PREDEVELOPMENT FLOW IN THE TERTIARY LIMESTONE AQUIFER, SOUTHEASTERN UNITED STATES; A REGIONAL ANALYSIS FROM DIGITAL MODELING

By Peter W. Bush

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 82-905

1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
75 Spring Street, S.W., Suite 772
Atlanta, Georgia 30303

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

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)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

PREDEVELOPMENT FLOW IN THE TERTIARY LIMESTONE AQUIFER, SOUTHEASTERN UNITED STATES; A REGIONAL ANALYSIS FROM DIGITAL MODELING

By Peter W. Bush

ABSTRACT

The Tertiary limestone aquifer of the southeastern United States is a sequence of carbonate rocks that underlies all of Florida, south Georgia, and adjacent parts of Alabama and South Carolina. It is the principal source of municipal, industrial, and agricultural water supply in south Georgia and most of Florida. The aquifer, known as the Floridan aquifer in Florida and the principal artesian aquifer in Georgia, Alabama, and South Carolina, includes various carbonate units of Paleocene to early Miocene age that are hydraulically connected in varying degrees. Very locally, in the Brunswick, Ga., area, a thin sequence of rocks of Late Cretaceous age is part of the system. In general the aquifer consists of either one vertically continuous permeable zone or two major permeable zones separated by a less permeable unit of highly variable water-transmitting characteristics. Aquifer conditions range from unconfined to confined depending upon whether the clayey Miocene and younger rocks that form the upper confining unit have been removed by erosion.

Digital model simulation shows that prior to development, most flow in the aquifer occurred in the unconfined and thinly confined areas of northwest and central Florida and southwest Georgia. Springs in these areas are visible evidence of major flow activity. Spring discharge to streams accounted for about 90 percent of the average predevelopment discharge from the regional aquifer. About 18,100 cubic feet per second left the limestone aquifer as spring flow, and 2,500 cubic feet per second discharged as diffuse upward leakage from the confined areas where the vertical head gradient was upward. Most of the 20,600 cubic feet per second recharge necessary to balance total discharge entered the limestone aquifer in the unconfined and thinly confined areas. Because the areas of greatest recharge before development were near the areas of highest discharge, flow paths were generally short. Much water went into and out of the limestone quickly. A very active shallow flow system at the expense of deep circulation has evolved in unconfined and slightly confined spring areas. Transmissivities commonly exceed 1,000,000 feet squared per day.

In contrast, predevelopment flow in the aquifer in the tightly confined areas of southeast and coastal Georgia, far west Florida, and in south Florida was sluggish. In these areas the aquifer is overlain by several hundred feet of sand and clay, except for the outcrop areas along the updip limit of the aquifer. This thick overburden severely retards discharge from the aquifer,

causing lethargic flow. Large-discharge springs are nonexistent. The south Florida and southeast Georgia segments of the flow system, which taken together occupy about 50 percent of the regional system, only accounted for slightly more than 3 percent of the predevelopment regional limestone discharge. Transmissivities are on the average lower (generally less than 250,000 feet squared per day) than those in areas of high-flow activity.

INTRODUCTION

The ground-water hydrology section of this report describes the predevelopment flow system of the highly productive limestones of Tertiary age that underlie all of Florida, south Georgia, and adjacent parts of Alabama and South Carolina. The primary tool used to develop a regional understanding of this flow system is the U.S. Geological Survey's three-dimensional digital ground-water model (Trescott, 1975; Trescott and Larson, 1976). The modeling section of this report documents the use of that model to simulate the regional flow system as it is conceptualized to have been before ground-water development.

