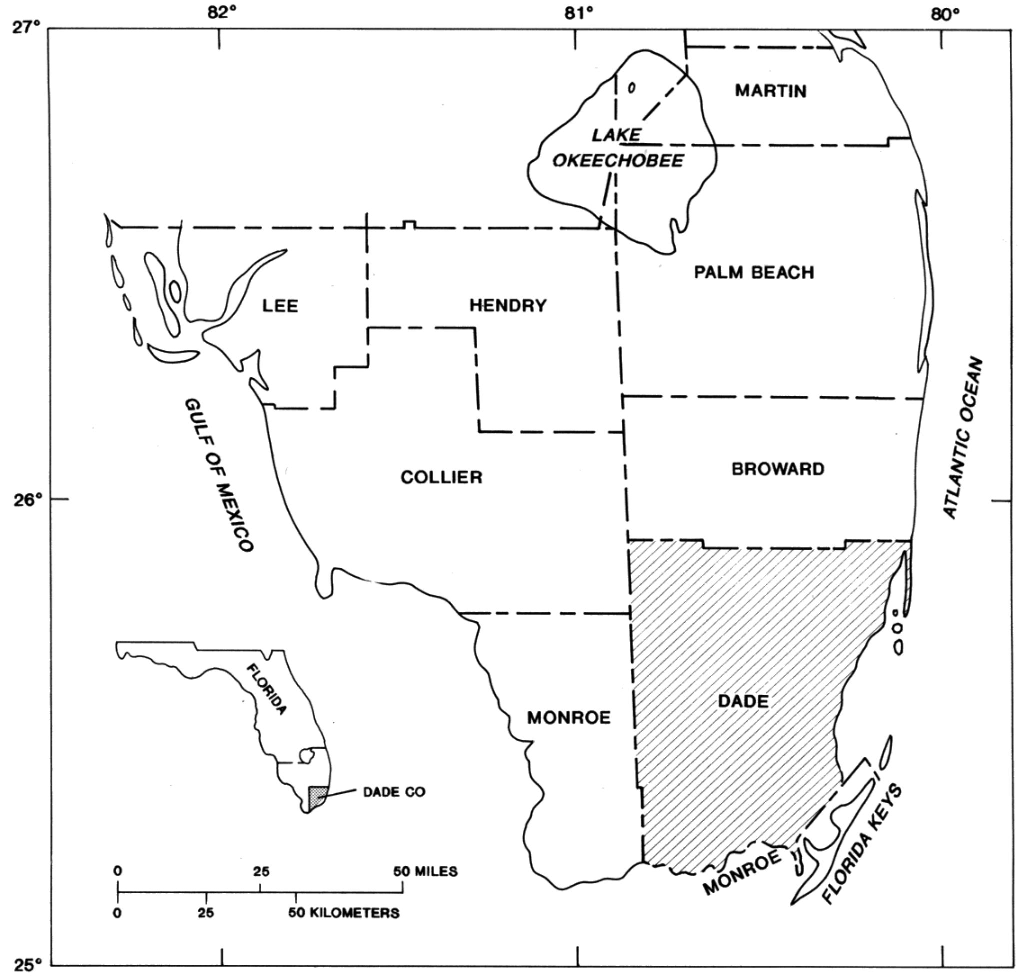
Hydrogeology of the Surficial Aquifer System Dade County, Florida

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 90-4108

Prepared in cooperation with the
SOUTH FLORIDA WATER MANAGEMENT DISTRICT



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Tallahassee, Florida
1991

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
foot per day	0.3048	meter per day
foot per mile	0.1894	meter per kilometer
foot squared per day	0.0929	meter squared per day
mile	1.609	kilometer
square mile	2.590	square kilometer
gallon per minute	0.00006309	cubic meter per second
gallon per minute per foot	0.2070	liter per second per meter
million gallons per day	0.04381	cubic meters per second

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in report:

µs/cm microsiemens per centimeter
mg/L milligrams per liter

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Abstract

An investigation of the surficial aquifer system in Dade County, begun in 1983, is part of a regional study of the aquifer system in southeastern Florida. Test drilling for lithologic samples, flow measurements during drilling, aquifer testing, and analyses of earlier data permitted delineation of the hydraulic conductivity distribution (on hydrogeologic sections), the aquifers in the system, the generalized transmissivity distribution, and interpretation of the ground-water flow system.

The surficial aquifer system, in which an unconfined ground-water flow system exists, is composed of the sediments from land surface downward to the top of a regionally extensive zone of sediments of low permeability called the intermediate confining unit. The aquifer system units, which vary in composition from clay-size sediments to cavernous limestone, are hydro stratigraphically divided into the Biscayne aquifer at the top; an intervening semiconfining unit that consists principally of clayey sand; a predominantly gray limestone aquifer in the Tamiami Formation in western and west-central Dade County; and sand or clayey sand near the base of the surficial aquifer system. The base of the surficial aquifer system ranges from a depth of about 175 to 210 feet below land surface in westernmost Dade County to greater than 270 feet in northeastern Dade County. Test drilling and aquifer-test data indicate a complex hydraulic conductivity distribution. Hydraulic conductivities of the very highly permeable zone of the Biscayne aquifer commonly exceed 10,000 feet per day; in the gray limestone aquifer, they range from 210 to 780 feet per day.

Transmissivities of the surficial aquifer system vary locally but have a recognizable areal trend. Estimated values generally are about 300,000 feet squared per day or greater in nearly all of central and eastern Dade County. Transmissivity is lower to the west, decreasing to less than 75,000 feet squared per day in western Dade County. High transmissivity usually is associated with thick sections of the Fort Thompson Formation within the Biscayne aquifer. The gray limestone aquifer of the Tamiami Formation has transmissivities that range from 5,800 to 39,000 feet squared per day in western Dade County. The transition from high transmissivity to relatively low transmissivity is often only a few miles wide and coincides with the decrease in thickness of the very highly permeable Fort Thompson Formation, which marks the western boundary of the Biscayne aquifer.

More effective drainage as a result of extensive canal systems and large-scale pumping from municipal well fields has greatly altered the predevelopment flow system in eastern Dade County by: (1) eliminating or greatly reducing a seasonal and coastal ground-water ridge; (2) reducing deep circulation; (3) reducing or eliminating seasonal westward movement of ground water; (4) causing accelerated stormwater runoff and short ground-water flow paths; and (5) generally lowering the water table and inducing saltwater intrusion. Under predevelopment conditions in western Dade County, water entered the gray limestone aquifer by lateral movement from Broward and Collier Counties, and by downward seepage from The Everglades and the Biscayne aquifer, and moved southward and southeastward into Dade County to coastal discharge areas. Circulation in the Biscayne aquifer inland also was primarily to the south and southeast. In eastern Dade

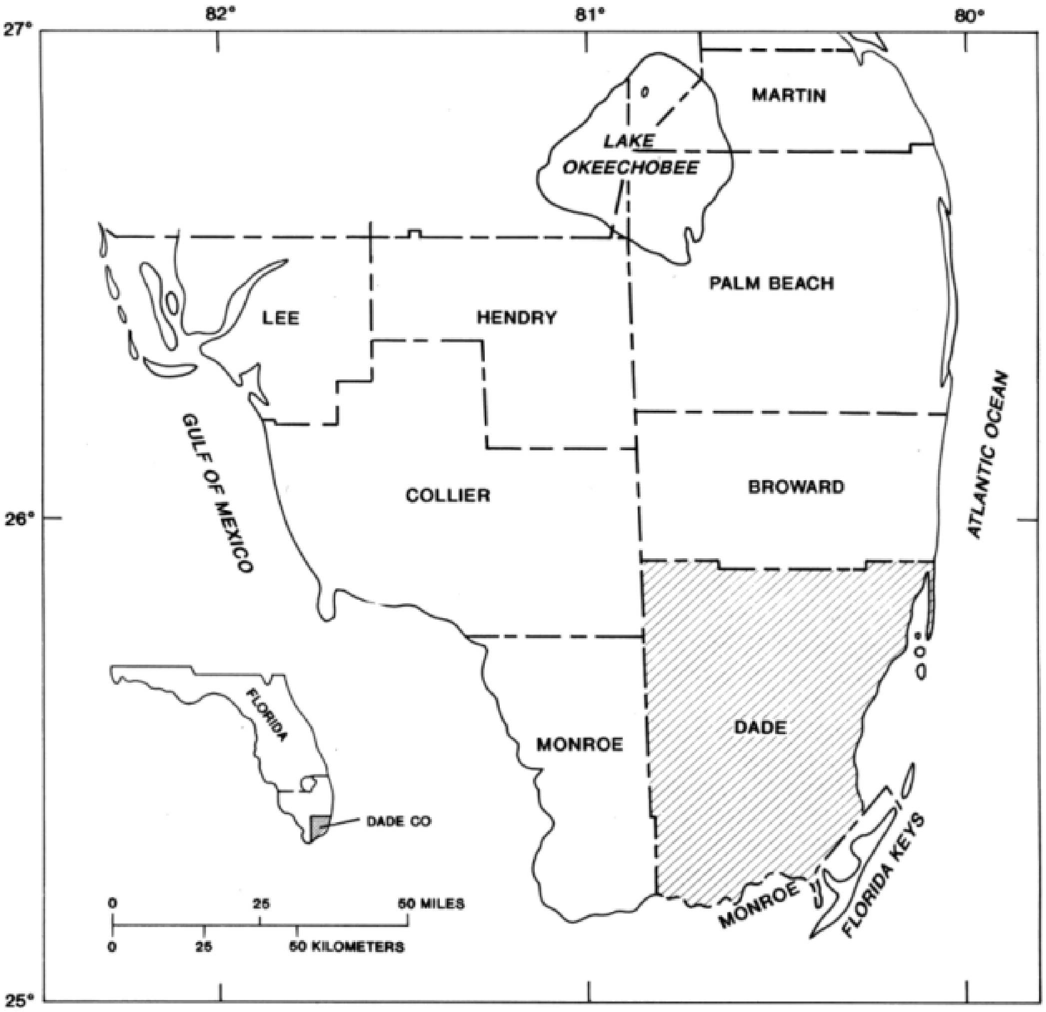


Figure 1. Location of Dade County, Florida.

County, the seasonal ground-water ridge that formed under predevelopment conditions supported both easterly and westerly ground-water flow away from the ridge axis. This seasonal flow created a zone of lower dissolved solids.

INTRODUCTION

Southeastern Florida (fig. 1) is underlain by geologic units of varying permeability from land surface to depths between 150 and 400 ft. These units form an unconfined aquifer system that is the source of most of the potable water used in the area. This body of geologic units is herein called the surficial aquifer system. In parts of Dade, Broward, and Palm Beach Counties, a highly permeable part of that aquifer system has been named the Biscayne aquifer (Parker, 1951; Parker and others, 1955). Adjacent to or underlying the Biscayne aquifer are less-permeable but potentially important water-bearing units that also are part of the surficial aquifer system.

Most previous hydrogeologic investigations in southeastern Florida concentrated on the populated coastal area. Drilling and monitoring activities were commonly restricted to zones used for water supply or to overlying zones. Hence, information on the characteristics of the western or deeper parts of the Biscayne aquifer and of sediments below the Biscayne aquifer in the surficial aquifer system was insufficient for present needs. Continuing increases in the demand for water from the surficial aquifer system in the highly populated coastal area of southeastern Florida and attendant concerns for the protection and management of the water supply have resulted in a study by the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District, to define the extent of the surficial aquifer system and its regional hydrogeologic characteristics.

The overall objectives of the regional study are to determine the geologic framework of the surficial aquifer system, the areal and vertical water-quality distribution, factors that affect water quality, the hydraulic characteristics of the components of the surficial aquifer system, and to describe ground-water flow in the aquifer system. Results of the investigation have been previously published in a series of reports that provide information for each county or area. Broward County was the first (Causaras, 1985; Howie, 1987; Fish, 1988) and Dade County the second (Causaras, 1987; Sonntag, 1987) to be investigated in this regional study.

Purpose and Scope

This report describes the hydrogeology of the surficial aquifer system and ground-water flow in the aquifer system in Dade County. It contains fundamental background information required for qualitative or quantitative evaluations of the ground-water resources and the hydraulic response of the system to natural or artificial stresses. Specifically, the report: (1) defines the surficial aquifer system, (2) characterizes hydraulic properties of the surficial aquifer system, (3) interprets ground-water flow directions in the surficial aquifer system, and (4) relates observed water-quality distributions to past and present flow systems.

This report is intended to provide a broad, countywide characterization of the surficial aquifer system, rather than detailed site-specific or local information. An extensive program of hydrogeologic test drilling, water-quality sampling, and aquifer testing was conducted during 1983-85. Most test holes in western and central Dade County were drilled about 200 to 250 ft deep, but some nearer the coast were drilled more than 300 ft deep. At most sites, drilling fully penetrated the surficial aquifer system, reaching into the upper part of the underlying confining unit. Other data, selected from existing geologic logs, historic water-level records, and aquifer or production well tests, were used to supplement the field data.

Previous Investigations

The most comprehensive previous water-resources investigation was that of Parker and others (1955), which provides information on the geology of the county; the occurrence, movement, and quality of ground water and surface water; and saltwater intrusion. Schroeder and others (1958) drilled shallow test holes and provided geologic sections in western Dade and Broward Counties and a contour map of the base of the Biscayne aquifer. More recent general summaries of information on the Biscayne aquifer and the surface-water management system are given in Klein and others (1975) and Klein and Hull (1978). A series of investigations of canal operations, surface-water and ground water relations, water conservation and drainage, and saltwater intrusion related to canals are reported in Klein and Sherwood (1961), Sherwood and Leach (1962), Leach and Sherwood (1963), Sherwood and Klein (1963a; 1963b; 1963c), Kohout and Leach (1964), Klein (1965), Leach and Grantharn (1966), Kohout and Hartwell (1967), Barnes and others (1968), Appel (1973), and Hull and Meyer (1973). A general summary of these investigations is contained in Leach and others (1972). The effects of bottom sediments on infiltration from the Miami Canal were investigated by Meyer (1972) and Miller (1978). Benson and Gardner (1974) describe a drought and its effect on the hydrologic system, Meyer (1974) considers the availability of ground water for the U.S. Navy Well Field near Florida City, and Schneider and Waller (1980) provide a summary of hydrologic data for the area in central Dade County between Levee 31 N, Canal C-111, and Everglades National Park.

Saltwater intrusion has been a concern in Dade County since coastal well fields began showing evidence of increasing salinity more than 40 years ago. A history of saltwater intrusion in Dade County through 1984 is reported by Klein and Waller (1985). Results of a study of the freshwater-saltwater interface are given in Kohout (1960a; 1960b; 1964) and Kohout and Klein (1967).

Table 1. U.S. Geological Survey (USGS) well numbers and site names for test sites

[See figure 3 for site locations]

USGS well number	USGS site identification number	Site name
G-3294	255707080254801	Opa-Locka West Airport
G-3295	255249080504401	Levee 28
G-3296	255224080380501	Levee 67A
G-3297	255058080290301	Levee 30
G-3298	255020080231001	Florida's Turnpike
G-3299	255022080163001	Hialeah
G-3300	255148080110701	Miami Shores
G-3301	254537080493601	Forty-Mile Bend
G-3302	254542080421701	Tamiami West
G-3303	254545080361701	Tamiami Central
G-3304	254539080300601	Tamiami East
G-3305	254536080230301	Florida International University
G-3306	254600080173701	Fairlawn School
G-3307	254538080140001	Bryan Park
G-3308	253927080455901	Shark Valley Tower
G-3309	253954080402501	Levee 67 extension
G-3310	253714080345901	Chekika Hammock State Park
G-3311	253746080295001	Levee 31N
G-3312	253842080225801	Canal 100
G-3313	253831080180201	Department of Agriculture Plant Experiment Station
G-3314	253018080333501	Homestead Airport
G-3315	253119080174801	Camp Owaissa-Bauer
G-3316	253010080225001	Air Force Base
G-3317	252326080475701	Sisal Pond
G-3318	252256080363501	Park Research Centec
G-3319	252507080342701	Levee 31W (at structure 175)
G-3320	252555080281001	Naval station
G-3321	252506080212801	Levee 31E
G-3322	251512080475301	Nine-Mile Pond
G-3323	251902080312401	Canal 111 (at structure 18C)
G-3324	251948080271801	US-1 South (Canal 109)
G-3344	252320080275401	US-1 North
G-3394	252944080395102	Context Road West
G-3395	251410080260401	US-1 Key

Methods

Hydrogeologic test drilling was conducted at sites arranged to form intersecting lines across Dade County. Table 1 lists the USGS well numbers and names for the test sites. A reverse-air, dual-tube drilling method, which circulates air (no drilling mud was used) downward in the annulus between the tubes and back to the surface in the inner tube with entrained cuttings and water, was used. This method alleviates problems of collecting representative geologic samples that are often encountered when using mud-rotary methods. The problems include lost circulation in cavities with loss of samples and "running water sands" that cause collapse of test holes. Drill cuttings of elastic materials are obtained from which hydraulic properties can be estimated. In addition, the samples were assigned a relatively accurate depth, and hydrologic observations were made of flow variations during drilling and at 10-ft intervals after completing each drill-pipe length.

After drilling each 10-ft length of drill pipe, air was circulated to obtain water from the aquifer. Circulation was continued, for several minutes if necessary, to obtain water as free from sediment as possible. Yields varied between 0 and 300 gal/min. Water samples were collected and analyzed for specific conductance in the field. Evidence has shown that specific conductance in water collected from circulation during drilling is similar, in most circumstances, to that for water samples collected by normal sampling techniques inside the drill rod or from finished wells at the test sites. The water produced by air circulation at a given depth generally is representative of the formation water at that depth. Profiles of specific conductance with depth can then be prepared. These profiles are useful for revealing gross water-quality characteristics and providing hydrologic or hydraulic inferences. A cluster of wells, open to various units of the surficial aquifer system, was installed at nearly all the sites.

Previously available aquifer tests and specific capacities of production wells were compiled for estimating transmissivity and hydraulic conductivity in eastern Dade County. On the basis of the geologic sections prepared by Causaras (1987), inspection of geologic samples, and hydrologic observations made during drilling, a hydraulic testing program was designed to provide estimates of transmissivity or hydraulic conductivity of selected zones or materials at selected sites, primarily in central and western Dade County.

Historical records of ground-water and surface-water levels were compiled from USGS and South Florida Water Management District files to prepare water-level maps useful for interpreting the direction of ground-water flow. Also, the wells at selected test sites for this investigation were tied to a common datum, and water-level measurements were made to determine vertical differences in water levels.

Acknowledgments

The authors greatly appreciate the interest and support of the South Florida Water Management District in this cooperative program. Permission and access were given to locate most of the test sites on their right-of-way. In addition, they provided stage data for the water-conservation areas. The authors are grateful for permission for access to other sites given by the National Park Service, State of Florida, Dade County, U.S. Air Force, U.S. Navy, U.S. Department of Agriculture, Florida International University, Miami Shore Village, City of Hialeah, and City of Miami. Special thanks are extended to the Miami-Dade Water and Sewer Authority, many other private or public water-supply utilities, and Harold G. Jaffe, Inc., for providing well-construction and specific-capacity data.

DESCRIPTION OF STUDY AREA

Geographic Features

Dade County, located near the southern tip of peninsular Florida, encompasses an area of about 2,000 mi^2 (fig. 1). The county is bounded by the Atlantic Ocean on the east, Broward County on the north, Collier and Monroe Counties on the west, and the Florida Keys (Monroe County) on the south. Geographic areas and place names of Dade County, referred to in this report, are shown in figure 2. The boundary between western and eastern Dade County is taken to be Levee 30, Levee 31N, and Canal 111 (C-111). Northern Dade County is the area from approximately Tamiami Trail (U.S. Highway 41 [US-41] and section *B-B'*) northward to Broward County, southern Dade County is the area at approximately Homestead southward, and central Dade County is the area between northern and southern Dade County. The locations of test drilling sites and hydrogeologic sections are shown in figure 3. Wells G-2316, G-2328, and G-2346 in Broward County, drilled as part of a previous investigation (Fish, 1988), are also included in the illustration to show traces of the hydrogeologic sections.

Early urbanization was primarily along coastal northeastern Dade County because of good drainage and access to the ocean. Artificial drainage by canals of land farther west opened up most of eastern Dade County for development, especially agriculture; however, urbanization has spread westward and southward from Miami. In addition to metropolitan Miami, other smaller urban centers are located along U.S. Highway 1 (US-I) from Miami to the Homestead-Florida City area.

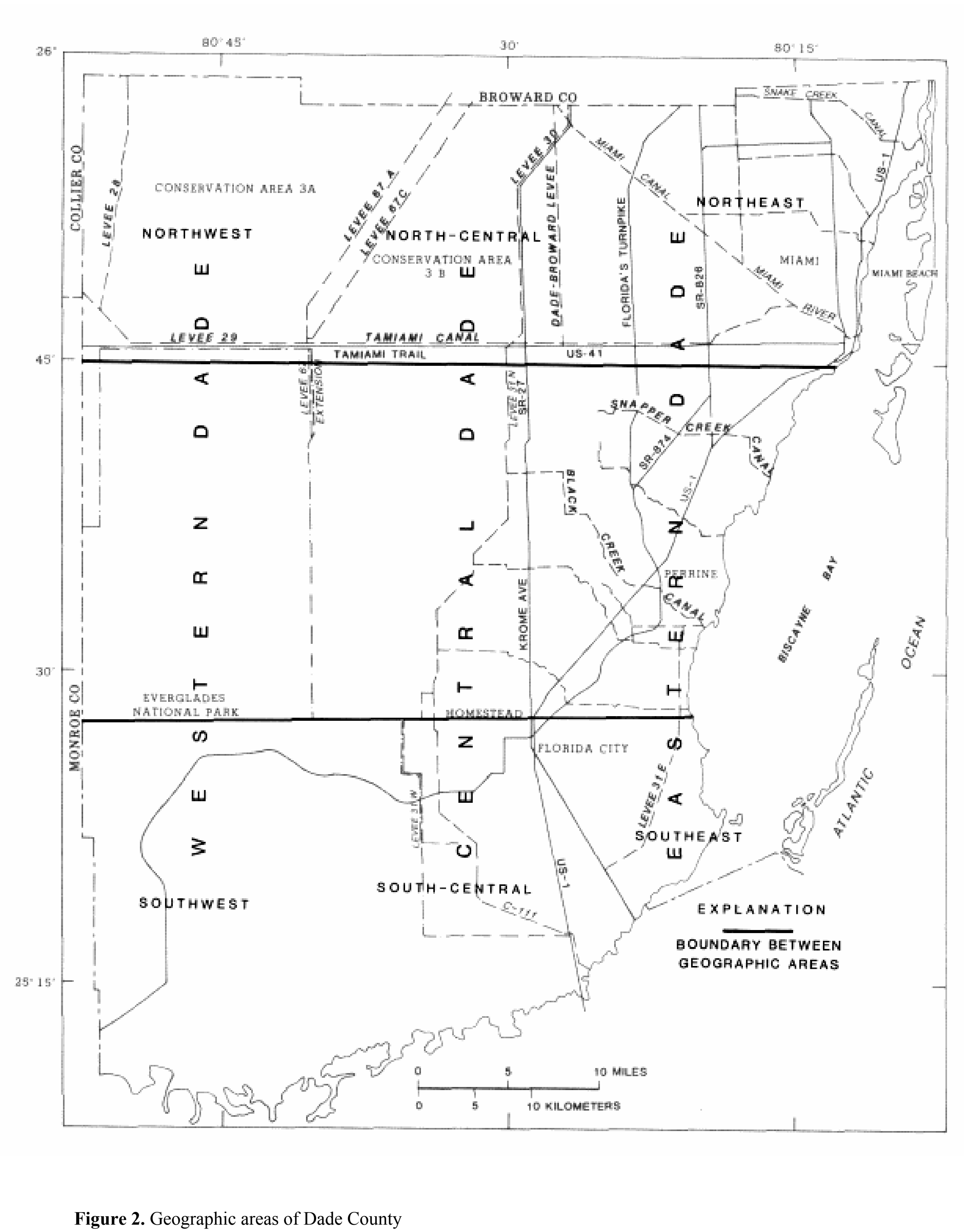


Figure 2. Geographic areas of Dade County

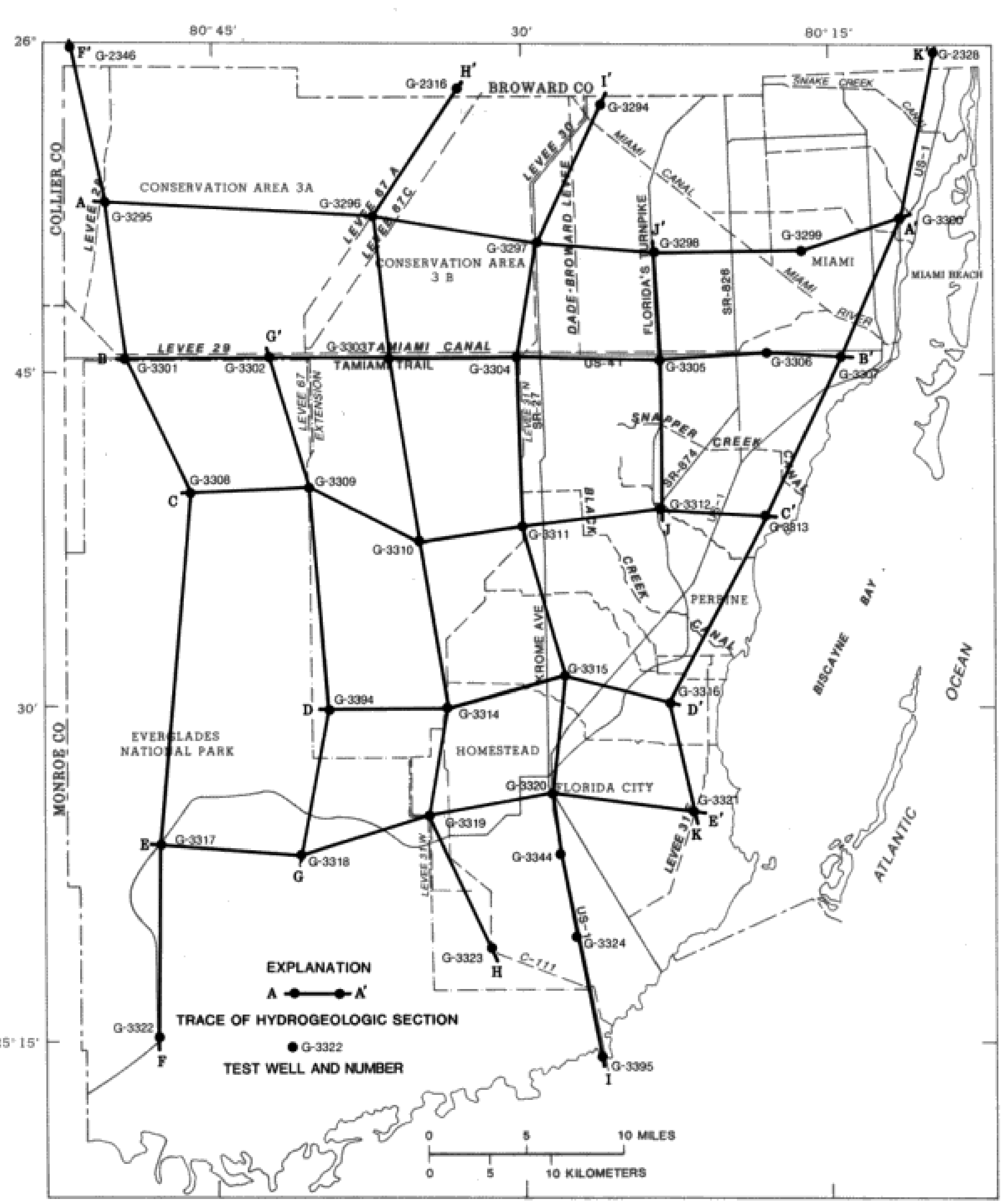


Figure 3. Location of test drilling sites and hydrogeologic sections. Hydrogeologic sections from Causaras (1987). Well numbers and site names are listed in table 1.

