd per ft. Because the aquifer in this area is only about 50 feet thick, the coefficient of permeability is about 80,000.

To the west, the Biscayne aquifer becomes thinner and generally less permeable because the rocks of the Fort Thompson formation are denser and the sandy sections are composed of finer grades of sand. The Miami oolite, however, is even more permeable to the west than to the east. It is through this thin layer of oolitic limestone that much of the ground-water flow to the east occurs.

Although it is generally more highly colored, the ground water in this area is very similar in quality to water obtained from the Miami well-field area.

DEVELOPMENT OF WELLS

Wells of open-hole, rock-wall construction can be easily made in this area and, if properly finished, will yield copious quantities of water with very slight drawdowns.

THE AREA WEST OF HIALEAH

Figures 32, 33, and 34 show contours on the water table representing periods of high, intermediate, and low water stages in the area west of Hialeah, which is located in the eastern part of the

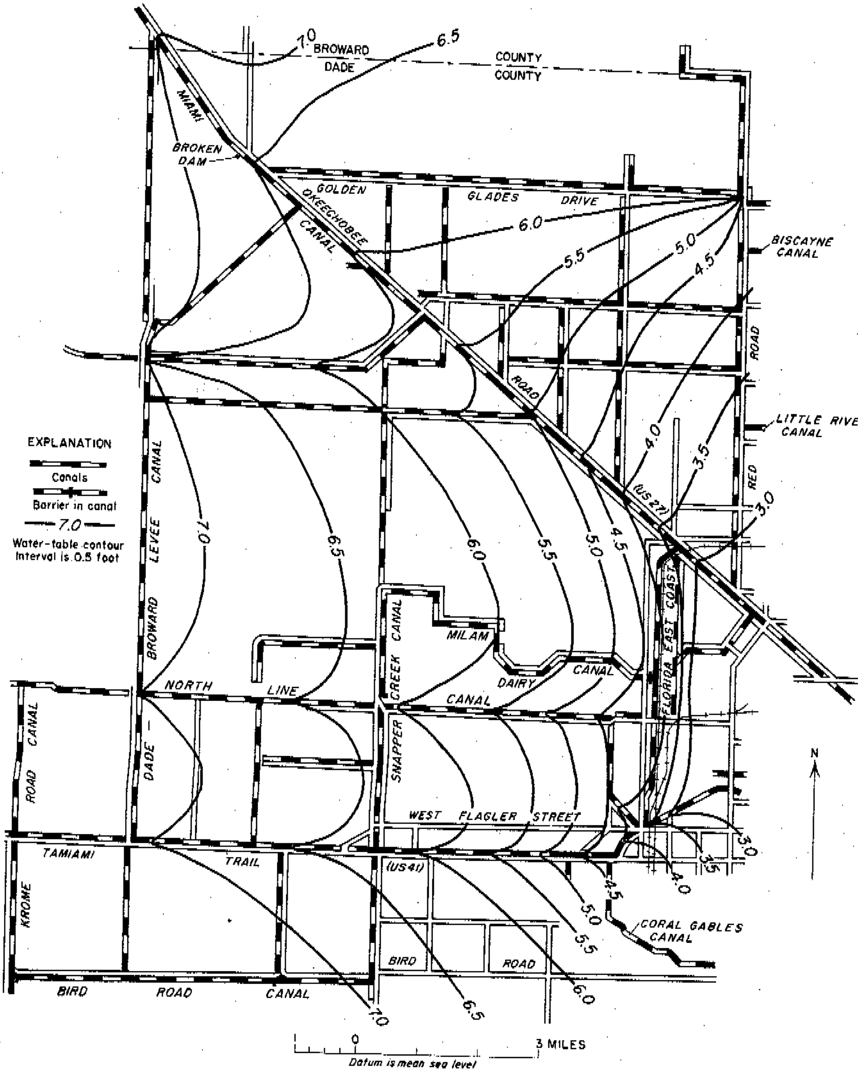

Figure 32. — Map of area west of Hialeah showing water table at high level on July 1, 1942.

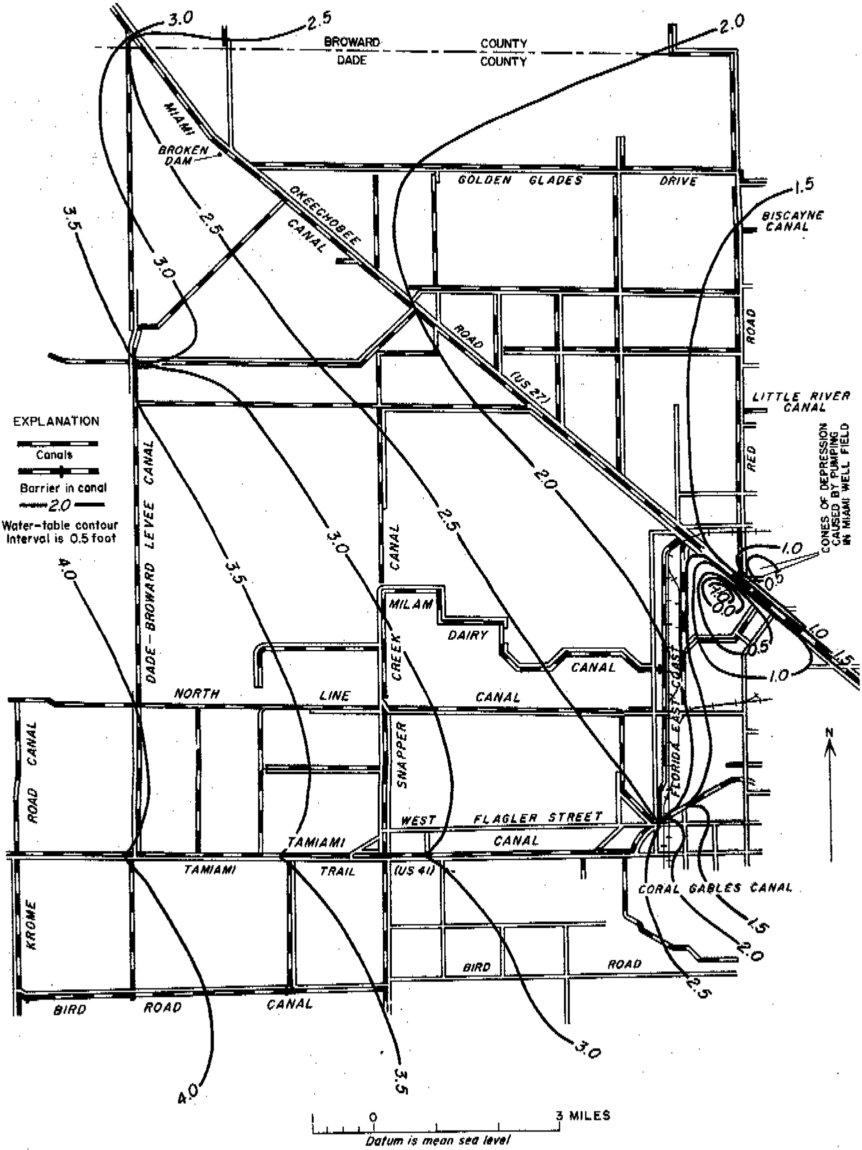

Figure 33. — Map of area west of Hialeah showing water table at intermediate level on April 26, 1946.

lower Everglades area. Lack of flow and stage data on some of the minor canals and ditches has made it necessary to interpolate the relationship of ground-water levels to the stage in the canal in these areas.

Figure 32 shows water-table conditions approximately as they exist during times of high water levels in the area. The water-table contours show that the movement of the ground water is to the east and southeast, except in areas adjacent to the larger canals. During such a period of high water level (June-July 1942), approximately

75 percent of the area was inundated and a small amount of overland flow occurred.

Water-table conditions as they exist during times of intermediate water levels are depicted on figure 33. During these periods, water levels are about 3 feet lower than those shown on figure 32, and the effect of the Miami Canal on ground-water flow is much more pronounced and extends over a considerably larger area. At the time of this study (April 1946), the water table was below the land surface over the entire area.

Figure 34 shows water-table conditions for a period of extremely low water levels, which occurred during the drought in the early

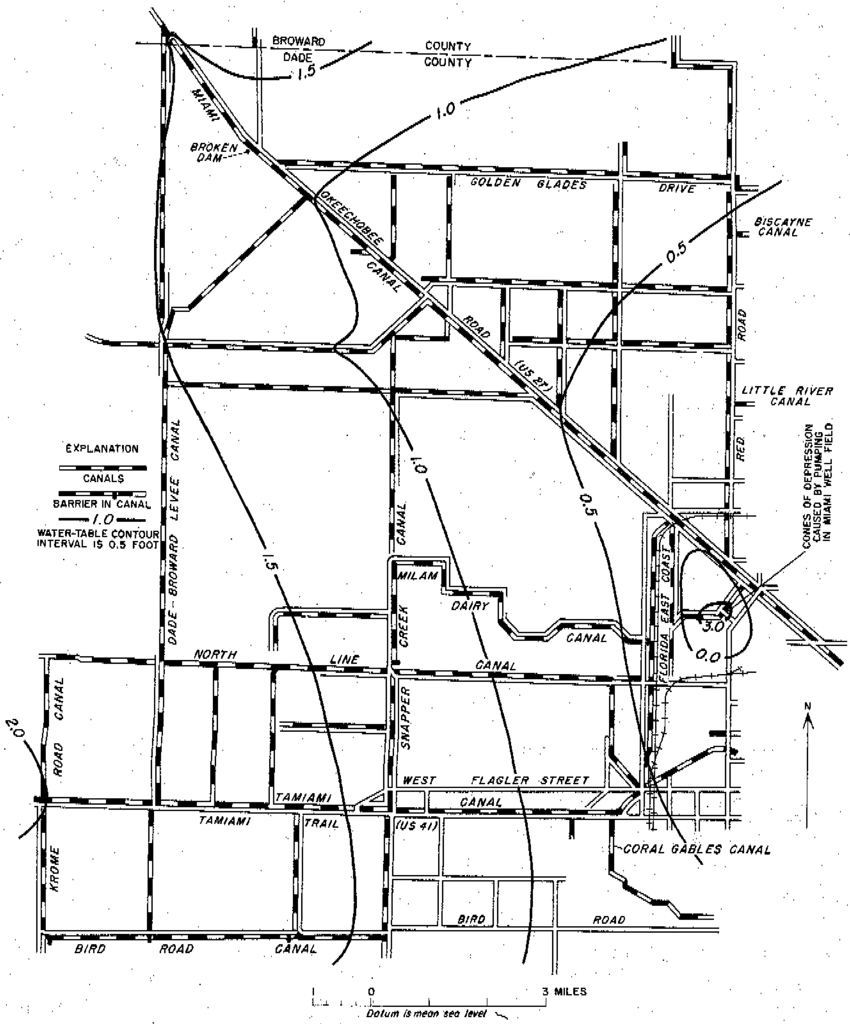

Figure 34. — Map of area west of Hialeah showing water table at low level on May 19, 1945.

part of 1945. The water level in approximately half the area is less than a foot above mean sea level and the level in the remaining part is less than 2 feet above mean sea level. The direction of ground-water flow is about the same as at higher stages, but owing to the low gradients of the water table, the rate of movement is low. It is readily apparent that because of the low water levels as shown on this map, the western boundary of which is 15 to 20 miles inland from Biscayne Bay, salt water has easy access into the aquifer along the coastal areas and uncontrolled tidal canals.