The study that generated this report is one of a series that comprise the U.S. Geological Survey's Regional Aquifer Systems Analysis program (RASA), a Federally funded nationwide effort to provide comprehensive descriptions of major aquifer systems in the United States. Specifically, the RASA projects are intended to define (1) the hydrology of the regional aquifers before significant development of ground water occurred; (2) the changes or stresses on the aquifers caused by man; and (3) the hydrology of the aquifers as they exist today including the effects of development. This is one of several interim reports summarizing "first phase" work on the 4-year Southeast Carbonates RASA project, which began in October 1978. Other reports include a series of interpretive maps depicting the hydrogeologic framework of the aquifer (Miller, 1982a, b, c, d, e) and the water chemistry of the aquifer (Sprinkle, 1982a, b, c, d). Regional potentiometric surface maps for predevelopment conditions and for 1980 have been prepared (Johnston and others, 1980; Johnston and others, 1981). In addition, other reports describe in more detail the subregional predevelopment flow systems in west-central Florida (Ryder, 1982), east-central Florida (Tibbals, 1981), and southeast Georgia (Krause, 1982). Each of the subregional reports is based on the results of separate digital model analysis of the respective subregional areas. The relation of these three subregional flow models to the regional flow model that is the basis for this report is discussed in the modeling section.

GROUND-WATER HYDROLOGY

Ground-water flow in the Tertiary limestones of the southeastern United States is controlled by (1) the hydrogeologic framework, that is, the extent, nature, and permeability of the rocks that are in and adjacent to the aquifer; and (2) the areal distribution and rate of recharge to and discharge from the aquifer. These are the topics of this section. Emphasis will be on the factors that most strongly influence the flow system: the areal variation of transmissivity, and recharge and discharge.

Hydrogeologic Framework

The Tertiary limestone aquifer consists of various carbonate units (permeable zones of different geologic formations and time-stratigraphic units), in different combinations, hydraulically connected in varying degrees, in different places. The rock units, which generally range in age from Paleocene to early Miocene, are collectively known as the Floridan aquifer in Florida and the principal artesian aquifer in Georgia, Alabama, and South Carolina. The relation of the term Tertiary limestone aquifer to the terms Floridan aquifer (as defined by Parker and others, 1955) and principal artesian aquifer (as redefined by Stringfield, 1966) is shown in table 1.

Study of the geology and permeability distribution within the limestone aquifer (Miller, 1982a) suggests that the aquifer in general consists of either one vertically continuous permeable zone, or two major permeable zones separated by a less-permeable unit of highly variable water-transmitting characteristics. Table 1 shows how the two permeable zones and the intra-aquifer low-permeability zone are related to various geologic units.

The estimated lateral extent of the predevelopment freshwater flow system of the two major permeable zones is shown in figure 1 (in pocket). In coastal areas, permeable limestone is presumed to extend seaward of the limits of freshwater flow in the upper and lower permeable zones shown in figure 1. A basic and major premise about the predevelopment limestone-aquifer flow system in and near coastal areas is that a stable freshwater-saltwater interface exists at depth, rising seaward toward and ultimately intersecting the top of the aquifer as distance from inland areas increases seaward. Beneath the interface static saltwater exists; flowing freshwater occurs above the interface. Thus the predevelopment flow system in the Tertiary limestone aquifer is conceptualized as an exclusively freshwater flow system with a sharp interface between the freshwater and static saltwater.

In theory the equilibrium position of a sharp freshwater-saltwater interface relative to a datum is directly proportional to the freshwater head on the interface. In reality the nature and position of the interface may be different. In some areas, zones of relatively low permeability, and (or) very sluggish flow through the system over geologic time, have resulted in transition zones from freshwater to saltwater that may or may not be abrupt; and the locations of which may be related to sea levels that existed in earlier gelogic periods. Determination of the seaward extent of the interface in each of the two major permeable zones is explained in the modeling section. (Note: The boundary of the freshwater flow system is placed at the estimated midpoint of the transition zone between freshwater and seawater, which would correspond to a chloride concentration of about 10,000 mg/L. Thus all water of less than 10,000 mg/L chloride is considered part of the freshwater flow system, even though for water-supply purposes freshwater is generally defined as water containing less than 250 mg/L chloride.)