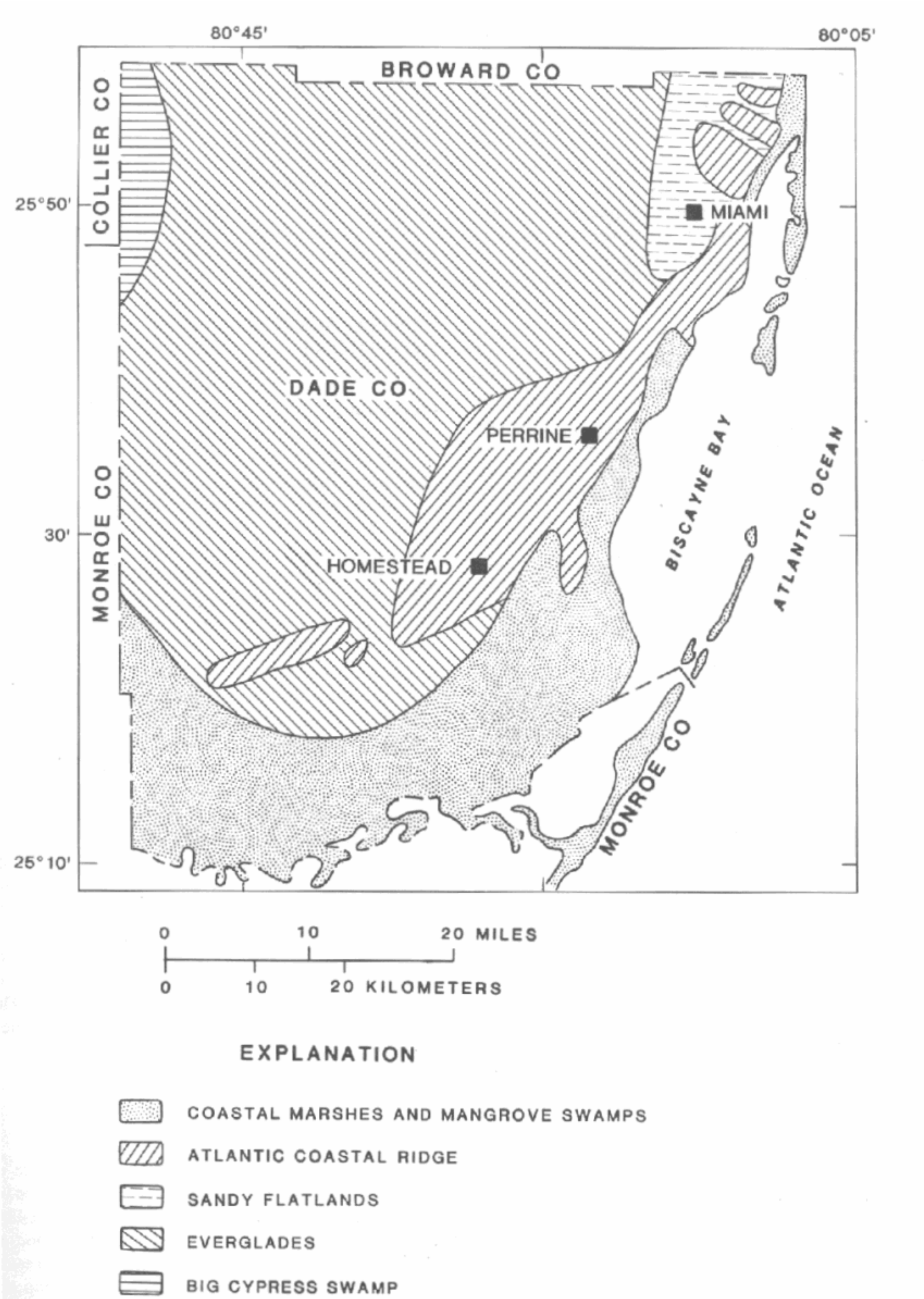


Figure 4. Physiographic features of Dade County prior to development (modified from Parker and others, 1955, plate 12).

Physiographic Features and Natural Drainage

Physiographic features (fig. 4) have significantly controlled the environment, drainage, and ultimately, the land use in Dade County. The Atlantic Coastal Ridge, 2 to 10 mi in width, forms the highest ground in the county. Elevations along the ridge range from about 8 to 15 ft above sea level between Homestead and north Miami (except in small areas that are higher) to 20 ft above sea level or greater in some places. West of Homestead, elevations of the Atlantic Coastal Ridge are from 5 to 8 ft above sea level. The Atlantic Coastal Ridge is a natural barrier to drainage of the interior, except where it is breached by shallow sloughs or rivers. The Sandy Flatlands west of the Atlantic Coastal Ridge in northeastern Dade County are lower (6-18 ft above sea level), and prior to development they were poorly drained. The Everglades, by far the largest feature, are slightly lower than the Sandy Flatlands and, before development, were wet most years and least subject to seasonal flooding. Drainage was slow and generally to the south and southwest, channeled behind the higher coastal ridge. The Everglades form a natural trough in north-central, central, and southwestern Dade County. Elevations range from about 9 ft above sea level in the northwestern corner to about 3 ft above sea level in southwestern Dade County, except for tree islands or hammocks, which may be a few feet higher than the surrounding land. Most of the eastern part of The Everglades within the county is now used for agriculture, rock quarrying, or urban development. A small part of the Big Cypress Swamp occupies northwestern Dade County; elevations here range from 7 to 10 ft above sea level. Coastward from The Everglades and the Atlantic Coastal Ridge lie coastal marshes and mangrove swamps at elevations that generally range from 0 to 3 ft above sea level.

The predominant soils of the area and their drainage characteristics are shown in figure 5. The best drainage, by way of infiltration, occurs on the rockland, especially the area west of Perrine and Homestead, and on sands of the Atlantic Coastal Ridge. In places, the sand cover over the Atlantic Coastal Ridge is very thin so that infiltration into the bedrock is enhanced. Marl or peat and muck cover much of the county and have poorer drainage characteristics. In northwestern and north-central Dade County, the peat and muck layer is several feet thick.

Water-Management Facilities

A complex water-management system, part of the South Florida Water Management System, has been developed to modify much of the natural environment to human needs. The principal land uses, agriculture and housing, require a few feet of unsaturated zone and rapid removal of floodwaters. To meet that need, the Everglades Drainage District was created in 1905. A system of major canals was dredged from Lake Okeechobee to the Atlantic Ocean, including the Miami Canal, which was completed in 1913. Many other canals along the coast were completed by 1930 (fig. 2), but because the canals were uncontrolled, the surficial aquifer tended to become overdrained during the dry season, creating saltwater intrusion problems. In response, a system of control structures in the canals was built to regulate canal discharge and maintain ground-water levels. Flooding, caused by hurricanes since 1930, has prompted the construction of many additional canals.

Several features of the water-management system are also used to store excess water in the wet season and transfer the excess water to areas of need during the dry season. A system of levees, completed in 1953, near the eastern edge of The Everglades, allows flooding in The Everglades and water removal east of the levees (fig. 2; Levees 30, 31N, and 31W in central Dade County). Much of The Everglades was subsequently enclosed to form water-conservation areas. The southernmost part of these areas, Water Conservation Areas 3A and 3B, encompass nearly all of western Broward County and northwestern Dade County. Water is added to the conservation areas by rainfall, by gravity drainage from Hendry County, and by several large pumping stations in Broward and Palm Beach Counties. These pumping stations lift excess wet-season water from drainage canals to the conservation areas. Stored water is released through structures and by seepage under levees to maintain flow to the Everglades National Park, to provide recharge for municipal well fields, and to maintain ground-water levels near the coast for the prevention or retardation of saltwater intrusion during periods of low water levels.

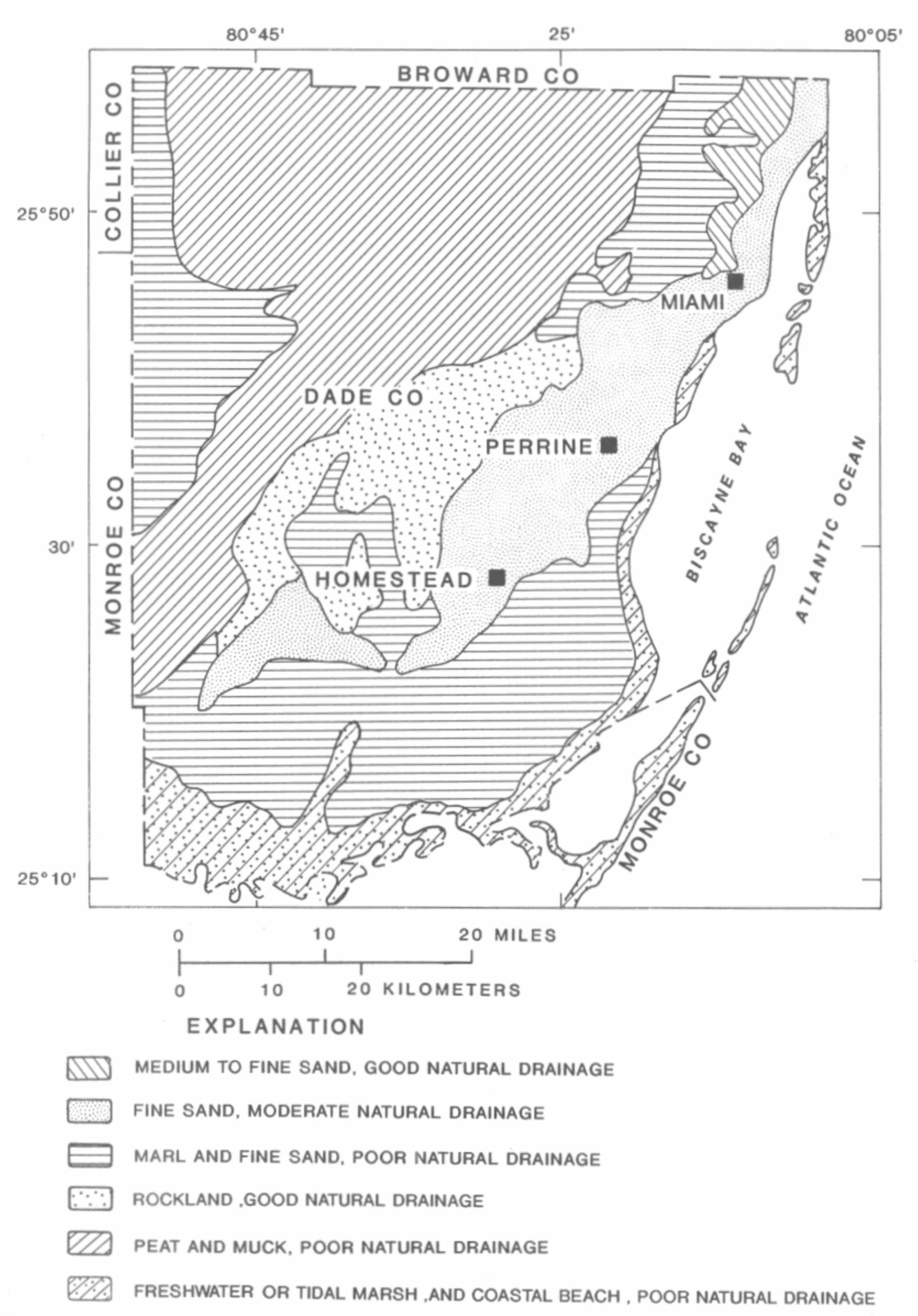


Figure 5. Distribution of soil types in Dade County and their drainage characteristics (modified from Klein and others, 1975, p. 11).

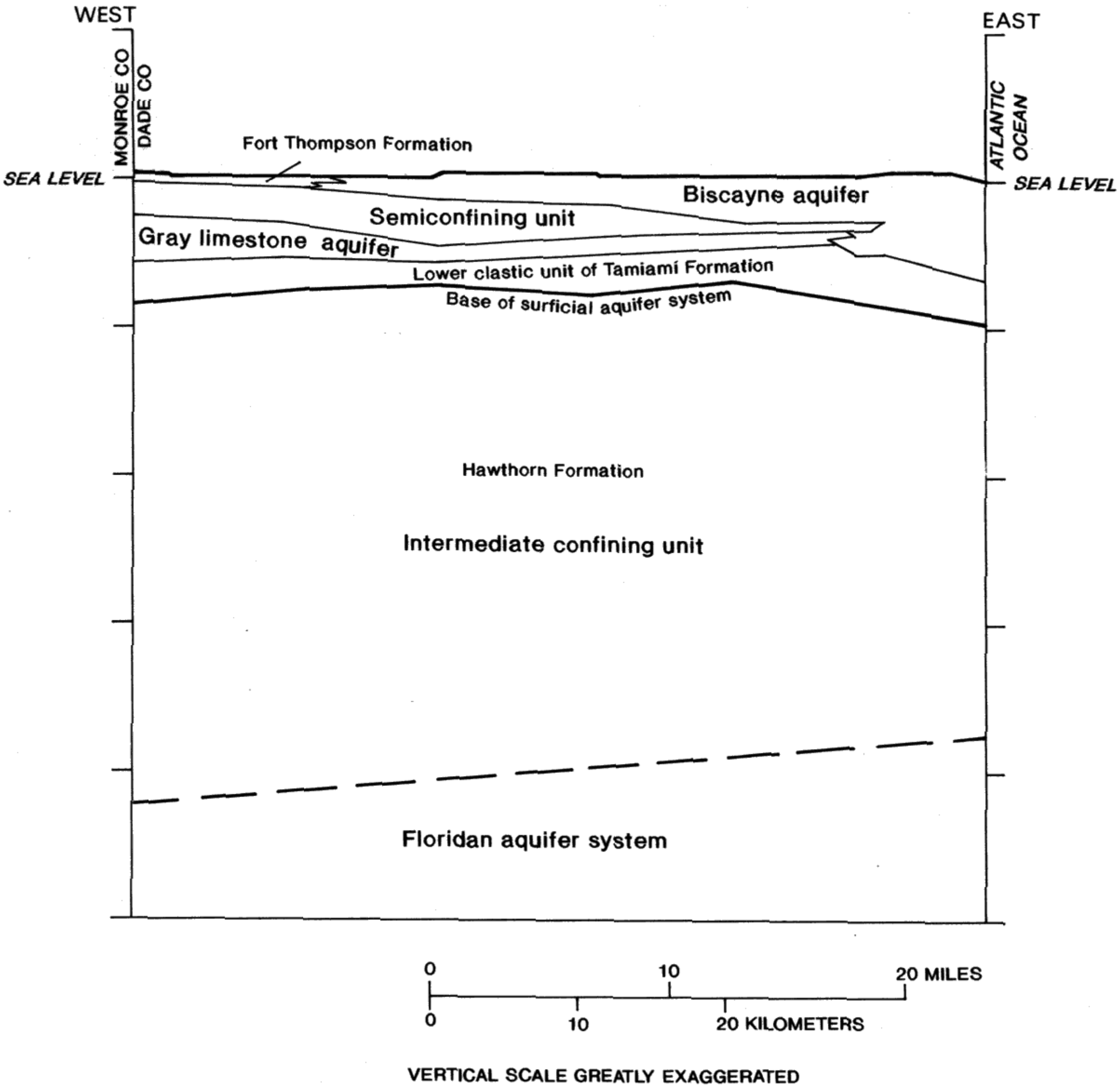


Figure 6a. Generalized hydrogeologic framework of aquifer systems in Dade County

GENERAL AQUIFER FRAMEWORK AND DEFINITIONS

Overview

Historically, two major aquifer systems have been identified in Dade County (fig. 6a). The lower aquifer system is commonly known as the Floridan aquifer (Parker and others, 1955, p. 189), but has recently been renamed the Floridan aquifer system (Miller, 1986) because it comprises two or more distinct aquifers. This areally extensive system is present in all of Florida and parts of adjacent states. In Dade County, the top of the Floridan aquifer system is about 950 to 1,000 ft below sea level. The upper part of the system contains confined water with heads of 30 to 50 ft above sea level.

Overlying the Floridan aquifer system in Dade County is a 550- to 800-ft thick sequence consisting of green clay, silt, limestone, and fine sand, referred to as the intermediate confining unit (previously called the

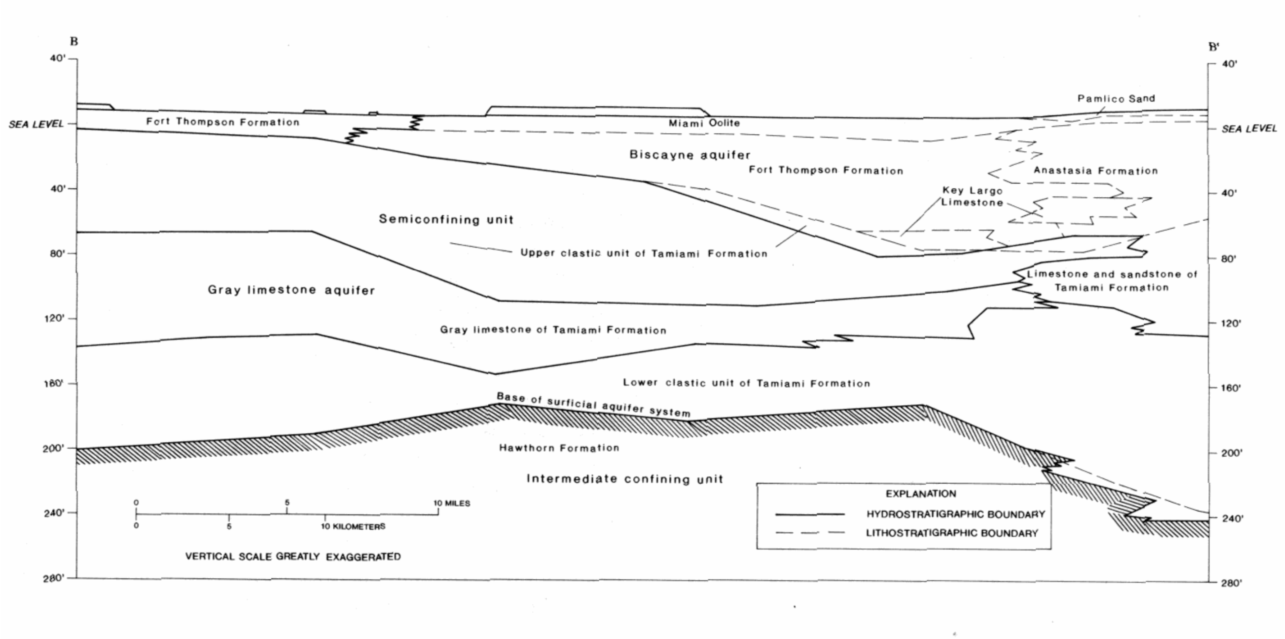


Figure 6b. Schematic relations of geologic formations, aquifers, and semipermeable units of the surficial aquifer system.

Floridan aquiclude by Parker and others, 1955, p. 189). A few zones within this sequence may be minor aquifers, but in general, the sediments have relatively low permeability. Most of this sequence is included in the Miocene Hawthorn Formation, but the upper most sediments of the sequence locally may be part of the Miocene-Pliocene Tamiami Formation. Overlying the intermediate confining unit is the surficial aquifer system, the source of freshwater supplies for Dade County and for most of southeast Florida. The intermediate confining unit and the surficial aquifer system are present in most parts of Florida (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986).

Surficial Aquifer System

The surficial aquifer system comprises all the rocks and sediments from land surface downward to the top of the intermediate confining unit. These rocks and sediments consist primarily of limestones and sandstones, sand, shell, and clayey sand with minor clay or silt and range in age from Pliocene to Holocene (Causaras, 1987). The top of the system is land surface, and the base of the system is defined hydraulically by a significant change in average permeability. This change, which can be mapped over a multicounty area, separates the underlying thick section of sediments having generally low permeability (the intermediate confining unit) from the overlying, higher permeability sediments of the surficial aquifer system. The upper part of the intermediate confining unit usually is green clay or silt, locally sandy, except near northeastern coastal Dade County and coastal Broward County where there is green, fine-grained calcarenite. Regionally, this green clay or silt usually is present at the top of the Hawthorn Formation (Southeastern Geological Society Ad Hoc Committee on Hydrostratigraphic Unit Definition, 1986).

Sediments of the surficial aquifer system have a wide range of permeability and locally may be divided into one or more aquifers separated by less-permeable or semiconfining units. Hydrogeologic sections that illustrate the relations of geologic formations, aquifers, and less-permeable units from west to east and from south to north are shown in figures 6b to 6d. The Biscayne aquifer is the best known aquifer and contains the most permeable sediments of the surficial aquifer system. Another permeable unit, informally termed the gray limestone aquifer in this report, was not previously named in Dade County. Separating or underlying the aquifers are less-permeable sand, limestone, silt, and clay which generally act as semiconfining units.

Permeable units (aquifers or smaller, higher permeability sections within aquifers) can exhibit semi-confined characteristics when stressed due to large permeability contrasts with adjacent sediments. However, hydraulic heads throughout the surficial aquifer system are at or close to water-table elevations, generally less than 10 ft above sea level. This contrasts sharply with heads in the confined Floridan aquifer system, which are well above water-table elevations.

Biscayne Aquifer

The Biscayne aquifer is the only formally named aquifer in the surficial aquifer system in Dade County. Because it is the principal aquifer in southeastern Florida (it has been declared a sole-source aquifer; Federal Register Notice, 1979) and because some refinement of the definition of the aquifer will be given in this report, previous definitions, maps delineating the aquifer, and some problems in definition are summarized below.

The Biscayne aquifer was named and defined by Parker (1951, p. 820) as follows:

> The name Biscayne aquifer is proposed for the hydrologic unit of water-bearing rocks that carries unconfined ground water in southeastern Florida.