SEEPAGE

The rock at, or near, the surface in this area is highly permeable and permits a large amount of seepage through the aquifer beneath levees. The amount of seepage under the levees varies from time to time, and from place to place, and is determined by the difference in head of the water on either side of the levees and by the coefficient of transmissibility of the Biscayne aquifer in the immediate locality.

THE CENTRAL EVERGLADES

AREA DEFINED

The area consists of Broward County west of the coastal ridge; its boundaries are roughly those shown in Area 11, figure 31.

THE AQUIFER AND GROUND WATER

The aquifer in this area represents a transition zone from very high permeability in the southern part of the area to low permeability in the northern part. The principal components of the Biscayne aquifer in the eastern and southern parts of the area are the Fort Thompson formation and the Miami oolite; in the western and northern sections the aquifer is composed of the Fort Thompson formation and the Caloosahatchee marl. The Fort Thompson formation grades into the Anastasia formation in the latitude of Fort Lauderdale (fig. 10).

The quality of shallow ground water in the central Everglades follows about the same pattern as the areas of high and low permeability; that is, water of better quality is in the areas of higher permeability, and water of poorer quality is in the areas of lower permeability. The quality of water in the eastern and southern parts is similar to that of the coastal ridge; however, the color may be somewhat higher because of the overlying organic soils. In the remainder of the area the water is generally of higher mineral con-

346881 O—55——14

tent and salinity. This is probably due to the fact that the aquifer, being of low permeability, has not been completely flushed of water deposited there during Pleistocene high-level seas. Well logs and other pertinent information are given in the Appendix; data on water analyses are given in the section on Quality of ground and surface waters.

DEVELOPMENT OF WELLS

Wells of open-hole, rock-wall construction can easily be made in the area, except perhaps in the extreme northern and western parts where, owing to the lack of consolidated rocks, screened wells may be necessary.

SEEPAGE

The amount of seepage through the aquifer beneath levees in the area is controlled by head differential of the water on either side of the levees, and by the transmissibility of the aquifer in the immediate area involved. In areas underlain by porous oolitic limestone, or by quartz sand, the seepage rate is relatively high, and in areas underlain by the dense limestones of the Fort Thompson formation, or by marl (Lake Flirt Marl), it is comparatively low. In the eastern and southern parts of the area the rate of seepage through the aquifer beneath levees is relatively high, and toward the north and west it becomes progressively lower. (See pages 291, 375-386, section on Characteristics of drainage basins and summaries of gaging-station records, for seepage studies along North New River Canal.)

THE UPPER EVERGLADES

AREA DEFINED

The area included in this description extends from Broward County on the south to, and including, Lake Okeechobee on the north, and from the coastal ridge on the east to the Devil's Garden area on the west. It includes practically all areas of muck and peat soils under cultivation in the Everglades, and it also includes the Hillsboro Lakes Marsh area. The boundaries are roughly those shown in area 12, figure 31.

THE AQUIFER AND GROUND WATER

The principal components of the aquifer in this area are the Caloosahatchee marl and the Fort Thompson formation, except in the extreme eastern part where the Fort Thompson grades into the Anastasia formation.

The permeability of the Caloosahatchee marl and the Fort Thompson formation varies considerably but, as a whole, the formations in this area are of relatively low permeability, and some wells ending in them yield little or no water. In the upper Everglades area the yield to wells is usually small, and the water is always hard, colored, and often highly mineralized. The high mineralization of the water is probably the result of Pleistocene invasions by the sea during interglacial ages and subsequent partial flushings or dilutions by fresh percolating ground waters. Some wells developed in the more permeable sand and shell beds of the Fort Thompson formation yield usable water because the rocks have been flushed of sea water. However, long-continued pumping has been known to cause residual mineralized water to be drawn from adjacent unflushed zones of lower permeability, resulting in some instances in the abandonment of wells. (See the section on Quality of ground and surface waters, for data on water analyses; see also the Appendix for well logs and other pertinent information.)

DEVELOPMENT OF WELLS

Both open-hole and screened wells are constructed in the area. However, most wells are of small diameter and are equipped with a sand point. The large-diameter wells also are usually screened, and sometimes they are gravel-packed. The yields from wells in this area are relatively small compared with yields from wells along the coastal ridge.

SEEPAGE

The amount of seepage through the aquifer underneath levees in the upper Everglades is small enough that effective and economical water control on producing agricultural lands could be maintained. Likewise, according to preliminary studies, the amount of underground flow from Lake Okeechobee into the Everglades is very small. This fact is partly borne out by the presence of considerable chloride in the ground water at shallow depths adjacent to the lake, while the chloride content of Lake Okeechobee is very low. (See pages 291, and 375-386, section on Characteristics of drainage basins and summaries of gaging-station records, for seepage studies along North New River Canal.)

THE BIG CYPRESS—DEVIL'S GARDEN AREA

AREA DEFINED

The area included in this description extends from the Everglades on the east to the low sandy flatlands on the west and from Glades County on the north to the Tamiami Trail on the south. The Big Cypress Swamp is in the southern part of the area and the Devil's Garden, including Okaloacoochee Slough, is in the northern part. The boundaries are approximately those shown in Area 13, figure 31.

THE AQUIFER AND GROUND WATER

The principal components of the aquifer are the Pamlico sand, the Anastasia formation, the Fort Thompson formation (northern part of the area), and the Tamiami formation (southern part of the area). Owing to the thinness of the aquifers and the type of material (usually sand, marl, shell marl, shell beds, and solution-riddled limestone filled with sand) the permeability and yield are generally low. The quality of water from wells varies considerably over the area but in general, although most wells yield potable water, it is rather poor. (See the section on Quality of ground and surface waters; see also Appendix for well logs, and p. 810 for water analyses of wells GS 4 and 5.)

DEVELOPMENT OF WELLS

Because the area is very sparsely populated, only a limited number of wells have been developed. Practically all are shallow (10 to 30 feet), small-diameter, sand-point wells, which were developed for domestic use. Except in the southern and southwestern parts of the area, yields from the shallow aquifers are small.

THE KISSIMMEE VALLEY

AREA DEFINED

The Kissimmee valley, as designated here, is principally the drainage basin of the Kissimmee River; it extends from Lake Okeechobee on the south to the town of Kissimmee on the north and is about 35 miles wide and 80 miles long. Its boundaries are approximately those shown in Area 14, figure 31.

THE AQUIFER AND GROUND WATER

The principal shallow aquifer is composed of the marine-terrace sands of Pleistocene age which mantle the entire area and which range from 1 foot to about 25 feet in thickness. Wells, necessarily screened in these unconsolidated sands, yield potable water; however, in many instances a high color makes the water objectionable. It is possible to develop wells of small yield below the surficial sand deposits in some areas, but usually the water is highly mineralized. This mineralization is a result of low permeability of the materials, which has prevented complete flushing of the water that was left when the Pleistocene seas flooded this area. (See the section on Quality of ground and surface waters for water analyses; see also Appendix for well logs and other pertinent data.)

DEVELOPMENT OF WELLS

Where large yields are required, wells are usually developed in one of the deeper artesian aquifers. Generally, however, small-diameter sand-point wells, driven deep enough into the terrace sands to be below dry-season low levels of the water table, will furnish potable water for domestic use. Batteries of such wells will yield water for public-supply systems of small communities.

THE HIGH MARINE TERRACES EAST OF KISSIMMEE VALLEY

AREA DEFINED

This area extends from Palm Beach County on the south to the latitude of Melbourne on the north and from the Kissimmee valley area on the west to the coastal ridge and St. Johns valley on the east. Its boundaries are approximately those shown in Area 15, figure 31.

THE AQUIFER AND GROUND WATER

The Pleistocene marine-terrace materials, the surfaces of which range 25 to 100 feet above mean sea level, are the principal components of the aquifer in this area. The aquifer is principally clean quartz sand and sand containing varying amounts of marl and clay. In general, shallow wells, 10 to 30 feet deep will yield small amounts of potable water in areas where the sand does not contain too large a percentage of marl or clay. However, in some areas the water from shallow wells has a very high color, which is caused by organic materials. The materials under the terrace sands are usually of such low permeability that satisfactory wells cannot be developed. (See the section on Quality of ground and surface waters, for water analyses; see also Appendix for well logs and other pertinent data.)

DEVELOPMENT OF WELLS

There are relatively few wells in the area. However, in most parts of the permeable sand layers of the marine terraces, screened wells could be developed that would yield potable water for domestic use, and in many instances fairly large supplies could probably be obtained.

ARTESIAN WATER

GENERAL STATEMENT

At the present time, very little artesian water is used in southeastern Florida. This is because of the relatively poor quality of the water, and also because the artesian aquifer is deeply buried and therefore expensive to tap. (See the section on Quality of ground and surface waters, table of analyses of artesian waters.) In general, the artesian water is saline, sulfurous, and corrosive. In southwestern Florida, especially in the area adjacent to the city of Everglades, in Collier County, one of the artesian aquifers supplies most of the water used. This is not because the water is of satisfactory quality, but because it is the best obtainable.

In southeastern Florida there is only one productive artesian formation, the Floridan aquifer, but in most of the remainder of southern Florida there may be several productive shallow artesian aquifers, each with its own characteristics. They are described below in the section entitled Shallow artesian aquifers (see p. 193-197).

THE FLORIDAN AQUIFER AND AQUICLUDE

The principal geologic formations carrying artesian water in the Florida peninsula, as described by Stringfield (1936), are the Ocala limestone of Eocene age and the Tampa limestone and Hawthorn formation of Miocene age. Earlier reports (Matson and Sanford, 1913, p. 67) included the Ocala limestone as part of the Vicksburg group, which is of Oligocene age. In 1928, the Ocala limestone (Cooke and Mossom, 1928, p. 48) was regarded as having a maximum thickness of about 500 feet, but according to more recent paleontological evidence the maximum thickness of the Ocala limestone is considerably less than that (see p. 69, and table, p. 67).

However, the Avon Park, Lake City, and Suwannee limestones (formations formerly included in the Ocala) have hydrologic and lithologic properties similar to that of the Ocala limestone and, together with the Tampa limestone and the lower limestone part of the Hawthorn formation of Miocene age, act as a hydrologic unit. In discussing this hydrologic unit in northeastern Florida and the coastal area of Georgia, Stringfield (Stringfield, Warren, and Cooper, 1941, p. 698-711) refers to it as the Ocala and associated limestones. Parker and Hoy (in press) called it the "principal artesian aquifer." It is here designated the Floridan aquifer and includes parts or all of the middle Eocene (Avon Park and Lake City limestones), upper Eocene (Ocala limestone), Oligocene (Suwannee limestone), and Miocene (Tampa limestone, and permeable parts of the Hawthorn formation that are in hydrologic contact with the rest of the aquifer).

Overlying the Floridan aquifer, and confining its water under artesian pressure, is a wedge-shaped blanket composed of one or more geologic formations of relatively low permeability. This confining unit, which is herein called the Floridan aquiclude, is nonexistent or very thin in the recharge areas of the Floridan aquifer, but it becomes very thick in all seaward directions and is about 600 feet thick in the Miami area.