The northern limit of freshwater flow in the limestone aquifer coincides with the updip limit of the aquifer. In updip areas, the limestone is thin and interbedded with calcareous sands and clays, ultimately grading into fully clastic units stratigraphically equivalent to the limestone units. Miller

Table 1.--Terminology applied to the Tertiary limestone aqufier

Series		Parker and others (1955) WSP 1255 Formations*	Parker and others (1955) WSP 1255 Aquifer	Stringfield (1966) PP 517 Formations	Stringfield (1966) PP 517 Aquifer	Miller (1982b, 1982d) WRI 81-1176, WRI 81-1178 Formations	Miller (1982b, 1982d) WRI 81-1176, WRI 81-1178 Aquifer	This report
Miocene		Hawthorn Formation	where permeable	Hawthorn Formation	PRINCIPAL ARTESIAN AQUIFER	Hawthorn Formation		Upper confining unit
		Tampa Limestone	FLORIDAN AQUIFER	Tampa Limestone		Tampa Limestone	where present and permeable	Upper permeable zone
Oligocene		Suwannee Limestone		Suwannee Limestone		Suwannee Limestone	TERTIARY LIMESTONE AQUIFER	
Eocene	Late	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	Considerable variation in base	Intra-aquifer low-permeability zone Lower permeable zone
	Early			Oldsmar Limestone		Oldsmar Limestone		
Paleocene						Cedar Keys Limestone		Lower confining unit

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

(1982b) arbitrarily placed the updip limit at the point where the limestone aquifer is less than 100 feet thick and where clastic beds of a particular unit make up about 50 percent of the section. The western limit of the limestone system (also assumed coincident with the limit of the freshwater flow system) is a fault zone in southwestern Alabama. A graben system there juxtaposes relatively impermeable beds against permeable limestone. At the northeast limit of the limestone aquifer, the upper permeable zone (and freshwater flow system) terminates just north of the Georgia-South Carolina line because of a facies change to low permeability rocks. The lower permeable zone is carried farther northeast until its transmissivity declines from tens of thousands to a few thousand feet squared per day in South Carolina.

Freshwater flow occurs in one vertically continuous permeable zone where no colored areas are shown on figure 1; colors delineate the areas where an intra-aquifer low-permeability zone separates the aquifer into an upper and lower permeable zone. Although a lower permeable zone exists in panhandle Florida and south Alabama, the chloride concentration of the water in it is generally greater than 10,000 mg/L. Accordingly, the zone is not considered to be part of the flow system. The intra-aquifer low-permeability zone is not present in the uncolored area within the boundary of freshwater flow in the lower permeable zone (fig. 1). For convenience of digital modeling of the flow system, the hydrogeologic framework in this area is considered as an upper and lower permeable zone with a "very leaky" intra-aquifer low permeability zone between them, rather than as one vertically continuous permeable zone.

The extensive colored area along the Atlantic coast (fig. 1) has been designated the Orlando-area intra-aquifer low-permeability zone by J. A. Miller (written commun., 1980). This zone consists of soft chalky limestone and dolomite, except for the northernmost part which consists of calcareous sands and clays. The lithologic differences between this zone and adjacent upper and lower permeable zones are subtle. The zone is thickest (400 to 700 feet) in the east-central Florida area from around Orlando south to Lake Okeechobee. North of Orlando, this zone thins to 100 to 200 feet. Slight head differences between the upper and lower permeable zones (on the order of 1 to 3 feet) and flowmeter data from wells imply that the zone acts as a semiconfining unit.

In central Florida, where the colors appear to overlap in figure 1 (darker blue area to left of dashed line), the Orlando-area semiconfining unit (Miller, 1982a) overtops a virtually nonleaky confining unit and the two zones are separated by a section of permeable limestone. Miller (1982b) calls this lower, tighter confining unit the Tampa area gypsiferous dolomite. Intergranular gypsum is largely responsible for this intra-aquifer layer's lack of permeability; this layer is thickest (300 to 400 feet) in the area around Tampa. Head data from aquifer tests show that virtually no water passes through this unit (P. D. Ryder, oral commun., 1980); that is, pumping from the upper zone results in no measurable head change in the lower zone.

Geohydrologic section A-A' (fig. 2, in pocket) adapted from J. A. Miller (written commun., 1980) shows the vertical relation between these two confining layers and to the upper and lower permeable zones in central Florida. The estimated position of the freshwater-saltwater interface has been superimposed on the section (interpolated with data from three wells) to show the shape (although with great vertical exaggeration) of the conceptualized "base" of the freshwater flow system there.