In a later comprehensive treatment of water resources in southeastern Florida, Parker and others (1955, p. 160, 162) give the following information:

> 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 formations: (1) Tamiami Formation (including only the uppermost part of the formation—a thin layer of highly permeable Tamiami limestone of Mansfield): (2) Caloosahatchee Marl

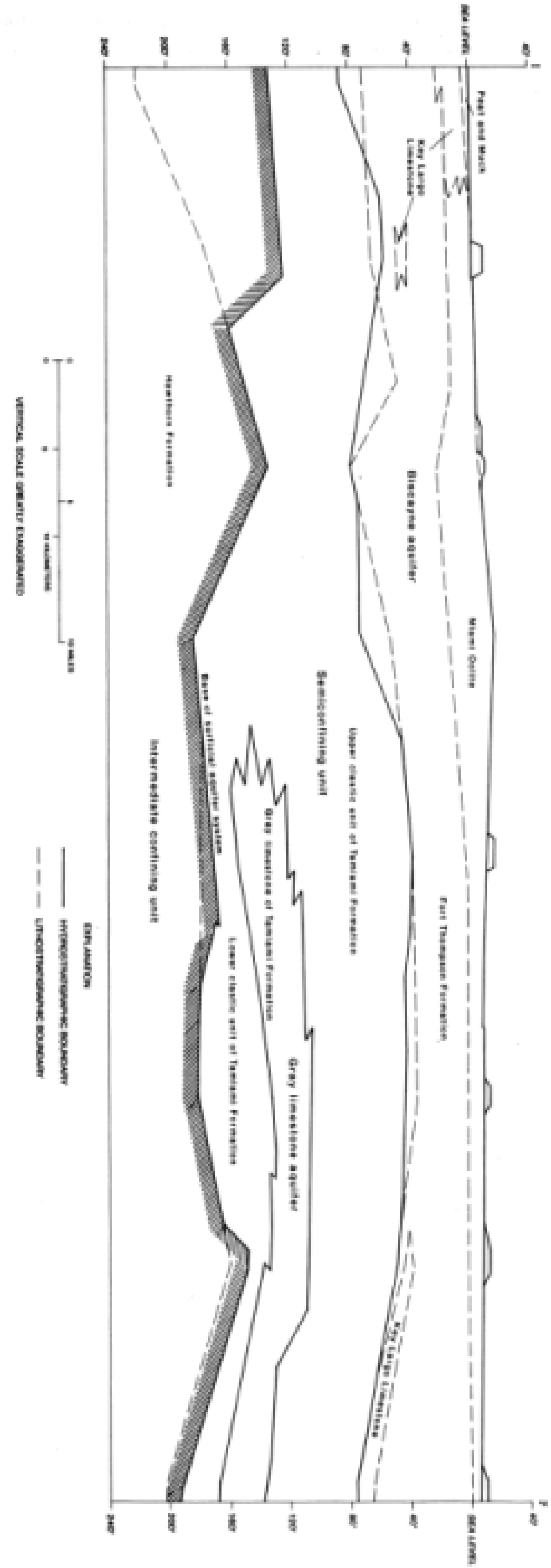


Figure 6c. Schematic relations of geologic formations, aquifers, and semipermeable units of the surficial aquifer system across west-central Dade County (section line *I-I'* on fig. 3)

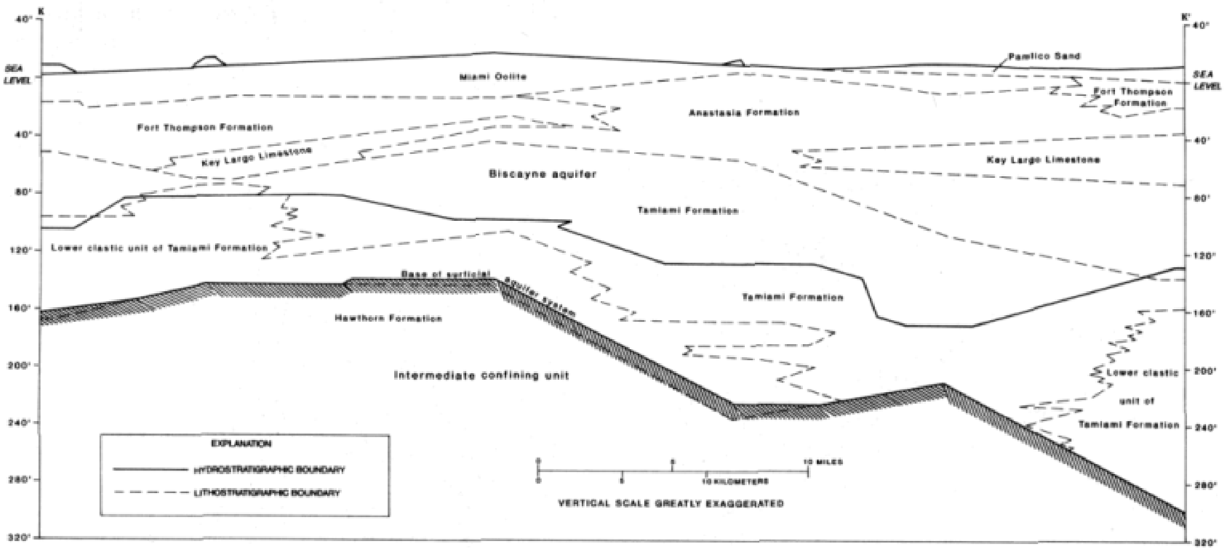


Figure 6d. Schematic relations of geologic formations, aquifers, and semipermeable units of the surficial aquifer system across coastal Dade County (section line *K-K'* on fig. 3).

(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.

Shallow core borings by the U.S. Army Corps of Engineers in western Dade County and Broward County, in conjunction with other well data, provided a basis for an additional description of the Biscayne aquifer and a contour map of the aquifer thickness over most of Dade County and southern Broward County (Schroeder and others, 1958). The contour map was later modified by Klein and others (1975, p. 31) and is shown in figure 7. A more recent summary description of the Biscayne aquifer is given by Klein and Hull (1978).

Despite the definitions and accumulated knowledge about the Biscayne aquifer, some ambiguities and problems remain. Schroeder and others (1958, p. 5) indicate that although the base of the Biscayne aquifer is readily determined as the top of the low permeability sand (marl) of the Tamiami Formation in the Miami area, it is more difficult to define the lateral and basal limits of the Biscayne aquifer in Broward and Palm Beach Counties where elastic materials predominate and interfingering, or gradations, of sands and calcareous sediments are common. Also, some geologic formations that compose the Biscayne aquifer extend beyond the area generally ascribed to the aquifer. Thus, to delineate the boundaries, changes of hydraulic properties within the geologic formations must be determined. The key criterion for defining the Biscayne aquifer apparently is the presence of highly permeable limestone or calcareous sandstone in the Fort Thompson Formation, Anastasia Formation, or Key Largo Limestone.

The hydraulic behavior of the Biscayne aquifer may also cause confusion. Parker (1951) stated that the Biscayne aquifer is unconfined. Throughout the area (except near well fields or margins of water-conservation areas), water levels at depth are almost identical to local water-table elevations. Water in the Biscayne aquifer is unconfined in that the potential distribution (as indicated by water levels in tightly cased wells) is closely related to the water table or to surface-water bodies. As a result of considerable stratification and local permeability variations of the aquifer, water-level responses to aquifer tests of highly permeable zones overlain by much less permeable sands may exhibit semiconfined behavior, particularly during early stages of pumping.

The Biscayne aquifer, as used in this report, is defined as that part of the surficial aquifer system in

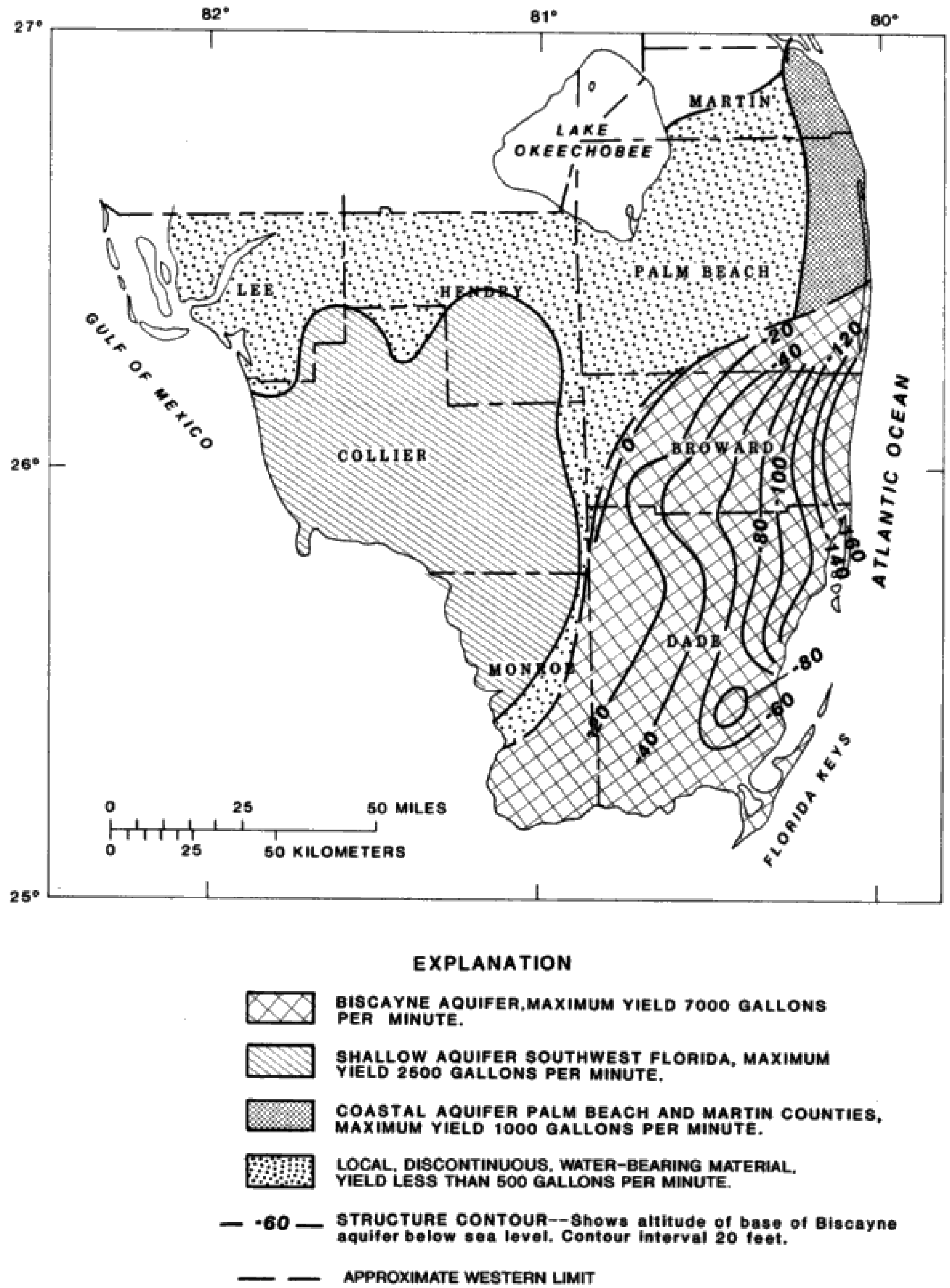


Figure 7. Areal extent and yield of wells in the Biscayne aquifer and other aquifers of the surficial aquifer system in southern Florida (from Klein and others, 1975, p. 31.).

southeastern Florida composed of (from land surface downward) the Pamlico Sand, Miami Oolite, Anastasia Formation, Key Largo Limestone, and Fort Thompson Formation (all of Pleistocene age), and contiguous, highly permeable beds of the Tamiami Formation of Pliocene and late Miocene age where at least 10 ft of the section is very highly permeable (a horizontal hydraulic conductivity of about 1,000 ft/d or more). Sandstones and limestones with well-developed secondary porosity of Dade and Broward Counties have hydraulic conductivities commonly exceeding 10,000 ft/d. The permeability requirement of this definition provides a means of estimating the aquifer boundary where the Fort Thompson Formation, Anastasia Formation, or Key Largo Limestone grade laterally into less-permeable facies. If there are contiguous, highly permeable (having hydraulic conductivities of about 100 ft/d or more) limestone or calcareous sandstone beds of the Tamiami Formation, the lower boundary is the transition from these beds to subjacent sands or clayey sands. Where the contiguous beds of the Tamiami Formation do not have sufficiently high permeability, the base of highly permeable limestones or sandstones in the Fort Thompson Formation, Anastasia Formation, or Key Largo Limestone is the base of the Biscayne aquifer.

Gray Limestone Aquifer

In addition to the Biscayne aquifer, an aquifer identified by Fish (1988) in Broward County, composed of predominantly gray (in places, greenish-gray or tan) limestone of the lower part and locally the middle part of the Tamiami Formation, was identified at depths of about 70 to 160 ft below land surface in western Dade County (figs. 6b and 6c). The gray limestone usually is shelly and sandy, and it is lightly to moderately cemented. Laterally, the gray limestone grades eastward and southward to less-permeable, sandy, clayey limestone and eventually sand and sandstone. Although it is less permeable than the Biscayne aquifer, the gray limestone aquifer is still significant and is a potential source of water, particularly west of the western limit of the Biscayne aquifer. It is defined as that part of the limestone beds (usually gray) and contiguous, very coarse, elastic beds of the lower to middle part of the Tamiami Formation that are highly permeable (having a hydraulic conductivity of about 100 ft/d or greater) and at least 10 ft thick. Above and below the gray limestone aquifer in western Dade County, and separating it from the Biscayne aquifer and the base of the surficial aquifer system, are sediments having relatively low permeability, such as mixtures of sand, clay, silt, shell, and lime mud, as well as some sediments having moderate to low permeability, such as limestone, sandstone, and claystone (figs. 6b and 6c).

Drilling has identified the gray limestone aquifer in western Broward County (Fish, 1988) and in southwestern Palm Beach County (W.L. Miller, U.S. Geological Survey, oral commun., 1984); in these areas, water in the aquifer contains high concentrations of dissolved solids. The aquifer may extend westward into Collier County, and it may be the source of water for irrigation of sugarcane fields in southeastern Hendry County and domestic use on the Seminole Indian Reservation.

ESTIMATES OF TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

The principal hydraulic characteristics determined for this investigation are horizontal hydraulic conductivity and transmissivity. The hydraulic conductivity (*K*) of material comprising an aquifer is a measure of the material's capacity to transmit water. The transmissivity (*T*) is the rate at which water is transmitted through a unit width of the saturated thickness of the aquifer under a unit hydraulic gradient. For a given uniform material, hydraulic conductivity and transmissivity are related by the expression:

$$T = K_b \qquad (1)$$

where

T is transmissivity (length^2/time);
K is hydraulic conductivity (length/time); and
b is thickness of the uniform material (length).

Three methods were used to obtain estimates of transmissivities and hydraulic conductivity: (1) calculation from specific capacities of municipal supply wells; (2) results of aquifer tests or other types of hydraulic analyses from reports by the USGS or by the U.S. Army Corps of Engineers; and (3) tests conducted during this investigation. The estimates provided the primary basis of the hydraulic conductivity distribution portrayed in the next section.

Where several layers of differing materials occur ("n" layers), the composite or total transmissivity of the aquifer is the sum of the transmissivities of the individual layers, expressed by:

$$T = \sum_{i=1}^{n} T_i = \sum_{i=1}^{n} K_i b_i \quad (2)$$

where

T is total transmissivity;

T_i is transmissivity of the i th layer of the n layers;

K_i is hydraulic conductivity of the i th layer of the n layers; and

b_i is thickness of the i th layer of the n layers.

The average hydraulic conductivity, K, of a sequence of layers is then:

$$\bar{K} = \frac{T}{\sum_{i=1}^{n} b_i} . \quad (3)$$

Hydraulic conductivities for individual layers or for composite sections are calculated from equation 3 after transmissivity estimates have been obtained.

Specific Capacity of Production Wells and Estimated Transmissivity

Theis and others (1963) suggested procedures for estimating transmissivity from specific capacity (Q/s) data by means of the Theis nonequilibrium equation, expressed as:

$$T = \frac{Q}{4\pi s} W(u) = \frac{W(u)}{4\pi}\frac{Q}{s} \quad (4)$$

where

$W(u)$ is well function of u and $u = r^2 S/4T_t$

t is time, in days;

r is distance from pumping well to point of observation, or effective radius of pumped well in single-well tests (length);

Q is pumping rate (length3/time);

s is drawdown (length); and

S is storage coefficient (unitless).

By substituting into the expression for u the extreme values of aquifer variables (T,S), effective well radius, and pumping time for a given area, the range of values of the term $W(u)/4\pi$ may be evaluated for that area (McClymonds and Franke, 1972). For Broward County, the range was found to be from 170 to 370, and averaged about 270, for T in feet squared per day when the specific capacity (Q/s) is expressed in gallons per minute per foot of drawdown (Fish, 1988, p. 22). The same value may be used in Dade County where similar extreme conditions occur. Thus, an approximate value of transmissivity may be obtained from:

$$T = 270\frac{Q}{S} \quad (5)$$

where

T is transmissivity, in feet squared per day;

Q is discharge, in gallons per minute; and

s is drawdown, in feet.

In addition to the potential errors in the original data and in using an average value of 270, any deviations from the Theis assumptions are limitations on the accuracy of the estimated transmissivity. For semiconfined conditions, the effects of leakage on drawdown are small near the production well; hence, deviations from ideal confinement are minimized at the production well (Neuman and Witherspoon, 1972). For unconfined conditions, the observed drawdowns in Dade County are very small compared to the saturated thickness, and the assumption of constant transmissivity is reasonable. In Dade County, the effective radius of a production well may be substantially larger than the nominal radius because most of the wells are open to cavity-riddled zones. This would result in a higher specific capacity and estimated transmissivity. However, turbulent flow may occur in cavities near wells, causing greater drawdown and, therefore, a small specific capacity and a smaller estimate of transmissivity. Finally, the development of equation 5 assumes a 100 percent efficient well. However, friction losses at the well screen or rock face and in the well also cause greater drawdown, and therefore, a small specific capacity and a smaller estimate of transmissivity. Thus, the limitations described partly offset each other.

Construction details and production test data for selected supply wells in Dade County are given in table 2; site locations are shown in figure 8. The data were compiled from information provided by the Metro-Dade Water and Sewer Authority, from other water-supply agencies or utilities, or from files of the South Florida Water Management District. Well diameters and type of finish are given because pumping capacity varies with these factors. Nearly all of the wells are finished with open hole; however, some are finished with screen. The production intervals identify highly perme-

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis- charge (gal./ min.)	Draw- down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv- ity (ft^2/day)
1	390	S-898	2526 8030	10		40-50					
	391	S-899	2526 8030	10		40-50					
	392	S-897	2526 8030	20		40-50					
	393	S-896	2526 8030	10		40-50					
	394	S-3053	2526 8030	18		30-60					
	395	S-3054	2526 8030	18		30-60					
	397		2526 8030	24		20-60					
	398		2526 8030	24		20-60					
	399		2526 8030	24		20-60					
2	396	S-3055	2526 8030	18		30-60					
3	1	S-3075	2527 8026	14	OH	32-35					
4	2	S-3050	2527 8029	10	S						
	3	S-3051	2527 8029	10	S	-- -47.5	900	1.1		820	220,000
	4	S-3052	2527 8029	10	S	42-60	590	.96		610	160,000
	5		2527 8029	10	S	-- -100					
5	1		2528 8022	18							
	2		2528 8022	18							
6	3		2528 8022	24					2.25		
	4		2528 8022	24							
7	A		2528 8028	18		-- -60					
	B		2528 8028	18		-- -60					
	C		2528 8028	18		-- -60					
	D		2528 8028	18		-- -60					
	F		2528 8028	14		-- -60					
	F		2528 8018	14		-- -60			4		
	G		2528 8018	14		-- -60			9		
	H		2528 8018	14		-- -60					
	K		2528 8028	14		-- -60					
	L		2528 8028	14		-- -60					
	5	S-3060	2528 8027	20	OH	40-62	3,000	3.33		900	240,000
	6	S-306l	2528 8027	20	OH	40-62	3,000	7.58		390	110,000
8	1	S-3056	2523 8029	16	OH	31-61					
	2	S-3057	2528 8029	16	OH	31-61					
	3	S-3058	2528 8029	16	OH	31-61					
	4	S-3059	2528 8029	16	OH	31-61					
9	1	S-1525	2529 8023	8	OH	-- -72					
	2	S-1526	2529 8023	8	OH	-- -72					
	3	S-1527	2529 8023	8	OH	-- -72					
	4	S-1528	2529 8023	8	OH	-- -72					
	5	S-1529	2529 8023	8	OH	-- -72					
	6	S-1550	2529 8023	8	OH	-- -72					
10	1		2529 8024	8	OH	-- -30					
	2		2529 8024	8	OH	-- -30	900	4.0		200	60,000
	3		2529 8024	16	OH	-- -63					
	4		2529 8024	16	OH	-- -63					

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis- charge (gal./ min.)	Draw- down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv- ity (ft²/day)
11	1		2529 8025	14	OH						
	2		2529 8025	14	OH						
	3		2529 8025	14	OH						
12	1	S-3067	2529 8026	8	OH	37-40					
	2	S-3068	2629 8026	8	OH	37-40					
	3	S-3069	2529 8026	14	OH	37-40					
	4	S-3070	2529 8026	14	OH	37-40					
	5	S-3071	2529 8026	14	OH	37-40					
	6	S-3072	2529 8026	14		-- -40					
13	1	S-3076	2529 8027	6		27- --					
	2	S-3077	2529 8027	8	OH	30-34					
14	1	S-3153	2529 8029	6	OH	35-40					
	2	S-3154	2529 8029	6	OH	35-40					
15	1	S-3073	2531 8025	14	OH	27-30					
	2	S-3074	2531 8025	8	OH	27-30					
	3		2531 8025	4		-- -30					
16	J-1	S-3078	2532 8022	8		27- --					
	J-2	S-3079	2532 8022	6		27- --					
17	1	S-3101	2534 8021	8	OH	38-43					
	2	S-3102	2534 3021	10	OH	57-68					
	3	S-3013	2534 8021	10	OH	44-60					
	4	S-3104	2534 8021	12	OH	42-44					
	5	S-3l05	2534 8021	16	OH	37-45					
18	1	S-3031	2535 8021	10	OH	40-60					
	2	S-3032	2535 8021	10	OH	40-65					
19	1	S-3029	2535 8021	10	OH	40-60					
	2	S-3030	2535 8021	10	OH	40-75					
20	1		2535 8021	4		35- --					
	2		2535 8021	4		35- --					
21	2	S-3120	2535 8022		OH	44-50					
22	1	S-3112	2536 8022	10	OH	44.5-53.0					
	2	S-3113	2536 8022	12	OH	34.7-42.0					
	3		2536 8022	16	OH	50-75					
23	1		2536 8023	14	OH	40-60					
	2		2536 8023	14	OH	40-60					
	3		2536 8023	8	OH	30-40	1,500	.84		1,900	510,000
	4		2536 8023	14	OH	40-60					
	5		2536 8023	8	OH	30-40					
24	1	S-3106	2537 8020	10	OH	41.7-55.0					
	2	S-3107	2537 8020	12	OH	44.3-54.0					
	3	S-3018	2537 8020	16	OH	41.0-60.3					
25	1	S-3124	2536 8020	10		-- -67					
	2	S-3125	2536 8020	4		-- -42					
	3	S-3126	2536 8020	6		-- -42					
	4	S-3127	2536 8020	6		-- -45					

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis-charge (gal./ min.)	Draw-down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv-ity (ft^2/day)
26	1	S-3114	2536 8021	10	OH	91-99					
	2		2536 8021	6	OH	20.8-24.0					
	3		2536 8021	6	OH	20.3-24.0					
27	1		2538 8018	8	OH	23-25					
	2	S-3109	2538 8018	12	OH	21-40					
	3	S-3110	2538 8018	12	OH	21-40					
	4	S-3111	2538 8018	16	OH	19.2-42.0					
28	1	S-31 16	2538 8021	10	OH	44.5-51.0					
	2	S-3117	2538 8021	16	OH	42-60					
	3	S-3118	2538 8021	16	OH	52.5-75.0	1,750	1.3		1,350	360,000
29	1	S-3115	2538 8022	6	OH	20-24					
	2	S-3138	2538 8022	12	OH	20-24					
30	1	S-986	2542 8020	30/18	OH	45-123					
	2	S-987	2542 8020	30/18	OH	45-112					
	3	S-988	2542 8020	30/18	OH	45-111					
	4	S-989	2542 8020	30/18	OH	45-103					
	5	S-995	2542 8020	30/18	OH	45-103					
30 cont'd	6	S-996	2542 8020	30/18	OH	45-100					
	7	S-997	2542 8020	30/18	OH	45-99					
	8	S-3033	2542 8020	42/24	OH	50-100					
	9	S-3034	2542 8020	42/24	OH	50-98					
	10	S-3035	2542 8020	42/24	OH	50-98					
31	21	S-3011	2541 8021	42/24	OHO	60.4-133.0	7,000	15.1	8	464	130,000
	22	S-3012	2541 8021	42/24	H	57-132	7,000	17.3	8	405	110,000
	23	S-3013	2541 8021	42/24	OH	61.9-132.0	7,000	13.6	8	515	140,000
	24	S-3014	2541 8021	42/24	OH	60.9-132.0	7,000	14.1	8	496	130,000
32	11	S-1275	2541 8023	30/20	OH	40-90					
	12	S-1276	2541 8023	30/20	OH	40-90					
	13	S-1277	2541 8023	30/20	OH	40-90					
	14	S-1278	2541 8023	30/20	OH	40-90					
32	15	S-1279	2541 8023	30/20	OH	40-90					
	16	S-1280	2541 8023	30/20	OH	40-90					
	17	S-3036	2541 8023	36	OH	40-90					
	18	S-3037	2541 8023	36	OH	40-91					
	19	S-3038	2541 8023	36	OH	39-90					
	20	S-3039	2541 8023	36	OH	39-90					
33	25		2541 8023		OH	40-60	2,780	1.42	2	1,960	530,000
	26		2541 8023		OH	40-60	4,170	1.58	2	2.640	710,000
	27		2541 8023		OH	40-60	2,780	.60	2	4,630	1,200,000
	28		2541 8024		OH	40-60	2,780	.52	2	5,350	1,400,000
34	1	S-3040	2542 8029	16	OH	20-40	1,350	1.13	2	1,200	320,000
	2	S-3041	2542 8029	16	OH	19-50	1,375	.25	2	5,500	1,500,000
35	1		2544 8016	12	OH	10-20					
	2		2544 8016	6	OH	10-20					
	3		2544 8016	12	OH	10-20					

