SUMMARY OF THE HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN FLORIDA AND IN PARTS OF GEORGIA, SOUTH CAROLINA, AND ALABAMA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–A

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By RICHARD H. JOHNSTON *and* PETER W. BUSH

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

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[Plates are in pocket]

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CONVERSION FACTORS

For readers who prefer to use SI units rather than inch-pound units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in./yr)	25.4	millimeters per year (mm/yr)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

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ABSTRACT

The Floridan aquifer system is one of the major sources of ground-water supplies in the United States. This highly productive aquifer system underlies all of Florida, southern Georgia, and small parts of adjoining Alabama and South Carolina, for a total area of about 100,000 square miles. About 3 billion gallons of water per day is withdrawn from the aquifer for all uses, and, in many areas, the Floridan is the sole source of freshwater.

The aquifer system is a sequence of hydraulically connected carbonate rocks (principally limestone and some dolomite) that generally range in age from Late Paleocene to Early Miocene. The rocks vary in thickness from a featheredge where they crop out to more than 3,500 ft where the aquifer is deeply buried. The aquifer system generally consists of an upper aquifer and a lower aquifer, separated by a less permeable confining unit of highly variable properties. In parts of north Florida and southwest Georgia, there is little permeability contrast within the aquifer system. Thus in these areas the Floridan is effectively one continuous aquifer. The upper and lower aquifers are defined on the basis of permeability, and their boundaries locally do not coincide with those for either time-stratigraphic or rock-stratigraphic units.

Low-permeability clastic rocks overlie much of the Floridan aquifer system. The lithology, thickness, and integrity of these low-permeability rocks have a controlling effect on the development of permeability and ground-water flow in the Floridan locally.

The Floridan aquifer system derives its permeability from openings that vary from fossil hashes and networks of many solution-widened joints to large cavernous openings in karst areas. Diffuse flow predominates where the small openings occur, whereas conduit flow may occur where there are large cavernous openings. For the Upper Floridan aquifer, transmissivities are highest (greater than 1,000,000 ft squared per day) in the unconfined karst areas of central and northern Florida. Lowest transmissivities (less than 50,000 ft squared per day) occur in the Florida panhandle and southernmost Florida, where the Upper Floridan aquifer is confined by thick clay sections. The hydraulic properties of the Lower Floridan aquifer are not well known; however, this unit also contains intervals of very high transmissivity that have been attributed to paleokarst development.

The dominant feature of the Floridan flow system, both before and after ground-water development, is Upper Floridan aquifer springs, nearly all of which occur in unconfined and semiconfined parts of the aquifer in Florida. Before ground-water development, spring flow and point discharge to surface-water bodies was about 88 percent of the estimated 21,500 cubic ft per second total discharge. Current discharge (early 1980's) is about 24,100 cubic ft per second, 75 percent of which is spring flow and discharge to surface-water bodies, 17 percent is withdrawal from wells, and 8 percent is diffuse upward leakage.

Pumpage has been and continues to be supplied primarily by the diversion of natural outflow from the aquifer system and by induced recharge rather than by loss of water from aquifer storage. The approximately 3 billion gallons per day pumped from the Floridan aquifer system has resulted in long-term regional water-level declines of more than 10 ft in three broad areas of the flow system: (1) coastal Georgia and adjacent South Carolina and northeast Florida; (2) west-central Florida; and (3) the Florida panhandle. Saltwater has encroached as a result of pumping in a few coastal areas.

In general, the water chemistry in the Upper Floridan is related to flow and proximity to the freshwater-saltwater interface. In the unconfined or semiconfined areas where flow is vigorous, dissolved-solids concentrations are low (less than 250 milligrams per liter). Where the system is more tightly confined, flow is more sluggish and concentrations are higher (greater than 250 milligrams per liter). Several distinct hydrochemical facies characterize the water chemistry in the Upper Floridan. In the unconfined or semiconfined areas, a calcium-bicarbonate facies is due principally to the dissolution of calcite. In coastal areas or where the system is more tightly confined, mixing of freshwater with recent or residual seawater produces a sodium-chloride facies. In the western Florida panhandle, cation exchange has produced a unique occurrence of a sodium-bicarbonate facies in the Upper Floridan.

A considerable area of the Floridan aquifer system's extent remains highly favorable for the development of large ground-water supplies. This area is largely inland and is characterized by high transmissivity and minimal development (as of early 1980's). The major constraint on future development is degradation of water quality rather than water-quantity limitations.

INTRODUCTION

The prolific Floridan aquifer system is one of the major sources of ground-water supplies in the United States The aquifer system underlies all of Florida, southern Georgia, and small parts of adjoining Alabama and South Carolina—a total area of about 100,000 mi^2. High average rainfall (about 53 in. per year) and generally flat topography combine to provide abundant recharge to the Floridan.

The aquifer system provides water supplies for many cities, including Daytona Beach, Jacksonville, Orlando, Tallahassee, and St. Petersburg in Florida and Brunswick and Savannah in Georgia. In many areas it is the sole source of freshwater. Pumpage for industrial and agricultural uses is even larger than for public supply. Withdrawals for irrigation have increased sharply in recent years; in 1980, about 3 Bgal/d were withdrawn from the Floridan for all uses. Although this stress has produced areas of regional water-level decline, and local cones of depression, more than one-half of the aquifer area has experienced no significant (greater than 10 ft) head decline in the early 1980's. However, despite the enormous amount of untapped water available from the Floridan, water is not always available where needed locally.

During 1978–83, the USGS (U.S. Geological Survey) conducted a regional assessment of the Floridan aquifer system that involved the review and synthesis of many previous studies of the Floridan, the acquisition of new data in selected areas, and the extensive use of computer models to simulate ground-water flow. This investigation, which is summarized in this report, is one of several studies of the USGS's RASA (Regional Aquifer-System Analysis) program. As discussed in the Foreword, the RASA program involves quantitative appraisals of the major ground-water systems of the United States.

REGIONAL ANALYSIS OF THE FLORIDAN AQUIFER SYSTEM

BACKGROUND, MAJOR OBJECTIVES, AND APPROACH

The Floridan aquifer system is made up of several Tertiary carbonate formations that are hydraulically connected to form a regional hydrologic unit; locally, however, there are significant differences in its water-bearing properties, water chemistry, and flow. Development has proceeded unevenly with large withdrawals concentrated in a few areas. For example, in northwest-central Florida, there is a very active near-surface flow system characterized by high permeability, high rates of recharge, very large spring flows, and insignificant development as of the early 1980's. In contrast, along the coastal strip from Savannah, Ga., to Jacksonville, Fla., the Floridan is deeply buried and prior to development had a very sluggish flow system. Currently, the heavy withdrawals along this strip have caused a regional decline in artesian head and significant changes to the flow system.

Specifically, the objectives of the Floridan aquifer-system study were: (1) to provide a complete description of the hydrogeologic framework and geochemistry of the aquifer system, (2) to define the regional flow system, and (3) to assess the effects of ground-water development on the system. Computer simulation was used extensively to understand the flow system, and locally the computer models were used to evaluate the effects of increased development. The approach to the Floridan study described here is two-tiered; to focus on (and document) local flow systems while tying together in a regional analysis the individual segments of the aquifer system.

Prior to the study, there existed much information on the geologic framework and aquifer hydraulic characteristics. In several areas, flow models had been developed with predictive capability. However, the greatest amount of data and the modeling efforts tend to be clustered around a few major pumping centers. Data are scarce in some areas where there are large untapped ground-water supplies.

To meet the project objectives, initial efforts concentrated on the assembly and analysis of the vast amount of data on the Floridan. A series of regional hydrogeologic, geochemical, and potentiometric-surface maps was prepared (Miller, 1982a, b, c, d, and e; Sprinkle 1982a, b, c, and d; Johnston, Healy, and Hayes, 1981; and Johnston and others, 1980).

A data-collection program was undertaken to fill data gaps. This work involved a program of exploratory drilling, aquifer tests, seismic surveys (onshore and offshore), selective geochemical sampling, and mass measurement of water levels and artesian pressures. A notable example of these activities was the collection of hydrologic and geochemical data from an abandoned oil exploratory well 55 mi offshore from the Florida coast (Johnston and others, 1982).

Computer simulation involved the design and calibration of a "coarse-mesh" regional model and four subregional models. The goal of the regional model was to understand major features of the regional flow system. The regional model design and simulation results of predevelopment conditions were described by Bush (1982). Four subregional models focus on the areas of greatest ground-water development. Preliminary reports describing model design and results of subregional predevelopment aquifer-system simulation have been prepared for three areas: southeast Georgia, including small adjacent parts of South Carolina and Florida (Krause, 1982); west-central Florida (Ryder, 1982); and east-central Florida (Tibbals, 1981).

PURPOSE AND SCOPE OF PROFESSIONAL PAPERS 1403-A THROUGH 1403-I

The Professional Paper 1403 series consists of nine Professional Papers that describe various aspects of the geology, hydrology, and geochemistry of the Floridan aquifer system. Emphasis is placed on descriptions of regional and local ground-water flow systems. In particular, the differences between predevelopment and current conditions are discussed in order to document the effects of ground-water development.

Professional Paper 1403-A (this report) summarizes important aspects of the hydrogeologic framework, hydraulic properties of the aquifers, regional flow system, effects of ground-water development, and geochemistry, which are discussed in detail in Professional Papers 1403-B through 1403-I.

Professional Paper 1403-B (Miller, 1986) presents the hydrogeologic framework of the Floridan aquifer system. The Floridan was subdivided into regional aquifers and confining units that provide a generalized permeability distribution so that we could analyze the flow system by computer simulation and relate the water chemistry to the flow system. Locally the aquifers and confining units may coincide with formally named geologic formations and groups. However, regionally neither the top nor base of the Floridan, nor its component aquifers and confining units, coincide with geologic-formation contacts. Thus Professional Paper 1403-B is concerned not only with descriptions of the stratigraphic units and hydrologic units but also the relations between them. It also addresses how geologic structure and the distribution of sedimentary facies have affected the pemeability distribution and provided controls on regional groundwater flow.

Professional Paper 1403-C (Bush and Johnston, in press) discusses ground-water hydraulics, including aquifer and confining-unit properties, and describes features of the regional flow system. Inferred conditions prior to development are discussed and are compared to documented current conditions that reflect the effects of pumping. This comparison is concerned primarily with long-term changes in water levels and with changes in the rates and distribution of recharge and discharge caused by development. This regional analysis relies heavily on the results of computer simulation of the regional flow system.

To address the hydrology in more detail and to investigate local water problems, the Floridan aquifer system was divided into five subareas on the basis of natural (predevelopment) ground-water divides. Figure 1 shows the five subareas, which are the subjects of Professional Papers 1403-D through H.

Professional Paper 1403-D (Krause and Randolph, in press) discusses the hydrology of the Floridan in southeast Georgia, including adjacent parts of South Carolina and northeast Florida. This part of the system is characterized by the largest area of artesian head decline within the Floridan. Differences between the relatively sluggish predevelopment flow system and the current heavily pumped system are emphasized. Computer simulation is used to evaluate various alternative development schemes for the future.

Professional Paper 1403-E (Tibbals, in press) summarizes the hydrology of the Floridan in east-central Florida. Currently (early 1980's), pumpage accounts for about one-third of the aquifer discharge; however, declines in the artesian head occur in only a few small areas. Computer simulation is used to evaluate the predevelopment and current flow systems as well as to evaluate the effects of future increases in pumpage. Large springs and drainage wells receive special attention in this report.

Professional Paper 1403-F (Ryder, 1986) describes the Floridan hydrology in west-central Florida. Withdrawals in this area are about 1 Bgal/d; however, the large springs in the northern part of this area still remain the dominant feature of the current flow system. Computer simulation is used to evaluate the effects of future additional development, which is expected to be largely new municipal wells rather than pumping by the phosphate mining industry (the largest user in the early 1980's).

Professional Paper 1403-G (Meyer, in press) discusses the hydrology in south Florida, where the Floridan contains saline water and has not been significantly developed for water supply. The lack of development results in a scarcity of geologic and hydrologic data; therefore, this study involved deep test drilling, geochemical sampling, and offshore seismic surveys. This report attempts to bring together new and existing data into a new hydrologic analysis of the Floridan aquifer system in south Florida. Waste injection in the deeper parts of the Floridan, which contain seawater, is also discussed.