The intra-aquifer low-permeability zone that straddles the Florida-Georgia line is shown on figure 1 with the same color as the Tampa-area gypsiferous dolomite because its composition is similar to that of the Tampa-area confining bed. Miller (1982b) has labeled this unit the Valdosta-area gypsiferous dolomites and limestones. Gypsum that occurs within the pore spaces, and to some extent occurs as lenses or layers within the dense dolomitic limestone, severely limits flow through this unit, making it a tight confining layer. It overlies part of the lower permeable zone like an overhanging "roof," attached and grading into low-permeability clastics that form the northern limit of the lower permeable zone.

Geohydrologic section B-B' (fig. 3, in pocket) shows the overhang configuration of the Valdosta-area confining layer, and its position relative to the Orlando-area low-permeability zone. This section also illustrates the thinning of the limestone aquifer in the direction of its outcrop in Georgia. No freshwater-saltwater interface appears in figure 3 because high-chloride water does not occur in either permeable zone within this inland section.

Much of the aquifer is overlain by a confining unit of clayey Miocene and younger rocks. Where the confining unit exists, it generally separates the limestone aquifer from a surficial sandy aquifer that contains water which is in unconfined or water-table conditions. The limestone aquifer contains water under water-table conditions where the overlying confining unit has been eroded to a minimal thickness or removed altogether. Figure 4 (in pocket) shows the degree of confinement of the aquifer broken down into three categories: (1) essentially unconfined conditions, (2) semiconfined conditions where the upper confining layer occurs but is less than 100 feet thick and (or) is breached by remnant sinkholes, and (3) thickly confined conditions. In the unconfined areas, for practical purposes, water-table conditions exist; or if a thin surficial aquifer is present, heads within it are essentially the same as those of the upper permeable zone. In the semiconfined areas, the sandy surficial aquifer vertically grades into tighter, more clayey material above the limestone aquifer which, taken as a composite layer, is less than 100 feet thick and (or) has relatively permeable vertical conduits within it; and the hydraulic connection between the water table and limestone aquifers is considered good. The thickly confined areas (shown as uncolored in fig. 4) are overlain by more than 100 feet of material.

In inland areas the base of the freshwater flow system coincides in places with the base of the aquifer as mapped by Miller (1982d). The base of the aquifer consists of rocks of varying age and lithology that are everywhere much less permeable than the limestone above them. In central peninsular Florida and the southeastern third of Georgia, the base of the aquifer is characterized by evaporite beds (gypsum or anhydrite). In panhandle Florida, the northern two-thirds of the Georgia coastal plain, and South Carolina, the base of the aquifer is made up of locally calcareous clastic rocks. As previously mentioned, the freshwater-saltwater interface is the base of the freshwater flow system in all coastal areas.

Regional Flow System and Aquifer Hydraulics

The discussion of transmissivity and recharge and discharge that follows is based largely on digital modeling of steady-state predevelopment conditions in the limestone aquifer. However, much spring discharge and aquifer transmissivity data provide constraints on the ranges of parameters used in modeling and therefore on the interpretations of the flow system given here. The results of modeling have not yet been verified by either transient or steady-state simulation of present-day pumping conditions, so interpretation of the flow system based on these results is preliminary at this time; however, the overall regional patterns of parameter variation are not expected to change appreciably.

The predevelopment regional distribution of ground-water recharge to and discharge from the upper permeable zone of the Tertiary limestone aquifer is shown in figure 5 (in pocket). A very high percentage of the annual recharge to and discharge from the aquifer occurs in the unconfined and thinly confined areas. Springs in these areas are visible evidence of major flow activity. The concentration of springs and spring like discharge to streams[1/] in the unconfined and thinly confined areas are the dominant feature of figure 5. The vast majority of known springs, about 300, occurs in Florida. Individual spring discharges average from near zero to about 1,600 ft^3/s (Rosenau and others, 1977; R. P. Rumenik, written commun., 1982). Springs and spring like discharge to streams account for about 90 percent of the predevelopment discharge from the regional aquifer. About 18,100 ft^3/s leaves the predevelopment limestone aquifer as spring flow. Two-thirds of this discharge is from known springs and one-third is spring like discharge to streams. (Table 2 lists known springs and spring like discharge used in simulating the flow system.)