The term "aquiclude" was proposed by Tolman (1937, p. 36) to describe a geologic unit that, although porous and capable of absorbing water slowly, will not transmit it quickly enough to furnish an appreciable supply for a well or spring.

The Floridan aquiclude, as here defined, is comprised chiefly of clays, silts, marls, dense limestones, and fine sediments with greater or lesser admixtures of sand, fine gravel, and shells—all these are materials of extremely low permeability, chiefly belonging to the Hawthorn and Tamiami formations of Miocene age. In southeastern Florida, the Floridan aquiclude not only caps the Floridan aquifer, it also forms the relatively watertight foundation upon which the Biscayne aquifer rests (p. 160 et seq.).

DISTRIBUTION

The Floridan aquifer underlies all of Florida and parts of the adjacent States of Georgia and Alabama. In southern Florida it is deeply buried, being about 900 feet below sea level at Miami and 800 feet at Everglades City. The Floridan aquiclude is less extensive because it is absent, or very thin, in the areas of recharge to the aquifer.

ARTESIAN PRESSURE

The piezometric surface of the Floridan aquifer in Florida was mapped by Stringfield (1936, p. 135; 1938, p. 457-458), and the surface in southeastern Georgia was mapped by Warren (1944, p. 18-a). Later editions of the map were prepared by Cooper (1944, p. 175; Cooper and Warren, 1945). The map in figure 35 is a product

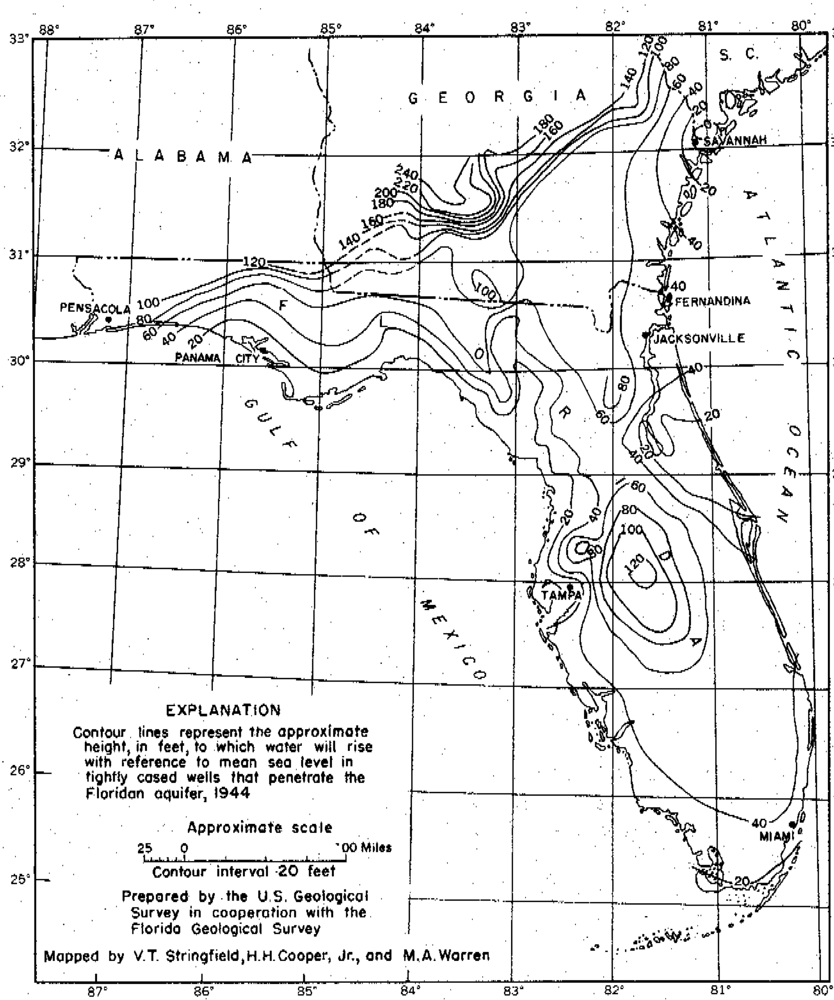

Figure 35. —Piezometric map of the Floridan aquifer in 1944.

of their work and shows by contour lines on the piezometric surface the approximate height, in feet (mean sea level), to which water would rise in tightly cased wells that penetrate the Floridan aquifer. As described by Stringfield (1936), the domed areas of the piezometric surface, such as that in Polk County (central Florida), indicate places of recharge to the aquifer, and depressed areas indicate regions of discharge from it. In general, the water moves from high to low areas and follows along flow lines normal to the contours, because this course gives rise to the steepest gradients.

The artesian pressure varies seasonally at all places; it varies momentarily with changes in atmospheric pressure; it changes in response to discharge from wells or to recharge in areas where drainage wells function; in some places it varies with the passage of trains; in places near the seashore it varies with the tides; and it changes in accordance with several other minor variable factors. Obviously, because of fluctuations of the artesian pressure, the position of the piezometric surface is changing constantly. However, the piezometric map (see fig. 35) shows the major features, which do not change except in detail from time to time. For example, the major features of the 1944 edition of the map are essentially the same as those of the 1934 edition. These retained major features indicate recharge, areas of discharge, and the direction of movement of the water.

YIELD TO WELLS

In reporting on yield of wells from the Floridan aquifer, Stringfield (1936, p. 158) states: "The yield of flowing artesian wells under natural flow ranges from a few gallons to more than 1,000 gallons a minute. The largest yields by natural flow are in the eastern and northeastern parts of the peninsula, where the artesian pressure is relatively large and the surface of the ground is only a few feet above sea level. One of the largest yields observed was about 2,000 gallons a minute from a well 8 inches in diameter at Crescent Beach [well 20, St. Johns County (northeastern Florida)]. The largest reported yield by natural flow is 6,200 gallons a minute from well 2 in Brevard County, a 12-inch well."

Flows from artesian wells ending in this aquifer in southern Florida depend upon the amount of penetration into the aquifer and upon the diameter of the well. Flows range from 75 gpm (well G 101, Dade County) to an estimated 2,300 gpm (well S 524, Dade County), and they average about 750 gpm.

UTILITY

All artesian water in southeastern Florida is hard, sulfurous, and corrosive. Its temperature ranges from 71° to 78° F but it averages about 72° or 73° F. (See the section on Quality of ground and surface waters.)

The temperature, which averages about 4 to 5 degrees lower than that of the shallow nonartesian ground water (average temperature 77° F), and the pressure, which causes the artesian water to rise to heights ranging between 20 and 40 feet above sea level in the Miami area, are advantages that industrialists, farmers, air-conditioning engineers, and others would like to utilize. However, the salinity and corrosiveness of the water, and the much greater cost of obtaining it (as compared with the cost of a well tapping the shallow aquifer), have greatly limited its use.

Prior to 1939, about 20 artesian wells had been drilled in the Miami area, but nearly all had been abandoned because of the poor quality of the water. Now there are several such wells in use: two are used for ornamental-fountain displays—one on Palm Island, Miami Beach, and the other is used at the Deering Estate off South Bayshore Drive, in Miami; three are used for limited irrigation of golf greens in Miami Beach, and one is used for lawn and garden irrigation in Fort Lauderdale; one (formerly in use, then abandoned) is used for cooling condenser tubes of an ice plant in Miami, and another was completed in 1948 for similar use. Formerly, condenser tubes were too vulnerable to the corrosive action of the artesian water, but now corrosion-resistant tubes are available, and it is possible that other industries will, in the future, make greater use of this flowing artesian water.

CONTAMINATION OF NONARTESIAN AQUIFERS BY LEAKY OR FLOWING ARTESIAN WELLS

Leaky or uncontrolled-flowing artesian wells in an area where the nonartesian aquifers contain only fresh, potable water could do much damage by contaminating the fresh-water aquifers with saline water. At the present time artesian wells in the Miami area are, for the most part, in the downtown area of Miami or on Miami Beach, where the shallow ground water is already contaminated with sea water and is generally more saline than the artesian water. Thus, the Miami area has nothing to fear from these existing wells.

The effects of leaky or flowing artesian wells in southeastern Florida may be illustrated by two examples: (1) Well S 142 is an abandoned artesian well in the downtown area of Miami. The casing is so thoroughly corroded that, although it is capped, the well discharge is practically unhindered, and the volume discharged is great enough that a mappable ground-water mound is always present—as shown for the peninsular area north of the Miami River and just west of Biscayne Bay in figures 42, 43, and 44. (2) Flow through the corroded casing of an abandoned oil-exploratory well (the "Gaston Drake well"), about 44 miles west of Miami near Pinecrest (northeast Monroe County) on Florida Route 94, has been taking place for many years. Over a radial distance of more than 100 feet from the well this water has killed most of the native vegetation and is contaminating fresh ground water for a much greater distance in the adjacent area. It is fortunate that this flowing well (chloride content is 18,800 ppm) is not nearer Miami. If it were nearer it could do serious damage to the potable water supply.

In Dade, Broward, and Palm Beach Counties there are no intermediate aquifers of low pressure that might be contaminated by the escape of water from an artesian well with higher hydrostatic pressure. The only danger is to the shallow nonartesian aquifers.

SHALLOW ARTESIAN AQUIFERS

In the past, little attention has been paid by well drillers and by the general populace to shallow artesian aquifers; most of the attention has been given to the deep artesian aquifer. However, in southeastern Florida the deep (Floridan) aquifer has been of only limited use (or it is not usable at all), and in many places the shallow nonartesian water is undesirable because of objectionable color, odor, or taste, or because of contamination or pollution. This has led to a search, in some parts of southern Florida, for usable water at intermediate depths, and it has led to the development of more wells in these shallow artesian aquifers during the last few years, especially along the Gulf coast in Lee and Charlotte Counties, where numerous wells are being completed at depths of 100, 200, and 400 feet in the Hawthorn formation of Miocene age.

PLEISTOCENE ARTESIAN AQUIFER AT INDIAN TOWN

At Indian Town, in Martin County, the public supply has been developed in Pleistocene marine-terrace deposits at depths of only 16 to 35 feet below land surface. A generalized geologic section follows:

Deposits	Thickness (feet)	Depth (feet)
Sand, quartz, gray to white, fine to coarse (averaging medium); permeable	12	12
Clayey sand (hardpan); relatively impermeable	4	16
Sandstone, calcareous, soft, friable, weakly cemented; permeable	19	35

The hardpan is not present everywhere in western Martin County, but it has sufficient areal extent near Indian Town to act as a confining layer to the water in the friable sandstone beneath. Prior to the pumping tests, the water level in sand-point wells ending above the hardpan stood at the same level as in the open-hole wells ending below the hardpan. When pumping began on the deeper wells, water levels immediately dropped (due to pressure relief), but the water levels in the shallow wells were unaffected. When pumping ceased, water levels in the pumped wells quickly recovered and again stood at the same level as in the shallow wells. If pumping had continued long enough, the water levels in the wells that were screened, above the hardpan, would eventually have been lowered because of the limited areal extent of the hardpan.

It is probable that this shallow artesian aquifer at Indian Town is largely replenished by local rainfall seeping down through discontinuities in the hardpan and that the system itself is comparatively local. There may be similar areas of local shallow artesian aquifers on the Pleistocene marine terraces bordering the Kissimmee valley.