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis- charge (gal./ min.)	Draw- down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv- ity (ft^2/day)
36	1		2545 8016	8	OH	10-20					
	2		2545 8016	6	OH	10-20					
	3		2545 8016	8	OH	10-20					
37	1		2545 8022	3		30-110					
	2		2545 8022	2		-- -110					
	3		2545 8022	4		30-200					
	4		2545 8022	2		-- -110					
	5		2545 8022	4		30-120					
	6		2545 8022	4		30-130					
	7		2545 8022	4		30-120					
	8		2545 8022	4		-- -200					
	9		2545 8022	4		30- --					
	10		2545 8022	4		30-115					
	11		2545 8022	2		-- -120					
	12		2545 8022	2		-- -120					
	13		2545 8022	2		-- -120					
	14		2545 8022	2		-- -120					
	15		2545 8022	2		-- -120					
	16		2545 8022	2		-- -120					
	17		2545 8022	2		-- -100					
	18		2545 8022	6		25- --					
	19		2545 8022	4		25- --					
	20		2545 8022	2		-- - --					
	21		2545 8022	3		30- --					
	22		2545 8022	6		30- --					
38	1		2549 8021	8		-- -60					
	2		2546 8021	12		-- -60					
	3		2546 8021	12		-- -70					
39	1	S-1476	2549 8017		OH	66-107	2,780	1.6		1,740	470,000
	2	S-1477	2549 8017		OH	66-107	2,780	3.4	2	818	220,000
	3	S-l478	2549 8017		OH	66-107	4,170	4.44		938	250,000
	4	S-1479	2549 8017		OH	66-107	2,780	1.70	2	1,640	440,000
	5	S-l480	2549 8017		OH	66-107	2,780	2.40	2	1,160	310,000
	6	S-1481	2549 8017		OH	66-107	2,780	5.82	2	490	130,000
	7	S-3000	2549 8017	42/35	OH	65.5-106.0	5,560	4.67	2	1,160	320,000
40)	11	S-11	2549 8017	14	OH	85-91					
	12	S-12	2549 8017	14	OH	83-90					
	13	S-13	2549 8017	14	OH	83-95					
41	9	S-3021	2549 8018	14	OH		3,330	8.5		392	110,000
	10	S-3022	2549 8017	14	OH						
	14	S-3140	2549 8017	14	OH		2,520	11.0		229	62,000
	15	S-15	2549 8017	14	OH		2,310	9.9		234	63,000
	16	S-16	2549 8017	14	OH		2,560	5.5		465	130,000
	17	S-17	2549 8017	14			2,450	5.3		462	120,000
	18	S-3023	2549 8017	14	OH		2,890	6.4		452	120,000
	19	S-324	2549 8018	14	OH		2,400	8.9		270	73,000
	20	S-3025	2549 8017	14	OH		2,490	6.0		414	110,000
	21	S-3026	2549 8017	14	OH		2,640	7.8		339	92,000
	22	S-3027	2549 8018	14	OH		2,470	4.5		548	150,000
	23	S-3028	2549 8018	14	OH		2,880	16.3		177	48,000

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis-charge (gal./ min.)	Draw-down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv-ity (ft^2/day)
42	1	S-I	2548 8017	14	OH	60-67	3,800	7.1		540	150,000
	2	S-2	2548 8017	14	OH	79-96					
	3	S-3	2548 8017	14	OH	52-62					
	4	S-4	2548 8017	14		84-94	2,730			407	110,000
	5	S-5	2548 8017	14	OH	82-100		6.7			
	6	S-3139	2548 8017	14		49-63					
	7	S-7	2548 8017	14	OH	49-62					
	8	S-8	2548 8017	14	OH	50-64	1,790	16.2		111	30,000
43	1	S-3005	2550 8018	42	OH	59-132	2,780	1.7	2	1,640	440,000
	2	S-3006	2550 8018	42	OH	54-131	2,780	3.5	2	794	210,000
	3	S-3007	2550 8018	42	OH	65.9-132.0	2,780	2.0	2	1,390	380,000
	4	S-3008	2550 8018	42	OH	54.5-128.5	2,780	4.0	2	695	190,000
	5	S-3009	2550 8018	42	OH	54.5-128.3	2,780	2.0	2	1,390	380,000
	6	S-3010	2550 8018	42	OH	55-131	2,780	2.0	2	1,390	380,000
44	1	S-3042	2549 8021	8		-- -60					
	2	S-3043	2549 8021	8		-- -60					
	A		2548 8020	10		-- -80					
	B		2548 8020	10		-- -80					
	C		2548 8020	10		-- -90					
	D		2548 8020	10		-- -90					
45	1		2549 8025	42/24	OH	40- --	2,780	.38	2	7,410	2,000,000
	2		2549 8025	42/24	OH	40- --	2,780	.77	2	3,610	970,000
	3		2549 8025	42/24	OH	40- --					
	4		2549 8025	42/24	OH	40- --					
	5		2550 8025	42/24	OH	40- --					
	6		2550 8025	42/24	OH	40- --					
	7		2550 8025	42/24	OH	40- --					
	8		2550 8025	42/24	OH	40- --	2,780	.42	2	6,670	1,800,000
	9		2550 8024	42/24	OH	40- --	2,780	.38	2	7,410	2,000,000
	10		2550 8024	42/24	OH	40- --					
	11		2550 8024	42/24	OH	40- --					
	12		2550 8024	42/24	OH	40- --	2,780	.38	2	7,410	2,000,000
	13		2550 8024	42/24	OH	40- --					
	14		2551 8024	42/24	OH	40- --					
	15		2551 8024	42/24	OH	40- --	2,780	.67	2	4,150	1,100,000
46	1		2550 8007	24	OH	144-171	3,900	4	2	980	260,000
47	I		2552 8010	8	OH	45-47	520	1.0	2	520	140,000
	2		2552 8010	8	OH	45-47	520	1.0	2	520	140,000
	3		2552 8010	8	OH	68-69	685	1.5	2	460	120,000
48	1	S-3129	2553 8013	12	011	78-110					
	2	S-3130	2553 8013	12	OH	89-104					
	3	S-3131	2553 8013	12	OH	46-60					
	4	S-3132	2553 8013	12	OH	57-65					
	5	S-3133	2553 8013	12	OH	66-107					
	6	S-3134	2553 8013	12	OH	47-56					
	7	S-3135	2553 8013	12	OH	52-60					
	8	S-3136	2553 8013	12	OH	52-61					

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diam eter (in.)	Finish	Production interval (ft below land surface)	Dis- charge (gal./ min.)	Draw- down (ft)	Pumping period (h)	Specific capa city (gal/min. per ft)	Estimated transmissiv- ity (ft^2/day)
49	1		2552 8014	6							
	2		2553 8014	6	OH						
	3			8		40- --	450		1.5		
50	1		2552 8022	16		-- -70					
	2		2552 8022	10	OH	20-24					
51	1		2553 8023	18		33-60					
	2		2553 8023	20	OH	30-59	3,890	4.2	.25	934	250,000
	3		2553 8023	20	OH	30-66	3,890	4.0	.5	973	260,000
	4		2553 8023	20	OH	30-54	3,890	3.2	.5	1,220	330,000
52	1		2553 8007	8	OH	83-97	1,000	3		330	89,000
53	1	S-981	2553 8011	12	OH	40-53	1,165	4.2	2.25	277	75,000
	2	S-982	2553 8011	12	OH	40-51					
	3	S-983	2553 8011	12		38-55	1,098	4.2	2	261	71,000
	4	S-985		12		-- -35					
	5	S-984	2553 8011	12		19-35					
	6		2553 8010	12		-- -35					
	7		2553 8010	12		-- -35					
54	1		2554 8014	6		-- -59					
	2		2554 8014	6		-- -58					
	3		2554 8014	6		60- --					
	4		2554 8014	10		150- --					
	5	S-3063	2554 8014	12	OH	52-64	600				
	6	S-3064	2554 8014	12	OH	51-64	500				
	7	S-3065	2554 8014	12	OH	103-115	1,200	4	8	300	81,000
	8	S-3066	2554 8014	12	OH	103-115	1,200	4	8	300	81,000
55	1	S-312	2554 8015	6	OH	58.5-64.0					
	2	S-311	2554 8015	6	OH	49.7-53.6					
56	4	S-3141	2555 8020	12		-- -74					
	5	S-3l42	2555 8010	12		-- -55					
	6	S-3143	2555 8010	12		-- -55					
	7	S-3144	2555 8010	12		-- -55					
	9	S-3145	2553 8009	12		-- -55					
	11	S-3146	2555 8010	12		-- -75					
	12	S-3147	2555 8009	12		-- -55					
	13	S-3148	2555 8009	12		-- -55					
	15	S-3149	2555 8010	12		-- -50					
	16	S-3150	2555 8010	12		-- -55					
	17	S-3151	2555 8010	12		-- -30					
	18	S-3152	2555 8010	12		-- -30					
57	32	S-3093	2556 8012	16	OH	90-121					
	33	S-3094	2556 8011	16	OH	90-121					
	34	S-3095	2556 8011	16	OH	90-120					
	35	S-3096	2556 8011	16	OH	90-120					
57 cont'd	36	S-3097	2556 8011	16	OH	90-140					
	37	S-3098	2556 8011	16	OH	90-111					
	38	S-3099	2556 8011	16	OH	90-124					
	39	S-3100	2556 8011	16	OH	90-127					
58	1	S-3128	2556 8012	8		70-70					
	2		2556 8012	2		50-50					
	3		2556 8012	2		50-50					
	4		2556 8012	2		50-50					

Table 2. Owners, construction details, and hydraulic data for supply wells in Dade County (Continued)

[See figure 8 for site locations. USGS, U.S. Geological Survey; transmissivity (270 x specific capacity); OH, open hole; S, screen]

Site No.	Owner's well No.	USGS well No.	Latitude/ longitude	Diameter (in.)	Finish	Production interval (ft below land surface)	Dis-charge (gal./ min.)	Draw-down (ft)	Pumping period (h)	Specific capacity (gal/min. per ft)	Estimated transmissivity (ft^2/day)
61	1	S-3081	2557 8013	12	OH	50-90					
	2	S-3082	2556 8012	12	OH	45-90					
	3	S-3083	2557 8013	12	OH	60-90					
	4	S-3084	2556 8013	12	OH	60-90					
	5	S-1438	2557 8013	12	OH	45-90	1,000	1.0		1,000	270,000
	6	S-1440	2557 8013	12	OH	45-90					
	7	S-l439	2557 8013	12	OH	45-90					
	8	S-3137	2557 8012	12	OH	54-90	1,500	2.2		682	180,000
	9	S-3085	2556 8012	20	OH	80-90					
	10	S-3086	2556 8012	16	OH	80-90					
62	1		2558 8011	8		20-30					
	2		2558 8011	8		20-30					
	2A		2558 8011	8		20-30					
	3		2558 8011	8		20-30					
	4		2558 8011	8		20-30					
63	1	S-3044	2557 8015	8	OH	101-113					
	2	S-3045	2557 8015	8	OH	111-118 101-	950	2.2	8	430	120,000
	3	S-3046	2557 8015	8	OH	106	1,000	2.8		360	97,000
	4	S-3047	2557 8015	12	OH	105-111					
	5	S-3048	2557 8015	12	OH	105-111	1,500	2.5		600	160,000

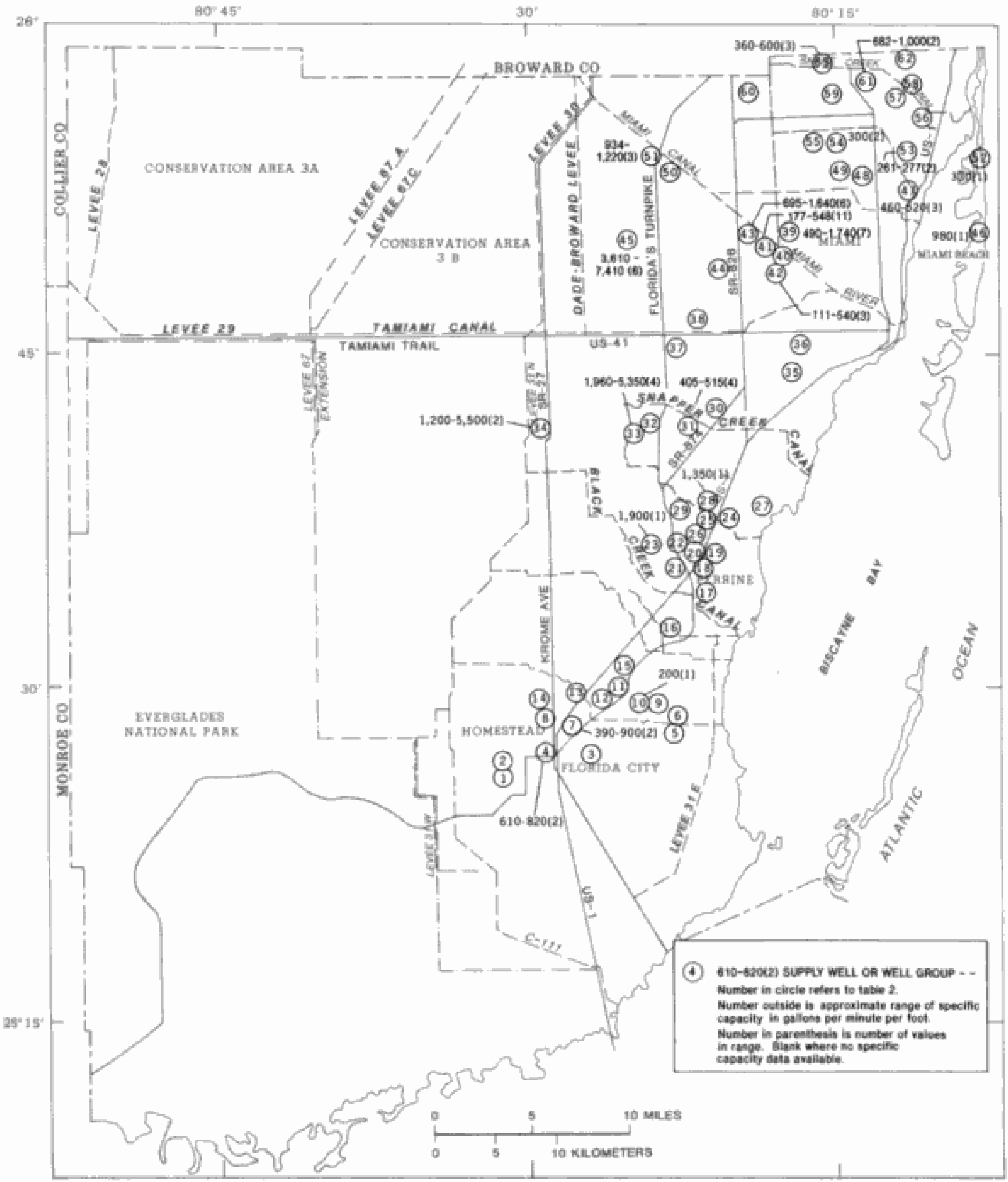


Figure 8. Location and range of specific-capacity data for supply wells in Dade County.

able zones at each site and were helpful in delineating the permeability distribution. The discharges and drawdowns are those reported on well completion tests rather than the rated capacity of the pump and well. Although in many cases, the pumping period is not known, examination of detailed test data from several wells shows that virtually all the drawdown occurs within a few minutes. Specific capacities were calculated, and the maximum and minimum values (range) for each site are shown in figure 8.

Values of specific capacity for production wells in Dade County range from 111 to 7,410 (gal/min)/ft (table 2). The highest values occur in central Dade County where there is commonly less sand in the aquifer than in northeastern Dade County and the limestone is considered to be more cavernous. However, some of the observed differences in specific capacity are caused by comparing more recently completed wells that have large diameters and longer open intervals with older wells that have smaller diameters and often shorter open intervals. At sites where specific-capacity data are available for more than one well, the values show a relatively small range of variation, usually less than a factor of 3 (fig. 8).

Where many wells that have specific-capacity data are available, estimates of transmissivity from the specific capacities may be used to characterize transmissivity in local areas and may reveal areal trends or patterns. Estimated transmissivities calculated from the relation $T = 270\ Q/s$ (eq. 5) are given in table 2. Virtually all the supply wells are open to only part of the highly to very highly permeable materials in the Biscayne aquifer. Therefore, the transmissivity of the aquifer should be greater than the estimated value. Two methods are commonly used to correct for partial penetration—one used by McClymonds and Franke (1972) on Long Island, N.Y., and also Bredehoeft and others (1983) for the Dakota aquifer; and the other proposed by Turcan (1963) and advocated by Walton (1970). However, the results obtained using these methods were considered unreasonably high for the Biscayne aquifer (Fish, 1988, p. 23). Correction methods are often not easy to apply in Dade County due to the following factors:

- Difficulty in determining the thickness of the highly permeable zone of the aquifer;
- The production intervals of the wells are commonly very short (sometimes 5 ft or less), and thus, water probably is drawn from much more of the aquifer than the production interval); and
- The methods assume homogeneous aquifer materials, whereas in detail the very highly permeable zone is heterogeneous having layers that range from sand or dense limestone to limestone with large cavities.

Because of the above-mentioned difficulties and the significance of well losses in the tests, values of transmissivity calculated from specific capacity data were used only at selected sites.

Earlier Aquifer Tests and Other Hydraulic Analyses

Conducting carefully controlled and successful tests of the surficial aquifer system in southeastern Florida is difficult because: (1) large wells and pumps are needed to adequately stress the highly transmissive aquifer: (2) the aquifer has a layered and nonuniform permeability distribution, thus, partial penetration and the approximate nature of analytical hydraulic models are common problems: (3) a long testing time is needed to determine the storage coefficient if a delayed yield type of response occurs; (4) boundary effects occur as drawdown propagates outward very rapidly and encounters surface-water recharge sources (canals, lakes, or quarries): (5) small and rapid drawdowns, which may also introduce inertial effects, make early time data difficult to collect; and (6) the pumped water must be removed a long distance from the well so that water levels in the test area are not affected by the return of the pumped water to the aquifer.

Test results available from published USGS reports or from studies by the U.S. Army Corps of Engineers are listed in table 3. Also included is a notation characterizing the method of analysis. Despite the problems mentioned above and the use of various analytical methods, the values listed provide an indication of aquifer transmissivity at each site. The site locations are shown in figure 9.

Flow nets, or some additional form of seepage analysis based on Darcy's law, and analyses of cyclic fluctuations of ground water in response to tides are other methods that have been used to calculate the transmissivity of the aquifer. Where canals are involved at these sites, the calculated transmissivity may be relatively low because canals only partially penetrate the aquifer. The published results of these methods are listed in table 4, and the site locations are shown in figure 9.

Table 3. Aquifer hydraulic properties determined in earlier aquifer tests

[See figure 9 for site locations. Method of test analysis: E, equilibrium (U.S. Army Corps of Engineers, 1953); ENP, Everglades National Park; L, leaky (Hantush and Jacob, 1955); NL, nonleaky (Theis, 1935); SC, specific capacity, USACE, U.S. Army Corps of Engineers]

Map letter	Locator or owner	Latitude/ longitude	Year of test	Method of test analysis	Transmis-sivity (feet squared per day)	Source of information	Pumping test
A	U.S. Navy Well Field	252615803030	1972	E	2,000,000	Meyer (1974)	
B	Perrine	253530802115			500,000	Kohout and Hartwell (1967)	
C	North of Canal C-100	253700801830			400,000	Kohout and Hartwell (1967)	Well G-552
D	Department of water and sewers	253705802519	1947	L	430,000	Schroeder and others (1958)	
E	Department of water and sewers	253902802019	1947	L	430,000	Schroeder and others (1958)	Well G-553
F	Department of water and sewers	254108802345	1947	L	1,300,000	Schroeder and others (1958)	Well G-551
G	South Miami	257445803403	1986	E	950,000	USACE (unpublished)	
H	South Miami	253906803213	1986	E	520,000	USACE (unpublished)	
I	Levee 67 Extension	253330804020	1965	SC	100,000	Appel and Klein (1969)	Well 6E
J	Levee 67 Extension	253430804020	1965	SC	240,000	Appel and Klein (1969)	Well 5E
K	Levee 67 Extension	253530804020	1965	SC	40,000	Appe1 and Klein (1969)	Well 4E
L	Levee 67 Extension	253645804020	1965	SC	29,000	Appel and Klein (1969)	Well 2E
M	Levee 67 Extension	253825804020	1965	SC	4,000	Appel and Klein (1969)	Well 1E
N	Levee 67 Extension	253910804020	1965	SC	6,700	Appel and Klein (1969)	Well 3E
O	US-41 near ENP	254538804600		SC	7,400	Appel and Klein (1969)	Well 10N
P	US-41 near ENP	254538804310		SC	4,000	Appel and Klein (1969)	Well 16N
Q	US-41 near ENP	254538804052		SC	19,400	Appel and Klein (1969)	Well 4N
R	US-41 near ENP	254538804040		SC	2,700	Appel and Klein (1969)	Well 3N
S	US-41 near ENP	254538804030		SC	6,200	Appel and Klein (1969)	Well 1N
T	US-41 near ENP	254538803340		SC	190,000	Appel and Klein (1969)	Well 18N
U	US-41 near Krome Avenue	254555803700	1951	E	890,000	USACE (1953)	Test 4
V	US-41 near Krome Avenue	254550802835	1951	E	2,900,000	USACE (1953)	Test 1
W	Coconut Grove	254400801400			1,000,000	Kohout and Hartwell (1967)	
X	Coconut Grove	254630801200			500,000	Kohout and Hartwell (1967)	
Y	Miami Springs Well Field	254853801714	1946	L	430,000	Schroeder and others (1958)	Well S-1
Z	Miami Springs Well Field	255020802305	1945	NL	500,000	Parker and others (1955)	Well G-218
AA	North Miami	255040801332	1940	NL	1,300,000	Parker and others (1955)	Well F-85
BB	Sunny Isles Well Field	255520801015	1961	L	330,000	Sherwood and Leach (1962)	
CC	Norwood Well Field	255908803314	1961	L	270,000	Sherwood and Leach (1962)	
DD	Snake Creek Canal	255722802455	1983	NL	800,000	Fish (1988)	Well G-2317
EE	West of SR-27	255725802555			390,000	Kohout and Hartwell (1967)	USACE test
FF	Miami Canal	255740802720	1952	E	640,000	USACE (1953)	Test 3
GG	Turkey Point	252600802000		NL, E	900,000	Watson and Herr (1985)	Estimated value from tests on a pit and 5 wells.

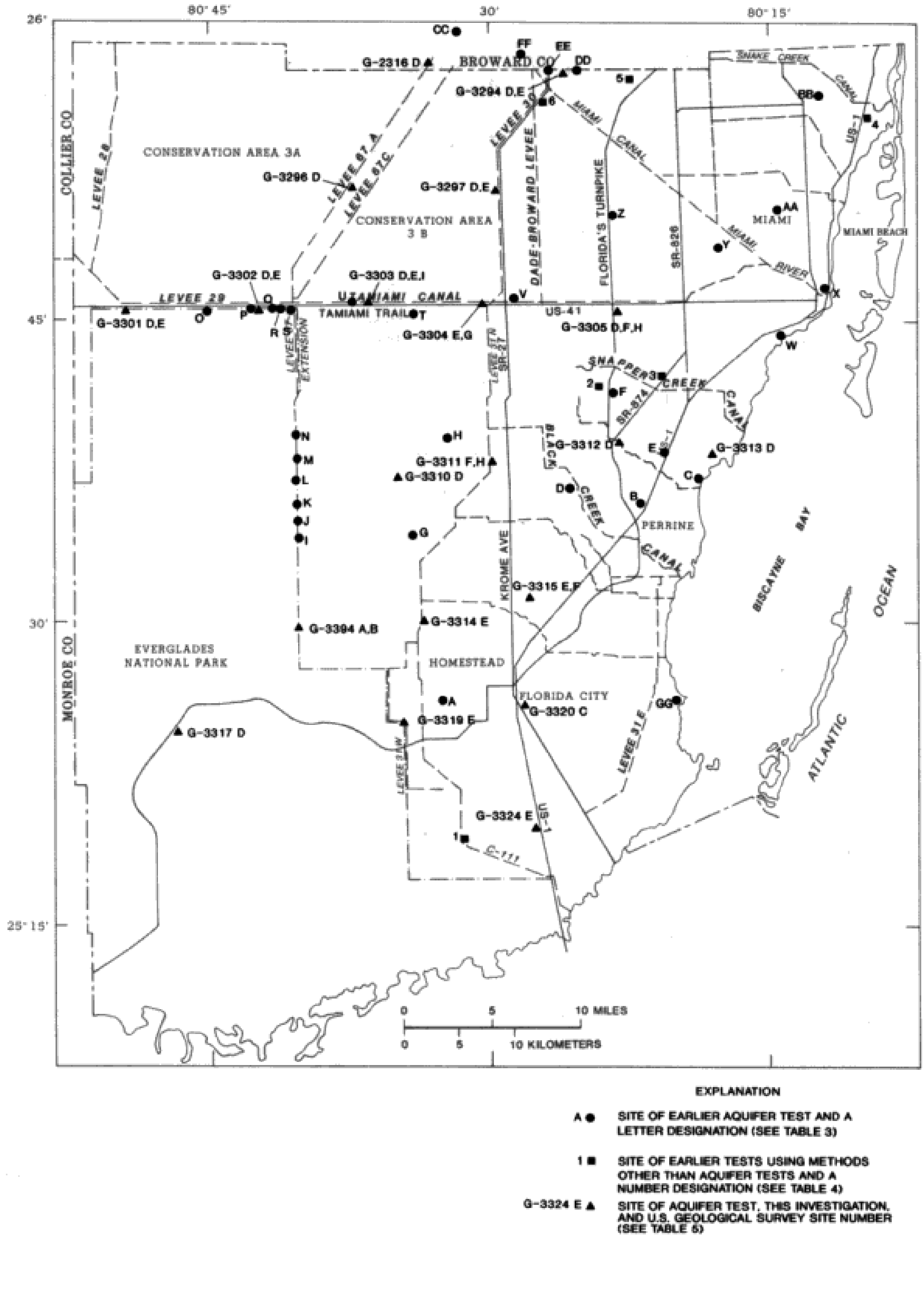


Figure 9. Location of earlier aquifer tests and hydraulic tests conducted during this investigation

Table 4. Aquifer hydraulic properties determined prior to theis study using methods other than aquifer tests

[See figure 9 for site locations. Method of analysis: D, seepage or flow net analysis; F, cyclic fluctuations of ground water related to tidal fluctuations. Transmissivity, in feet squared per day]

Map No.	Location	Latitude/ longitude	Method of analysis	Transmis- sivity	Source of information
1	Canal C-111	252130803130	D	610,000	Barnes and others (1968)
2	Southwest Well Field	254139802334	D	1,100,000	Sherwood and Leach (1962)
3	Alexander Orr Well Field	254221802008	D	740,000	Sherwood and Leach (1962)
4	Snake Creek Canal	255541800922	F	[1]470,000	Sherwood and Leach (1962)
5	Snake Creek Canal	255709802237	F	670,000	Sherwood and Leach (1962)
6	Levee L-30	255600802700	D	[2]480,000	Klein and Sherwood (1961)

[1]Assumed a storage coefficient of 0.15.