The simulated predevelopment flow system occupies an area of about 123,000 mi^2, 20 percent of which is offshore. About 53,000 mi^2 is discharge area (vertical head gradient upward) and about 70,000 mi^2 is recharge area. The approximately 2,500 ft^3/s discharge from the system that is not spring flow

---

[1/]Many springs occur in limestone outcrops along streams in the unconfined areas. Along reaches in these same streams, measurable discharge (determined by pickup between gaging stations over and above that which could occur as surface runoff) occurs where no named springs or locations of specific points of discharge have been identified. There is no difference in the mechanism of discharge along streams from known springs and from unidentified or unnamed vents in the limestone. Therefore the term "spring like discharge" refers to those unidentified points of discharge along streams that are not known springs, but for practical purposes, are the same as known springs. Henceforth in this report, unless otherwise stated, references to springs will mean springs and spring like discharge to streams inclusively.

Table 2.--Springs and spring like discharge used in simulating the flow system

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
1	16, 66	169 (161)	Blue Springs	41
			estimated discharge to Choctawahatchee River and Holmes Creek	128
2	16, 67	100 (94)	Morrison Spring	82
			estimated discharge to Choctawahatchee River	18
3	16, 68	50 (48)	Jackson Spring	2
			Ponce de Leon Springs	19
			Vortex Blue Spring	7
			estimated discharge to Choctawhatchee River tributaries	22
4	17, 66	300 (286)	estimated discharge to Holmes Creek	300
5	17, 67	135 (133)	estimated discharge to Choctawahatchee River	135
6	18, 64	276 (279)	Blue Spring	12
			Williford Spring	31
			Gainer Springs	159
			Pitts Spring	6
			estimated discharge to Econfina Creek	68
7	18, 66	185 (205)	Beckton Springs	42
			Cypress Spring	84
			estimated discharge to Holmes Creek	59
8	21, 65	73 (84)	Black Spring	73
9	21, 66	163 (188)	Blue Hole Spring	57
			Double Spring	38
			Gadsen Spring	18
			Mill Pond Spring	33
			Springboard Spring	17

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
10	22, 63	300 (278)	estimated discharge to Apalachicola River	300
11	22, 66	263 (253)	Bosel Spring	73
			Blue Springs	190
12	22, 67	18 (18)	Hays Spring	18
13	22, 68	10 (11)	Bazemore Spring	10
14	23, 64	400 (400)	estimated discharge to Apalachicola River	400
15	24, 57	82 (79)	Crays Rise	82
16	24, 64	50 (44)	estimated discharge to Lake Seminole	50
17	24, 65	50 (47)	estimated discharge to Lake Seminole	50
18	24, 66	130 (121)	estimated discharge to Chattahoochee River	130
19	24, 67	120 (112)	estimated discharge to Chattahoochee River	120
20	24, 68	150 (142)	estimated discharge to Chattahoochee River	150
21	24, 69	50 (46)	estimated discharge to Chattahoochee River	50
22	25, 58	1600 (1663)	Spring Creek Rise	1600
23	25, 64	30 (26)	estimated discharge to Flint River	30
24	25, 65	80 (89)	estimated discharge to Spring Creek	80

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
25	26, 59	715 (725)	Wakulla Springs	375
			Kini Spring	176
			River Sink Spring	164
26	26, 65	130 (123)	estimated discharge to Flint River	130
27	27, 58	8 (9)	Newport Springs	8
28	27, 59	672 (695)	Horn Spring	29
			Natural Bridge Spring	106
			Rhodes Springs	18
			St. Marks Spring	519
29	27, 66	220 (199)	estimated discharge to Flint River	220
30	28, 59	374 (364)	Wacissa Spring	374
31	28, 67	220 (206)	estimated discharge to Flint River	220
32	29, 67	180 (176)	estimated discharge to Flint River	180
33	30, 27	30 (26)	Warm Mineral Springs	30
34	30, 37	5 (8)	Health Spring	5
35	30, 55	5 (7)	Waldo Springs	5
36	30, 67	25 (24)	estimated discharge to Flint River	25
37	30, 68	175 (163)	estimated discharge to Flint River	175
38	31, 39	20 (24)	Salt Springs	5
			Horseshoe Spring	6
			Magnolia Springs	9
39	31, 40	4 (22)	Boat Spring	4