PLIOCENE AND MIOCENE AQUIFERS AT FORT PIERCE, ST. LUCIE COUNTY, AND IN THE KISSIMMEE VALLEY

At the present time, only a small amount of field research has been made on the shallow artesian aquifers of the Kissimmee valley; however, in the northern and central parts of the valley numerous shallow-flowing and some nonflowing artesian wells have been investigated. Many of these wells are developed in the Pliocene (Caloosahatchee marl), and it is likely that the rest are developed in the upper Miocene (Tamiami) formation.

Geologic conditions in the Kissimmee valley in the shallow aquifers are idealized in figure 30. This illustration is greatly simplified; instead of only one confining layer (B in fig. 30) there actually are several (each of unknown, but probably different, areal extent). These confining layers (some are doubtless only lenticular bodies of relatively large areal extent) generally slope toward the center of the valley from the higher lands on either side. Their irregular areal and vertical distribution accounts for the fact that, whereas on one farm an artesian flow can be obtained through a well 100 feet deep, on an adjacent farm, with equal land-surface elevation, water can be obtained only at depths of 120 feet or more. Heads in these shallow artesian wells do not rise much above the land surface—the average rise is about 3 to 4 feet during years of normal rainfall. Usually, flows can be obtained from similar shallow wells in all parts of the valley where the altitude above mean sea level does not exceed 70 feet.

From the highland area (Pleistocene Osceola Island, pl. 10), which separates the Kissimmee valley from the Atlantic coastal strip, confining layers (similar to, and perhaps of similar origin as, the layers described above for the Kissimmee valley) slope eastward beneath permeable Pleistocene sands to, and beyond, the present shoreline. As a result of these geologic conditions, shallow artesian aquifers exist in most of the coastal zone lying between Melbourne, in Brevard County, and Stuart, in Martin County, and may extend somewhat farther, both north and south.

As in the Kissimmee valley, very little research on the shallow artesian aquifers has been done in this coastal zone. However, an intensive, small-scale study made at Fort Pierce, St. Lucie County, has provided valuable data.

Figures 36 and 37 are generalized cross sections through the Fort Pierce municipal well field showing the shallow strata, the local ground-water conditions, and the arrangement of the wells.

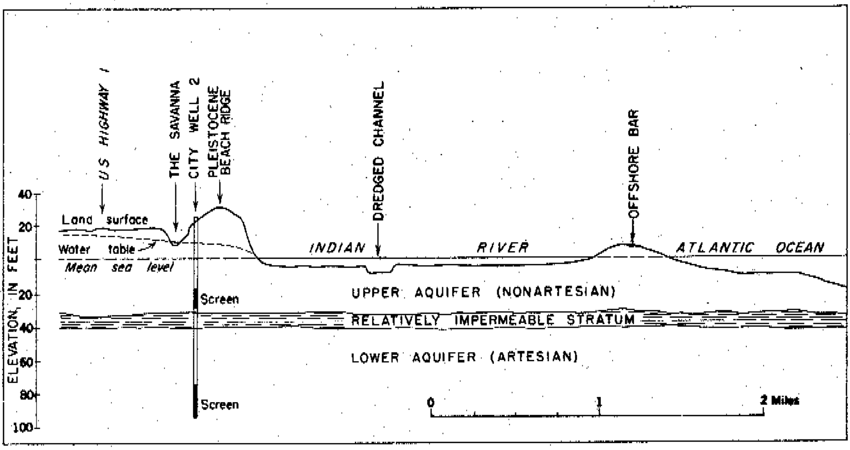

Figure 36. —Generalized east-west cross section through Fort Pierce municipal well field showing shallow strata and water table on August 3, 1944.

Figure 36 is a greatly foreshortened cross section normal to the shore, showing the principal topographic and geologic features and the location of one of the municipal wells. The upper (nonartesian) aquifer is composed chiefly of white quartz sand at the surface, grading through tan to brown below (see log of well St. L 4, in Appendix); it is separated from the lower (artesian) aquifer by a bed of dark-gray sandy and clayey marl which is relatively impermeable. The artesian aquifer is composed chiefly of various grades of quartz sand, shell marl, and shell beds.

Figure 37 is a generalized cross section parallel to the shore and shows the heights of the water table and the piezometric surface during pumping of city wells on June 6, 1944. Note that the water table above the relatively impermeable stratum is unaffected by pumping, but that the piezometric surface is greatly affected. Drawdowns are greatest in the vicinity of each pumped well. The greatest drawdown is in well 3, in which the water level fell from 10 feet above mean sea level, before the pumps were started, to 43 feet below, during pumping; this is a total drawdown of 53 feet. It would appear from figure 37 that pumping from city wells 1, 2, and 4 would draw the water table down; however, thin layers of relatively impermeable material in the upper aquifer prevent this action.

In wells distant from the ocean, or distant from Indian River (which is really a salt-water lagoon with direct connections to the open ocean), no serious consequences arise from such depressions in the piezometric surface. However, where the wells are situated as close to salt water as they are in the Fort Pierce well field, such drawdowns could eventually bring about the local ruination of the aquifer through salt-water encroachment. The fact that the municipal well field is not already ruined is due to a combination of several factors: (1) The relatively impermeable stratum probably

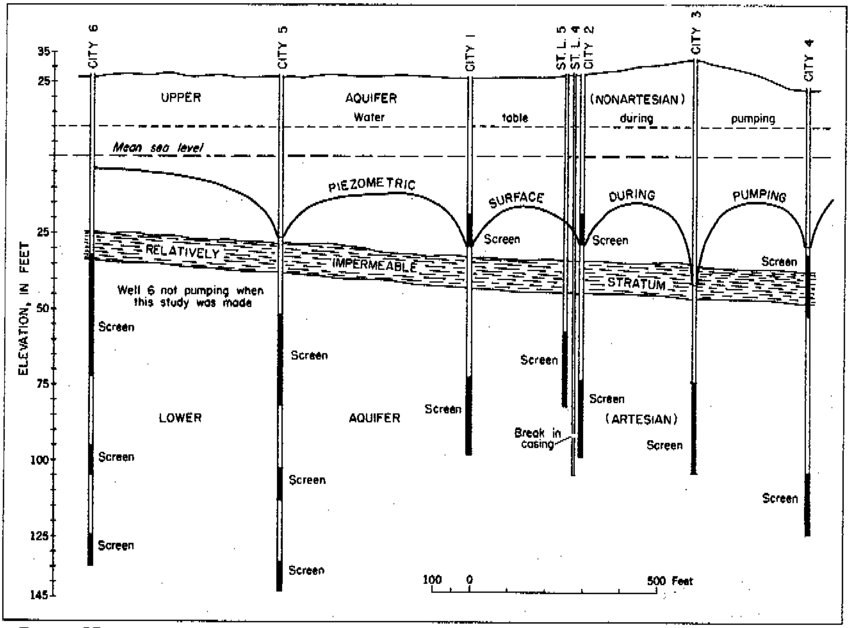

Figure 37. — Generalized north-south cross section through Fort Pierce municipal well field showing shallow strata and ground-water levels on June 6, 1944.

extends beneath Indian River and the Atlantic Ocean, thus preventing direct transfer of overlying salt water into the underlying fresh-water artesian aquifer; (2) both the piezometric surface and the water table between the Savanna and Indian River are usually relatively high—high enough that the weight of the fresh water above sea level overbalances any inland salt-water movement that would occur because of an upset equilibrium between salt and fresh water caused by pumping or drought conditions; and (3) the wells are not pumped at a very high rate. In fact, most of the Fort Pierce supply is obtained from the ponded water of the Savanna. If, however, it were necessary to pump large quantities of ground water from the existing wells over a period of several years, it is likely that such pumping would result in salt water being drawn into the aquifer.

Geologic and hydrologic conditions of the shallow aquifers as discussed above for Fort Pierce probably prevail along the coastal zone from Brevard into Palm Beach County, and any proposed large-scale development should be preceded by adequate local ground-water studies to determine the importance of these factors that relate to the perennial yield of the aquifers and thus to the security of the proposed supply.

MIOCENE AQUIFER AT EVERGLADES, COLLIER COUNTY

Everglades, the county seat of Collier County, is a small fishing and vacationing resort on the shores of the Gulf of Mexico in the Ten Thousand Islands area. The town water supply is obtained from three flowing wells, ranging in depth (reported) from 409 to 521 feet, and believed to be developed in limestone of the Hawthorn formation. The water is hard and slightly saline (chloride content is about 250 ppm) but is of much better quality than either the deeper artesian water from the Floridan aquifer or the shallow unconfined ground water in the coastal area (for analyses see the section on Quality of ground and surface waters).

The quantity of flow from these wells is reported to be 80 gpm from No. 1, 60 gpm from No. 2, and 120 gpm from No. 3.

No detailed geologic or hydrologic investigation has been made at Everglades, as was done at Fort Pierce (see p. 194-196). However, it is believed that if a heavy draft were placed upon the aquifer near the coast, salt water would soon be drawn into the aquifer and thus ruin the existing supply. Large quantities of usable water might be obtained from this aquifer several miles inland from the shore, but before any large-scale development is attempted a careful study should be made of all the geologic and hydrologic factors involved.

QUANTITATIVE STUDIES IN THE MIAMI AREA

By M. A. Warren and Garald G. Parker

INTRODUCTION

GENERAL STATEMENT

Wherever it is proposed to develop large supplies of ground water it is wise to determine whether or not the project is possible or feasible, and whether or not the perennial yield of the formation will be exceeded by the demand.

The perennial yield of an aquifer may be defined as the quantity of water that can be withdrawn from the aquifer year after year without exceeding the rate of replenishment or causing impairment to the quality of water in the aquifer.

GROUND-WATER INVENTORY

In making detailed studies of an aquifer it is essential to have thorough knowledge of the ground water. A complete inventory necessitates reliable knowledge of the quantity and quality of the water stored in the aquifer and the changes in storage that take place from time to time. Also it includes information regarding the quantity and quality of the water entering and leaving the aquifer in the area of investigation.

Water entering the area includes subsurface flow across its boundaries from other areas; surface flow that enters the aquifer in the area from adjacent areas; recharge by precipitation within the area; and recharge by artificial addition of water from other sources, either through drainage wells or galleries, or by application to the land surface from which it seeps to the water table.

Water leaving the area includes subsurface outflow, some of the water that is discharged from wells or galleries, water that percolates into surface streams and canals and flows out of the area, and water that is withdrawn from the aquifer and discharged into the atmosphere by evapotranspiration.

Several methods for estimating ground-water supplies have been used by various investigators (Meinzer 1931). However, some of the methods used by investigators in other areas are not applicable to the Miami area.

THE BISCAYNE AQUIFER

The Biscayne aquifer, its extent, and its thickness have been discussed in detail in the sections on Geology and occurrence of ground water. Basically, it consists of a permeable limestone, called the Fort Thompson formation, which increases in thickness toward the east and extends under Biscayne Bay. It has an average effective thickness of about 100 feet under most of the coastal ridge. Recharge to the aquifer is mostly from local rainfall, and the natural outlet for the subsurface flow is Biscayne Bay.