Professional Paper 1403-H (Maslia and Hayes, in press) describes the Floridan in southwest Georgia and the Florida panhandle. This report is primarily concerned with an analysis of two parts of these areas: (1) the 15-county Dougherty Plain area of southwest Georgia, where seasonal withdrawals for irrigation are very large and (2) the Fort Walton Beach area of the Florida panhandle, where light pumping has produced a deep widespread cone of depression.

A sixth subarea in northwest Florida and adjoining south Georgia (fig. 1) is characterized by little groundwater development and limited available hydrologic

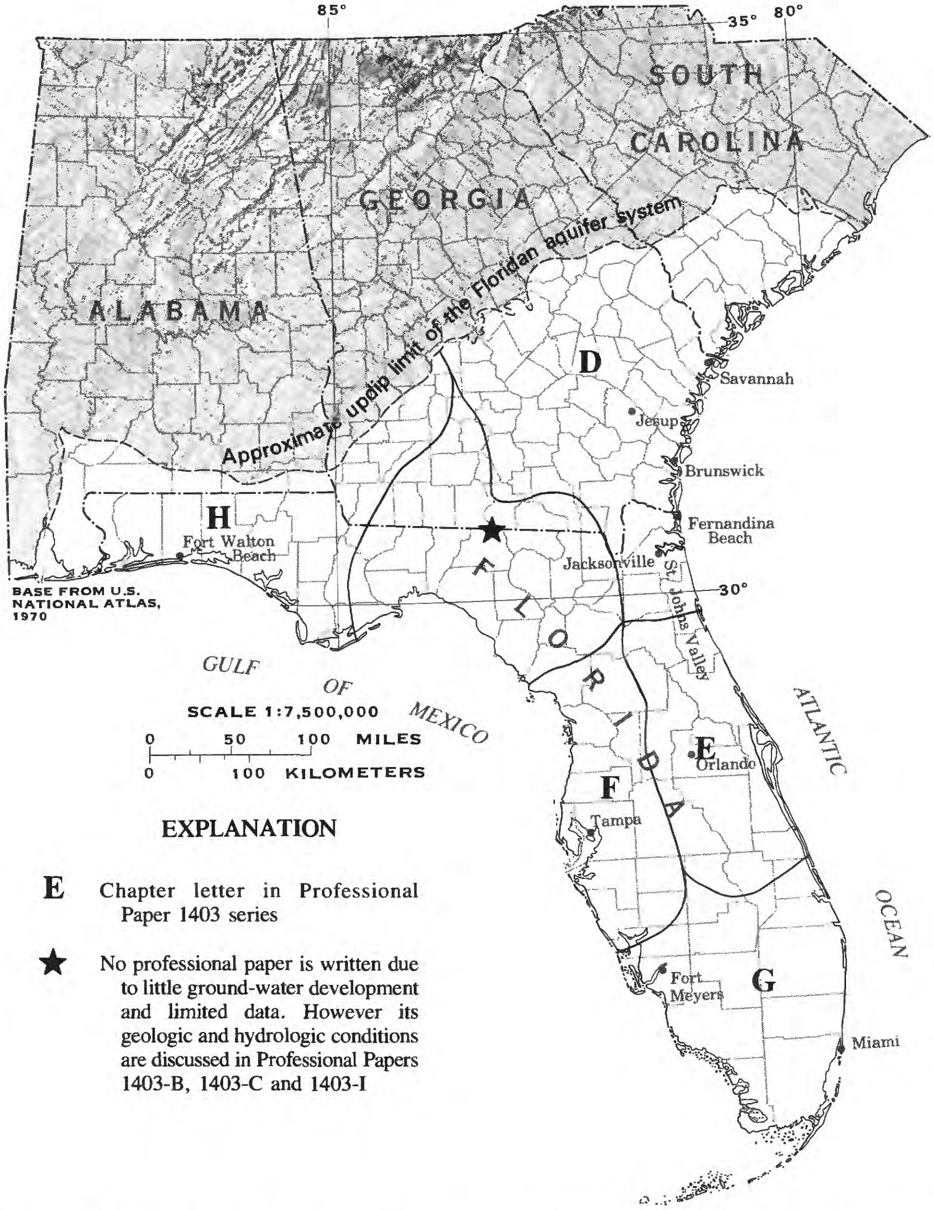


FIGURE 1.—Extent of the Floridan aquifer system, showing subareas whose hydrology is discussed in Professional Papers 1403–D through 1403–H.

data. No Professional Paper was written for this area; however, certain aspects of its hydrology are discussed in Professional Papers 1403–B, 1403–C, and 1403–I.

Professional Paper 1403–I (Sprinkle, in press) describes the geochemistry of the Floridan. The principal chemical processes that are operating in the ground-water flow system are explained using previously published and newly collected data. Quantification of the principal chemical reactions is illustrated for major segments of the flow system.

SUMMARY OF PREVIOUS WORK

Hundreds of reports describing the hydrology, geology, and water chemistry of the Floridan have been published. Many of these were used in making the observations described in the Professional Paper 1403 series, and they are referred to throughout the series. A few provided major contributions to the knowledge of the Floridan aquifer system and are noted here.

Matson and Sanford (1913) in Florida and Stephenson and Veatch (1915) in Georgia provided the first comprehensive descriptions of the hydrogeology, ground-water resources, and development of the aquifer system on a county-by-county basis. Their interpretations, which were based on limited data, are truly impressive and provide the best descriptions of the aquifer system prior to extensive development.

The earliest known potentiometric-surface map of the Floridan was prepared by Gunter and Ponton (1931), based on water-level measurements made in 1928, and covers most of northern peninsular Florida. The pioneer work of Stringfield in the early 1930's identified a regional flow system in Florida that included several Tertiary limestone units. Stringfield (1936) presented a potentiometric surface map which showed for the first time the essential features of this flow system in peninsular Florida. The contours on this map suggest areas of natural recharge and discharge and indicate general directions of ground-water movement from recharge to discharge areas. A major area of high head and thus potential recharge was shown to exist in central Florida. Later Parker and others (1955) concluded that this flow system represented a single hydrologic unit (composed of several Tertiary carbonate formations) and named the unit the "Floridan aquifer."

Important contributions to the paleontology and stratigraphy of the Tertiary limestone units include those by Applin and Applin (1944, 1964), Herrick (1961), and Puri and Vernon (1964). Herrick and Vorhis (1963) first recognized and named the "Gulf Trough," an important subsurface structural feature that exerts major control on regional ground-water flow and water chemistry in southeast Georgia.

Saltwater has encroached locally near some coastal pumping centers. Notable studies of this problem include an early State-wide summary in Florida by Black and others (1953) and an analysis of rising saline water at Brunswick, Ga. (Wait and Gregg, 1973).

The relation of the regional flow system to water chemistry has been investigated by Back and Hanshaw (1970), who described changes in water chemistry from recharge to discharge areas. They also proposed a hypothesis for dolomitization based on mixing of freshwater and saline water along a moving freshwater-saltwater interface (Hanshaw and others, 1971).

Studies of the ground-water hydraulics have proceeded from simplified analytical approaches in the 1940's to computer simulation in recent years. A notable early study was made by Warren (1944), who related widespread changes in artesian head to variation in the pumping rates at Savannah, Ga. Warren calculated head declines that would occur with increased pumping. More recently Counts and Krause (1976) used a computer model to analyze the effects of pumping at Savannah. Wilson (1982) used computer simulation to project water-level declines resulting from proposed phosphate mining in west-central Florida. Solute transport modeling was used by Bredehoeft and others (1976) to simulate the movement of saline water in the Floridan at Brunswick, Ga.

The definitive reference for the hydrogeology of the Floridan aquifer system is by Stringfield (1966). This 226-page volume presents areal hydrogeologic descriptions by county, with emphasis on the water-bearing properties of the various geologic units forming the Floridan aquifer system. Considerable hydraulic and geochemical data and regional interpretation are also presented.

Finally, it should be noted that the greatest source of information on the aquifer system is contained in the hundreds of reports published primarily by the States of Florida, Georgia, and South Carolina and in the USGS's Open-File Report and Water-Resources Investigations series. Many of these studies were made by the USGS in cooperation with various State, county, and municipal governments and Florida's water-management districts. These reports provide the basic hydrologic data as well as interpretations of the local hydrology without which this regional study could not have been successfully made.

HYDROGEOLOGY

GEOLOGIC SETTING

The Coastal Plain physiographic province of the southeastern United States is underlain by a thick sequence of unconsolidated to semiconsolidated sedimentary rocks that range in age from Jurassic to Holocene. These rocks thicken seaward in the study area from a featheredge where they crop out against older metamorphic and igneous rocks of the Piedmont and Applachian provinces to a maximum measured thickness of more than 21,100 ft in Mobile County in southern Alabama and a projected thickness of more than 25,000 ft in south Florida. Coastal Plain rocks generally dip gently toward the Atlantic Ocean or the Gulf of Mexico, except where they are warped or faulted on a local to subregional scale. Coastal Plain sediments were laid down on an eroded surface developed upon igneous intrusive rocks, low-grade metamorphic rocks, mildly metamorphosed Paleozoic sedimentary rocks, and graben-fill sedimentary deposits of Triassic to Early Jurassic age (Barnett, 1975; Neathery and Thomas, 1975; Chowns and Williams, 1983).

The poorly consolidated Coastal Plain rocks are easily eroded. Where they consist of carbonate rocks, the strata are partially dissolved by percolating water, resulting in the development of karst topography where such rocks are at or near the surface. Accordingly, the topography developed in much of the study area is characterized by extensive slightly dissected plains, low, rolling hills, and widely spaced drainage. A series of sandy marine terraces of Pleistocene age has been developed in much of the area.

Coastal Plain rocks in the project area can be separated into two general facies: (1) predominantly clastic rocks, containing minor amounts of limestone, that extend southward and eastward toward the Atlantic Ocean and the Gulf of Mexico from the Fall Line that marks the inland limit of the Coastal Plain; and (2) a thick continuous sequence of shallow-water platform carbonate rocks that underlies southeast Georgia and all of the Florida peninsula (Miller, 1986). In north-central Florida and in southeast Georgia, where these clastic and carbonate rocks generally interfinger with each other, facies changes are both rapid and complex. In general, the carbonate facies of successively younger units extends progressively farther and farther updip, encroaching to the northwest upon the clastic rocks in an onlap relation—at least until the end of Oligocene time. Miocene and younger rocks form a predominantly clastic facies that, except where removed by erosion, covers the older carbonate rocks everywhere. The various stratigraphic units within both the clastic- and carbonate-rock areas are separated by unconformities that represent breaks in sedimentation.

Cretaceous rocks generally crop out in a band adjacent to the crystalline rocks and folded strata of the Piedmont and Appalachian physiographic provinces. Rocks of Tertiary age, whose carbonate facies form most of the Floridan aquifer system, crop out in a discontinuous band seaward of the Cretaceous rocks and are also exposed in an area in west peninsular Florida. Still farther seaward is an exposed band of predominantly clastic rocks of Miocene age, which forms an upper confining unit in the Floridan aquifer system. Miocene rocks generally separate the Floridan from Pliocene and Quaternary strata that are mostly sands and form surficial (unconfined) aquifers.

FLORIDAN AQUIFER SYSTEM

DEFINITIONS AND HYDROGEOLOGIC TERMINOLOGY

The Floridan aquifer system is a sequence of carbonate rocks mostly ranging in age from Paleocene to early Miocene that are hydraulically connected in varying degrees. This carbonate sequence includes units of very high to low permeability that form a regional flow system. The existence of this flow system was first identified in peninsular Florida by Stringfield (1936), who referred to the carbonate units as the "principal artesian formations." Later Warren (1944) described an extension of this flow system in south Georgia and applied the term "principal artesian aquifer" to the carbonate units involved. Stringfield (1953, 1966) also applied the term "principal artesian aquifer" to these rocks. Parker (in Parker and others, 1955) noted the hydrologic and lithologic similarities of the Tertiary carbonate formations in southeast Florida, concluded that they represented a single hydrologic unit, and named that unit the "Floridan aquifer." Table 1 shows the geologic formations and ages of units included by Parker and Stringfield in their aquifer definitions.

The term "Floridan aquifer" is entrenched in the Florida ground-water literature and is widely used in national and international hydrologic publications. However, Stringfield's term "principal artesian aquifer" generally has been used in hydrologic reports from Georgia and South Carolina.