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
40	31, 68	210 (208)	estimated discharge to Flint River	210
41	31, 69	140 (129)	Radium Springs	40
			estimated discharge to Flint River	100
42	32, 34	12 (13)	Buckhorn Spring	12
43	32, 35	12 (30)	Lettuce Lake Spring	10
			Eureka Springs	2
44	32, 36	44 (39)	Sulphur Springs	44
45	32, 40	259 (235)	Bobhill Springs	3
			Weeki Wachee Springs	176
			Mud Spring	50
			Salt Spring	30
46	32, 41	65 (68)	Blind Springs	40
			Unnamed #7	25
47	32, 69	50 (53)	estimated discharge to Flint River	50
48	33, 34	51 (45)	Lithia Springs	51
49	33, 41	30 (51)	Unnamed #9, 10, 11, 12	30
50	33, 42	342 (344)	Chassahowitzka Springs	138
			Ruth Spring	8
			Potter Spring	22
			Homosassa Springs	174
51	33, 43	916 (819)	Crystal River Springs	916
52	33, 49	181 (183)	Manatee Spring	181

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
53	33, 50	194 (208)	Copper Spring	25
			Little Copper Spring	2
			Bell Springs	5
			Otter Springs	10
			Fannin Springs	102
			estimated discharge to Suwannee River	50
54	33, 55	245 (278)	Allen Mill Pond Spring	22
			Blue Spring	93
			Peacock Springs	15
			Tilford Spring	40
			Charles Springs	18
			estimated discharge to Suwannee River	57
55	33, 69	25 (23)	estimated discharge to Flint River	25
56	33, 70	25 (25)	estimated discharge to Flint River	25
57	34, 36	60 (45)	Crystal Springs	60
58	34, 46	56 (41)	Wekiva Springs	56
59	34, 48	9 (5)	Blue Spring	9
60	34, 51	354 (396)	Lumber Camp Springs	6
			Rock Bluff Springs	34
			Sun Springs	28
			Guaranto Spring	12
			Hart Springs	75
			estimated discharge to Suwannee River	199
61	34, 52	81 (80)	Fletcher Spring	40
			Turtle Spring	41

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
62	34, 53	280 (265)	Branford Springs	18
			Little River Springs	84
			Ruth Spring	12
			Troy Spring	166
63	34, 54	184 (182)	Running Springs	77
			Convict Spring	5
			Mearson Spring	51
			Owens Spring	51
64	34, 56	200 (213)	Falmouth Spring	125
			estimated discharge to Suwannee River	75
65	34, 57	200 (203)	Suwanacoochee Spring	37
			Ellaville Spring	50
			estimated discharge to Withlacoochee and Suwannee Rivers	113
66	34, 58	273 (272)	Blue Spring	123
			estimated discharge to Withlacoochee River	150
67	34, 59	100 (104)	McIntyre Spring	70
			estimated discharge to Withlacoochee River	30
68	34, 61	23 (17)	Blue (Wade) Spring	23
69	34, 71	25 (25)	estimated discharge to Flint River	25
70	34, 72	10 (9)	estimated discharge to Flint River	10
71	35, 44	763 (506)	Rainbow Springs	764
72	35, 52	328 (390)	estimated discharge to Santa Fe River	328

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
73	35, 57	897 (774)	Alapaha Rise	608
			Holton Spring	289
74	36, 32	15 (12)	Kissengen Spring	15
75	36, 43	69 (37)	Wilson Head Spring	3
			Blue Spring	16
			Gum Springs	50
76	36, 51	801 (692)	Hornsby Spring	163
			Poe Springs	72
			Blue Springs	70
			Ginnie Spring	46
			estimated discharge to Santa Fe River	450
77	36, 52	358 (395)	Ichatucknee Springs	358
78	36, 56	160 (160)	estimated discharge to Suwannee River	160
79	36, 58	170 (199)	estimated discharge to Alapaha River	170
80	37, 41	45 (60)	Fenny Springs	15
			Springs around SE end of Lake Panasoffkee	30
81	37, 51	80 (74)	estimated discharge to Santa Fe River	80
82	37, 52	80 (77)	estimated discharge to Santa Fe River	80
83	37, 55	44 (44)	White Springs	44
84	38, 40	22 (15)	Bugg Spring	15
			Blue Springs	3
			Holiday Springs	4
85	38, 44	819 (788)	Silver Springs	819