RESPONSE TO SUDDEN PRESSURE CHANGES

PUMPAGE

Ground water occurs in the Biscayne aquifer essentially under water-table conditions. In many places, however, there is a section of less permeable material intervening between the upper and lower parts of the aquifer, and when sudden changes in pressure occur in the lower part, such as the lowering caused by heavy pumping from a well that is cased throughout the upper part of the aquifer, the water levels in the nearby deeper wells respond very rapidly to these changes, while those in adjacent shallow wells show a more gradual decline. However, after a period of a few hours to a day or more, the differential head between the upper and lower parts of the aquifer disappears. This difference in the response of the water level in the deep and shallow wells becomes less noticeable as the distance from the pumped well increases, but it may be noticeable 1,000 feet or more from the pumped well. Thus, the deeper part of the aquifer may sometimes have artesian characteristics.

EARTHQUAKE SHOCKS AND PASSING TRAINS

Sudden changes in pressure caused by earthquake shocks and passing trains are registered in some of the deeper wells, whereas usually no response is indicated in wells less than 20 feet deep (see Parker and Stringfield, 1950). The water table responds to heavy showers almost as quickly in the deep wells as in the shallow wells, because little transfer of water through the less permeable section of the aquifer is required to increase the pressure in the lower part.

VARIABLE HYDROLOGIC FACTORS AFFECTING THE AQUIFER

A quantitative accounting of ground water in the Miami area is made difficult by the great variation in hydrologic factors. The areas contributing to runoff of streams and canals cannot be determined with any degree of exactness. Neither can the areas of natural ground-water discharge be accurately outlined. This is largely because these areas are constantly changing in size according to the intensity and duration of localized rainfall, the stage of the water table, the stage in canals, and tidal and periodic changes in sea level. It is not unusual for the direction of flow of both ground and surface water to be reversed in some areas several times each year. Local rainfall (the source of recharge) varies widely—in a distance of 10 to 15 miles the annual rainfall may differ by 20 to 25 inches (page 28).

The coefficient of transmissibility of the aquifer, which is a measure of its ability to transmit water, is very great, but it varies as much as 500 percent or more within relatively short distances. The variability of the specific yield of the upper part of the aquifer, over which the water table fluctuates, makes it difficult to accurately compute the changes in ground-water storage in the aquifer as the water table rises or falls.

The water table is near the surface over most of southeastern Florida, and it is within easy reach of plants. As a result, a large percentage of the precipitation that reaches the water table is returned to the atmosphere by evapotranspiration. The quantity thus returned varies widely with location, depth to the water table, character of the vegetation, and weather conditions.

The water surface in Biscayne Bay, the base level with regard to canal and ground-water flow, has an average daily tidal range of about 2.0 feet, and the daily mean level in the Bay may vary a foot within a few days. The highest point on the water table during the rainy seasons rarely exceeds 10 feet above mean sea level. Thus, the variances in sea level are 20 percent or more of the total head affecting ground-water flow toward the sea.

346881 O—55——15

SALT-WATER ENCROACHMENT

The history, occurrence, and extent of salt-water encroachment in the Miami area are discussed in detail in the section on Salt-water encroachment (p. 580 et seq.). The contact between the fresh and salt water may be near the shore in some locations and several miles inland in others. In general, owing to the greater density of salt water, the encroaching body of salt water has advanced much farther inland along the bottom of the aquifer than near the top. Thus, there are zones, a mile or more wide, roughly paralleling the shoreline and major canals, in which the depth to the fresh-water—salt-water contact varies. In these zones the shallower wells may obtain fresh water while the deeper wells furnish only salt water. As explained in the section on Salt-water encroachment, a delicate balance exists between the fresh-water head in the aquifer and the average stage in Biscayne Bay. The difference between these two elevations largely determines the extent and rate that salt water either will invade the aquifer or be flushed out by fresh water moving seaward. Because the fresh-water head and sea level are constantly fluctuating (each in a different manner), a condition of static equilibrium for the contact zone between fresh and salt water is never attained.

PERENNIAL YIELD

The question of primary importance in the Miami area, with reference to the ground-water resources, is the perennial yield. The Biscayne aquifer is known to be permeable enough to yield copious quantities of water without the pumping lift becoming excessive; but the perennial yield is determined by the level that must be maintained to keep salt water out of the wells. The amount of water that can be safely withdrawn under these conditions is determined by the several hydrologic factors previously discussed, each related to the other in a highly complex manner. These factors will be discussed and evaluated in the sections that follow.

In working with this problem it is necessary to use average figures for the hydrologic data collected over a period of several years, and the longer the period of time, the better. Trying to integrate the effects of all the factors that enter the problem as they change, or as they go through their cycles or fluctuations, one finds the problem so complex that a strictly mathematical solution is virtually impossible to achieve; however, a practical solution, accurate within allowable working error, is possible.

THE WATER TABLE

GENERAL STATEMENT

The water table, in materials permeable enough to permit circulation of ground water, is the upper surface of that body of free (unconfined) water that completely fills all opening and interconnected passages in the rock materials. See p. 157-158.

The water table is seldom stationary; instead, it is constantly changing shape, rising and falling, sometimes so slowly as to be almost imperceptible, but at other times fluctuating very rapidly. The minor fluctuations, many of them being only of momentary duration, are ordinarily unobserved because they are detectable only by measuring and recording devices. Major fluctuations, usually of longer duration, are noticeable, and many of these fluctuations cause alarm when aquifers overfill and the land becomes flooded, or when, during a drought, wells become dry.

All fluctuations of the water table, whether minor or major, are of concern to the hydrologist. Determination of such fundamental hydrologic factors as the coefficients of permeability, transmissibility, and storage; areas of recharge and discharge; direction of ground-water movement; perennial yield; and other pertinent, related factors are based wholly, or in part, upon water-level measurements in wells. But these water-level readings, if not properly understood and weighted, may be entirely misleading. Water levels fluctuate as a result of several factors other than recharge to, and discharge from, the aquifer (principal factors in a quantitative ground-water study). Chief among these other factors are: tides—both oceanic and earth, atmospheric pressure, winds, earthquakes, and passing trains.

In the Biscayne aquifer, all these phenomena have been observed and reported by Parker and Stringfield (1950). It should be noted, however, that the effects of ocean tides, discussed subsequently in greater detail, were observed only in wells located within a relatively narrow coastal band. In well F 179, for example, in the Silver Bluff area at a distance of 6,680 ft from the bay, the range of tidal fluctuations was 0.01 ft. Farther inland, at well S 182 (fig. 39) the water level is affected only remotely by fluctuations in Biscayne Bay.

Figures 38—41 are hydrographs showing average monthly water levels in 10 key observation wells tapping the Biscayne aquifer in southern Florida. Because these hydrographs were derived by averaging the daily readings for each month, they do not show either the highest or lowest water levels recorded, and because the records for all wells except S 196 were obtained largely during a series of dry years, the hydrographs give a picture of low-level, instead

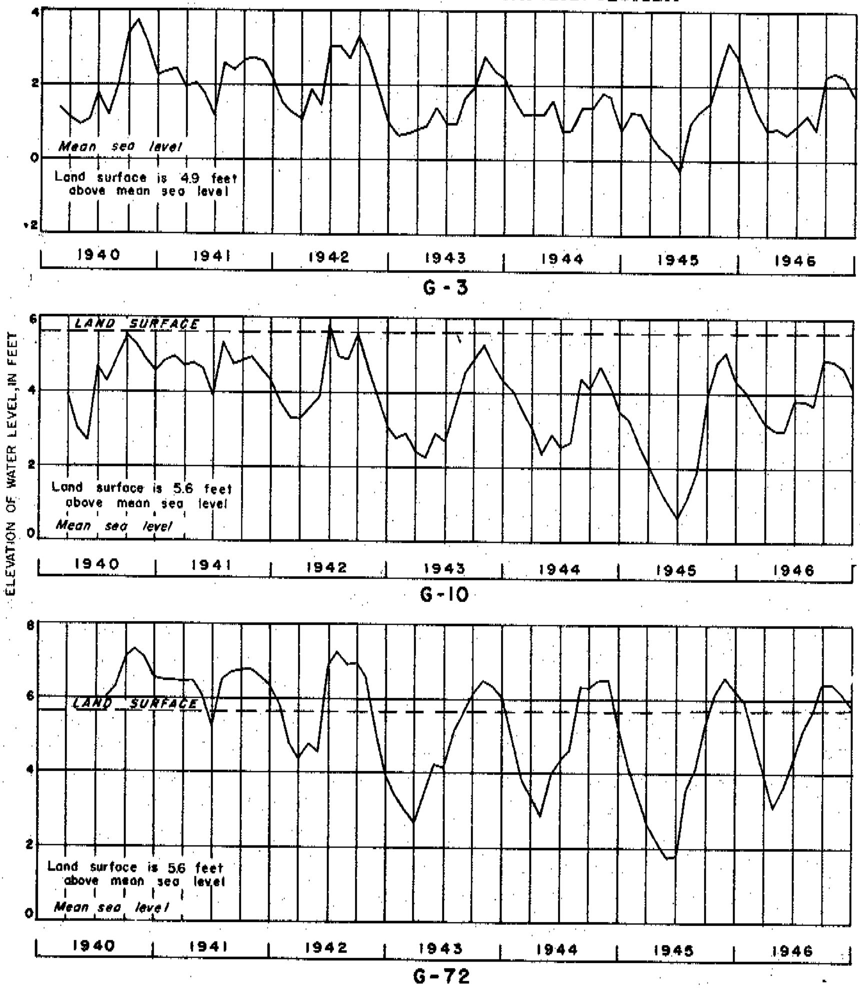

Figure 38. —Hydrographs showing average monthly water levels in key observation wells G 3, G 10, and G 72.

of high-level, fluctuations of the 10 wells here recorded. Nine are in Dade County and one well, S 329, is in Broward County on the Atlantic Coastal Ridge, at the eastern margin of the Fort Lauderdale well field. Unfortunately, well S 329 was out of commission during the drought of 1945, so no record is available for that time. Tables 116 and 118 list well locations and other pertinent data.

The fluctuations shown on these four figures are caused largely by changes in aquifer storage brought about by recharge to, and discharge from, the Biscayne aquifer. These factors are of sufficient importance to merit major sections being devoted to them (p. 212–236).