[2]If seepage under the canal occurs (regional flow), transmissivity would be higher than given value.

Tests Conducted During this Study

The field tests may be divided into two types: single-well aquifer tests in which only the pumped wells were used for observations of response in the production zone; and multiple-well aquifer tests, in which one or more separate observation wells in the pumped zone were also monitored. The single-well aquifer tests included step drawdown, drawdown recovery, and specific capacity. Discharge as much as 1,000 gal/min was obtained by use of a 6-in, suction pump, and discharge as much as 500 gal/min was obtained by a 4-in. pump. Well construction data, transmissivities, and hydraulic conductivities obtained from the aquifer tests are listed in table 5. The test sites are shown in figure 9. The wells were installed using an air-circulation method (no drilling mud). As a result, clogging of pore spaces or cavities and the effects of clogging on the test results were minimized.

Step-drawdown tests were conducted at sites with moderate to high transmissivities. For zones that had high transmissivity, pumping rates typically were about 350, 530, 730, and 950 gal/min, but for zones that had low transmissivity, the pumping rates were reduced as needed. For the lowest transmissivity zones, only specific-capacity tests were conducted at low pumping rates to minimize well losses. The step-drawdown tests were usually run as independent cycles (30 minutes of pumping followed by a recovery period for each cycle). The Biscayne aquifer recovered within 1 or 2 minutes, which was much too quickly to provide satisfactory measurements during the recovery. However, because recovery was slow in the gray limestone aquifer drawdown-recovery tests, step-drawdown tests were performed at most sites.

Jacob (1947) expressed drawdown in a pumped well by the relation:

$$S_W = BQ + CQ^2 \qquad (6)$$

where

S_W is drawdown in pumped well

BQ is aquifer loss term,

CQ^2 is well-loss term

B, C are constants, and

Q is discharge.

The step-drawdown test is a method of evaluating the aquifer loss (B) and well loss (C) constants and assigning proportional amounts of drawdown (head loss) to the aquifer and to the well. Bierschenk (1963) used the relation between S_W/Q and Q to determine B (the Y-intercept) and C (the slope of the line). Once B is determined, the specific capacity of an ideal well (one that measures only aquifer losses) can be calcu-

Table 5. Aquifer hydraulic properties determined in aquifer tests during this investigation

[See figure 9 for well locations and table 1 for site names. OH, open hole; S, screen; Hydrogeologic units: B, Biscayne aquifer; BS, basal sand unit; GL, gray limestone aquifer; S, semiconfining unit. Geologic formation: Qa, Anastasia formation; Qf, Fort Thompson Formation; Qk, Key Largo Limestone; Qm, Miami Oolite; Tt, Tamiami Formation. Type of test: 1, Step drawdown (Jacob, 1947; Bierschenk, 1963); 2, Multiple-well aquifer (Theis, 1935; Cooper and Jacob, 1946; Hantush and Jacob, 1955; Cooper, 1963); 3 Specific capacity (Theis and others, 1963; McClymonds and Franke, 1972)]

USGS well number	USGS site identification number	Well finish	Diameter of open interval (inches)	Open interval (feet below land surface)	Hydro geo logic unit	Geologic formation	Type of test	Transmis sivity (feet squared per day)	Estimated hydraulic conductivity (feet per day)
G-3294D	255707080254805	OH	7.5	21 — 86	B	Qf,Qk	1	1,000,000+	15,000+
G-3294E	255707080254806	OH	6.0	90 — 110	B	Tt	3	39,000	2,000
G-3296D	255224080380501	OH	7.5	20 — 45	B	Qf	1	1,000,000+	40,000+
G-3297D	255058080290301	OH	7.5	20 — 55	B	Qf,Qk	1	1,000,000	29,000
G-3297E	255058050290301	OH	6.0	60.0 — 78.4	B	Tt	3	8,600	470
G-3301D	254537080493605	OH	7.5	11.0 — 16.8	SCU	Qf	3	3,100	530
G-3301E	254537080493606	OH	6.0	101 — 149	GL[1]	Tt	2	39,000	780
G-3302D	254542080421705	OH	7.5	11 — 17	SCU	Qf	3	2,700	450
G-3302E	254542080421706	OH	6.0	81 — 138	GL[1]	Tt	2	25,000	420
G-3303D	254545080361705	OH	7.5	20 — 34.8	B	Qf	1	600,000	40,000
G-3303E	254545080361706	OH	6.0	121 — 150	GL[1]	Tt	2	13,000	430
G-3303I	254545080361710	S	2.0	59 — 72	SCU[1]	Tt	3	1,200	94
G-3304E	254539080300606	OH	7.5	30 — 55	B	Qf	1	1,000,000+	40,000+
G-3304G	254539080300608	OH	6.0	80.0 — 95.9	B	Tt	3	3,800	240
G-3305D	254536080230305	OH	7.5	21 — 87	B	Qf,Qk	1	1,000,000	15,000
G-3305F	254536080230307	S	2.0	164.2 — 171.2	B	Tt	3	430	61
G-3305H	254536080230309	S	2.0	131.7 — 141.7	B	Tt	3	49	4.9
G-3310D	253714080345905	OH	7.5	10 — 45	B	Qm,Tt	1	1,000,000+	29,000+
G-3311F	253746080295007	OH	7.5	32 — 56	B	Qf	1	1,000,000+	42,000+
G-3311H	253746080295009	OH	6.0	145 — 173	GL	Tt	3	5,800	210
G-3312D	253842080225805	OH	7.5	26 — 94	B	Qf,Qa,Tt	1	220,000	3,300
G-3313D	253831080180205	OH	7.5	32 — 114	B	Qf,Qk,Qa,Tt	1	710,000	8,700
G-33l4E	253018080333505	OH	7.5	21 — 48	B	Qf	1	1,000,000+	37,000+
G-3315E	253119080274806	OH	7.5	32 — 69	B	Qf	1	1,000,000+	27,000+
G-33l5F	253119080274806	OH	6.0	94.0 — 111.5	SCU	Tt	3	65	3.7
G-3317D	252326080475705	OH	6.0	8 — 28	B	Qm,Qf	1	730,000	36,000
G-3319E	252507080342706	OH	7.5	21.0 — 39.3	B	Qf	1	1,000,000+	55,000+
G-3320C	252555080281004	OH	7.5	32 — 80	B	Qf	1	1,000,000+	21,000+
G-3324E	251948080271806	OH	7.5	16 — 58	B	Qm,Qf,Qk	1	1,000,000+	24,000+
G-3394A	252944080395102	OH	7.5	10 — 34	B	Qm,Qf	1	1,000,000+	42,000
G-3394B	252944080395103	S	6.0	110 — 145	GL	Tt	2,3	14,000	400
G-2316D	255732080325605	OH	7.5	15 — 54	B	Qf	1	1,000,000+	26,000+

[1]At well G-3301E, the interval from 100 to 150 feet below land surface is the more permeable part of the aquifer. At well G-3302E, the gray limestone aquifer extends from 77 to 136 feet below land surface. At well G-3303E, the gray limestone from 120 to 150 feet is the main part of the aquifer, but slightly cemented, calcareous sandstone from 150 to 165 feet may exceed a hydraulic conductivity of 100 feet per day. At well G-3303I, shell layer in semiconfining unit.

Table 6. Approximate ranges of hydraulic conductivity of sediments that compose the surficial aquifer system, Dade County

[Range, in feet per day. <, less than; >, greater than; Geologic formation: Qa, Anastasia Formation; Qf, Fort Thompson Formation; Qk, Key Largo Formation; Qm, Miami Oolite; Qp, Pamlico Sand; Th, Hawthorn Formation; Tt, Tamiami Formation; Tth, undifferentiated Tamiami Formation and Hawthorn Formation; Ttl, Tamiami Formation, lower part; Ttu, Tamiami Formation, upper part]

Horizontal hydraulic conductivity		Sediments—lithology and porosity	Geologic formation
Qualitative description	**Range**		
Very high	>1,000	Solution-riddled limestone, commonly shelly or sandy.	Qf,Qa,
		Calcareous sandstone, may be shelly or have shell fragments; solution holes or riblike channels.	Qa,Tt
		Coralline limestone, reefal, very porous.	Qk
		Oolitic limestone.	Qm
High	100—1,000	Gray, shelly limestone, locally sandy, relatively soft.	Tt
		Limestone or calcareous sandstone interbedded with sand or with sand partially filling cavities.	Qa,Tt,Qf
		Coarse shell sand and quartz sand.	Tt
		Dense, charcoal gray to tan limestone with some solution channels, usually shelly or sandy.	Ttu
		Oolitic limestone.	Qm
Moderate	10—100	Very fine to medium, relatively clean, quartz sand.	Qp,Qa,Tt Tt
		Fine to medium quartz and carbonate sand.	Qf,Qa
		Cream-colored limestone with minor channels.	Tt
		Ian, cream, or greenish limestone, locally containing shelly sand.	Tt,Qa
		Calcareous sandstone and sand.	Tt
		Slightly clayey or sandy, gray limestone.	Th
		Light-green, foraminiferal limestone, locally sandy or shelly.	
Low	0.1—10	Very fine to medium sand with some clay, silt, or lime mud; locally shelly.	Tt,Qf,Qa
		Soft gray or buff limestone with silt and fine sand.	Tt
		Dense. calcareous sandstone.	Tt
		Light-green, fine-grained foraminiferal limestone with very fine quartz sand.	Tt
		Dense, hard limestone with very small cavities or channels. Approximately equal mixtures of sand. shell fragments, and lime mud.	Qf
Very low to practically impermeable	<0.1	Green clay or silt; locally with very fine sand: siltstone, claystone, often sandy.	Tth,Ttl,Ttu
		Sandy, shelly lime mud.	Tt
		Very dense, hard limestone with no apparent solution cavities or fractures.	Qf
		Dense, hard oolitic limestone with no apparent solution cavities or fractures.	Qm

lated from Q/s = 1/B, and a transmissivity can be estimated from this specific capacity. The average constant 270 was used, as before, for the Biscayne aquifer.

Aquifer tests were performed at five sites with one or more observation wells in the production zone. The observation wells were placed near the pumped wells to minimize the effects of leakage and to obtain measurable drawdowns. The observation well data were analyzed by a nonleaky semilog drawdown method described by Cooper and Jacob (1946) and by the recovery method (Theis, 1935; Todd, 1980, p. 131-135).

An estimate of average horizontal hydraulic conductivity can be calculated from the transmissivities obtained from the tests (table 5) using equation 3. For the single-well tests (specific capacity or step drawdown), the length of open hole or screen is a reasonable estimate of the thickness of the aquifer that contributes most of the flow to the well, if the aquifer has significantly greater horizontal hydraulic conductivity than vertical hydraulic conductivity (as shown by layering), and if the open interval is relatively long (McClymonds and Franke, 1972, p. E11). In the aquifer tests, the hydraulic conductivity is calculated for the main permeable zone in the aquifer and excludes adjacent sand beds or slightly cemented calcareous beds.

HYDROGEOLOGY

Hydraulic Conductivity Distribution and Hydraulic Conductivity of the Sediments

The distribution of hydraulic conductivity in the surficial aquifer system is shown (pls. 1-11) by superimposing ranges of hydraulic conductivities on the 11 geologic sections prepared by Causaras (1987). Some aspects of areal variations in the lithology of the geologic formations are included here as part of the discussion of the hydraulic conductivity distribution because of relations between lithology and hydraulic conductivity. Detailed lithologic logs for each well and a description of the geology of the surficial aquifer system are contained in Causaras (1987). In addition to the hydraulic data and municipal well data reported in the previous section, other information for constructing the hydraulic conductivity distribution included:

- Flow rates obtained while drilling the test holes;
- Hydrologic inferences from inspection of geologic samples;
- Published values of hydraulic conductivity as related to grain size and sorting for clastic sediments and sandstone; and
- Grain-size descriptions by Causaras (1987) and sieve-size analyses of selected samples.

The hydraulic conductivities of the geologic units that compose the surficial aquifer system range over seven orders of magnitude; from more than 10,000 ft/d for highly permeable limestones to about 0.001 ft/d or less for dense, green clay. For the hydraulic conductivity sections, this range is divided into five categories, and general lithologies are given in table 6. At test sites for this investigation, sediments that have hydraulic conductivities greater than 1,000 ft/d occur only in the Biscayne aquifer. Municipal supply wells are usually finished in sediments that have very high (greater than 1,000 ft/d) or high (100-1,000 ft/d) hydraulic conductivities. Sediments that have moderate hydraulic conductivities (10-100 ft/d) are considered the lower limit of those that may be useful for water supply, such as for domestic purposes. Sediments with low hydraulic conductivity (0.1-10 ft/d) are not generally used for supply but permit seepage or leakage of water to more permeable beds. Sediments with very low hydraulic conductivities (less than 0.1 ft/d) retard ground water circulation considerably when present in thicknesses of a few feet or more.

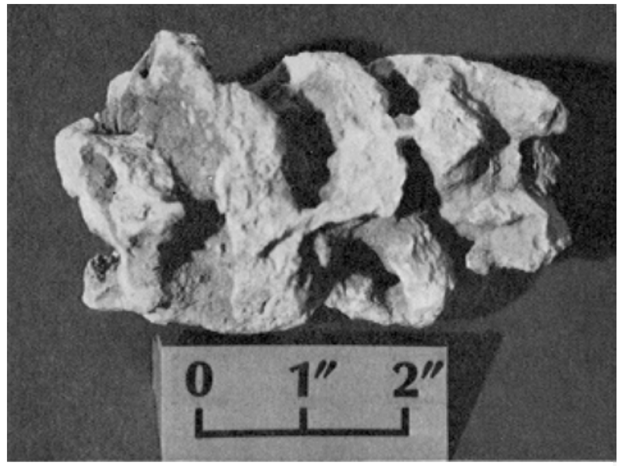
The sections (pls. 1-11) provide an indication of the horizontal hydraulic conductivity of the rocks or sediments. Rapid vertical changes in lithology and hydraulic conductivity could not be shown because of the scale of the sections. Where it appears that several thin zones of high or very high hydraulic conductivity are present but are separated by less-permeable sediments (for example, dense limestone), the higher range is shown. In such instances, the sections give a more accurate portrayal of the capability of the formation to permit lateral movement of water rather than vertical movement of water. Also, because of limitations of scale, the occurrence of several thin (a few inches to a few feet) layers of sediments that have low or very low hydraulic conductivity is represented as a composite single layer.

Western Dade County

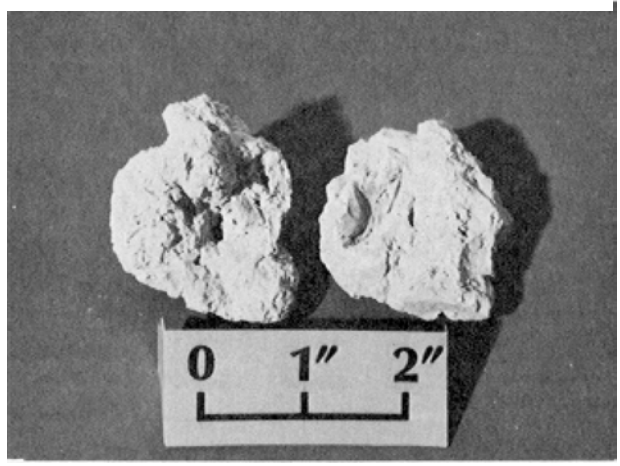
A generalized western Dade County hydrogeologic section (fig. 6c) begins in the northwestern area with a few feet of peat, muck, and lime mud. At most drill sites, some or all of these sediments have been replaced with road or levee fill. Although no tests were performed in the organic deposits (peat and muck) for this investigation, Parker and others (1955, p. 109) indicate a relatively low permeability for these sediments. The lime mud layers, referred to as the Lake Flirt Marl (Holocene age), lie between the organic deposits and the rock floor of The Everglades or as thin layers intercalated with the organic deposits. These marl layers are unconsolidated to relatively indurated and are relatively impermeable, thereby retarding movement of water down ward to, or upward from, more permeable layers below. These marls are absent or very thin in west-central Dade County, but lime mud is present in the lower Everglades and coastal marshes of southwestern Dade County.

The Miami Oolite forms the bedrock that underlies The Everglades over all of western Dade County, except the northwesternmost corner where it does not occur (pl. 1, well G-3296; pl. 6, wells G-3301 and G-3295). It thickens eastward and southward in western Dade County, reaching a maximum thickness of about 16 ft (pls. 5 and 6, well G-3318). In northwestern Dade County, the Miami Oolite may be either well cemented and very hard throughout its thickness (pl. 2, well G-3302), or have alternating layers of harder and softer limestone. The hydraulic conductivity of the Miami Oolite in this area is low to moderate, depending upon the presence of soft layers that have minor development of secondary-solution porosity. To the south and east, hydraulic conductivity increases as secondary porosity becomes better developed (pls. 6-9 and fig. 10a). Pumping of several wells open only to the Miami Oolite indicates that large yields can be obtained from this formation in some areas. However, test drilling also indicates that the cavities in many areas are at least partly clogged with lime mud and sand, thereby reducing the average hydraulic conductivity to much less than the underlying limestone. In general, the Miami Oolite does not appear to have as well developed a network of open cavities as the Fort Thompson Formation.

The Fort Thompson Formation occurs throughout western Dade County. It underlies the Miami Oolite everywhere in the county, except in the northwesternmost corner where the Fort Thompson Formation is the uppermost rock unit. The Fort Thompson Formation is only a few feet thick in the latter area, but it increases in thickness southward and eastward (pls. 1-7). Marly limestone or hard, dense limestone layers with low hydraulic conductivity are predominant at or near the top of the Fort Thompson Formation in northwestern Dade County (pls. 1, 2, and 6-8). Only a few feet of highly permeable limestone of the Fort Thompson Formation are found at the two westernmost sites along the Tamiami Trail (pl. 2, wells G-330l and G-3302; table 5, wells G-3301D and G-3302D). Hence, the Biscayne aquifer, as defined by Fish (1988) and in this report, is



A.



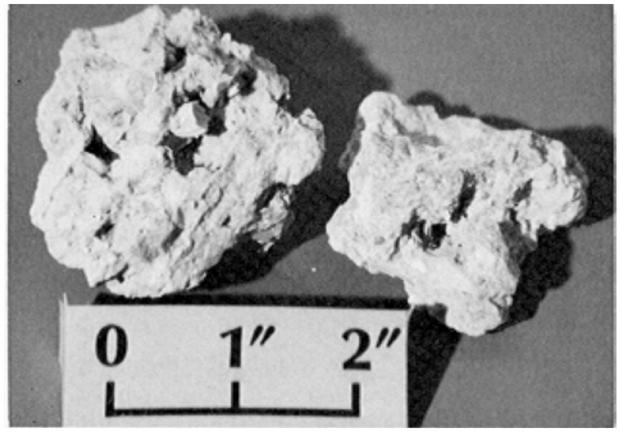
B.

Figure 10. (a) Highly porous and permeable Miami Oolite in western Dade County (from 8-10 feet below land surface, site G-3311), and (b) porous, shelly, highly permeable limestone of the Fort Thompson Formation in western Dade County (from 28 feet below and surface, site G-3296).

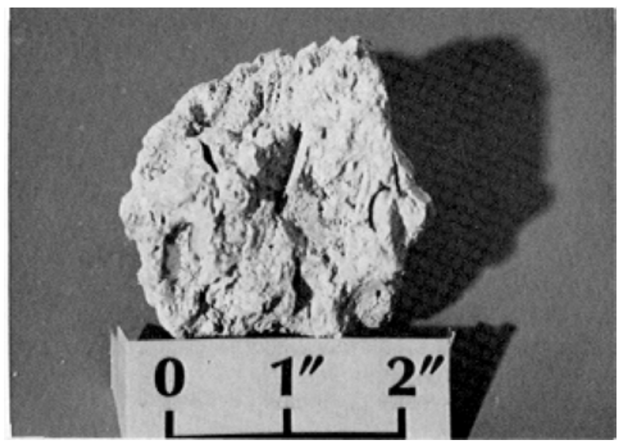
not present in the western part of northwestern Dade County (fig. 6b); however, the thin permeable zone is contiguous with the Biscayne aquifer to the south and east. Eastward and southward from that area, the permeable part of the Fort Thompson Formation thickens (pls. 1, 2, 6, and 7). The marine limestones of the Fort Thompson Formation generally are riddled with secondary-solution cavities and are very highly permeable (fig. 10b). The cavities generally are 2 in. or less across but are so abundant that the limestone resembles a sponge, making collection of representative samples difficult. Interbedded with the marine limestones are much more dense, less-permeable, freshwater limestones. Tests conducted during this investigation (table 5) and other studies (tables 3 and 4) indicate the average hydraulic conductivity of the Fort Thompson Formation over most of the area is tens of thousands of feet per day, possibly exceeding an average of 40,000 ft/d. Therefore, in western Dade County, the Fort Thompson Formation is the most significant unit of the Biscayne aquifer in total volume and in hydraulic conductivity. No attempt was made to distinguish the freshwater limestones on the hydraulic conductivity cross sections.

In places, highly to very highly permeable limestones or calcareous sandstones of the Tamiami Formation (fig. 11a) immediately underlie the Fort Thompson Formation. These limestones and sandstones form the basal zone of the Biscayne aquifer where they occur, primarily along the eastern boundary of western Dade County (pls. 2 and 9). The hydraulic conductivity of these rocks ranges from 240 to 2,000 ft/d (table 5, wells G-3294E. G-3297E, and G-3304G), much less than limestones of the Fort Thompson. Where the hydraulic conductivity of the uppermost Tamiami Formation rock or rock and sand is less than 100 ft/d (for example, well G-3294 in pl. 9 and well G-3309 in pl.7), those sediments are excluded from the Biscayne aquifer and are included in the underlying hydrogeologic unit.

A sequence of sand, silt, clay, shell, organic sediment, and mixtures of these components, as well as minor limestone and sandstone, occur below the Biscayne aquifer. These sediments are hydrogeologically grouped as a semiconfining unit that separates the overlying Biscayne aquifer from the underlying gray limestone aquifer (figs. 6b and 6c). The unit is thinner in northwestern Dade County than in west-central and southwestern Dade County, ranging from about 15 ft thick (pl. 9. well G-3304) to more than 100 ft thick (pl. 8, well G-3314). Causaras (1987) assigns the sequence to the Tamiami Formation.



A.



B.

Figure 11. (a). Calcareous sandstone with shells, porous and highly permeable, of the Tamiami Formation in southwestern Dade County (from 47-50 feet below land surface, site G-3323); and (b) gray, sandy, shelly, highly permeable limestone of the Tamiami Formation in western Dade County (from 117-120 feet below land surface, site G-3301).

The hydraulic conductivity of the semiconfining unit generally is low to moderate because silty or clayey sand and relatively clean sand, sometimes partly cemented, are the most common lithologies. A low-rate, specific-capacity test of a poorly sorted mixture of fine sand and shell fragments indicates a hydraulic conductivity of 94 ft/d (table 5, well G-3303I), which approaches the upper limit of the hydraulic conductivity range. Clean sands in the area usually have a lower hydraulic conductivity. Locally, shelly beds or shell fragment layers that contain less fine sand than the tested zone in well G-3303I probably have hydraulic conductivities of several hundred feet per day. Examples of such highly permeable beds within this unit are from 70 to 87 ft deep at the Context Road West site (pls. 4 and 7, well G-3394) and from 64 to 70 ft deep and 90 to 114 ft deep at the Levee 31N site (pls. 3 and 9, well G-3311). Silty limestones or sand stones in the semiconfining unit may have low hydraulic conductivities. Locally, silt or clay may be abundant and hydraulic conductivity is very low. An example is the thick layer at about 110 ft below land surface at the Levee 67 extension and Tamiami central sites (pls. 7 and 8). The sediments of the semiconfining layer-commonly have hydraulic conductivities that are 2,000 to 100,000 times less than the average for the Biscayne aquifer and 10 to 1,000 times less than the average for the gray limestone aquifer.

Underlying the semiconfining unit in nearly all of western Dade County is the gray limestone aquifer. It is composed primarily of gray, shelly, occasionally sandy lime stone (fig. 11b) of the middle to lower part of the Tamiami Formation, but minor sandstone (pl. 6, 88-120 ft in well G-3322) or contiguous shelly beds (pls. 4 and 7, 110-126 ft in well G-3394) are also included in the aquifer. This aquifer occurs throughout western Broward County (Fish, 1988) and in part of southwestern Palm Beach County (W.L. Miller, U.S. Geological Survey, oral commun., 1984). In Dade County, the aquifer is closest to land surface and is thickest in the northwestern area, reaching a maximum thickness of 95 ft at the Levee 67A site (pls. 1 and 8, well G-3296). The aquifer generally becomes thinner to the east and south as the upper part of the limestone is replaced with sand, silt, and clay. In the southeastern part of western Dade County, the aquifer thins and becomes less than 10 ft thick; however, in northern Dade County, the aquifer continues from the west into the eastern part of the county (fig. 6b and pls. 1 and 2).