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
86	39, 38	30 (30)	Apopka Springs	30
87	40, 45	10 (25)	estimated discharge to Oklawaha River	10
88	40, 46	88 (95)	Orange Spring	8
			estimated discharge to Oklawaha River	80
89	41, 38	129 (121)	Wekiwa Springs	74
			Witherington Spring	4
			Miami Springs	5
			Palm Springs	10
			Sanlando Springs	19
			Starbuck Spring	17
90	41, 39	65 (62)	Rock Springs	65
91	41, 40	56 (39)	Messant Spring	20
			Seminole Springs	36
92	41, 41	1 (1)	Camp La-No-Che Spring	1
93	41, 42	130 (121)	Alexander Springs	100
			estimated discharge to Alexander Springs Creek	30
94	41, 43	214 (192)	estimated discharge to Juniper Creek	70
			Juniper Springs	16
			Fern Hammock Springs	16
			Silver Glen Springs	112
95	41, 44	80 (79)	Salt Springs	80
96	41, 45	80 (80)	Croaker Hole Spring	80
97	41, 46	50 (50)	estimated discharge to Oklawaha River	50
98	42, 38	3 (3)	Clifton Springs	2
			Lake Jessup Spring	1

Table 2.--Springs and spring like discharge used in simulating the flow system--Continued

Number (refer to figure 5)	Grid block row, column	Total block discharge (ft^3/s) meas. or est. (simulated)	Component discharges (ft^3/s)	
99	42, 39	8 (8)	Gemini Spring	8
100	42, 40	160 (137)	Blue Spring	160
101	42, 41	30 (36)	Alexander Springs Creek	30
102	42, 43	14 (15)	estimated discharge to Lake George	14
103	42, 44	7 (7)	estimated discharge to Lake George	7
104	42, 45	9 (10)	Beecher Springs	9
105	42, 46	2 (2)	Satsuma Spring	2
106	43, 38	15 (17)	estimated discharge to Lake Jessup	6
			estimated discharge to St. Johns River below Lake Harney	9
107	43, 42	31 (31)	Ponce de Leon Springs	31
108	44, 38	45 (40)	estimated discharge to Lake Harney	45

occurs as diffuse upward leakage, mostly in coastal areas. This discharge is equivalent to about 0.6 in/yr over the discharge area. Figure 5 shows that most of the 20,600 ft^3/s recharge necessary to balance total discharge enters the aquifer in the unconfined and thinly confined areas surrounding springs. This recharge is equivalent to about 4.2 in/yr over the entire recharge area.

The highest discharge is from the delineated areas of greatest recharge to the predevelopment flow system. This implies a relatively high rate of ground-water flow in these areas where the aquifer is unconfined or partially confined, compared to that of areas where the limestone aquifer lies well below land surface under a fairly thick cover of sands and clays (southeast Georgia, extreme west Florida, and south Florida on fig. 4). Another implication of high recharge and discharge in the same areas is that flow paths are relatively short; much water goes into and out of the limestone quickly. The bulk of the recharge does not move many tens of miles from recharge areas to discharge areas. Rapid flow along short flow paths suggests a very active shallow flow system in unconfined and thinly confined parts of the limestone. The average dissolved solids in water from the known springs accounted for in this study is well below 250 mg/L. But the majority of these springs are in areas where analyses of samples from wells open to the upper permeable zone show dissolved-solids content to be greater than 250 mg/L, and often greater than 500 mg/L (Sprinkle, 1982b).