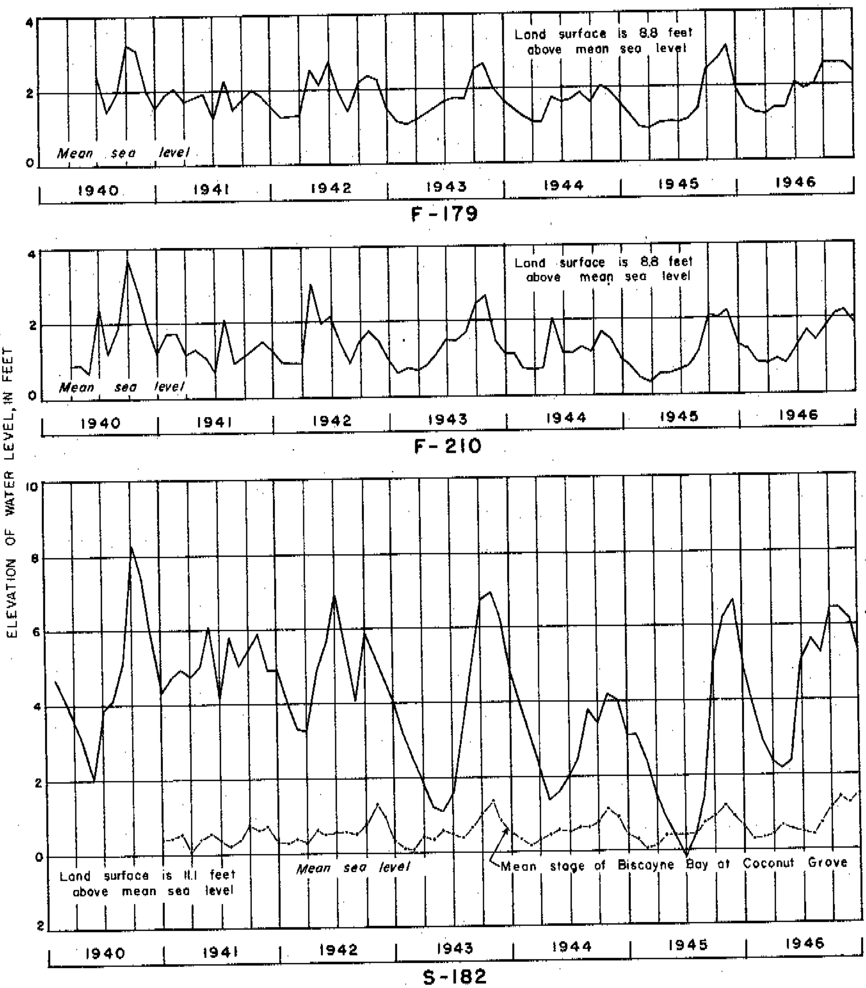

Figure 39. —Hydrographs showing average monthly water levels in key observation wells F 179, F 210, and S 182.

EFFECT OF CANALS ON THE WATER TABLE

Except when heavy and long-continued rainfall results in floods, the canal system of the Miami area is an effective outlet for discharge of ground water; it lowers the water table rapidly after a short, heavy rainfall. However, when the Everglades are flooded and the aquifer is filled to overflowing, the capacity of the canals is not great enough to remove flood waters in time to prevent damage to crops and structures on low lands.

Ground water is free to discharge through the bottoms (provided there is not a thick layer of sediment) and through both sides of drainage canals cut into the aquifer. Ground water can readily discharge directly into Biscayne Bay only along one side of the Bay;

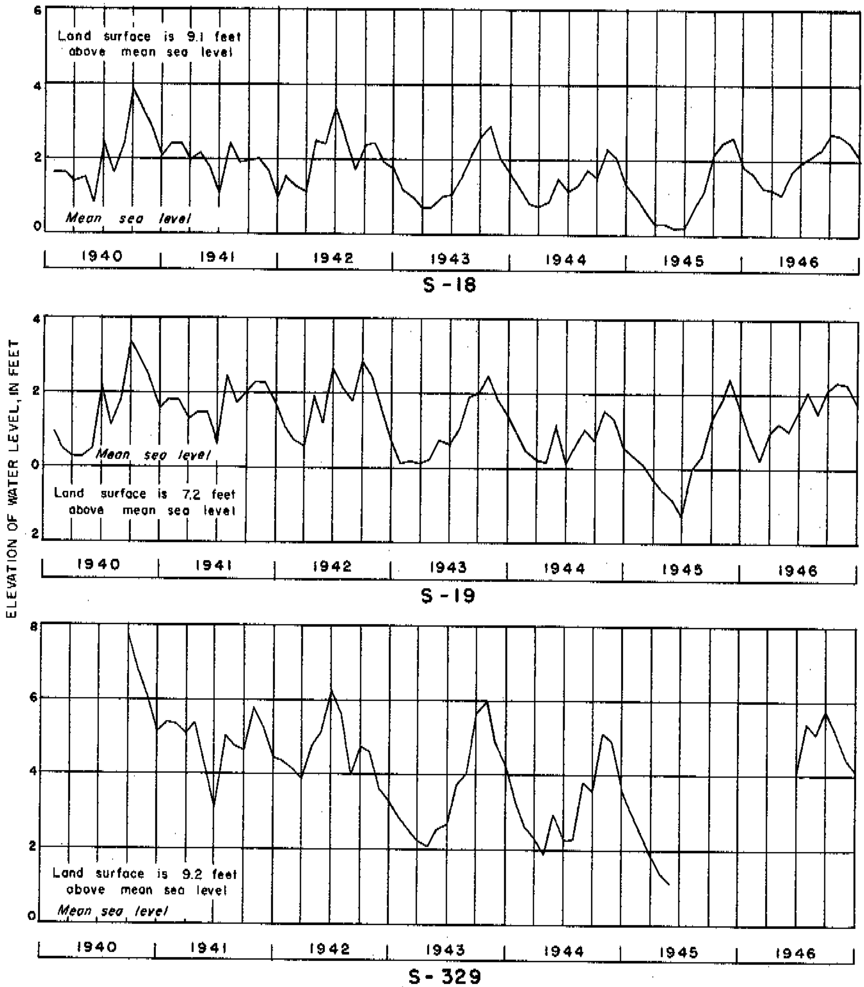

Figure 40. —Hydrographs showing average monthly water levels in key observation wells S 18, S 19, and S 329.

however, this movement is not as effective as discharge into the canals through their highly-permeable, cut-rock faces. As an outlet for ground-water flow, a mile of deepened canal appears to be more effective than 4 miles of bay shore. A study of the water-table maps, figures 42–44, will help make this clear.

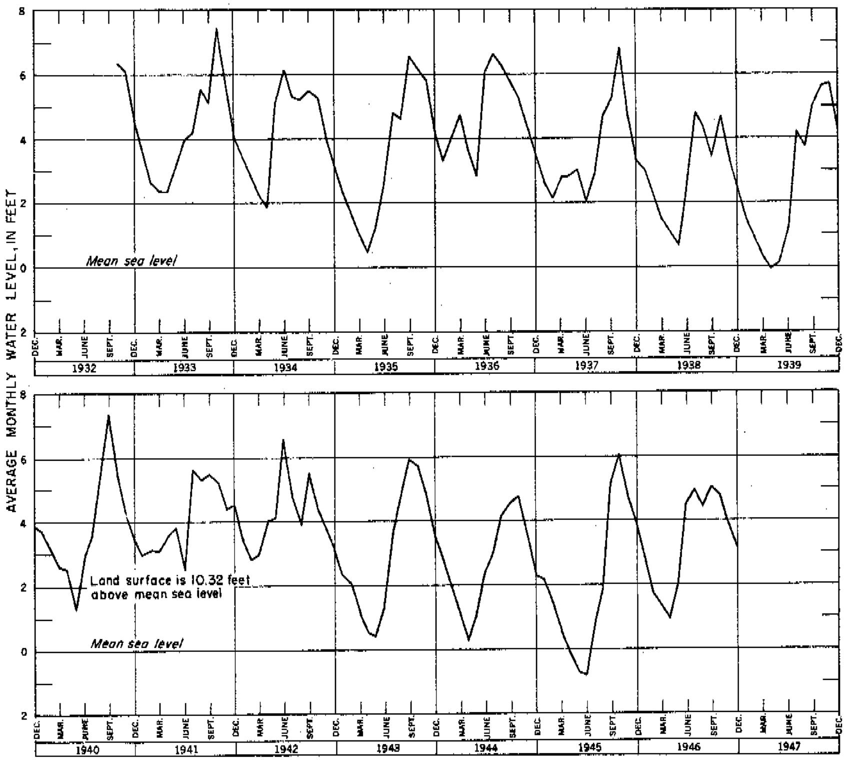

Figure 41. —Hydrographs showing average monthly water levels in well S 196, Univ. of Florida Expt. Sta., Homestead, 1932-46.

WATER-TABLE STUDIES OF THE MIAMI AREA

Contour maps of the water table (also called water-table maps) are very helpful in depicting the shape and position of the water table. These features of the water table are constantly changing in response to several factors, including: the movement of water due to gravity; additions through recharge by rainfall or irrigation; losses due to pumpage, evaporation, and transpiration; and losses or gains due to flow into or out of streams.

Mapping of the water table provides the most reliable method of locating areas of recharge and discharge and of determining the direction of flow. Contours are lines of equal elevations; therefore, the direction of flow is at right angles to the contours because the steepest gradients are in that direction. The fundamental law of laminar ground-water flow is that the velocity varies directly as the slope and inversely as the permeability. By application of this law, quantitative values for the amount of ground-water flow may be obtained, provided that reliable average values for permeability are known. The slope may be obtained from water-table maps or profiles.

Figures 42—44 show the Miami area when the water table is at low, medium, and high stages. Because the gradients are gentle, the area is dissected by a network of canals that radically modify the water table within several miles of the deeper canals, and because heavy local rains change the shape of the water table, it is necessary to have a large number of observation wells and staff gages to get enough points of access to the ground-water body to contour the water table accurately. For the same reason, it is necessary to determine the elevations of the reference points for the observation wells and staff gages by careful instrumental leveling with reference to a common datum plane. Datum used is U. S. Coast and Geodetic Survey mean sea level datum of 1929.

WATER TABLE AT LOW STAGE, FEBRUARY 3, 1942

February 3, 1942, was a time when the water table was relatively low (fig. 42). The general direction of ground-water flow, which is normal to the contours, is toward the east; but in the vicinity of the canals (particularly the deeper ones, not controlled by locks or dams) the contours indicate a discharge of ground water into the canals (effluent condition). However, during some low stages the canals in places may be influent, thus raising the water table in the influent area. An example of this is the Miami Canal opposite the Hialeah well field. The 0.5- and 0.0-ft contours encircle the well field, whereas the canal stage opposite the well field is about 1.0 ft above sea level. Under these conditions, a considerable part of the water pumped from the well field was diverted from the canal. The 1.0-ft contour near Biscayne Bay, enclosing a large part of the Miami residential and business areas, indicates a low ground-water mound, which probably is maintained during dry periods by recharge from used municipal water being returned through the soil to the water table through septic tanks, drainage wells, and by the watering of lawns.

WATER TABLE AT MEDIUM STAGE, JULY 26, 1941

The map for July 26, 1941, shows the water table at an intermediate stage (fig. 43). The steeper gradients indicate greater discharge of ground water, but the discharge areas have not changed greatly from the time when the stage was low.