For this investigation, three aquifer tests were conducted in the gray limestone aquifer (table 5). At the Forty-Mile Bend site (well G-3301E), the average hydraulic conductivity is 780 ft/d (table 5), which is slightly lower than values of about 900 ft/d indicated by tests in western and southwestern Broward County (Fish, 1988, table 4). At the next two sites (wells G-3302E and G-3303E), eastward along Tamiami Trail, measured hydraulic conductivities are 420 and 430 ft/d, respectively (table 5). This is consistent with drilling data, which indicate a general decrease in hydraulic conductivity and transmissivity from west to east in the aquifer in western Dade County. At the Levee 31N site (well G-3311H), along the eastern margin of western Dade County and about 8 mi south of Tamiami Trail, the gray limestone is more dense, with a hydraulic conductivity of 210 ft/d; at the Context Road West site (well G-3394B), which includes both a shell layer and gray limestone, the hydraulic conductivity is about 400 ft/d (table 5).

Underlying the gray limestone is a sandy unit usually with some silt, clay, or shell that forms the lowest part of the Tamiami Formation. These sediments may be unconsolidated or loosely cemented into calcareous sandstone. Where the gray limestone aquifer does not occur in the southeastern part of western Dade County, a clastic unit in the lower part of the Tamiami Formation merges with the semiconfining unit of the upper part of the Tamiami Formation. The sediments of this unit are predominantly of moderate or low hydraulic conductivity. However, a shelly layer forms a local zone of high hydraulic conductivity at a depth of about 140 ft in southwestern Dade County (pl. 6, wells G-3322 and G-3317) that may not be connected with the gray limestone aquifer. Also, thin and silty sandstone, siltstone, and claystone layers (usually less than a few inches thick) are common and are grouped together on the hydrogeologic sections as relatively thicker, low or very low hydraulic conductivity layers because of the scale of the sections. The base of this unit is also the base of the surficial aquifer system, which regionally is considered the top of the Hawthorn Formation. The top of the Hawthorn Formation usually is marked by a significant increase in clay and silt and a decrease in hydraulic conductivity. However, there are many sandy interbeds in the upper part of the Hawthorn Formation in western Dade County in contrast with western Broward County (Fish, 1988).

Eastern Dade County

In northeastern Dade County, generally north of the Tamiami Trail, the uppermost sediments are a thin blanket of late Pleistocene marine-terrace deposits grouped together as the Pamlico Sand (Parker and Cooke, 1944, p. 75). The greatest thickness penetrated by test wells for this investigation was about 12 ft. but the Pamlico Sand thickens in north easternmost Dade County and eastern Broward County. The sands are quartzose, usually fine to medium grained, and well sorted, but lime mud or silt partly fills the interstices between grains in some layers. Two tests in southern Broward County of fine- to medium-grained sands with minor lime mud indicated hydraulic conductivities of 27 and 44 ft/d (Fish, 1988, table 5). In the western part of north eastern Dade County, a thin layer of peat may overlie the Pamlico Sand (pl. 2, well G-3306).

The Miami Oolite was penetrated by every test well in eastern Dade County, except at the US-1 Key site (pl. 9, well G-3395) at the southern Dade County boundary. North of Tamiami Trail, the Miami Oolite is overlain by the Pamlico Sand or peat, but it crops out in much of the rest of eastern Dade County. The thickness of the formation is about 10 ft or less, except along the Atlantic Coastal Ridge (fig. 4), where the thickness may exceed 30 ft (pls. 3 and 11, well G-3313; pls. 4 and 9, well G-3315). As in western Dade County, the Miami Oolite in eastern Dade County is riddled with secondary-solution holes (fig. 12a) that commonly are partly to completely filled with lime mud and sand. Although the formation is very permeable, yields tests of wells indicate its hydraulic conductivity is less than that of the underlying Pleistocene limestones.

Underlying the Miami Oolite is an interfingering sequence of three formations: the Anastasia Formation, the Key Largo Limestone, and the Fort Thompson Formation. The Anastasia Formation consists of porous to very porous, sandy, shelly limestone and nodular and shelly sandstone interbedded with sand. It is thickest in coastal northeastern Dade County and occurs at depths of 100 ft below land surface or more (pl. 1, well G-3299; pl. 11, well G-3300). To the west and southwest, the Anastasia Formation pinches out and is replaced with the Fort Thompson Formation and the Key Largo Limestone. No test-drilling data were collected that would indicate the extent of the Anastasia Formation to the east or to the south under Biscayne Bay.

The Key Largo Limestone appears as localized lenses that interfinger primarily with the Anastasia and Fort Thompson Formations (pls. 1, 2, and 11). Near the southeastern boundary of Dade County (fig. 18, well G-3395), the Key Largo Limestone is the uppermost rock unit, and it interfingers with the Miami Oolite to the north (Causaras, 1987). The Key Largo Limestone is crystalline, very porous, coralline limestone (fig. 12b).

The largest component of the very highly permeable materials in eastern Dade County is the Fort Thompson Formation. The pattern of eastward thickening of the formation found in western Dade County is also found in eastern Dade County, until it is partly or completely replaced with the Anastasia Formation or Key Largo Limestone near the coast (pls. 1-5). The Fort Thompson Formation consists of a series of marine,

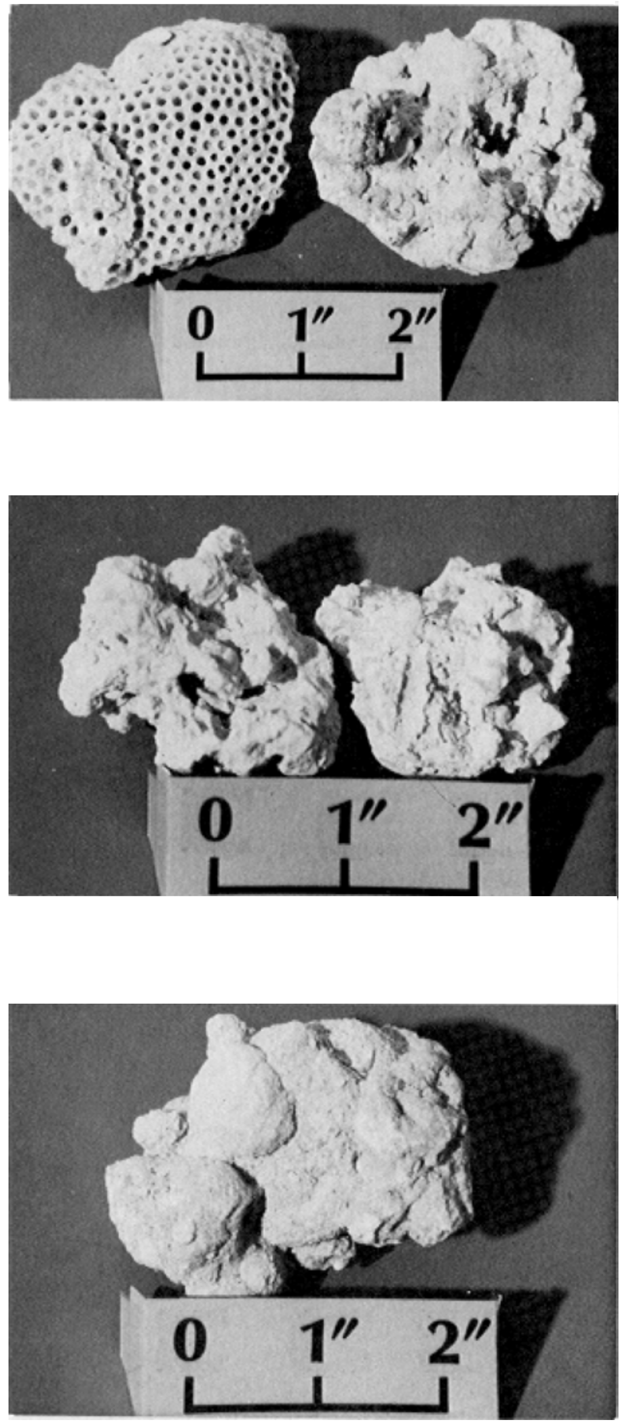


Figure 12. (a) Highly porous and permeable Miami Oolite in eastern Dade County (from 20-22 feet below land surface, site G-3320), and (b) Key Largo limestone with sandy limestone and coral in northeastern Dade County (from 60-70 feet below land surface, site G-3300); and (c) calcareous, permeable sandstone of the upper part of the Tamiami Formation in eastern Dade County (from 114-117 feet below land surface, site 3307).

brackish-water, and freshwater limestones ranging from slightly to very porous.

The Anastasia Formation, the Key Largo Limestone, and the Fort Thompson Formation constitute the bulk of the very highly permeable sediments of the Biscayne aquifer in eastern Dade County. The average hydraulic conductivity of the three formations probably exceeds 10,000 ft/d over much of the area (tables 4 and *5).* The Anastasia Formation in northeastern Dade County has the lowest average hydraulic conductivity of the three formations. Most of the municipal and industrial supply wells (fig. 8 and table 2) are open to one of these formations, except in northeastern Dade County where a few wells may also be open to the Tamiami Formation.

Along coastal Dade County, the upper part of the Tamiami Formation consists of limestone, calcareous sand stone, and sand (fig. 12c). These sediments underlie the permeable Pleistocene limestones and are highly to very highly permeable; hence, they are included in the Biscayne aquifer. At the Miami Shores site (pls. 1 and 11, well G-3300), the highly to very highly permeable rocks of the upper part of the Tamiami Formation extended from about 110 ft to greater than 180 ft below land surface (the deepest found in this study). A disposal well in Miami Beach (site no. 46 in fig. 8 and in table 2), with an open-hole interval from 144 to 171 ft below land surface probably is developed in this unit. A well tested at 3,900 gal/min indicated a specific capacity of 980 (gal/min)/ft of drawdown (Bill McCluskey, U.S. Geological Survey, written commun., 1988).

In northeastern Dade County, the semiconfining unit of the upper part of the Tamiami Formation (unconsolidated sediments, sandstone, and limestone) terminates as the sediments grade laterally into the more permeable rocks described above (figs. 6b and 6c and pls. 1 and 2). It also becomes thinner and contains a higher percentage of limestone and sandstone than in western Dade County. In southeastern Dade County, the semiconfining unit is continuous over the area and usually is 50 ft thick or greater. In this area, it is mostly composed of silty or clayey sand with some siltstone, sandstone, and silty and sandy, limestone. A specific-capacity test in a limestone at about 110 ft deep at the Camp Owaissa-Bauer site (pls. 4 and 9, well G-3315) indicated a low hydraulic conductivity of 4 ft/d (table 5, well G-3315F).

The gray limestone aquifer continues eastward from western Dade County, approaching the vicinity of Florida’s Turnpike in northeastern Dade County. There, it grades into limestone and calcareous sandstone that are included in the Biscayne aquifer (fig. 6b and pls. 1 and 2). In southeastern Dade County, the gray limestone does not occur, except as thin beds near the boundary in western Dade County (pl. 5, well G-3319). South of the Tamiami Trail, the gray limestone is replaced laterally with sand, silt, and clay that have moderate to very low hydraulic conductivity (pls. 3-5). At the Levee 31 N site (pls. 3 and 9, well G-3311), an aquifer test in the limestone at 145 to 173 ft below land surface indicates a hydraulic conductivity of 210 ft/d (table 5, well G-3311 H).

The distribution and character of the basal sand unit in eastern Dade County are complex. In northeasternmost Dade County, the sand grades into a moderately permeable, sandy limestone (pls. 1 and 11, well G-3300). Farther south, the unit consists mostly of interbedded sand, sandstone, silt, and clay as in western Dade County (pls. 2 and 3). In the central part of eastern Dade County, the basal sand unit merges with the semiconfining unit (pls. 3 and 4) as the gray limestone aquifer pinches out. In southeastern Dade County, the basal sand pinches out against a topographic high on the top of the sediments of the upper part of the intermediate confining unit (pl. 5).

As in western Dade County, the Hawthorn Formation is principally composed of interbedded siltstone, claystone, and sand, except at the Miami Shores site (pls. 1 and 11, well G-3300) where a green, sandy limestone is present. Laboratory tests of four similar samples from eastern Broward County indicate an average hydraulic conductivity of about 4 ft/d (Fish, 1988, table 6). The hydraulic conductivity of the Hawthorn Formation in eastern Dade County generally is lower than that in the overlying units. As previously discussed, the base of the surficial aquifer system and the top of the intermediate confining unit are considered to be the top of the Hawthorn Formation.

Delineation of the Surficial Aquifer System

Contour maps were prepared to delineate the surficial aquifer system and the aquifers within the system (figs. 13-16). These maps are based on aquifer definitions, aquifer-test results, and the vertical profiles of hydraulic conductivity determined at the hydrogeologic test sites. Contours of the base of the surficial aquifer system are shown in figure 13. The base of the aquifer system occurs at a relatively uniform elevation

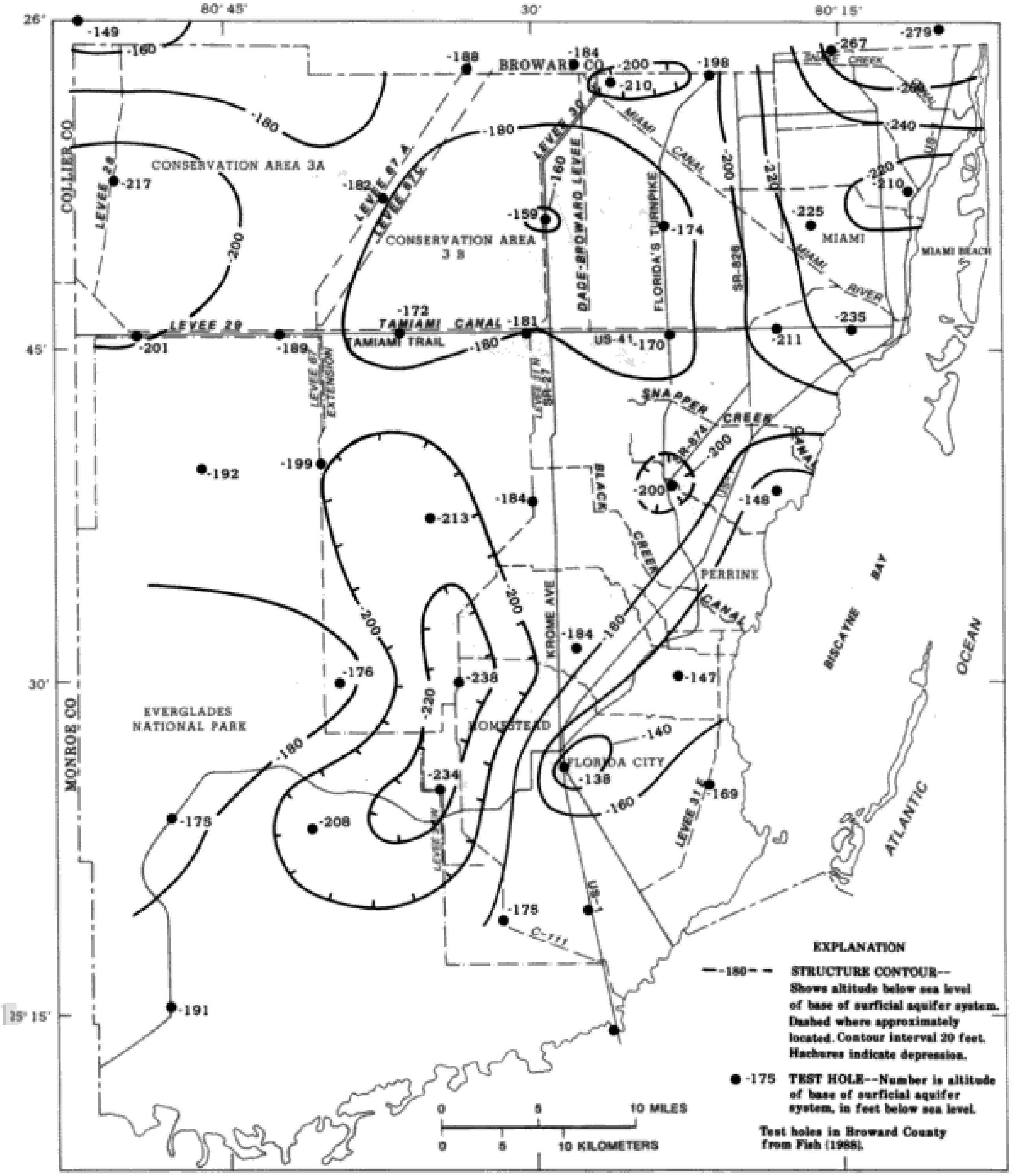


Figure 13. Configuration of the base of the surficial aquifer system in Dade County.

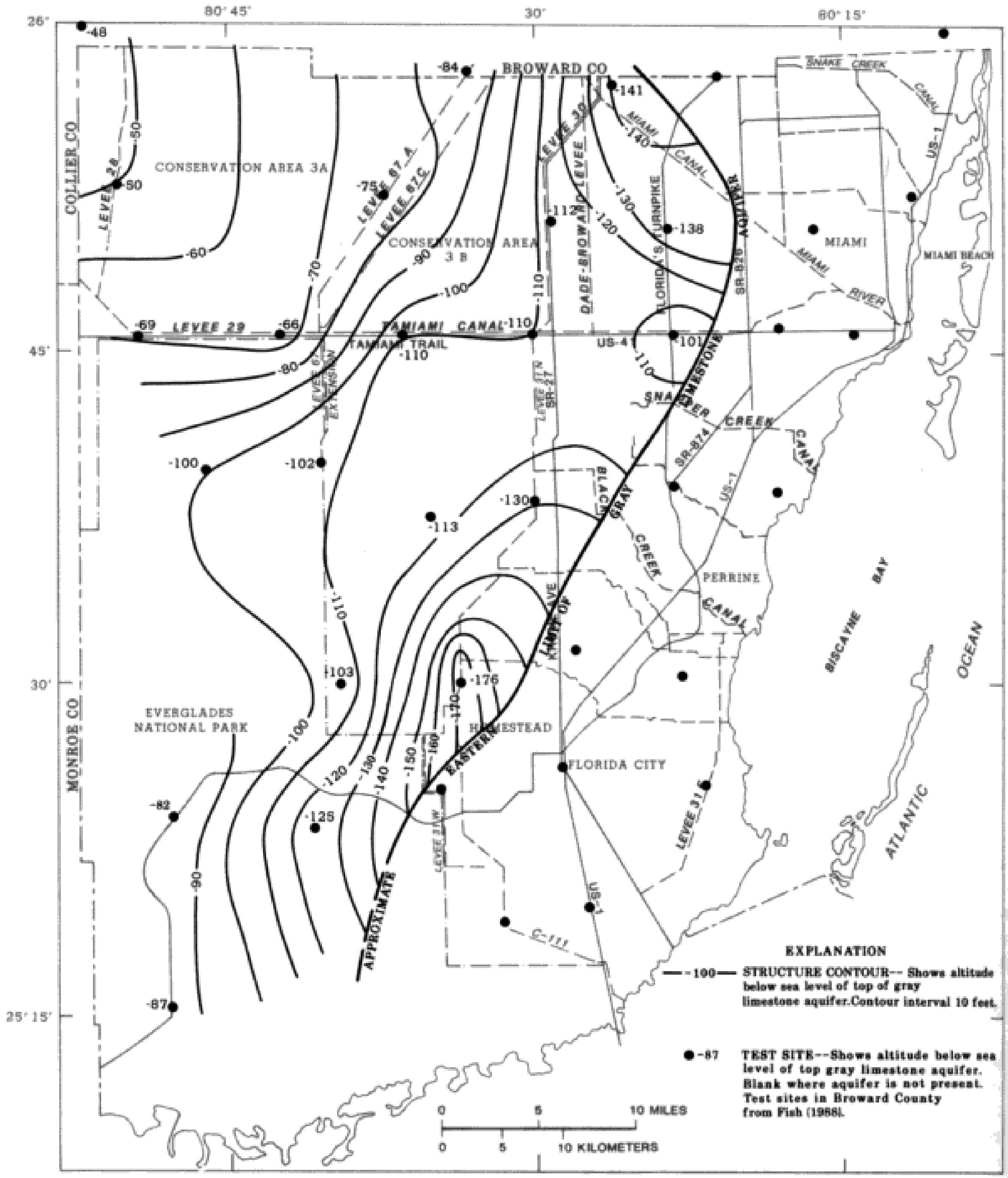


Figure 14. Configuration of the top and approximate eastern limit of the gray limestone aquifer in Dade County.

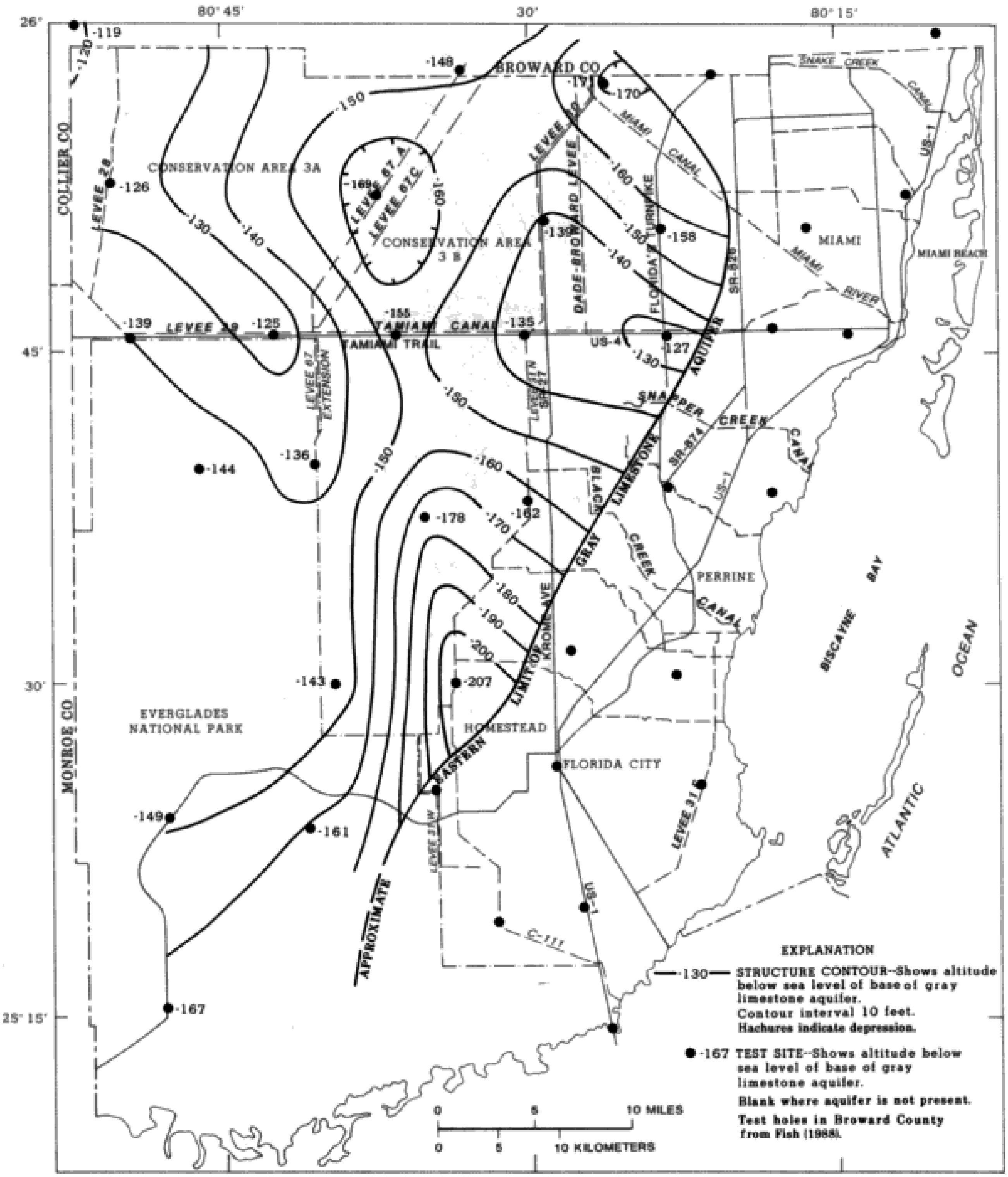


Figure 15. Configuration of the base and approximate eastern limit of the gray limestone aquifer in Dade County.