More recently Miller (1982a, b, c, d, e) provided the first detailed regional definition of the aquifer system, presenting maps of the top, base, and thickness of the system and its major hydrologic components. The term "Tertiary limestone aquifer system" was used in interim reports of this study by Bush (1982), Johnston and others (1980 and 1981), Miller (1982a, b, c, d, and e), and Sprinkle (1982a, b, c, and d). This term was used because it combined the age of the rocks and their general lithology into the name of the aquifer system.

At a later stage in the study described in the Professional Paper 1403 series, the term "Floridan aquifer system" was proposed for use throughout the four-State extent of the aquifer system, and the term was thus used throughout these Professional Papers. The current widespread usage of "Floridan" argues against proposing any new term. Because distinct, regionally mappable hydrogeologic units occur within the Floridan, the term "aquifer system" is preferred to simply "aquifer." Usage of "system" follows Poland and others (1972, p. 2) who stated that an aquifer system "***comprises two or more permeable beds separated at least locally by aquitards that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system." This definition describes the Floridan aquifer system throughout most of its area of occurrence.

The Floridan aquifer system is defined as a vertically continuous sequence of carbonate rocks of generally high permeability that are of Tertiary age, that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude

TABLE 1.—*Terminology applied to the Floridan aquifer system*

SERIES/STAGE		PARKER AND OTHERS (1955)		SPRINGFIELD (1966)		MILLER (1982b, 1982d)		MILLER (1986)	
		Formations[1]	Aquifer	Formations[1]	Aquifer	Formations[1]	Aquifers	Formations[1]	Aquifers
MIOCENE		Hawthorn Formation	▨ Where permeable	Hawthorn Formation	▨ Principal artesian aquifer	Hawthorn	▨	Hawthorn	▨
		Tampa Limestone	Floridan aquifer	Tampa Limestone		Tampa Limestone	Where permeable	Tampa Limestone	Where permeable
OLIGOCENE		Suwannee Limestone		Suwannee Limestone		Suwannee Limestone	Tertiary limestone aquifer system	Suwannee Limestone	Floridan aquifer system
EOCENE	Upper	Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone	
	Middle	Avon Park Limestone Lake City Limestone		Avon Park Limestone Lake City Limestone		Avon Park Limestone Lake City Limestone		Avon Park Formation	
	Lower	▨	▨	Oldsmar Limestone		Oldsmar Limestone		Oldsmar Formation	
PALEOCENE		▨	▨	▨	▨	Cedar Keys Limestone		Cedar Keys Formation	

[1] Names apply only to peninsular Florida and southeast Georgia except for Ocala Limestone and Hawthorn Formation.

greater than that of those rocks that bound the system above and below. As shown in table 1, the Floridan includes units of Late Paleocene to Early Miocene age. Locally in southeast Georgia, the Floridan includes carbonate rocks of Late Cretaceous age (not shown in table 1). Professional Paper 1403-B presents a detailed geologic description of the Floridan, its component aquifers and confining units, and their relation to stratigraphic units.

The top of the Floridan aquifer system represents the top of highly permeable carbonate rock that is overlain by low-permeability material—either clastic or carbonate rocks. Throughout much of the area, this upper confining unit consists largely of argillaceous material of the Miocene Hawthorn Formation (table 1). Similarly the base of the Floridan is that level below which there is no high-permeability rock. Generally the underlying low-permeability rocks are either fine-grained clastic materials or bedded anhydrite. These sharp permeability contrasts at the top and base of the Floridan commonly occur within a formation or a time-stratigraphic unit as described by Miller (1986).

AQUIFERS AND CONFINING UNITS

The Floridan aquifer system generally consists of an Upper Floridan aquifer and a Lower Floridan aquifer, separated by less-permeable beds of highly variable properties termed the middle confining unit (Miller, 1986, p. B53). In parts of north Florida and southwest Georgia, there is little permeability contrast within the aquifer system. Thus in these areas the Floridan is effectively one continuous aquifer. The upper and lower aquifers are defined on the basis of permeability, and their boundaries locally do not coincide with those of either time-stratigraphic or rock-stratigraphic units. The relations among the various aquifers and confining units and the stratigraphic units that form them are shown on plate 1, a fence diagram modified from Miller (1986, pl. 30). A series of structure contour maps and isopach maps for the aquifers as well as the seven principal stratigraphic units that make up the Floridan aquifer system and its contiguous confining units is presented in Professional Paper 1403-B. These maps and associated cross sections were prepared by Miller (1986) based on geophysical logs, lithologic descriptions of cores and cuttings, and faunal data for the stratigraphic units, plus hydraulic-head and aquifer-test data for the hydrogeologic units.

The fence diagram shows the Floridan gradually thickening from a featheredge at the outcrop area of Alabama-Georgia-South Carolina to more than 3,000 ft in southwest Florida. Its maximum thickness is about 3,500 ft in the Manatee-Sarasota County area of southwest Florida. In and directly downdip from much of the outcrop area, the Floridan consists of only one permeable unit. Further downdip in coastal Georgia and much of Florida, the Upper and Lower Floridan aquifers become prominent hydrogeologic units where they are separated by less-permeable rocks.

Overlying much of the Floridan aquifer system are low-permeability clastic rocks that are termed the upper confining unit. The lithology, thickness, and integrity of this confining unit has a controlling effect on the development of permeability in the Upper Floridan and the ground-water flow in the Floridan locally. (See later sections on transmissivity and regional ground-water flow.)

Plate 2 shows where the Upper Floridan is unconfined, semiconfined, or confined. Actually the Upper Floridan rarely crops out, and there is generally either a thin surficial sand aquifer or clayey residuum overlying the Upper Floridan. Sinkholes are common in the unconfined and semiconfined areas and provide hydraulic connection between the land surface and the Upper Floridan. In the semiconfined and confined areas, the upper confining unit is mostly the middle Miocene Hawthorn Formation, which consists of interbedded sand and clay that are locally phosphatic and contain carbonate beds. In southwest Florida, the carbonate beds locally form aquifers. Professional Papers 1403-E and 1403-F discuss these local aquifers in detail.

There are two important surficial aquifers overlying the upper confining unit locally: (1) the fluvial sand-and-gravel aquifer in the westernmost Florida panhandle and adjacent Alabama and (2) the very productive Biscayne aquifer (limestone and sandy limestone) of southeast peninsular Florida. Both of these aquifers occur in areas where water in the Floridan is saline; hence they are important sources of freshwater.

The Upper Floridan aquifer forms one of the world's great sources of ground water. This highly permeable unit consists principally of three carbonate units: the Suwannee Limestone (Oligocene), the Ocala Limestone (upper Eocene), and the upper part of the Avon Park Formation (middle Eocene). Detailed local descriptions of the geology and hydraulic properties of the Upper Floridan are provided in many reports listed in the references and especially in the summary by Stringfield (1966). The hydraulic properties section of this report discusses the large variation in transmissivity (as many as three orders of magnitude) within the Upper Floridan. Professional Paper 1403-B discusses the geologic reasons for these variations.

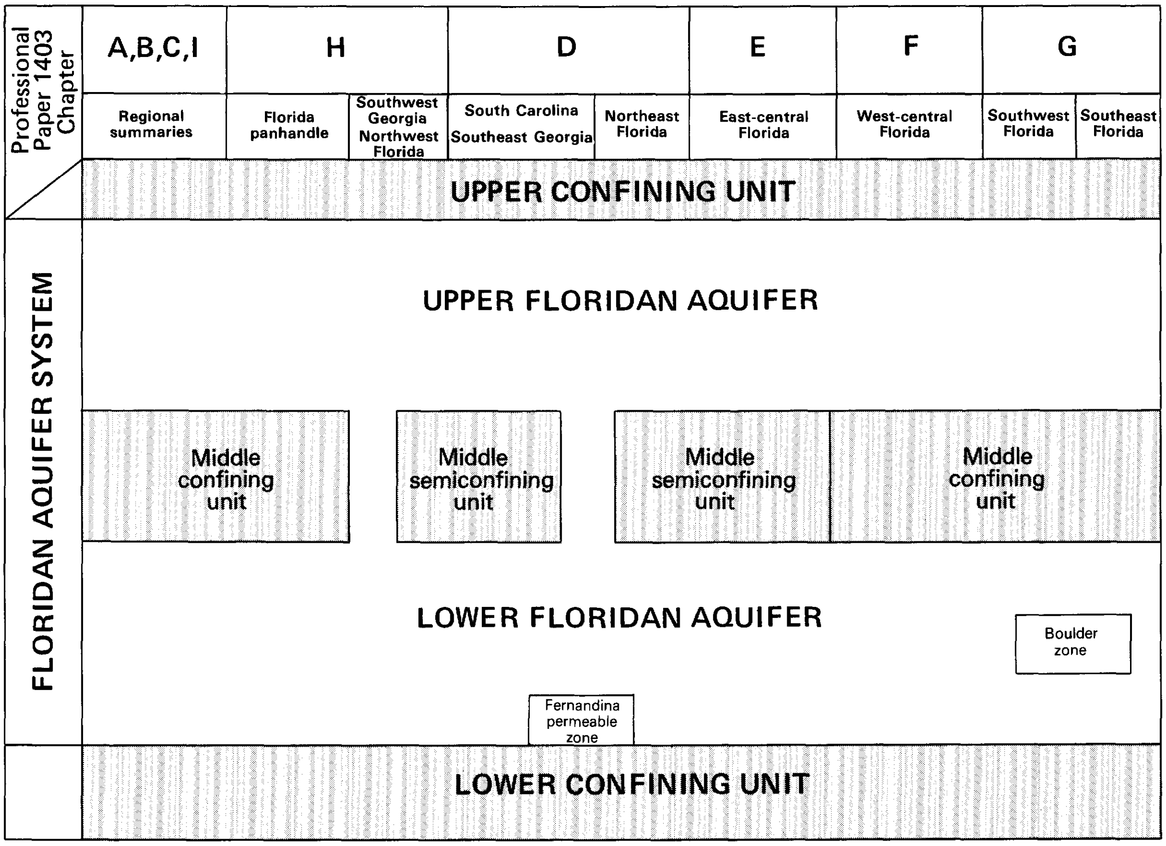
Within the Upper Floridan aquifer (and the Lower Floridan where investigated) there are commonly a few highly permeable zones separated by carbonate rock whose permeability may be slightly less or much less than that of the high-permeability zones. Many local studies of the Floridan have documented these permeability contrasts, generally by use of current-meter traverses in uncased wells. For example, Wait and Gregg (1973) observed that wells tapping the Upper Floridan in the Brunswick, Ga., area obtained about 70 percent of their water from (approximately) the upper 100 ft of the Ocala Limestone and about 30 percent from a zone near the base of the Ocala. Separating the two zones is about 200 ft of less-permeable carbonate rock. Leve (1966) described permeable zones of soft limestone and dolomite and less-permeable zones of hard massive dolomite in the Upper Floridan of northeast Florida.

The Upper and Lower Floridan aquifers are separated by a sequence of low-permeability carbonate rock of mostly middle Eocene age. This sequence, termed the middle confining unit, varies greatly in lithology, ranging from dense gypsiferous limestone in south-central Georgia to soft chalky limestone in the coastal strip from South Carolina to the Florida Keys. Seven subregional units have been identified and mapped as part of the middle confining unit (see detailed descriptions in Professional Paper 1403-B). Much of the middle confining unit consists of rock formerly termed Lake City Limestone but referred to here as the lower part of the Avon Park Formation (table 1).

The Lower Floridan aquifer is comparatively less known geologically and hydraulically than the Upper Floridan. Much of the Lower Floridan contains saline water. For this reason and because the Upper Floridan is so productive, there is little incentive to drill into the deeper Lower Floridan in most areas. The Lower Floridan consists largely of middle Eocene to Upper Paleocene carbonate beds, but locally in southeast Georgia also includes uppermost Cretaceous carbonate beds. There are two important permeable units within the Lower Floridan: (1) a cavernous unit of extremely high permeability in south Florida known as the Boulder zone and (2) a partly cavernous permeable unit in northeast Florida and southeast coastal Georgia herein termed the Fernandina permeable zone. These units are further described in Professional Papers 1403-G and 1403-D, respectively.