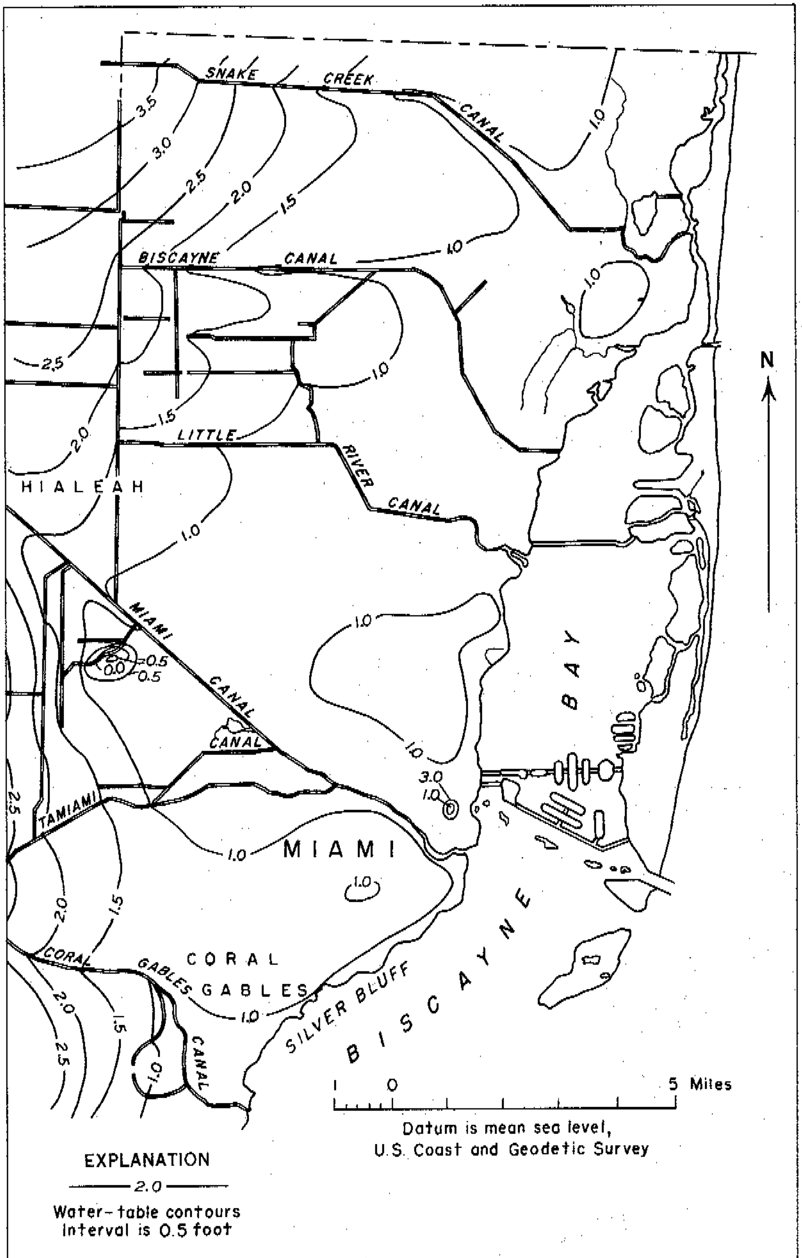

Figure 42. —Water-table map of the Biscayne aquifer in the Miami area showing low stage, February 3, 1942.

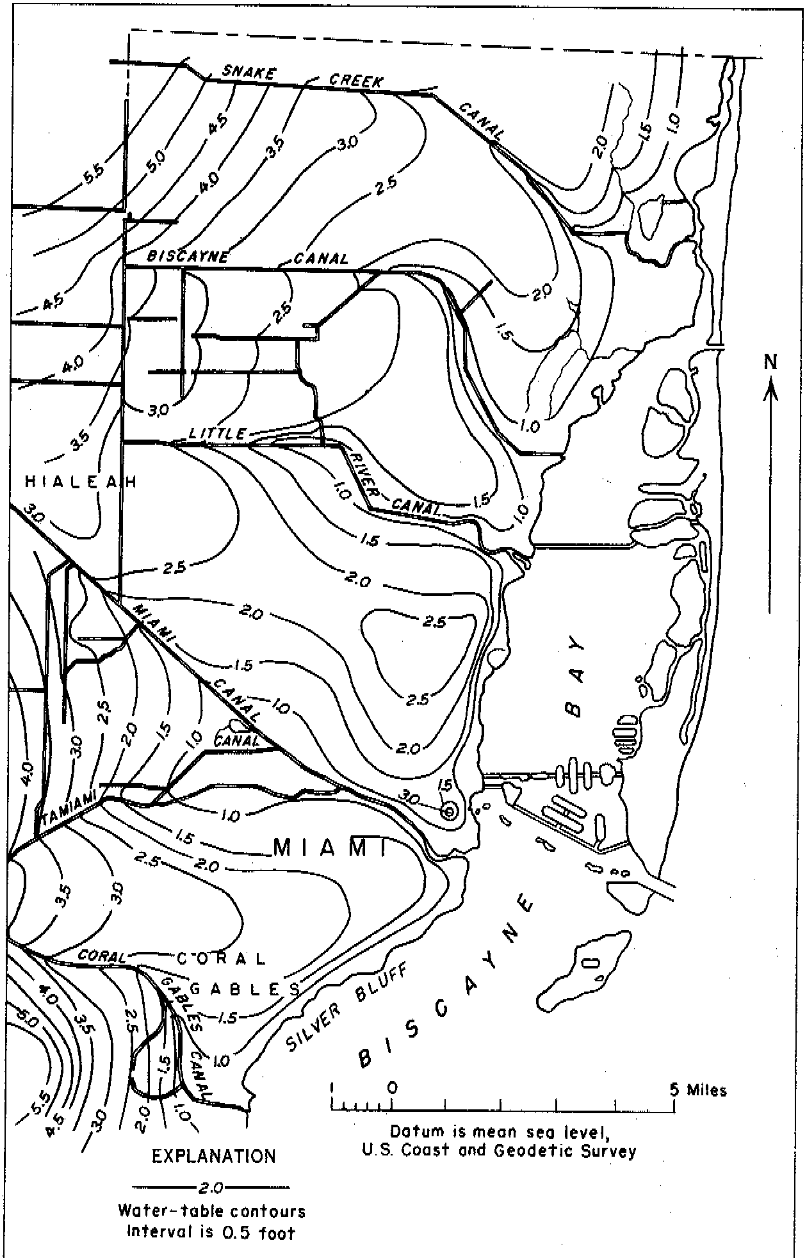

Figure 43. —Water-table map of the Biscayne aquifer in the Miami area showing medium stage, July 26, 1941.

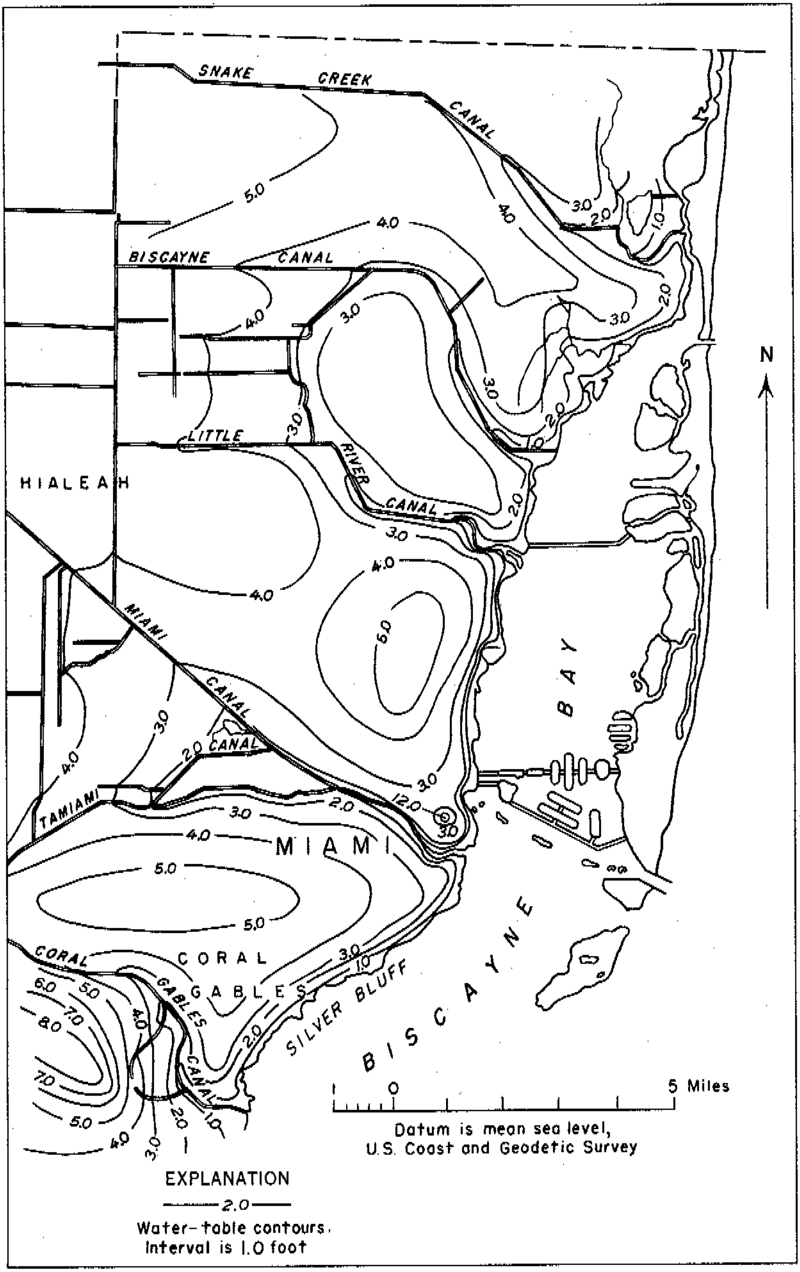

Figure 44. —Water-table map of the Biscayne aquifer in the Miami area showing high stage, September 30, 1940.

WATER TABLE AT HIGH STAGE, SEPTEMBER 30, 1940

The water-table map for September 30, 1940, is for a time when the water levels were comparatively high (fig. 44). The flow pattern is similar to that for the intermediate and low stages, but the gradients are steeper. The ground-water mounds prove that the recharge is local and that the major part of the ground water does not move in from distances of many miles to the west or north, as has been the popular belief; in fact, ground-water movement on the western sides of these mounds is to the west—toward the Everglades, not toward the ocean.

WATER-TABLE STUDIES OF DADE COUNTY

WATER TABLE AT LOW STAGE, MAY 19, 1945

Figure 45 shows the water table for May 19, 1945, which was almost the lowest stage that occurred during the period of investigation here reported (1939-1946). In the northern part of the county the water table slopes toward the east. If this low-stage condition were maintained for a long time, the water table would not have sufficient head above sea level to prevent salt water at depth in the Biscayne aquifer from encroaching several miles farther inland than it is at present. However, because of the low velocity of encroaching salt water, lateral movement over a period of a few months is very small.

In the southern part of the county the water table sloped inland toward a low area in the vicinity of Royal Palm State Park, where evapotranspiration loss had lowered the water table to slightly more than 3 ft below average level in Biscayne Bay, which, during this investigation, was about 0.6 ft above U. S. Coast and Geodetic Survey mean sea level datum. The exceedingly low water table developed here mainly because of its geographic location. Evapotranspiration rates are rather uniformly high over the glades area of Dade County. This particular area could not develop closer to the sea because of recharge from the sea, nor could it develop farther inland because of recharge from the normally higher water table in the area to the north and west.

WATER TABLE AT MEDIUM STAGE, MARCH 17, 1941

Figure 46 shows the water table as mapped for March 17, 1941, and it was selected because it shows the water table when it was very near medium stage for the period of record. At this stage, the water table slopes from the Everglades toward the east and southeast.