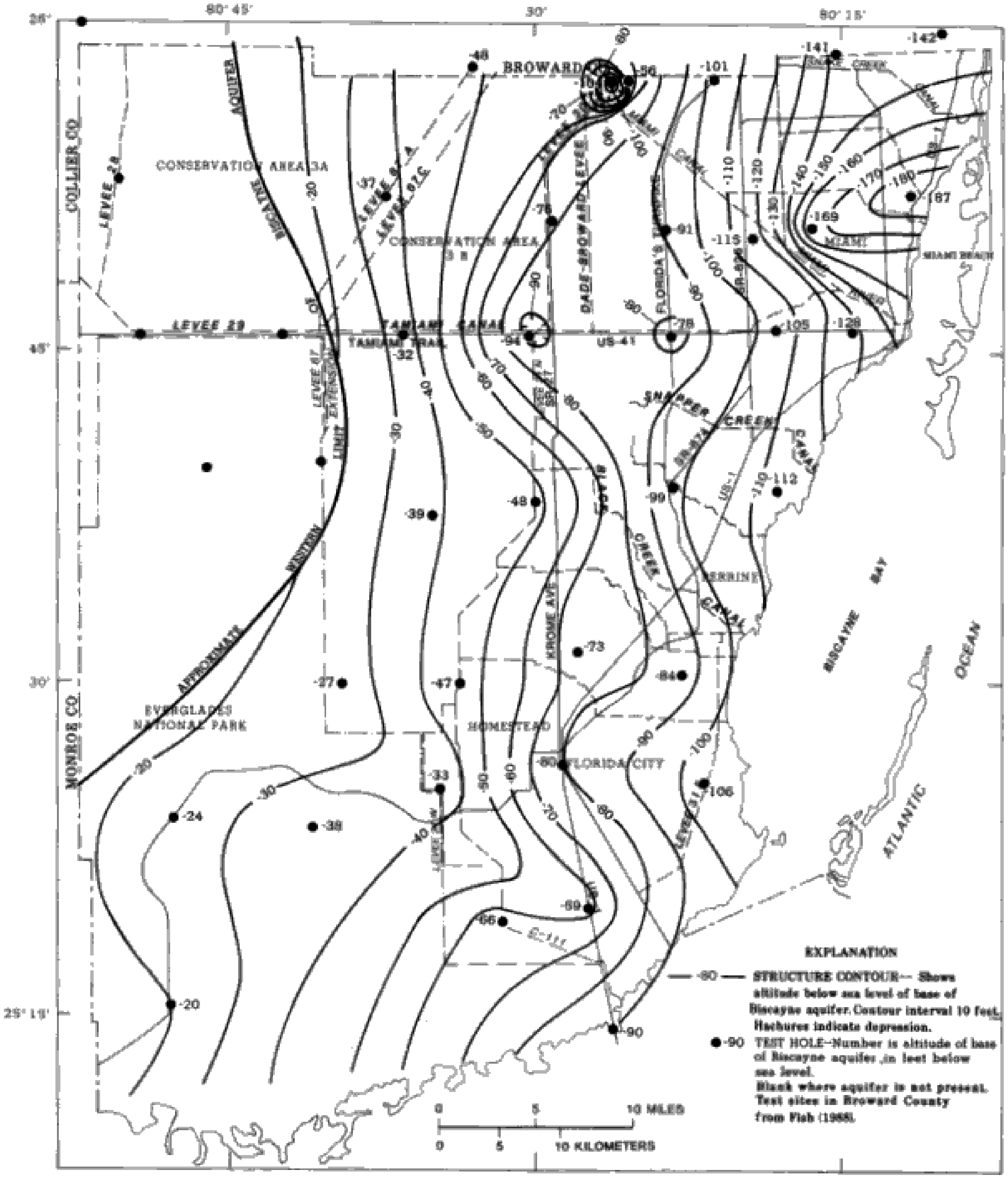


Figure 16. Configuration of the base and approximate western limit of the Biscayne aquifer in Dade County.

of 180 to 220 ft below sea level over most of Dade County. The highest bottom elevation (138 ft below sea level) and minimum thickness of the surficial aquifer occur in southeastern Dade County. Two other high areas at about 150 to 160 ft below sea level occur in northwestern and north-central Dade County. A shallow basin reaching a depth of 238 ft below sea level occurs in west-central and southwestern Dade County. The lowest elevation of the base and greatest thickness of the surficial aquifer system occur in northeastern Dade County where the base slopes downward to greater than 260 ft below sea level, as it does in eastern Broward County (Fish, 1988, fig. 35).

Contours of the elevation of the top and base of the highly permeable gray limestone aquifer in the Tamiami Formation are shown in figures 14 and 15, respectively. The aquifer, as mapped, includes all intervals of the gray limestone that are at least 10 ft thick and have an estimated hydraulic conductivity of at least 100 ft/d. Also included are highly permeable beds of coarse, shelly sands (sometimes with sandstone) that are contiguous with limestone above or below or are likely to connect laterally with the limestone (pl. 2, well G-3303; pl. 4, well G-3394). An example of a highly permeable, shelly sand that probably is not connected with the gray limestone and, therefore, only a local source of water, is the layer at about 80 ft below land surface at the Context Road West site (pls. 4 and 7, well G-3394).

The base and the top of the gray limestone aquifer have similar configurations. They are highest in the northwestern corner of the county (about 120 and 50 ft below sea level. respectively) and slope downward to the east and to the south. Both maps (figs. 14 and 15) indicate a trough in the southeastern part of the gray limestone aquifer which overlies a basin in the base of the surficial aquifer system (fig. 13). The lowest elevations of the base and top of the gray limestone aquifer (207 and 176 ft below sea level) occur within this trough. Figures 14 and 15 also show a local high area centered near US-41 and Florida's Turnpike.

In northwestern Dade County, the approximate eastern limit of the gray limestone aquifer is shown where the aquifer merges with the Biscayne aquifer and the intervening semi-confining unit pinches out. South of Tamiami Trail, the boundary marks the transition to less-permeable clastic sediments.

The base and approximate western limit of the Biscayne aquifer are shown in figure 16. Near the western limit of the Biscayne aquifer, the base is about 20 ft below sea level and then slopes downward to the east at an average of about 3 to 4 ft/mi, forming a wedge-shaped aquifer. In coastal southeastern Dade County, the base is 100 to 120 ft below sea level, but in coastal northeastern Dade County, a basin or trough reaches a depth of at least 187 ft below sea level. However, this basin is not as deep as the basin in eastern Broward County where the base reaches depths of more than 300 ft below sea level (Fish, 1988, fig. 37). Data and contours from the map of adjacent Broward County were considered along with the new Dade County data for the preparation of figure 16 in this report. An unusual configuration occurs along Tamiami Trail near State Road 27 (SR-27) because a thick section of highly permeable limestone in the upper part of the Tamiami Formation in that area is included in the Biscayne aquifer.

The western limit of the Biscayne aquifer is drawn where the thickness of very highly permeable limestone is estimated to be 10 ft. Although the Fort Thompson Formation continues to the west of the designated boundary, test drilling and specific-capacity tests reported by Appel and Klein (1969; see fig. 8 and table 3 of this report) and also conducted in this investigation (pls. 1-3, 6, and 7 and table 5) indicate a relatively thin formation with low transmissivity and hydraulic conductivity. From about 4 to 5 mi east of the boundary to the indicated boundary, the transmissivity decreases from several hundred thousand feet squared per day to only a few thousand feet squared per day, and the hydraulic conductivity decreases from tens of thousands feet per day to several hundred feet per day.

Transmissivity Distribution of the Surficial Aquifer System

Transmissivity data and the generalized distribution of transmissivity of the surficial aquifer system in Dade County are shown in figure 17. Also shown is the approximate western limit of the Biscayne aquifer from figure 16. The transmissivity values at the two westernmost sites along the Tamiami Trail are the sum of results from tests in the gray limestone aquifer and the minor water-bearing zone in the Fort Thompson Formation.

The lines shown in figure 17 represent approximate boundaries that separate areas of general ranges of transmissivity. The data suggest that local variations in transmissivity for Dade County are smaller than in Broward County (Fish, 1988, fig. 38). However, site-specific investigations of transmissivity and hydroge-

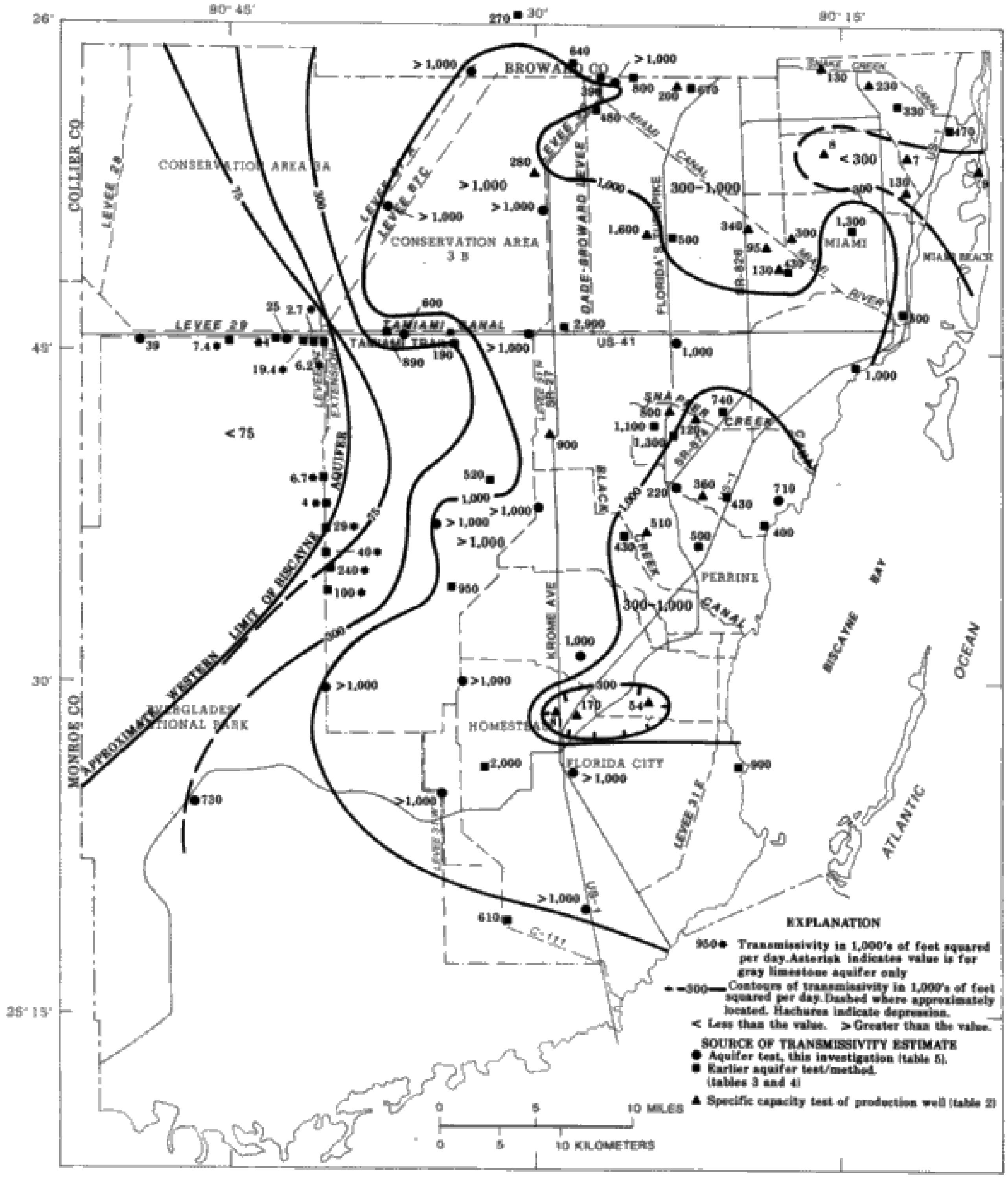


Figure 17. Generalized distribution of transmissivity of the surficial aquifer system in Dade County.

ology may often be necessary for local development of the water resources. In addition to the aquifer-test data, other information used to guide mapping includes the hydrogeologic test drilling results (particularly in areas where aquifer-test data are unavailable), water-level gradients, and well-field drawdowns.

The transmissivity of the surficial aquifer system increases from less than 75,000 ft^2/d in westernmost Dade County to greater than 1,000,000 ft^2/d in a large area centered around Krome Avenue SR-27 in central and south eastern Dade County. Transmissivities near Homestead may exceed 2,000,000 ft^2/d. Most of Dade County lies within an area of very high transmissivity (greater than 300,000 ft^2/d), and the rest of the county mainly lies within an area of relatively low transmissivity (less than 75,000 ft^2/d). A steep gradient of transmissivity, associated with the westward pinching out of highly permeable zones in the Fort Thompson Formation and possibly the Miami Oolite, occurs between these two areas. The boundary between transmissivities greater than 75,000 ft^2/d and those less than 75,000 ft^2/d closely follows the approximate western limit of the Biscayne aquifer.

Transmissivity of the Biscayne aquifer varies with the lithology of the geologic formations present and with the thickness of zones with well-developed secondary-solution porosity. The area that has transmissivities greater than 1,000,000 ft^2/d coincides with the thickest sequence of the Fort Thompson Formation or the Key Largo Limestone. These units have little sand in that area. The decrease in transmissivity to the west corresponds to the thinning of highly permeable marine beds in the Fort Thompson Formation. The relatively lower transmissivity of northeastern and coastal east-central Dade County (fig. 17) corresponds with the predominance of the Anastasia Formation, the Miami Oolite, and the upper part of the Tamiami Formation limestones or sandstones. This decrease occurs although there is an increase in thickness of the Biscayne aquifer (fig. 16) because sand and calcareous sandstone become the principal lithologies. West of the western limit of the Biscayne aquifer, most of the transmissivity of the surficial aquifer system is associated with the gray limestone aquifer. Transmissivities of the gray limestone, determined in this investigation, ranged from 5,800 to 39,000 ft^2/d.

GROUND-WATER FLOW SYSTEM

Present Flow System

The sources of recharge to the surficial aquifer system in Dade County are: (1) infiltration of rainfall or irrigation water through surface materials to the water table; (2) infiltration of surface water imported by overland flow from the north in the water-conservation areas or by canal; (3) infiltration of urban runoff by way of drains, wells, or ponds; and (4) ground-water inflow from southwestern Broward County. Soil types (fig. 5) have significant control on the rate of recharge. Seasonal variations in recharge also occur. Recharge by rainfall is greatest during the wet season, from June to November, and recharge by canal seepage is greatest during the dry season, from December to May.

Discharge from the surficial aquifer system is by: (1) evapotranspiration; (2) ground-water flow to canals, to the sea, and to Monroe County along western Dade County; and (3) wells pumped for municipal, industrial, domestic, and agricultural supplies. Evapotranspiration and ground water discharge are greatest during the wet season when water levels, temperature, and plant growth rates are high. Most of the water that circulates within the surficial aquifer system is discharged by canals. Quantitative information on canal-aquifer relations in Dade County has been provided by Leach and others (1972). Although pumpage constitutes only a small part of the total discharge from the aquifer, its effect is amplified because it is greatest during the dry season when recharge and aquifer storage are smallest. Municipal pumpage currently is about 350 Mgal/d (Garrett Sloan, Metro-Dade Water and Sewer Authority, oral commun., 1987).

Ground-water level maps for the surficial aquifer system at the end of the wet and dry seasons are shown in figures 18 and 19, respectively. The maps represent the aver age of water levels for September (wet season) and for April (dry season) during the period 1974-82, respectively. Some areas of recharge and discharge and generalized directions of flow may be interpreted from the maps, as shown by arrows in figure 18.

The highest water levels in Dade County are maintained in Water Conservation Areas 3A and 3B. The September average water levels are about 10 to 11 ft above sea level along the Dade-Broward County line in Conservation Area 3A, and about 7 to 8 ft above sea level in Conservation Area 3B (Fish, 1988, fig. 40).

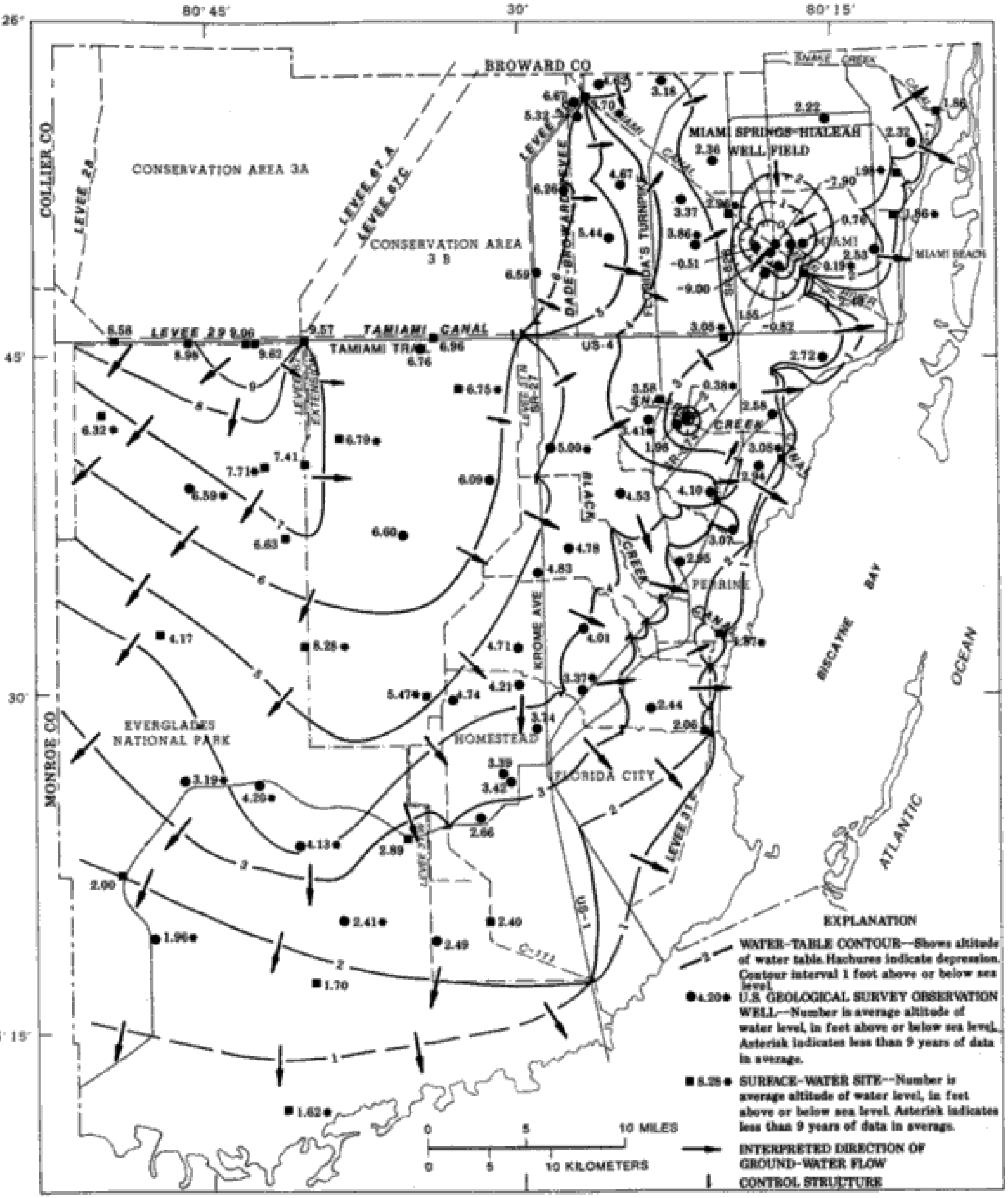


Figure 18. Average configuration of the water table in Dade County in September and interpreted directions of ground-water flow based on the period 1974-82.

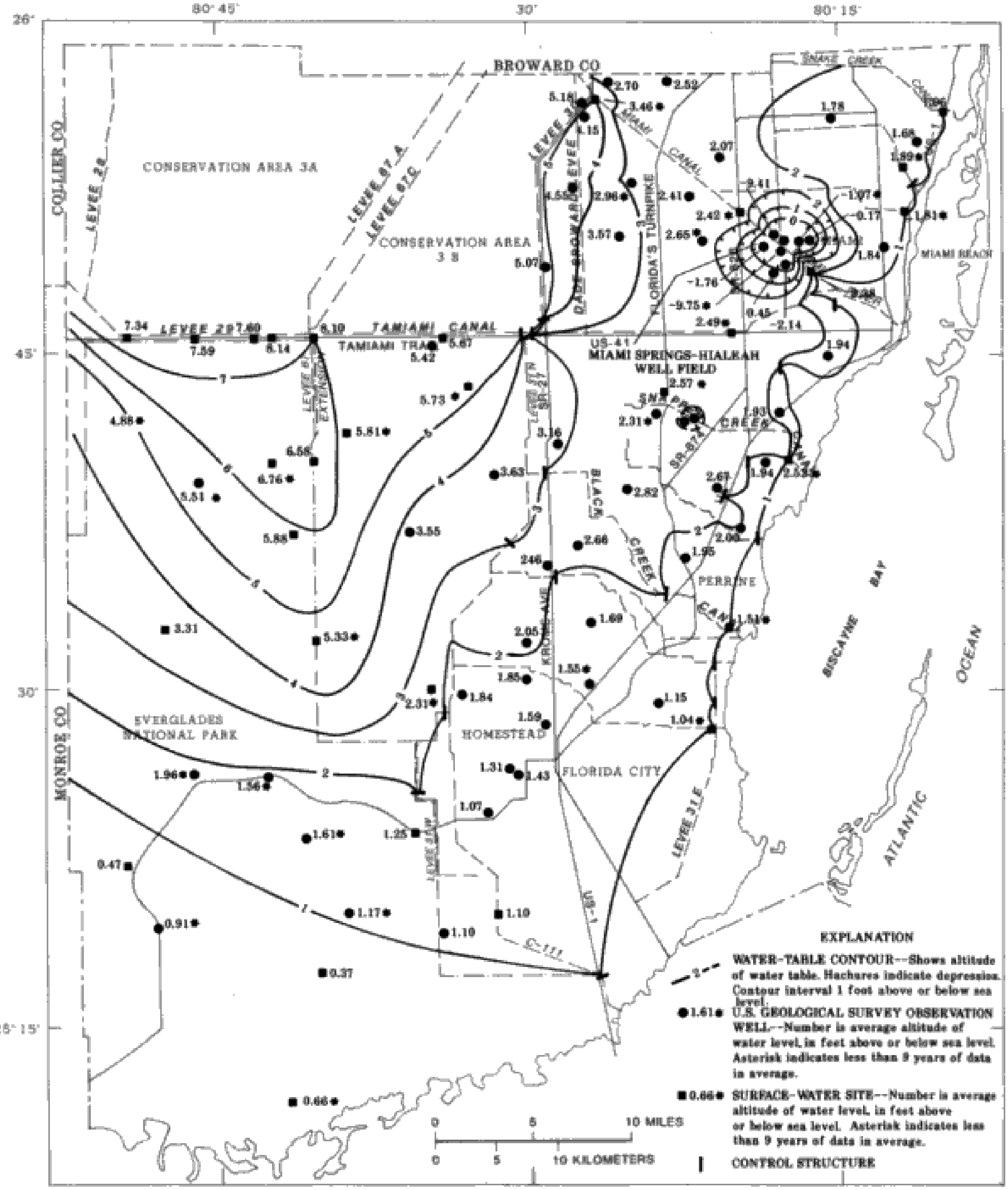


Figure 19. Average configuration of the water table in Dade County in April based on the period 1974-82.

During the wet season, ground-water seepage from the water-conservation areas is partly captured by the peripheral canals, but large quantities of water pass under the canals or across the canals, especially through openings in the south bank of the Tamiami Canal. From a regional perspective, ground water moves eastward or southward from the water-conservation areas to the sea. Canals, control structures, or large well fields cause local variations in flow pattern. Although the highest monthly average water levels occur in September, nearly all of the urbanized areas of Dade County have water levels less than 4 ft above sea level during that month. The lowest water levels are within the cones of depression around the major well fields. The largest drawdown cone for the mapped period was at the Miami Springs-Hialeah Well Field (fig. 9 and table 2, sites 40 and 41) where the lowest average water level was at least 9 ft below sea level (fig. 18).

Although recharge occurs over most of Dade County during rainstorms, the low coastal water levels and the low, but continuous, seaward gradient (fig. 18) indicate the very high transmissivity of the aquifer, the high degree of interconnection between the aquifer and the canals, and the effectiveness of the present canal system in rapidly draining floodwaters. This is evident by comparing figure 18 with the temporary high water conditions, shown in figure 20, caused by extreme rainfall in September 1960, before the south Dade County drainage system was completed. The water table formed an elongated mound that closely follows the coastal ridge. Since the completion of the southern Dade County drainage system in 1968, smaller intercanal mounds form as a result of heavy rains, and water-level recession rates are faster (Klein and others, 1975, p. 89).

The contour map of average water levels for April, near the end of the dry season (fig. 19), indicates the same ground water flow pattern as under wet-season conditions (fig. 18). However, the average water levels and the water-level gradients are lower in the dry season than in the wet season. In northeastern and coastal central and southeastern Dade County, water-level declines during the dry season generally ranged from 0.5 to 1 ft. Within Everglades National Park and along Tamiami Trail, declines were about 0.7 to 1.6 ft. The largest declines (about 2-3 ft) occurred from the area east of Everglades National Park to just east of Krome Avenue.

Predevelopment Flow System

Predevelopment hydrologic conditions in Dade County have been described by Parker and others (1955, p. 580-584). During that time, ground-water and surface-water levels were higher than at present, many springs discharged along the shoreline and on the bottom of Biscayne Bay, and freshwater wells flowed near the mouth of the Miami River. In the Coconut Grove area, water filled The Everglades and ponded behind the Atlantic Coastal Ridge (sometimes termed a "reef" in historical reports) to within 3 mi of Biscayne Bay. Dry-season water levels were about 10 ft above sea level. During the wet season, water rose sufficiently high to flow the "reef" through low spots in the Atlantic Coastal Ridge and the Miami River.

The first serious efforts to change the natural hydrologic conditions began in 1907 in the New River Basin in Fort Lauderdale (outside the study area) and in 1909 in the Miami River. Dredging operations deepened the Miami River through the Atlantic Coastal Ridge and extended a channel (canal) into The Everglades. As a result, the water level near the canal was lowered from land surface to 6 ft below land surface (Parker and others, 1955, p. 584). Water formerly stored in The Everglades was allowed to flow freely to the ocean. By 1913, both the New River Canal and the Miami Canal had been completed to Lake Okeechobee. The result was drainage of The Everglades and a general lowering of water levels by several feet.