Table 2 summarizes the geographic occurrence of aquifers and confining units within the Floridan aquifer system and shows the hydrogeologic nomenclature used in each Professional Paper. The units given in the table are hydraulic equivalents intended for use in describing and simulating the regional flow system. No stratigraphic equivalency or thickness connotation is intended in this table. For example, the Upper Floridan aquifer in the western Florida panhandle consists principally of the Suwannee (Oligocene) Formation. However, in central Florida the Ocala and Avon Park Formations constitute much of the high-permeability rock in the Upper Floridan.

TABLE 2.—*Aquifers and confining units of the Floridan aquifer system*



HYDRAULIC PROPERTIES OF THE AQUIFER SYSTEM

The permeability of the Floridan varies greatly because of differences in the character of its water-bearing materials. These materials include: (1) detrital units of foraminiferal remains and coarse sand-sized particles that hydraulically act as sand or gravel; (2) micritic limestone in the Florida panhandle that acts hydraulically as silt or clay; (3) networks of many small solution openings along joints or bedding planes that on a gross scale provide a uniform distribution of permeability; and (4) large cavernous openings developed in karst or paleokarst areas. In areas where the Floridan is characterized by the first three types, diffuse flow predominates; however, in areas with large cavernous openings, conduit flow predominates.

For the areas where diffuse flow predominates, the methods of aquifer-test analysis developed for porous media are applicable. The response curves of aquifer tests outside the karst terrains generally match the classic nonleaky, leaky, or delayed-yield type curves. Many tests in the confined areas are characterized by a Theis (nonleaky) response throughout nearly the entire test duration. In contrast, porous-media flow theory cannot be applied, at least on a local scale, in the karst areas where conduit flow predominates. However, on a regional scale, analyses of the ground-water flow system using flow nets and "coarse-mesh" digital models have been done successfully in the karst areas, as discussed in Professional Papers 1403–C through H.

TRANSMISSIVITY

The transmissivity of the Upper Floridan aquifer varies by more than three orders of magnitude as a result of the wide variation in hydrogeologic conditions. The conditions that most affect transmissivity are the degree of solution development in the aquifer and, to a lesser extent, the aquifer thickness. High transmissivities usually occur in the areas having less confinement because circulation of flow helps to develop solution openings in the aquifer. Table 3 illustrates the combinations of these hydrogeologic characteristics that produce the variations in transmissivity for the geographic areas underlain by the Upper Floridan.

TABLE 3.—*Transmissivity and hydrogeologic conditions of the Upper Floridan aquifer and the upper confining unit in various localities*

LOCALITY		TRANSMISSIVITY (feet squared per day)	UPPER FLORIDAN AQUIFER				UPPER CONFINING UNIT		
			Thick		Thin (less than 200 feet)		Thick	Thin (less than 100 feet)	
			Solution cavities		Solution cavities		Some clayey beds	Clayey	Sandy or breached
			Minor	Major	Minor	Major			
Western Florida panhandle		1000 - 25,000	▨				▨		
Southwest Georgia (Dougherty Plain)		10,000 - 200,000			▨	▨		▨	▨
Florida, south of Lake Okeechobee		10,000 - 60,000	▨				▨		
Savannah, Georgia, to Jacksonville, Florida, coastal area		25,000 - 250,000	▨				▨		
Central Florida, northern Florida, and adjacent Georgia	Major springs area	Greater than 1,000,000		▨					▨
	Elsewhere	Mostly 20,000 - 250,000 locally 250,000 - 1,000,000	▨	▨			▨	▨	

The low values of transmissivity (less than 50,000 ft²/d) occur in the Florida panhandle and southernmost Florida (where the aquifer is confined by thick clay sections and contains thick sections of low-permeability limestone) and in the updip areas of Alabama, Georgia, and South Carolina (where the aquifer is thinnest). Transmissivities are highest (greater than 1,000,000 ft²/d) in the karst areas of central and northern Florida, where the aquifer is generally unconfined or semiconfined.

The areal distribution of transmissivity of the Upper Floridan aquifer is shown on figure 2. The map portrays the most probable ranges of transmissivity based on values derived from 114 aquifer tests, computer simulation, and geology. A tabulation of the aquifer tests, including method of analysis and source of test data, is presented in Professional Paper 1403–C. At sites where test wells are fully penetrating, the field-test values and the model-derived values generally are in agreement. However, where test wells do not fully penetrate the Upper Floridan, the field-test values are generally less than the model-derived numbers. The field-test data tend to be concentrated in the areas of heavy withdrawals. Where there has been little or no ground-water development, the transmissivity estimates used to prepare figure 2 are based primarily on model calibration. This includes the area of very large spring flows in central and northwest Florida. Within this area, simulation indicates transmissivities ranging from 250,000 ft²/d to as much as 10,000,000 ft²/d. An appraisal of the reliability of the transmissivity map based on the availability of aquifer-test data and the sensitivity of a regional flow model to transmissivity is presented in Professional Paper 1403–C.

The distribution of transmissivity shown on figure 2 is closely related to the degree of confinement of the Upper Floridan. Comparison of figure 2 with plate 2, which shows confined and unconfined conditions for the Upper Floridan, indicates that the confined areas generally have lower transmissivity than semiconfined or unconfined areas. All of the very high transmissivity area (greater than 1,000,000 ft²/d) and much of the high-transmissivity area (250,000 to 1,000,000 ft²/d) occurs where the aquifer is either unconfined or semiconfined.

The very high transmissivity areas are characterized by the extensive development of solution features in the carbonate rock. The development of these features is related to the geologic history, and is discussed further in Professional Paper 1403–B and has been described in detail by Stringfield (1966). Where there is extensive karst development, the permeability distribution is extremely complex, with marked differences in transmissivity occurring in short distances. For example in a flow-net analysis of the Silver Springs drainage area, Faulkner (1973, p. 95) calculated transmissivities varying by more than three orders of magnitude: 11,000 to 25,000,000 ft²/d for individual cells within the 92-mi² area of his flow net.

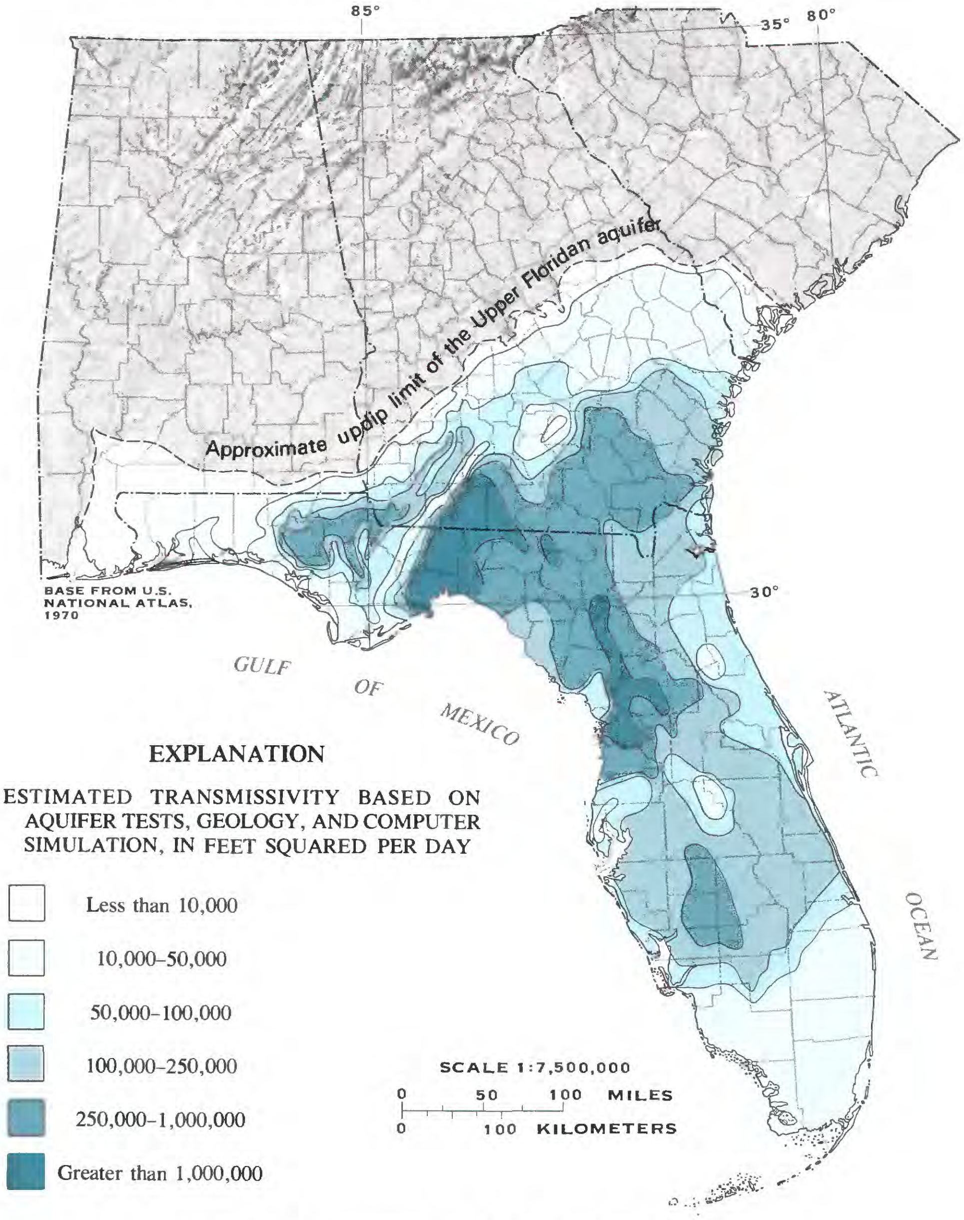


FIGURE 2.—Transmissivity of the Upper Floridan aquifer.

The low values of transmissivity (less than 50,000 ft^2/d) occur in the Florida panhandle, southernmost Florida, and the updip areas of Alabama, Georgia, and South Carolina. In the updip areas, the decreased transmissivity results simply from thinning of the aquifer. However, the development of karst in the outcrop area of southwest Georgia causes a sharp increase in transmissivity just downdip from the featheredge of the aquifer. The low transmissivity in the thick downdip sections of the Florida panhandle and southernmost Florida results from facies changes in the carbonate rock. As discussed in Professional Paper 1403-B, the aquifer in these areas contains large amounts of micritic limestone that has very low permeability.

Areal variations in the transmissivity of the Lower Floridan aquifer cannot be defined because of a lack of aquifer test data. The digital flow models provided little basis for improving initial estimates of transmissivity, inasmuch as the models were insensitive to changes in transmissivity of the Lower Floridan. In southeast Florida, the Lower Floridan contains a cavernous unit termed the "Boulder zone" (pl. 1) that is increasingly being used for injection of treated sewage and industrial wastes. Aquifer tests in the Boulder zone suggest a transmissivity in excess of 3,000,000 ft²/d (Meyer, 1974; Singh and others, 1983).

STORAGE COEFFICIENT

The storage coefficients calculated from aquifer tests for the Upper Floridan range from a low of 1×10^{-5} to a high of 2×10^{-2} with most values in the 1×10^{-3} to 1×10^{-4} range. In the Floridan aquifer system, reported storage coefficients bear no discernible relation to thickness of aquifer tested on a regional basis. The higher values, 1×10^{-2} to 1×10^{-3}, reflect the semiconfined nature characteristic of some parts of the system, such as southwest Georgia, where the aquifer is very close to land surface. The higher values indicate that some of the water from aquifer storage comes from dewatering of the aquifer rather than totally from compression of the aquifer skeleton and expansion of water. Where the confining unit on the Upper Floridan is thin or nonexistent, the Upper Floridan together with the surficial sand aquifer overlying it can behave as a single aquifer. The response to pumping may involve dewatering only in the overlying sands or it may also involve dewatering of the Upper Floridan depending upon pumping rates.