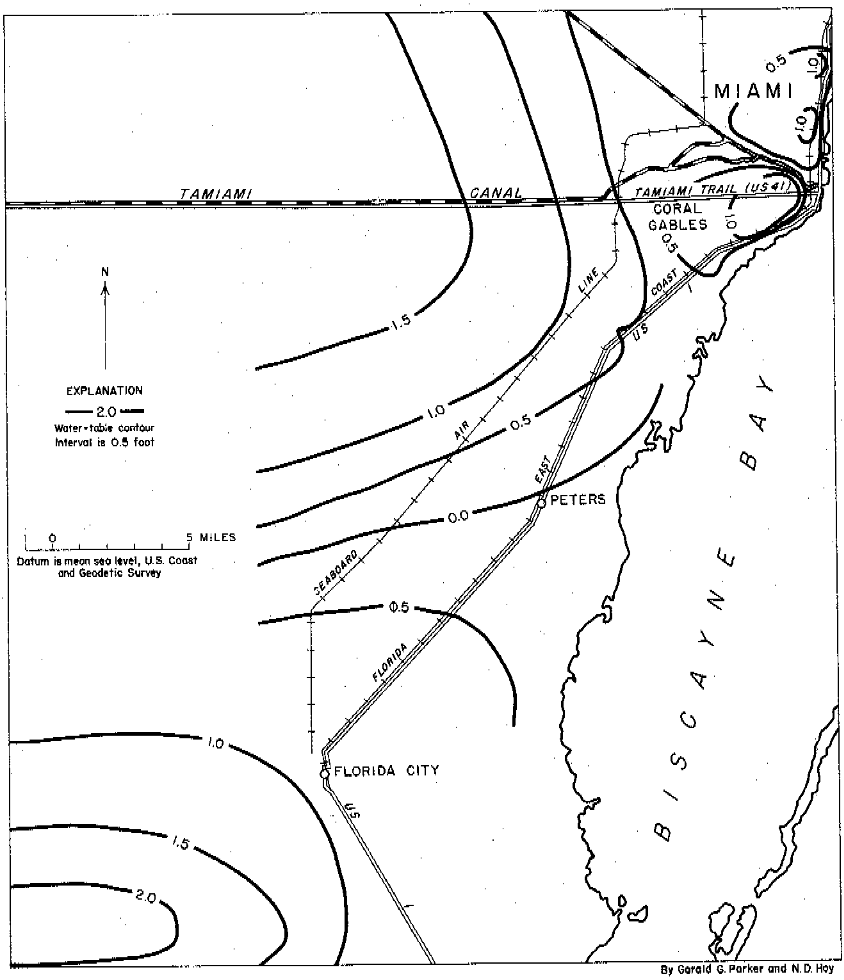

Figure 45. —Water-table map of the Biscayne aquifer in southeastern Dade County showing low stage, May 19, 1945.

WATER TABLE AT HIGH STAGE, SEPTEMBER 23, 1940

Figure 47 shows the water table for September 23, 1940, which was almost the highest stage that occurred between 1939-46. At this stage, the water table in the western part of the coastal ridge south of Miami had been built up by recharge from rainfall until it was above the water level in the adjacent part of the Everglades. Therefore, ground water was flowing in all directions from this mound, part of it being discharged westward into the Everglades. This condition commonly occurred in this area prior to the construction of the drainage canals, as attested by the observations of Sanford (1913, p. 289) who reported that, " * * * along the rock ridges of the Biscayne pineland are a number of springs, some of considerable size. The largest noted rises on the west side of the

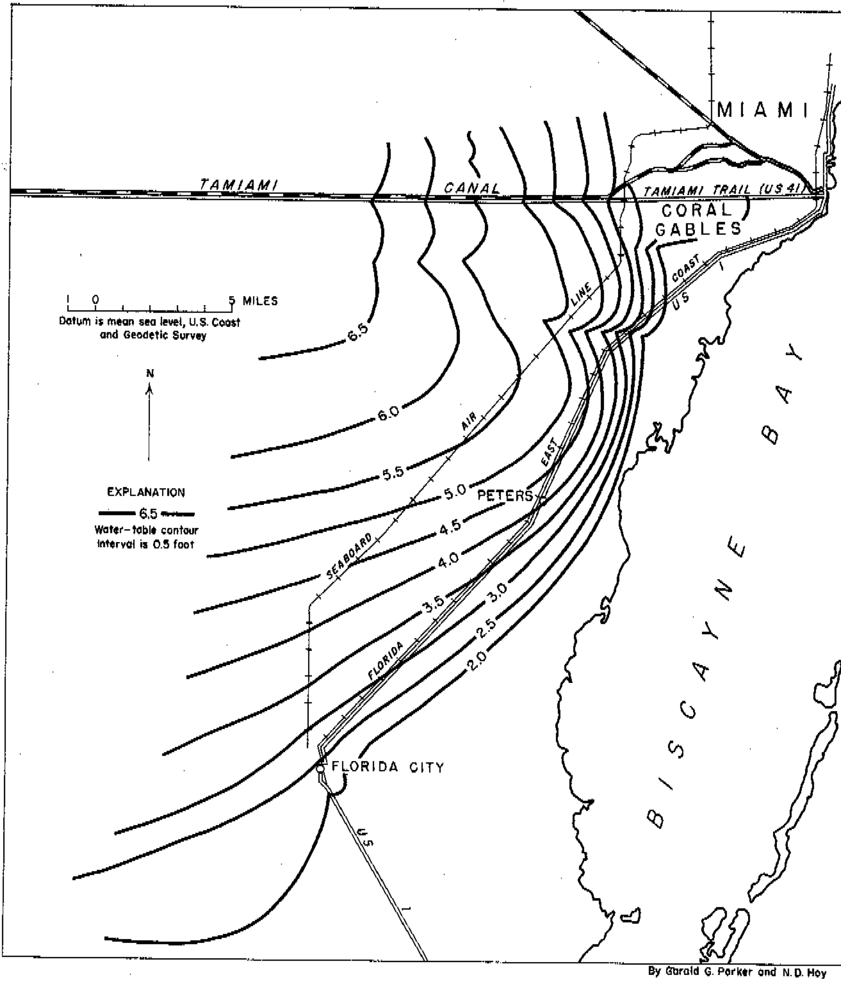

Figure 46. —Water-table map of the Biscayne aquifer in southeastern Dade County showing medium stage, March 17, 1941.

crest of the ridges just north of Miami and flows into a swamp from Miami River. It is supplied by rainfall on the slightly higher ground of the pineland." The occurrence of this large spring on the west side of the high land required a higher water table to the east, which probably reached a crest under the highest part of the coastal ridge.

GROUND-WATER RECHARGE

GENERAL STATEMENT

Over most of the coastal ridge from Miami southwest to Homestead, the Miami oolite, which underlies the entire area, is at the

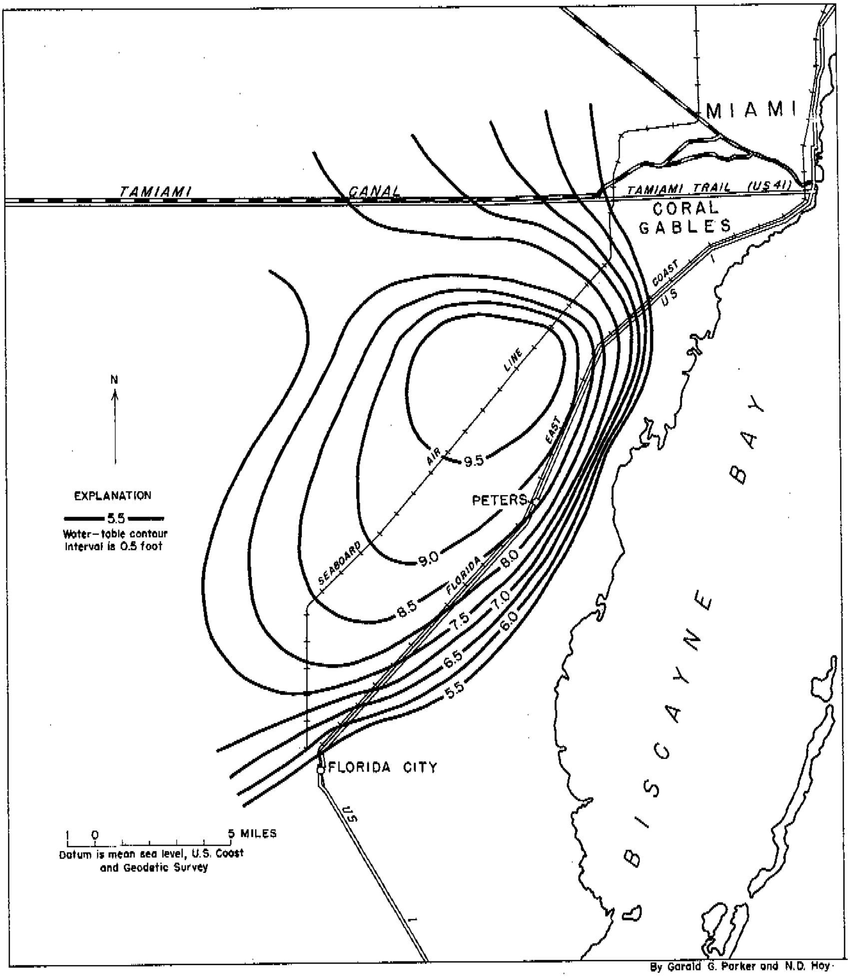

Figure 47. — Water-table map of the Biscayne aquifer in southeastern Dade County showing high stage, September 23, 1940.

surface or is covered with only a thin sandy soil mantle. The oolite has high vertical permeability; rain falling on the surface rapidly percolates downward to join the water table, which is seldom more than 10 ft below the land surface and which, at times of high water-table conditions, is at or near the surface over a considerable part of the area. Thus, there is little opportunity for rainfall to flow into surface drainage channels and reach the ocean without first entering the ground.

Rain falling in the glades recharges the Biscayne aquifer until the water table reaches the surface. Additional rainfall floods the glades, and, as the stage increases, the flow into canals and overland to the south, through the glades, and to the east, through transverse glades, also increases proportionately (see the section on Geomorphology).

A rapid rise of the water table occurs within a few hours after the rain begins if the rainfall is of sufficient magnitude and intensity to saturate the soil and rock above the water table. The rise of the water table, correlated with the rainfall, gives reliable information in some locations as to the amount of rainfall reaching the water table, and it may give information regarding the porosity and specific yield of the part of the aquifer through which the water table rises.

DEFINITIONS

Porosity.—According to Meinzer (1942, p. 387): "The porosity of a rock is its property of containing interstices. It is expressed quantitatively as the percentage of the total volume of the rock that is occupied by interstices or that is not occupied by solid rock material. A rock is said to be saturated when all its interstices are filled with water. In a saturated rock the porosity is practically the percentage of the total volume of the rock that is occupied by water."

Specific yield.—The specific yield has been defined by Meinzer (1923b, p. 28) as the ratio, expressed as a percentage, of (1) the volume of water a rock or soil will yield by gravity to (2) its own volume.

Specific retention.—Specific retention (Meinzer, 1923b, p. 29) has been called the ratio, expressed as a percentage, of (1) the volume of water which a rock or soil will retain against the pull of gravity to (2) its own volume.

Under natural water-table conditions the sum of the percentages representing specific retention and specific yield should equal the percent porosity. It should be recognized, however, that during the period following drainage of a zone of saturation, the water retained by the rock or soil, against the pull of gravity, will gradually be dissipated by evaporation and transpiration. Thus, theoretically, in a rock or soil the actual air space available for receiving ground-water recharge can vary from the value given by the porosity minus the specific retention, immediately following complete gravity drainage of the zone of saturation, to the value given by the porosity alone after sufficient time has elapsed to permit complete evaporation and transpiration of all the retained water. Therefore, in any discussion of quantitative analysis of ground-water storage and recharge, due consideration must be given to the elapsed time between the antecedent climatic and hydraulic events.