The lowering of water levels in The Everglades had several major hydrologic consequences. The natural flow system was disturbed so that the coastal springs and artesian wells no longer flowed. More importantly, the freshwater-saltwater interface, originally along the coast because of the high water table, began to encroach landward. Gradually, many private supply wells near the coast and the Miami public well field had to be moved farther inland. Other uncontrolled coastal drainage canals were installed, and the lowest water levels of record occurred in May and June 1945 (Klein and others, 1975) at the end of a prolonged drought (fig. 21). In northern Dade County, the hydraulic gradient was seaward, but only 1.5 ft in 18 mi, and in southern Dade County water levels were below sea level because of evapotranspiration. After this drought, control structures were placed in the canals near the coast to prevent overdrainage, and canals were gradually extended inland to provide better stormwater drainage.

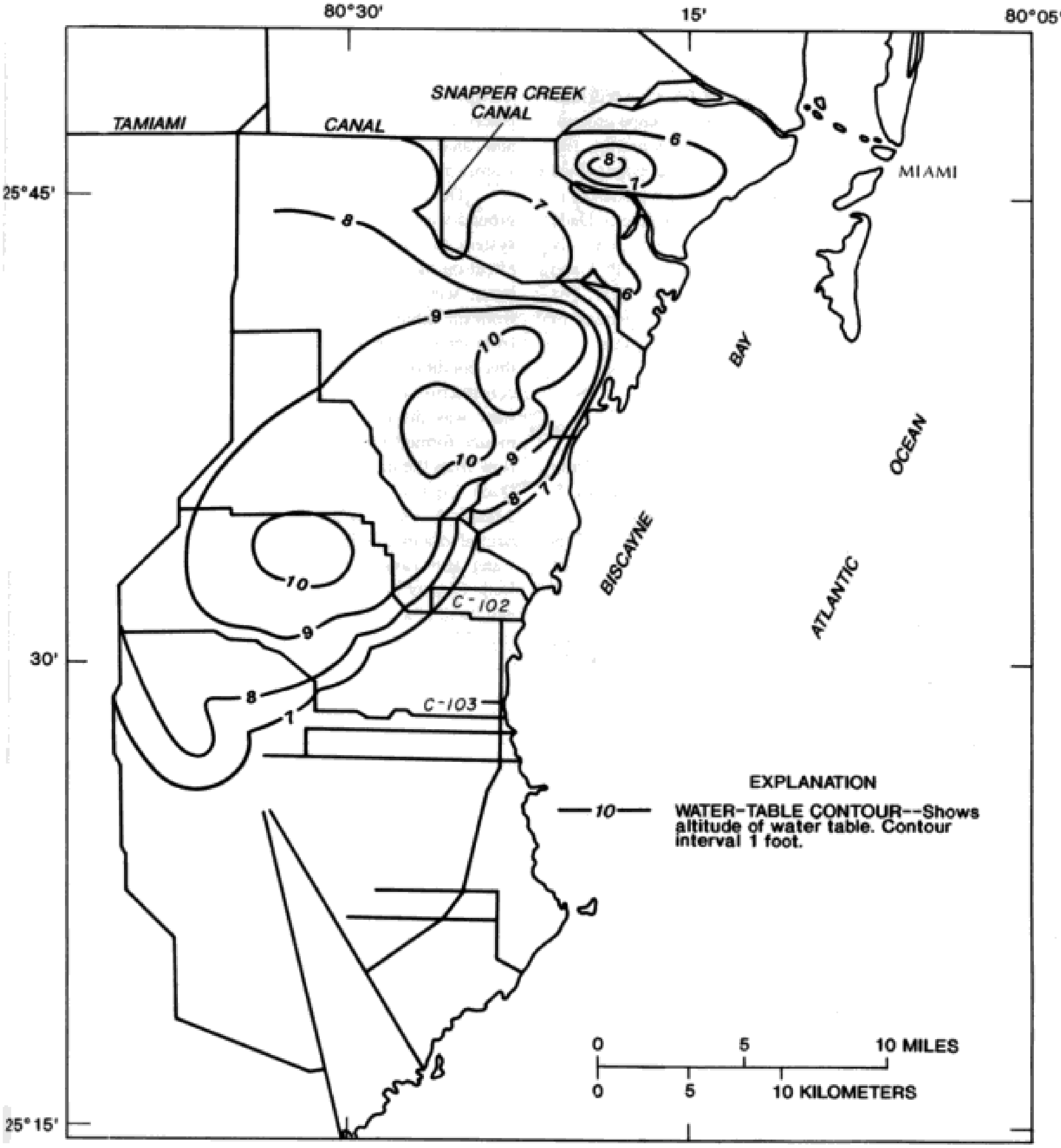


Figure 20. Average configuration of the water table in eastern Dade County for September 1960 (from Klein and others, 1975, p. 63).

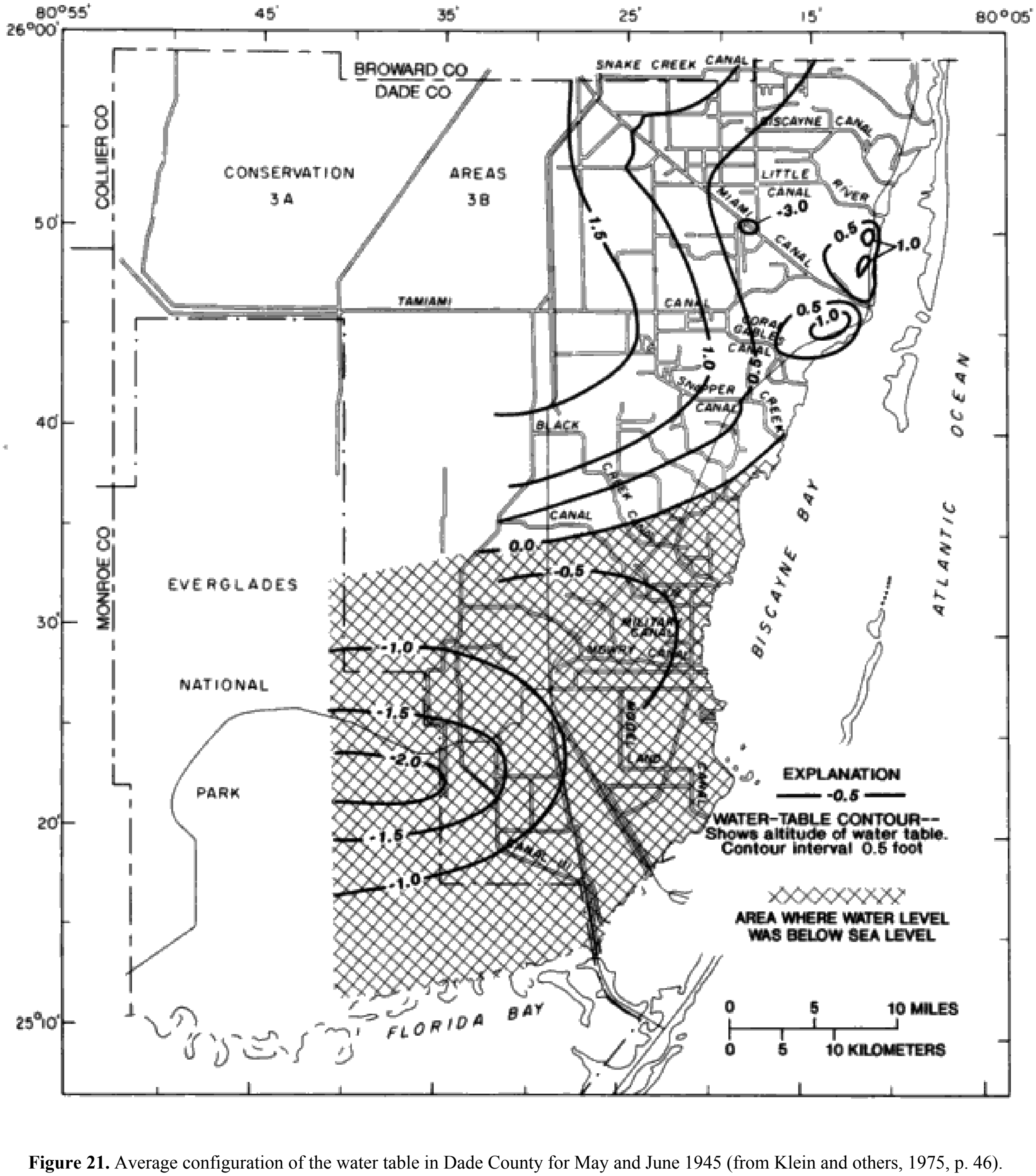


Figure 21. Average configuration of the water table in Dade County for May and June 1945 (from Klein and others, 1975, p. 46).

The reduction or elimination of a seasonal or temporary ground-water mound by construction of the present drainage system, as shown in figures 18 and 20, has had a substantial effect on the ground-water flow system. Under predevelopment, wet-season conditions, ground water flowed away from the mound in all directions, including westward away from the coast. Parker and others (1955, p. 211) stated that this condition commonly occurred in this area before the construction of the drainage canals. Some of the westward flow was discharged to The Everglades by springs. The mound formed a temporary ground-water divide or barrier to flow from the interior toward eastern or southeastern coastal Dade County. It was approximately coincident with the Atlantic Coastal Ridge (fig. 4) and areas that have good natural drainage (fig. 5). Specific conductance of ground water at various depths in the surficial aquifer system of Dade County indicates that the lowest values occur approximately under and immediately to the west of the ridge (fig. 22) (Sonntag, 1987, pls. 1 and 2). The low values of specific conductance (fig. 22) indicate that the high heads of the mound allowed recharge in that area to reach the deepest parts of the surficial aquifer system. When the mound dissipated during the dry season so that a seaward hydraulic gradient again existed, ground water would flow under the ridge to the ocean. Although recharge is still significant along the ridge, temporary mounds now are much lower and are shorter in duration because many canals have been cut into or across the ridge for flood protection (Klein and others, 1975, p. 89). These canals effectively short circuit the flow paths, thereby causing more rapid drainage of ground water.

Fish (1988) presents data and describes part of a regional ground-water flow system in which water enters northwestern Dade County from continuations of the Biscayne aquifer, the gray limestone aquifer, and the basal sand unit in Broward County. Water enters the gray lime stone aquifer by downward leakage in parts of western Broward County and southeastern Hendry Counties. The specific conductance of water in the gray limestone aquifer and basal sand unit in western Broward County generally ranges from 1,000 to 7,000 μS/cm. Topographic relief in The Everglades is very low, and under predevelopment conditions, water-table gradients were very low, which would have restricted recharge to the ground-water system and allowed only sluggish ground-water flow. Also, in northwestern Dade and southwestern Broward Counties, the top of the surficial aquifer is composed of low permeability peats and marls that inhibit recharge by downward seepage from The Everglades. Water quality in the gray limestone aquifer, west of the western limit of the Biscayne aquifer in northwestern Dade and southwestern Broward Counties, reflects the low recharge rates, low hydraulic gradients, lower transmissivities, and probably very low vertical and horizontal ground-water flow velocities that existed under predevelopment conditions. The lower permeability sediments of the upper clastic unit of the Tamiami Formation, which separate the gray limestone from the overlying Fort Thompson Formation in northwestern Dade County, also restrict recharge of fresher waters to the gray limestone aquifer. To the east under the coastal ridge, where the upper clastic unit sediments grade into highly permeable

Table 7. Water levels in wells at site U.S. Highway 1 south, February 20, 1986
[USGS, U.S. Geological Survey]

USGS well number	USGS site identification number	Open interval (feet below land surface)	Water level (feet above sea level)
G-3324A	251948080271802	17--18	1.63
G-3324B	251948080271803	28--30	1.63
G-3324C	251948080271804	57--60	[1]1.07
G-3324D	251948080271805	87--90	2.19
G-3324	251948080271801	235--238	2.61

[1]Water level uncorrected for denstinty. All wells were open to freshwater, except for well G-3324C. During Drilling, the specific conductance at a depth of 60 feet was 33,000 microsiements per centimeter

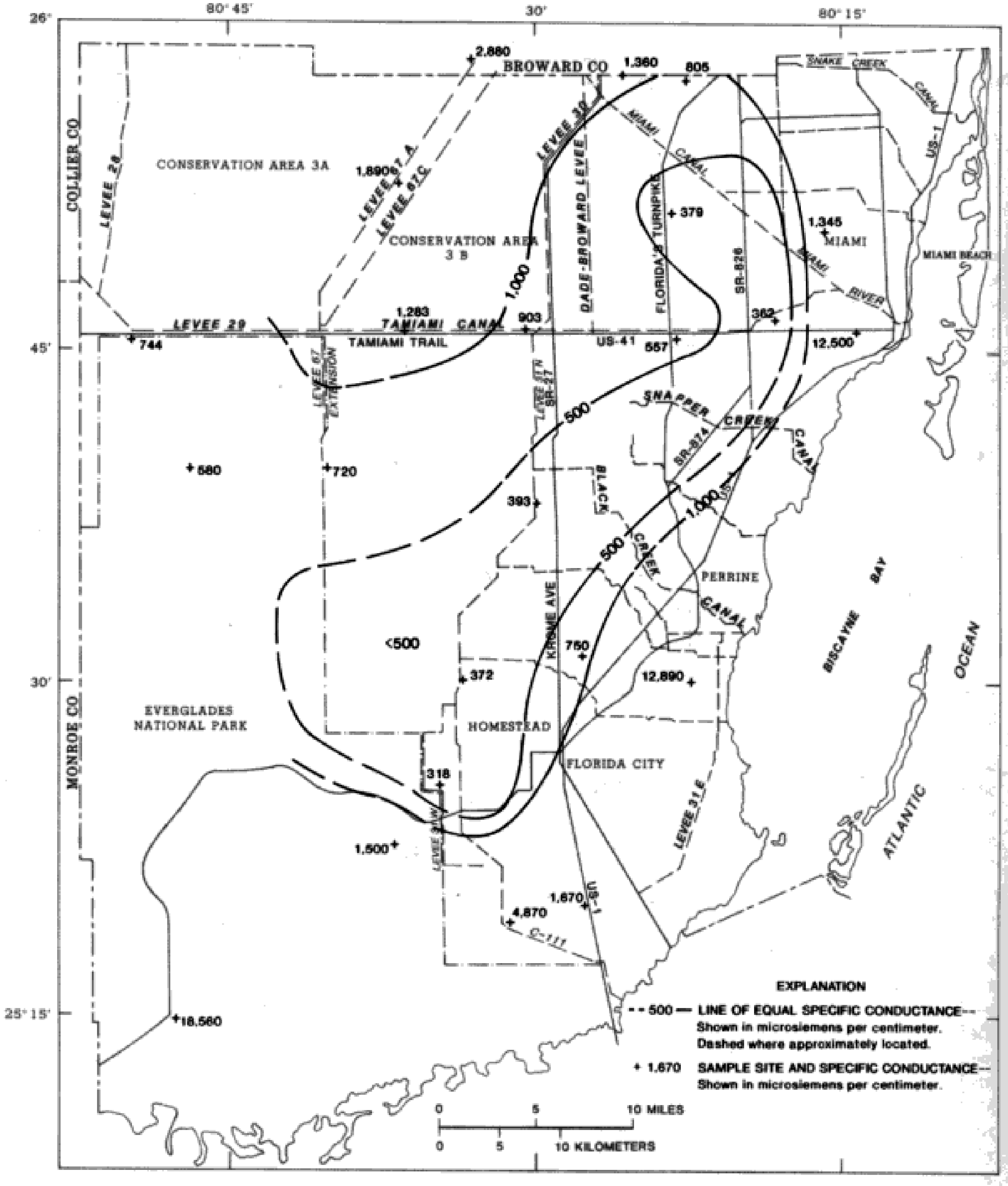


Figure 22. Specific conductance of ground water in wells open to zones between 150 and 250 feet below land surface in Dade County.

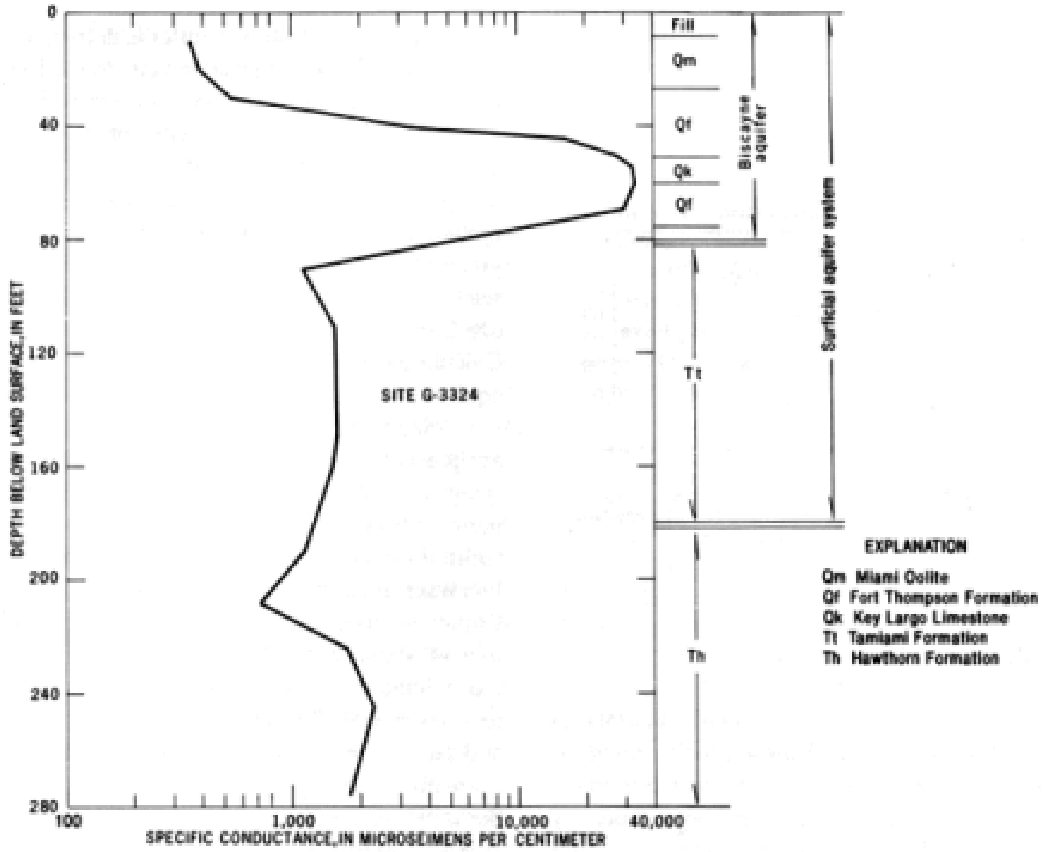


Figure 23. Depth of specific conductance in ground water in well G-3324, southeastern Dade County.

limestones and sand stones, water quality improves in the deeper parts of the surficial aquifer.

The area with specific conductance values of ground water less than 500 µS/cm between depths of 150 and 200 ft in the surficial aquifer system (fig. 22) corresponds closely to the locations of: (1) the ground-water mound that formed under predevelopment wet-season conditions (fig. 20); (2) the high recharge areas of the Atlantic Coastal Ridge and the rockland to the west (figs. 4 and 5); and (3) the very highly transmissive area of the Biscayne aquifer (fig. 17). The deep, active ground-water flow system, which formed seasonally in this area under predevelopment conditions, provided large volumes of low dissolved-solids waters that flowed downward, eastward (forcing the saltwater interface toward the coast), and westward into the gray limestone aquifer, displacing the higher dissolved-solids waters in the gray limestone to the northwest.

Along the coast where discharge from the ground-water flow system occurs, there is a freshwater-saltwater interface. The interface in the Biscayne aquifer has been studied and described in several reports (see "Previous Investigations"). However, in southeastern Dade County at the US-1 south site (G-3324), data collected during test drilling do not show the normal increase in specific conductance with depth once the zone of mixing is encountered (fig. 23). The top of the zone of mixing is encountered at a depth of 30 ft, and specific conductance reaches 33,000 µS/cm at 60 ft. A semiconfining layer at the base of the Biscayne aquifer separates the saltwater (specific conductance about 35,000 µS/cm) in the lower part of the aquifer from an underlying zone of freshwater (specific conductance averaging about 1,700 µS/cm below 90 ft). Water levels in wells (table 7) indicate an upward gradient with head differences of 0.98 ft from the deepest well to the water table and 0.56 ft from the 90-ft well to the water table.

SUMMARY AND CONCLUSIONS

The surficial aquifer system in Dade County is composed of all sediments from land surface to the top of the intermediate confining unit. Ground-water circulation in the surficial aquifer system is unconfined and determined by water-table elevations. The base of the surficial aquifer system in most places is marked by the strong contrast in permeability between slightly clayey sand in the lower part of the Tamiami Formation and thick deposits of clay, silt, and sandy clay either in the upper part of the Hawthorn Formation or the lowermost part of the Tamiami Formation. The surficial aquifer system, having sediments that range more than about seven orders of magnitude of hydraulic conductivity, is comprised of the Biscayne aquifer and gray limestone aquifer, which are separated by a mostly clayey sand semiconfining bed.

The previous definition of the Biscayne aquifer has been redefined to include specific hydraulic conductivity and thickness criteria. The Biscayne aquifer is composed of all or parts of the Pamlico Sand, Miami Oolite, Anastasia Formation, Key Largo Limestone, Fort Thompson Formation, and contiguous, underlying, highly permeable limestone or sand stone of the Tamiami Formation where at least 10 ft of the section is very highly permeable, having horizontal hydraulic conductivities of 1,000 ft/d or greater. This definition of the Biscayne aquifer differs from previous studies in that less of western Dade County is included within the boundaries of the aquifer, and the aquifer is substantially thicker near the coast. The upper part of the Biscayne aquifer is composed primarily of quartz sand in the east and dense limestone, peat, and lime mud with sand in the west; the lower part consists of highly to very highly permeable limestone and calcareous sandstone that has abundant solution cavities and some inter-bedded quartz sand. Hydraulic conductivities of the very highly permeable zone of the Biscayne aquifer may exceed 10,000 ft/d.

The gray limestone aquifer is defined as that part of the predominantly gray limestone beds in the lower, and locally the middle, part of the Tamiami Formation that is highly permeable (hydraulic conductivities of about 100 ft/d or greater) and at least 10-ft thick. Lateral changes of this limestone to less-permeable, clayey, sandy limestone or carbonate sand are included in the aquifer where hydraulic conductivities are greater than 100 ft/d. The top of the aquifer is at 50 ft below sea level in northwestern Dade County and reaches a maximum depth of more than 170 ft below sea level near Homestead. Calculated hydraulic conductivities in the gray limestone aquifer range from 210 to 780 ft/d in Dade County.

Sediments that have moderate to very low permeability are present within semiconfining beds separating or under lying aquifers of the surficial aquifer system, and as less-permeable layers within the aquifers, especially the Biscayne aquifer. On the basis of two tests and values reported in the literature, most of the relatively clean sands found in Dade County are moderately permeable, with hydraulic conductivities of about 30 to 100 ft/d. Clayey or silty sands, such as those in the upper clastic unit of the Tamiami Formation, are less permeable. Silt, clay, and mixtures of lime mud, shell, and sand in the upper and lower clastic units of the Tamiami Formation have hydraulic conductivities of 0.001 to 1 ft/d. Some dense limestones within the surficial aquifer system also have relatively low hydraulic conductivities.

Analysis of test drilling results, specific capacities, and pumping tests indicates that the transmissivity of the surficial aquifer system is locally variable but has a definite areal pattern. Transmissivity exceeds 300,000 ft^2/d in nearly all of central and eastern Dade County and abruptly decreases to less than 75,000 ft^2/d in western Dade County. The decrease in transmissivity is coincident with the western boundary of the Biscayne aquifer. The very high transmissivity areas are associated with limestones and calcareous sandstones of the Biscayne aquifer, principally within the Fort Thompson Formation. Transmissivity of the gray limestone aquifer in western Dade County ranges from about 5,800 to 39,000 ft^2/d.

Circulation in the ground-water flow system has changed since development of the area because water levels, areas of discharge, and patterns of recharge have changed. Features of the water-management system that affect circulation include drainage canals, irrigation or artificial recharge, water-conservation areas, pumping stations, control structures on canals, and well fields. Canals that quickly remove large amounts of ground water during periods of high water levels greatly shorten ground-water flow paths compared to predevelopment conditions. However, it is often unclear whether canals act as fully penetrating boundaries, thereby dividing the flow system into many independent cells or as partly penetrating boundaries of flow systems. Drainage canals and pumping from large well fields have lowered coastal water levels, especially during the wet season, making the threat of saltwater encroachment into coastal well fields a serious concern.

Under predevelopment conditions, a ground-water ridge formed in eastern Dade County during the wet season. Ground-water flow was to the east and southeast on the eastern part of the ridge and generally westward into The Everglades on the western part of the ridge. Now, this ridge either does not form or is greatly reduced in elevation and duration, allowing generally eastward and southeastward flow of ground water in central and eastern Dade County throughout most of the year. Ground-water flow in western Dade County generally is to the south and probably is similar to the interpreted predevelopment pattern. Locally, deviations may occur because of drainage by major canals (such as the Tamiami Canal), differences in water level between water-conservation areas, and underflow along the southern and eastern boundaries of the water-conservation areas.

The natural water-quality characteristics of Dade County are primarily related to the flushing of seawater from the aquifer by circulation of fresh ground water prior to development and to solution of calcite. Circulation in the predevelopment ground-water flow system was controlled by water levels (such as the seasonal ground-water ridge), areas of discharge, patterns of recharge, and by the hydraulic conductivity distribution of the surficial aquifer system. Circulation was restricted, both vertically and laterally, in areas where hydraulic gradients, transmissivities, and recharge rates were low, and was more vigorous in areas where these features were high. The freshest waters were found under the coastal ridge and immediately to the west of it, and the most mineralized waters were found under The Everglades in northwestern Dade County and along the coast. Present-day water-quality distribution reflects this predevelopment flow system.

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