The areal distribution of the storage coefficient of the Upper Floridan could not be developed from transient simulation due to the lack of steady-state initial conditions and historical pumping and associated water-level data. However, transient simulation provided insight into the relative importance of storage in different hydrogeologic areas. Depending on hydrogeologic conditions and the estimated value of storage coefficient, the time required from the start of a new pumping period for the system to reach a new steady-state condition can range from days to years. The time needed from the start of a new pumping period for the system to reach steady state in confined areas depends on the fraction of water pumped that must come from aquifer storage. If the water necessary to sustain a given pumping rate is readily available from vertical leakage (induced recharge) or from adjacent areas within the aquifer (diversion of natural discharge), then only a small part of the water pumped will come from aquifer storage, and a steady-state condition will be achieved relatively quickly. Thus, leaky, high-transmissivity areas are relatively quick to reach equilibrium, and conversely, tightly confined, low-transmissivity areas, which of necessity are more dependent on water from aquifer storage when pumped, are relatively slow to reach equilibrium.

The difference in time required to reach equilibrium can be illustrated by contrasting the aquifer's response to pumping in a low-transmissivity, tightly confined area near Fort Walton Beach, Fla. (where transmissivity and leakage coefficient are 2,000 ft²/d and 5.4×10^{-7} per day, respectively) with a more transmissive, less tightly confined area in Polk County, Fla. (where transmissivity and leakage coefficient are 130,000 ft²/d and 2.8×10^{-5} per day, respectively). Simulation shows a relatively low dependence on water from aquifer storage in Polk County, whereas proportionately much more water must come from storage near Fort Walton Beach. Thus the system reaches steady state quickly (a few weeks) at Polk County but slowly (more than a year) near Fort Walton Beach.

LEAKAGE COEFFICIENT

The leakage coefficient of the upper confining unit is highly variable, especially in the semiconfined areas where the confining beds may be either sandy or clayey. Leakage coefficient values of the upper confining unit derived from simulation range from less than 0.01 (in./yr)/ft in tightly confined areas to more than 1.00 (in./yr)/ft in semiconfined areas. The leakage coefficients calculated from aquifer-test data are in general very much larger than those obtained from simulation, ranging from 0.44 to 88 (in./yr)/ft.

In the majority of locations, leakage coefficients from aquifer-test data are too large to realistically represent the exchange of water between the surficial aquifer and the Upper Floridan. The values obtained from aquifer-test data can reflect not only downward leakage from the surficial aquifer, but upward leakage from permeable rocks beneath the pumped interval, as well as leakage from beds of relatively low permeability that might exist within the pumped interval. Upper-confining-unit leakage coefficients derived from Floridan aquifer-test data are composite, or lumped, properties that include leakage from all available sources. Wells in the Floridan aquifer system are usually partially penetrating and often intersect local low-permeability units. Thus in most Floridan test situations it is probable that leakage coefficients obtained from the test data will characterize leakage from all sources, not just downward leakage from the upper confining unit or the surficial aquifer. A map portraying the values of leakage coefficient required to deliver vertical flow between the surficial aquifer and the Upper Floridan aquifer during simulations is presented in Professional Paper 1403–C.

No quantitative field data on the water-transmitting characteristics of the middle confining unit exist. Miller (1986) used lithology and thickness to qualitatively assess the degree of confinement offered by each of seven low-permeability units of subregional extent that together form the middle confining unit. Leakage coefficient values of the middle confining unit used in simulation were arbitrarily assigned based on Miller's geologic assessment of the confinement. However, due to the insensitivity of Upper and Lower Floridan heads to changes in middle-confining-unit leakage coefficients, simulation was unsuccessful in developing better estimates of the leakage coefficients.

THE REGIONAL FLOW SYSTEM

The existence of a regional flow system in the Floridan has been recognized since the early 1930's when Stringfield (1936) published his classic "Artesian Water in the Florida Peninsula." Stringfield was the first to identify a regional flow system in the carbonate rocks of Florida. His potentiometric-surface map of the Upper Floridan aquifer suggested the natural recharge and discharge areas and the general direction of ground-water movement from recharge to discharge areas. A major potential recharge area was implied in central Florida. Major discharge areas were implied in the coastal areas of Florida and Georgia.

Later Stringfield and others (1941) demonstrated the hydraulic continuity of this carbonate system across three States. They documented a widespread decline of head caused by large ground-water withdrawals at the coastal cities of Savannah and Brunswick, Ga., and Fernandina Beach and Jacksonville, Fla. By the early 1940's, the cones of depression around these cities coalesced to form a troughlike depression in the potentiometric surface extending from Jacksonville to near Hilton Head, S.C., a distance of 150 mi. Since the early work of Stringfield and others (1941), there have been many hydrologic investigations of the Floridan aquifer system. However, the studies described in the Professional Paper 1403 series represent the first attempt to quantify regional rates of ground-water recharge and discharge.

A three-dimensional finite difference model (Trescott, 1975; Trescott and Larson, 1976) was used to study the regional flow system and to quantify flow rates. A regional model of the entire aquifer system and several subregional models were constructed for this purpose. The basic structure of the models is similar, although the subregional models depart from the regional model in detail to accomodate local conditions or features. The Upper and Lower Floridan aquifers were simulated as active layers; the surficial aquifer was treated as a source-sink bed; the lower confining unit (fine-grained clastic beds or bedded anhydrite) and the freshwater-saltwater interface (below and laterally) were assumed to be no-flow boundaries. However, the Upper Floridan, in a strip adjacent to its updip limit in Georgia, was bounded below by constant heads to simulate a small amount of upward leakage from the sand aquifer system beneath the Floridan. The updip limit of the system (pl. 2) was considered a no-flow boundary, because it is generally a pinchout of the carbonate rocks.

The design, assumptions, and application of the regional flow model to simulating the predevelopment flow system have been described in a preliminary report by Bush (1982). Each node, or grid block, is 8 mi on a side and thus represents a 64-mi^2 area. For simulation, the properties of an aquifer layer are assumed constant within each grid block. The value of a particular aquifer property in a grid block is an average over the block area. The subregional models have grids that are coincident with those of the regional model but smaller—4 mi on a side. Design of three of the four subregional models and preliminary simulation results are discussed by Krause (1982), Ryder (1982), and Tibbals (1981).

Regional simulation results including the major effects of present-day withdrawals are described in Professional Paper 1403–C. Results of subregional simulations and local pumping effects are described in Professional Papers 1403–D through F and 1403–H. (See fig. 1 for area described in each Professional Paper.)

A major assumption in applying the flow models is that flow in the Floridan behaves as flow in a porous medium. As discussed in the hydraulics section of Professional Paper 1403–C, this assumption is probably valid on a scale of several hundred feet (the scale of a typical aquifer test) except in the karstic spring areas and, thus, should be acceptable on the larger scale of the digital models. In the karst areas of central and northwest Florida, especially near major springs, conduit flow occurs on a local scale (hundreds to thousands of feet per Sinclair, 1978). At the scale of the regional and subregional models (with 4- or 8-mi grid-block spacing), the assumption of flow in the karst areas behaving as flow in a porous media probably is also valid.

MAJOR FEATURES

The major features of the flow system can be illustrated and summarized by a potentiometric-surface map of the Upper Floridan aquifer. Plate 2 is an aquifer-wide potentiometric-surface map constructed from more than 2,700 water-level and pressure-head measurements made in May 1980. Superimposed on plate 2 are areas where the aquifer is unconfined, semiconfined, or confined.

The configuration of the potentiometric surface indicates that in South Carolina and Georgia, the direction of flow is generally east and southeast from the topographically high outcrop areas toward the Atlantic Coast and Florida. In Alabama and west Florida, flow is generally south from the outcrop areas toward the Gulf Coast. In peninsular Florida, the general flow direction is toward the Gulf and Atlantic Coasts from the central inland areas. Thus, it is implied that recharge occurs in the northern outcrop and peninsular inland areas, and that discharge occurs in the coastal areas.

The degree of confinement on the Upper Floridan is the characteristic of the system that most strongly influences the distribution of natural recharge, flow, and discharge. Most of the natural recharge, flow, and discharge occurs in unconfined and semiconfined areas. Potentiometric contours that are distorted as they cross streams indicate Upper Floridan discharge and typify unconfined and semiconfined aquifer conditions. Smoother, less-distorted contours are associated with confined parts of the system that are well "insulated" from surface drainage features.

The dominant feature of the Floridan flow system, both before and after ground-water development, is discharge from springs (the locations of which are shown on plate 2). Nearly all of the springs occur in unconfined and semiconfined parts of the aquifer system in Florida. Currently (early 1980's) the combined average discharge from about 300 known Upper Floridan springs probably ranges between 12,500 and 13,000 ft^3/s—more than one-half of the total Floridan discharge. Potentiometric contours tend to be distorted around groups of springs, especially inland from the coast.

The impact of pumping from wells is evident in the confined areas as shown by cones of depression and areas of long-term water-level decline on plate 2. The steeper cones at Fort Walton Beach and Savannah are caused by lower transmissivity rather than higher withdrawal rates than other pumping centers. In contrast, large withdrawals near Orlando, northwest of Tampa, and in southwest Georgia—all located in areas of higher transmissivity and in unconfined or semiconfined areas—have produced only shallow localized cones of depression that cannot be shown at the scale of the regional potentiometric-surface map.

COMPARISON OF PREDEVELOPMENT AND CURRENT CONDITIONS

Before development, the flow system was in a state of dynamic equilibrium in which natural recharge to the Floridan aquifer system was balanced by natural discharge. It is estimated that about 67,000 mi^2 was recharge area and about 27,000 mi^2 was land discharge area (estimated total predevelopment discharge area, including offshore area, is 55,000 mi^2). The total predevelopment recharge and, therefore, discharge simulated by the regional flow model was about 21,500 ft^3/s. This is equivalent to 4.4 in./yr of water over the recharge area.

Springs and aquifer discharge to streams and lakes, nearly all of which occurs in unconfined and semiconfined areas (pl. 2), accounted for a very high percentage of the total predevelopment discharge. Simulated spring flow and aquifer discharge to streams and lakes were 88 percent of the 21,500 ft^3/s simulated predevelopment discharge, or about 19,000 ft^3/s. Diffuse upward leakage, which occurs primarily in confined areas, accounted for the remaining fraction of the total simulated predevelopment discharge, 12 percent or about 2,500 ft^3/s.

Most of the recharge necessary to sustain spring flow and aquifer discharge to streams and lakes occurred relatively close to springs and to areas of point discharge to surface-water bodies. Recharge to the Upper Floridan was highest in unconfined and semiconfined spring areas, averaging 10 to 20 in./yr. The proximity of high recharge to high discharge implies a vigorous and well developed shallow flow sytem in the unconfined and semiconfined parts of the Upper Floridan aquifer.

The estimated predevelopment discharge from the major ground-water areas of the Upper Floridan aquifer (as derived from simulation) is shown on figure 3. Regionally, and in every ground-water area except south Florida, the predominance of spring discharge and aquifer discharge to surface-water bodies over diffuse upward leakage is apparent. Not surprisingly, the five ground-water areas that are predominantly unconfined or semiconfined (Dougherty Plain-Apalachicola, Thomasville-Tallahassee, Suwannee, west-central Florida, and east-central Florida), although accounting for only about 50 percent of the Upper Floridan's area of occurrence, contribute nearly 90 precent of the simulated total predevelopment discharge. The Suwannee area is the most active part of the aquifer system in terms of ground-water flow; more than one-fourth of the total predevelopment discharge, close to 6,000 ft^3/s, occurred in this area.

In the mostly confined Florida panhandle area, diffuse upward leakage occurred over the major part of the area. But confinement is lacking in the eastern third of the area and along the Upper Floridan outcrop area to the north, allowing direct aquifer discharge to streams. Similarly, in the southeast Georgia—northeast Florida—south South Carolina area, about three quarters of the simulated predevelopment discharge

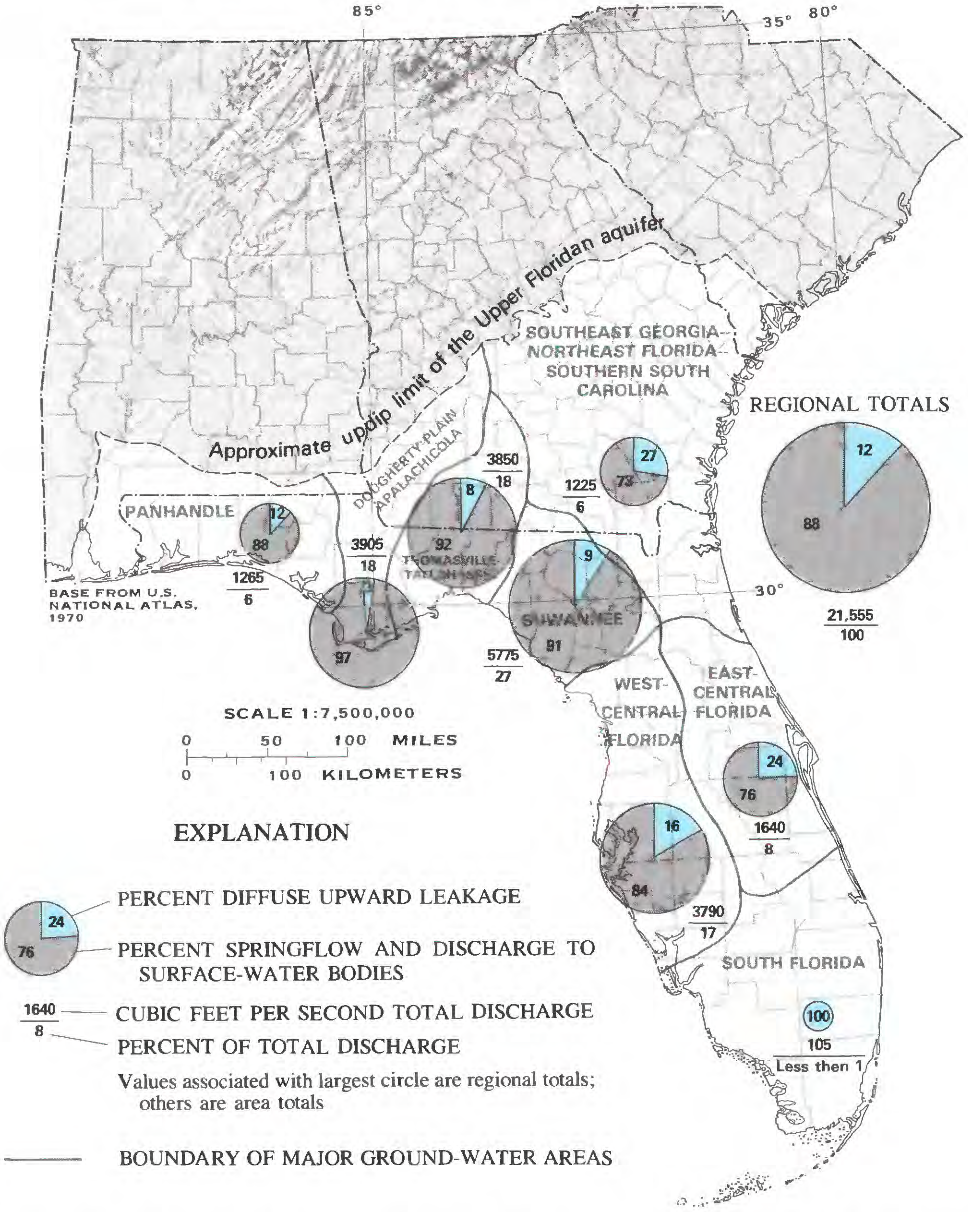


FIGURE 3.—Estimated predevelopment discharge from major ground-water areas of the Upper Floridan aquifer.

went to the four major rivers crossing the areally small northern outcrop. Diffuse upward leakage occurred over a much larger area, but accounted for a minor part of the area discharge. Only in south Florida, where no unconfined or semiconfined areas exist, was diffuse upward leakage the major form of predevelopment discharge; and the approximately 100 ft³/s simulated predevelopment discharge from south Florida represents less than 1 percent of the total regional discharge.

The general characteristics of the natural flow system have not been appreciably altered by ground-water development. Currently, as before development, discharge from Upper Floridan aquifer springs continues to be the dominant feature of the regional flow system; and the degree of confinement on the Upper Floridan is still the major hydrogeologic control on the distribution of recharge, discharge, and ground-water flow. However, similarity of the current flow system to the predevelopment flow system does not mean that ground-water development has not brought significant changes. In 1980, about 3 Bgal/d were pumped from the aquifer system (almost all from the Upper Floridan) for all uses, an amount equal to about 20 precent of the estimated predevelopment recharge or discharge. This pumpage has resulted in long-term regional water-level declines of more than 10 ft in three broad areas of the flow system, as shown on plate 2: coastal Georgia—adjacent South Carolina—northeast Florida, west-central Florida, and panhandle Florida. The effect of ground-water development on the potentiometric surface is particularly evident at Savannah, Ga., and at Fernandina Beach and Fort Walton Beach, Fla., where deep cones of depression have formed. Saltwater has encroached as a result of pumping in some coastal areas, but its documented extent has been local.

Pumpage has been and continues to be supplied primarily by the diversion of natural outflow from the system and by induced recharge rather than by loss of water from aquifer storage. The aquifer system's transient response to changes in withdrawal rates dissipates fairly rapidly (days or weeks) in most areas. Thus on the average (that is, excluding the effects of seasonal changes in stresses), the current aquifer system is still considered to be approximately at equilibrium, except during periods following sustained increases in pumping.

Figure 4 shows the estimated current (early 1980's) discharge from the major ground-water areas of the Upper Floridan aquifer. Simulation suggests that current discharge is about 24,100 ft^3/s, of which about three-fourths leaves the aquifer system as spring flow or discharge to surface-water bodies. The remaining one-fourth of the simulated discharge is split between pumpage (17 percent of total discharge) and diffuse upward leakage (8 percent of total discharge). Pumpage is now a major part of the aquifer discharge, especially in four of the ground-water areas. Diffuse upward leakage is markedly reduced from predevelopment rates in two ground-water areas where flow is sluggish (southeast Georgia—northeast Florida—south South Carolina, and south Florida); but regionally, diffuse upward leakage is not greatly reduced. Ground-water development has not resulted in significant movement of the divide separating the Suwannee area from the southeast Georgia—northeast Florida—south South Carolina area. The divide between the west-central Florida area and the east-central Florida and south Florida areas has shifted slightly southeast, thereby slightly enlarging the southern part of the west-central Florida area. The percentage of total system discharge that occurs in each area currently is not signficantly different from the percentage contributed by the same area before ground-water development.

Simulation indicates that ground-water development has caused the rates of both downward and upward leakage between the Upper and Lower Floridan to increase about 16 percent. Lateral inflow to the system in the central Georgia outcrop area of the Upper Floridan has not changed significantly from its predevelopment rate. Simulation indicates a tremendous change from predevelopment in the rate of upward leakage from the Fernandina permeable zone. The change results from heavy pumping in the Jacksonville—Fernandina Beach—Brunswick areas, which has increased the vertical gradient from the Fernandina permeable zone toward the upper part of the Lower Floridan.

In summary, the major part of the flow system is largely unchanged from predevelopment conditions. Springs whose discharge is large are still the dominant feature of the system. Although pumping has caused recharge rates to increase locally, the greatest recharge still occurs near the springs. Even after development, ground-water flow remains sluggish in areas where the aquifer is deeply buried in comparison to flow in areas where the aquifer is close to the land surface.

GROUND-WATER DEVELOPMENT

Ground-water development of the Floridan aquifer system began in the late 1800's. The cities of Jacksonville, Fla., and Savannah, Ga., were probably the earliest communities to obtain freshwater from wells in the Floridan aquifer system, beginning in the 1880's. By the early part of this century, development of the Upper Floridan in Florida was well under way. Matson and Sanford (1913, p. 233), in their comprehensive report on the geology and ground waters of Florida, stated that "*** large numbers of wells have been sunk to the artesian water beds ***along the east coast, from Fernandina southward, in the St. Johns Valley, and along the west coast from Tampa to Fort Meyers." Since the early 1900's, pumpage has steadily increased. By 1950, withdrawals from the Floridan aquifer system exceeded 600 Mgal/d; by 1980, withdrawals were about 3 Bgal/d.

Figure 5 shows the 1980 regional distribution of estimated pumpage from the Floridan aquifer system, by county, for all uses. Central Florida has become the most heavily developed region of the Floridan aquifer system, in terms of water withdrawn. The phosphate industry and irrigation account for the major part of that pumpage. Pumpage in the area comprised of Pinellas, Hillsborough, Pasco, Polk, and Orange Counties amounted to about 820 Mgal/d in 1980, or about 27 percent of the total 3 Bgal/d Floridan pumpage. Polk County continues to be the most intensely pumped local area; total 1980 Floridan pumpage in Polk County was about 310 Mgal/d. Orange County (encompassing the Orlando-Winter Park area) was second in 1980 pumpage; an estimated 200 Mgal/d was withdrawn.

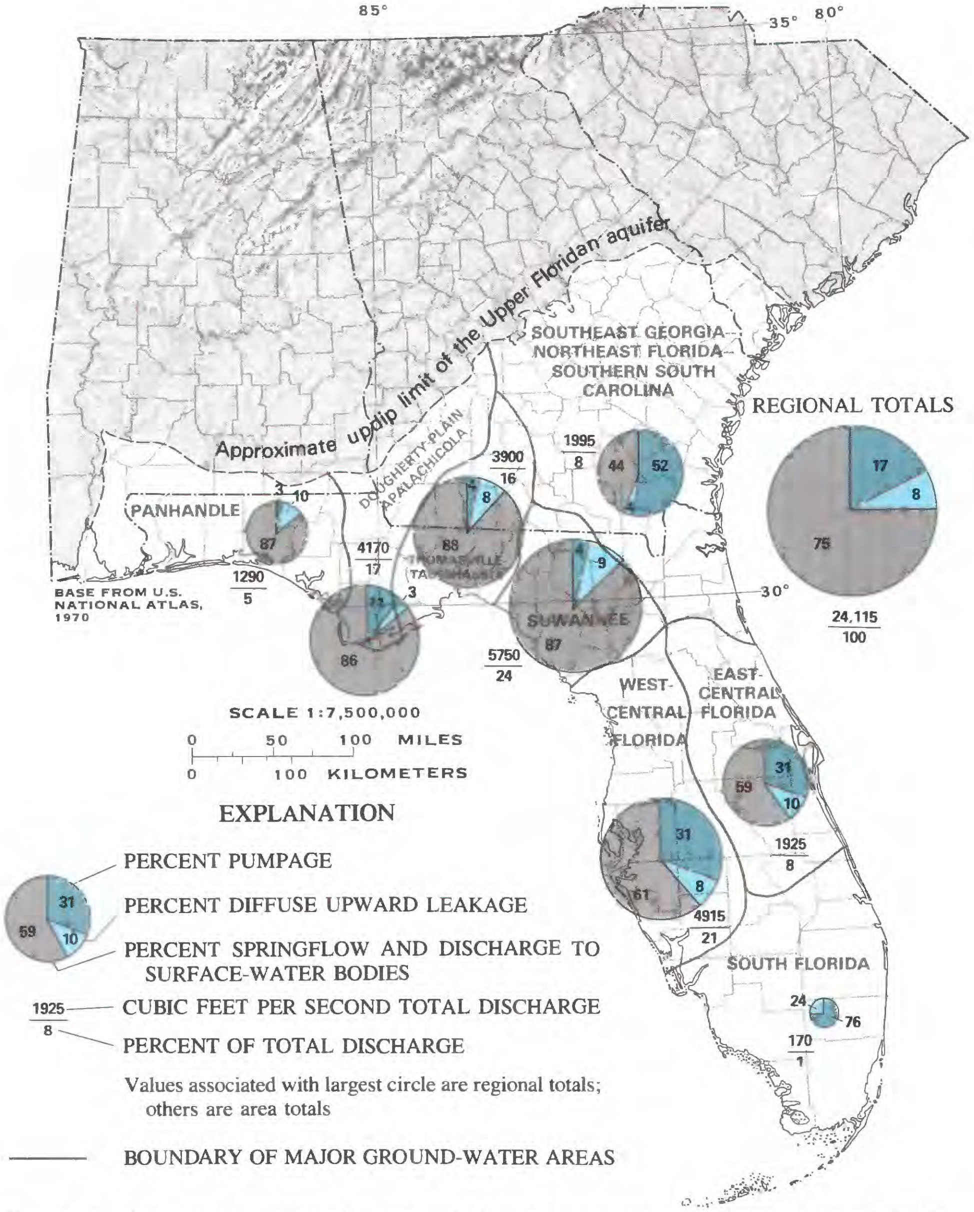


FIGURE 4.—Estimated current (early 1980's) discharge from major ground-water areas of the Upper Floridan aquifer.

Another heavily developed area is the coastal strip of southeast Georgia-northeast Florida where about 470 Mgal/d, mostly for industrial use, were being withdrawn in 1980. In northeast Florida, Duval County (Jacksonville area) and Nassau County (Fernandina Beach area) accounted for about 160 Mgal/d pumpage in 1980. In coastal Georgia, largest withdrawals from the Floridan in 1980 occurred in Glynn County, which includes the Brunswick area; estimated total pumpage was about 100 Mgal/d. Pumpage in 1980 in Chatham County (Savannah area) and Wayne County (Jesup area) was moderately heavy; about 75 Mgal/d were withdrawn in each of those counties.

The uses for ground water withdrawn from the Floridan have changed significantly since 1950. Figure 6 shows the major shift in water use between 1950 and 1980 from industrial and thermoelectric to irrigation. The percentage of total pumpage for irrigation more than tripled between 1950 and 1980. The percentage for industrial and thermoelectric use during the same period dropped by more than one-half. The combined pumpage for public supply and rural use was slightly less than one-quarter of the total pumpage in 1950 and slightly more than one-quarter in 1980.

An important use of the Floridan aquifer system in

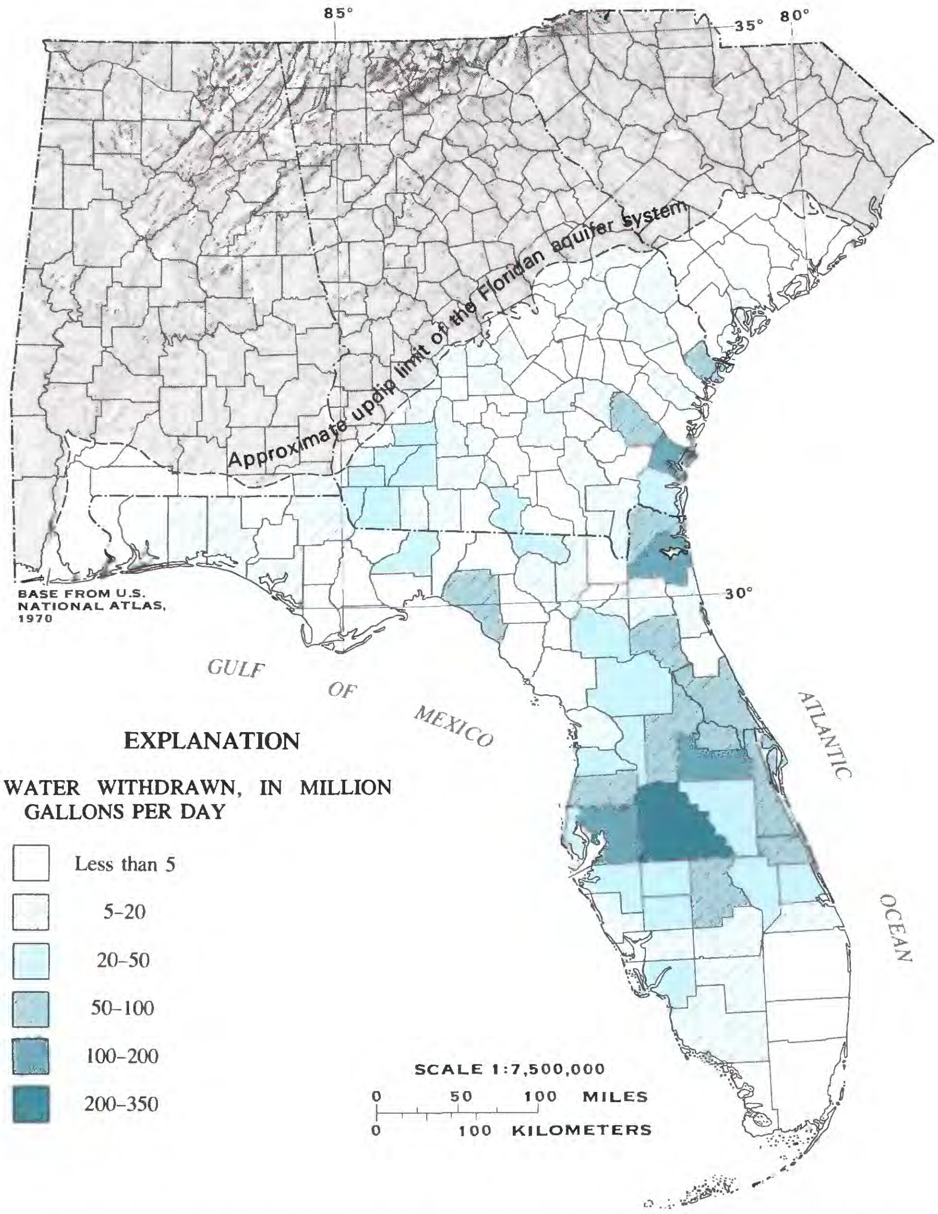


FIGURE 5.—Estimated pumpage from the Floridan aquifer system by county, 1980.

recent years is the subsurface storage of wastes. As discussed in Professional Paper 1403–G, the injection of treated sewage and industrial wastes into saline parts of the Lower Floridan has increased sharply since the 1970's. Injection of treated sewage into the Boulder zone is being used as an alternative to ocean outfalls in the Miami-Palm Beach coastal area.

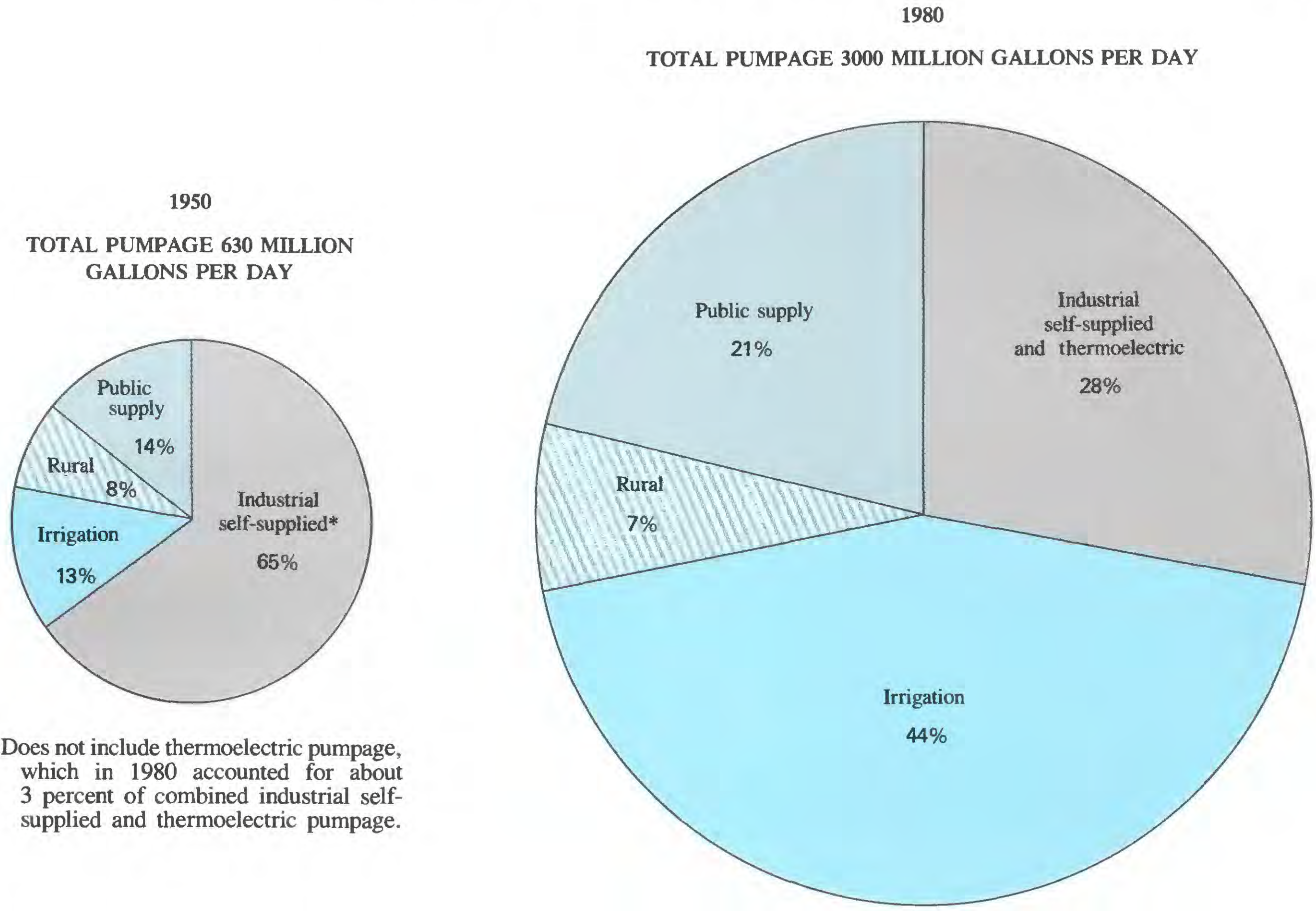
Another use of the Floridan is the disposal of excess storm runoff via drainage wells tapping the Upper Floridan. Such wells are used extensively in the Orlando area, as described in Professional Paper 1403–E.

GROUND-WATER CHEMISTRY

The chemistry of water in the Floridan aquifer system is briefly discussed here; the geochemistry of the system is discussed in detail in Professional Paper 1403–I.

DISSOLVED SOLIDS AND MAJOR CONSTITUENTS

In general, the dissolved-solids concentrations of water at any point in the Upper Floridan are related to flow and proximity to the freshwater-saltwater interface. In the unconfined or semiconfined areas where flow



*Does not include thermoelectric pumpage, which in 1980 accounted for about 3 percent of combined industrial self-supplied and thermoelectric pumpage.

FIGURE 6.—Comparison of uses for ground water withdrawn from the Floridan aquifer system, 1950 and 1980.

is vigorous, dissolved-solids concentrations are low. Where the system is tightly confined, flow is more sluggish and concentrations are higher. In Florida south of Lake Okeechobee and in parts of the St. Johns River valley, residual saltwater remains unflushed from the system and dissolved-solids concentrations are high. Concentrations also become increasingly higher in coastal areas as the freshwater-saltwater interface is approached.

In the Upper Floridan, dissolved-solids concentrations vary from less than 25 mg/L near outcrop areas to more than 25,000 mg/L along the coasts. Within the system the dominant cations are Ca, Mg, Na, and K; the dominant anions are HCO_3, Cl, and SO_4. Locally, smaller amounts of dissolved iron, manganese, nitrate, phosphate, fluoride, strontium, sulfide, and silica contribute to the dissolved-solids concentration.

Figure 7 shows the general distribution of dissolved-solids concentrations in water produced from wells that yield from the entire Upper Floridan. Throughout most of the Upper Floridan, dissolved-solids concentrations are maintained at less than 500 mg/L by saturation with calcite and dolomite, and by the limited occurrence of more soluble minerals like gypsum. Higher concentrations are generally due to the presence of seawater in the system. In coastal areas of Florida, northeast Georgia, and South Carolina, seawater should occur in the lower part of the Upper Floridan where predevelopment heads were low; high chloride concentrations in fully penetrating coastal wells have indicated that seawater is present in these areas. High dissolved-solids concentrations along the coast of southeast Georgia and northeast Florida cannot be attributed to seawater, however, because chloride concentrations in the Upper Floridan are not high. Declining heads in the Upper Floridan apparently have induced highly mineralized, low-chloride water from the Lower Floridan to move upward, gradually increasing dissolved-solids concentrations over a large area. According to Brown (1984), highly mineralized, low-chloride water may have been present throughout most of the Fernandina permeable zone of the Lower Floridan prior to development.

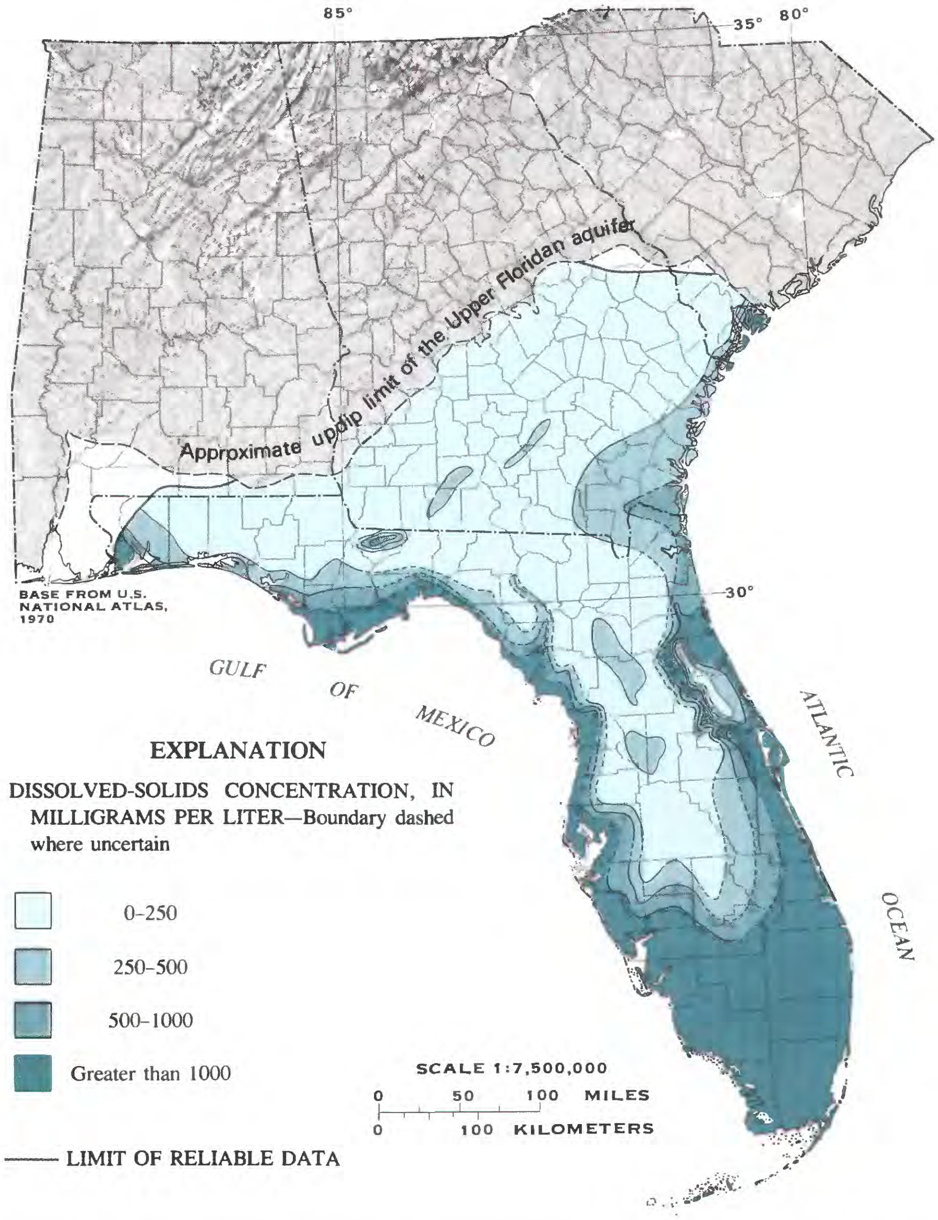


FIGURE 7.—Map showing dissolved-solids concentration of water from the Upper Floridan aquifer.

HYDROCHEMICAL FACIES

Several distinct hydrochemical facies characterize the water chemistry in the Upper Floridan as shown on plate 3. The principal chemical processes leading to the development of the hydrochemical facies in the Upper Floridan are: (1) dissolution of aquifer minerals toward equilibrium as ground water moves from recharge to discharge areas; (2) mixing of ground water with seawater along the freshwater-saltwater interface in coastal areas, or with residual saline water in low-permeability rocks where the Upper Floridan is unflushed, or with recharge water; (3) cation exchange between water and aquifer minerals. Each of these processes exhibits distinctive chemical traits; thus the hydrochemical facies map, when combined with hydrogeologic data, can generally identify the predominant processes in any part of the Upper Floridan system.

In most of Georgia and central Florida, dissolution of calcite produces low to moderate increases in dissolved solids; ground water in these areas is generally calcium-bicarbonate dominated. Where incongruent dissolution of dolomite adds sufficient Mg to the water, a calcium-magnesium-bicarbonate facies develops. Along the coast of Georgia and northeast Florida, gypsum dissolution adds SO_4 and a calcium-magnesium-bicarbonate-sulfate facies develops. In southwest Florida, residual gypsum occurs in moderate quantities in the Upper Floridan; in this area of sluggish flow, sulfate is the predominant anion, and a calcium-magnesium-sulfate facies occurs. This same facies has developed in the Gulf Trough area of southwest Georgia and in adjacent northwest Florida. The Gulf Trough is a narrow band of low-permeability rocks extending northeastward across south-central Georgia that impedes ground-water circulation and slows dissolution of residual gypsum in the Upper Floridan. Other data presented in Professional Paper 1403-I indicate that small amounts of residual seawater also contribute to the high dissolved-solids concentrations occurring in Gadsden County, Fla., although the quantities of seawater are insufficient to affect the hydrochemical facies mapped in the area.

Within the Upper Floridan vertical mixing of freshwater and seawater occurs naturally in the zone of dispersion along the transition zone between freshwater and saltwater. In this zone the water chemistry gradually changes from calcium-magnesium-bicarbonate type with low dissolved solids near the top, to seawater at the bottom. Lateral changes in hydrochemical facies also occur along the coasts of central Florida and southeast South Carolina because of increasing amounts of seawater in the Upper Floridan. Inland a few miles from the coast, a calcium-magnesium-bicarbonate facies generally occurs. Nearer the sea, the Upper Floridan contains some seawater at depth, and the small amounts of seawater change the water from calcium-magnesium-bicarbonate dominated to water with approximately equal proportions of all major constituents (designated "Mixed" on plate 3). As the seawater content of the Upper Floridan increases, there is a change to sodium-chloride facies. The effects of freshwater-saltwater mixing on deep wells in coastal areas is dependent on the depth (position) of the interface, the depth of the well, and the rate of pumpage. Water from lightly pumped, shallow wells in most coastal areas would not be as affected by the seawater, and might be quite similar to freshwater from wells farther inland.

Mixing of freshwater with residual saline water produces changes in hydrochemical facies and dissolved-solids concentrations similar to mixing freshwater and present-day seawater. In south Florida flow is very sluggish due to very thick confinement of the system, and residual saline water occurs in the Upper Floridan.

Mixing of residual seawater in the Upper Floridan with freshwater could also produce the high dissolved-solids concentrations and sodium-chloride facies mapped in the valley of the St. Johns River. However, an alternative explanation for the highly mineralized water occurring in that area was offered by Wyrick (1960) and Leve (1983). They suggested that saline water from deeper units is rising into the Upper Floridan along fault zones in northeast Florida. Invasion of the Upper Floridan by more mineralized water has been documented in Valdosta, Ga. (Krause, 1979), Brunswick, Ga. (Wait, 1965), and Nassau County, Fla. (Fairchild and Bentley, 1977). Only in the Brunswick area, however, has invasion of saline water caused higher dissolved-solids and a change to sodium-chloride facies in the Upper Floridan. The narrow band of calcium-magnesium-sulfate facies mapped along the valley in northeast Florida supports the theory that upwelling of mineralized water may occur along fault zones. Prior to development the system was discharging to the St. Johns River where the narrow band is mapped; the 1980 potentiometric-surface map (pl. 2) indicates that the current system is discharging to the river and to a center of pumping on the south side of Jacksonville. These discharge patterns seem to have prevented the spread of the calcium-magnesium-sulfate facies eastward toward the coast.

Recharge to the Upper Floridan mixes with ground water in the aquifer and has variable chemical effects depending on both chemistry and amount of the recharge. Recharge from underlying sand aquifers in southwestern Georgia locally affects both Ca and HCO_3 concentrations, but as discussed in Professional Paper 1403-I, the rate of upward leakage is believed to be very small as there is no change detected in the predominant ions. A change in hydrochemical facies suggests that recharge of Ca and HCO_3 type water occurs immediately southeast of the Gulf Trough. This recharge is probably low in dissolved solids, as dissolved-solids concentrations change from 250 to 500 mg/L in the vicinity of the Trough to 0 to 250 mg/L downgradient (southeast of the trough). Upward leakage from underlying sand aquifers also occurs in east-central Georgia, where it has lowered Ca concentrations and raised Na/Cl molal ratios (Sprinkle, in press) but has had no effect on dissolved-solids concentrations or hydrochemical facies. Nearer the coast in east-central Georgia, a mixed-bicarbonate facies is mapped. In this area, the Lower Floridan is probably discharging small amounts of water to the Upper Floridan because this was a predevelopment discharge area for the Upper Floridan. Upward leakage of water from the Lower Floridan increases Na concentrations in the Upper Floridan, indicating Na concentrations may be relatively high in the Lower Floridan.

Only in the western Florida panhandle does ion exchange seem a probable mechanism for developing a unique hydrochemical facies. In that area, the typical calcium-magnesium-bicarbonate water of recharge areas evolves into a sodium-bicarbonate facies. The source of additional Na is not well established, although preliminary chemical data indicate sodium-silicate dissolution is not the sole source. Infiltration of Na rich water is not possible because this is a discharge area for the Upper Floridan, nor is upward leakage a plausible source, because, except in western Okaloosa County, the almost impermeable Bucatunna Formation separates the Upper and Lower Floridan aquifers in most of the area. Taken together the chemical and hydrologic data strongly imply that ion exchange is the mechanism for producing the sodium-bicarbonate facies occurring in the Upper Floridan in the western Florida panhandle.

POTENTIAL FOR FUTURE DEVELOPMENT

Large quantities of fresh ground water are available for future development from the Upper Floridan aquifer. This is indicated by the fact that the original flow system has not been changed extensively by pumpage of about 3 Bgal/d, which currently represents less than 20 percent of the flow through the Floridan. However, very large withdrawals and the resulting head declines can induce poor-quality water to move into the Upper Floridan (by both lateral and upward movement of saltwater in coastal areas and by upcoming of saline waters in some inland areas). Thus the major constraint on future development is degradation of water quality rather than water-quantity limitations. Saltwater encroachment in coastal areas and upcoming of saline waters in some inland areas are important constraints to consider in planning additional development.

An appraisal of potentially favorable areas for large ground-water development is presented in Professional Paper 1403–C and summarized here. The appraisal is based primarily on minimizing head decline and thereby reducing the chances of water-quality deterioration. The potentially favorable areas were selected on the basis of aquifer and confining-unit properties, current water chemistry, heads, and pumpage. The criteria that had to be met in order for an area to be considered "highly favorable" are as follows:

- Transmissivity greater than 50,000 ft^2/d in unconfined or semiconfined areas; transmissivity greater than 100,000 ft^2/d in confined areas.
- Altitude of 1980 heads higher than 25 ft. In theory (which is conservative) this insures at least 1,000 ft of freshwater in the subsurface where permeable carbonate rock extends to that depth. This criterion is intended to eliminate all coastal areas where the potential for saltwater encroachment exists.
- The Upper Floridan aquifer contains freshwater of acceptable quality; dissolved-solids concentrations of less than 500 mg/L as of 1980. Contamination of ground water by pesticides and other toxic chemicals, although documented in a few isolated instances, has not been considered in this regional evaluation.
- Long-term water-level decline in the Upper Floridan due to ground-water development is less than 40 ft.
- Pumpage during the early 1980's was light; less than 10 Mgal/d within a 64-mi^2 area.

Plate 4 shows the extent of the highly favorable areas that meet all of the five criteria previously listed. This map is intended as a qualitative overview of promising areas where large ground-water development (as much as 100 Mgal/d) can proceed with minimal detrimental effects. As shown on plate 4, most of the highly favorable areas occur in the lightly developed northern half of central peninsular Florida and adjoining south Georgia.

Locally, of course, the effects of large future increases of ground-water pumpage will vary. To test the effects of such increases, computer simulation was applied in some of the favorable as well as less favorable areas. Discussions of various scenarios of increased pumpage are presented in Professional Paper 1403–D through F and 1403–H.

In summary, there remains a considerable area of the Upper Floridan aquifer's extent that is highly favorable for the development of large ground-water supplies. This area is largely inland from the coasts and characterized by high transmissivity as well as minimal development in 1985.

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