Rhoades and Sinacori (1941) hypothesize that increasing shallow ground-water flow and decreasing deep ground-water flow is the natural progression of a limestone circulation system over geologic time. Initially, if a limestone system had intersecting joint patterns of more or less uniform distribution, its overall flow pattern would be roughly like that proposed by Hubbert (1940) for flow between points of recharge and discharge in uniformly permeable material. But this type of flow pattern favors more aggressive solution along the shorter, shallower flow paths; this is because the water there, due to its relatively short residence time, will generally be richer in carbon dioxide and more undersaturated with respect to calcium carbonate than water deeper in the limestone. Thus, the more aggressive solution leads to the formation of large-diameter conduits and more direct connection to points of discharge in the upper parts of the aquifer. Ultimately these large conduits develop into "master" conduits by coalition of adjacent channels, capable of carrying very large lateral flows, and resulting in greatly decreased deep circulation.

A simpler explanation for a highly developed upper-aquifer-zone flow system at the expense of deep circulation may be that, over geologic time, water has merely taken the path of least resistance. The primary permeability of the layered sedimentary material that was to become the aquifer was inherently greater in the lateral direction than the vertical. Many authors have commented on the fact that in nearly horizontal carbonate rocks, openings parallel to bedding are more important to ground-water flow than vertical openings along joints (Freeze and Cherry, 1979, p. 155). This characteristic (in the saturated zone) would encourage lateral flow and hence lateral solution over vertical flow and solution.

Solution of limestone is responsible for high transmissivity in this aquifer. It follows, then, that transmissivity in the unconfined and thinly confined areas of the aquifer, particularly where natural recharge and discharge are highest, should be high.

Figure 6 (in pocket) shows the areal variation of transmissivity in the upper permeable zone. The open-ended "range" of greater-than-1,000,000 ft^2/d used in figure 6 is purposely general. Transmissivities of this order of magnitude reflect the dominance of large solution-channel, or conduit, flow toward springs; and the location of the conduits in the vicinity of any large spring is random. Thus transmissivity in these areas, on a local scale, is highly variable. In a flow-net analysis of the upper part of the Floridan aquifer in the vicinity of Ocala (Marion County, Fla.), Faulkner (1973) calculated flow-tube transmissivity values ranging from 40,000 to 25,000,000 ft^2/d, with an average of just over 2,000,000 ft^2/d; hence the necessity for portraying high transmissivity in a general way on a regional scale.

Although the transmissivity distribution shown in figure 6 is based on modeling, the transmissivities do not differ greatly from field values derived from aquifer tests with fully penetrating wells. However, where transmissivities in excess of 250,000 ft^2/d are shown on figure 6, field data confirming such values rarely exist.

Segments of the flow system in southeast and coastal Georgia, in south Alabama and far west Florida, and in south Florida are extremely sluggish as compared to parts of the predevelopment flow system in most unconfined and thinly confined regions of the aquifer. As shown on figure 4, each is overlain by several hundred feet of sand and clay, except for the outcrop areas along the updip limit of the system. This thick overburden severely retards discharge from the system, causing lethargic flow in these three areas. Large-discharge springs are nonexistent. There is some spring like discharge where the aquifer crops out along the Ocmulgee, Oconee, and Ogeechee Rivers in and south of the outcrop area of southeast Georgia; but on a regional basis and compared to point discharges in northwest Florida and southwest Georgia, spring like discharge to southeast Georgia rivers is minimal. With no significant spring flow, water must leave the system as diffuse upward leakage, most of which probably evaporates or is transpired from land areas, or leaks into the sea offshore. Even though the limestone aquifer is unconfined along its northern limit, figure 5 shows that recharge is very low there. Recharge is rejected in much of the aquifer's outcrop area because of the tight discharge control downdip--there's simply no high-volume discharge areas (predevelopment) in coastal Georgia or west panhandle Florida, so there can be no high-volume recharge updip.

No outcrop area occurs in the southern half of peninsular Florida. Figure 5 shows that the area where recharge can occur in the southern half of the peninsula is quite small compared to the area where discharge can occur. Thus even though recharge to the limestone from the surficial aquifer along the ridge areas in northwest Highlands and central Polk Counties probably averages about 5 in/yr, diffuse upward leakage over the vast lowland swamp and coastal areas of south Florida is at least an order of magnitude less. In fact, the flow system is so sluggish that upward leakage over much of the area is probably less than 0.1 in/yr; and most of the recharge occurring in the Highlands County-Polk County ridge areas probably discharges close to those areas.

The three areas of low recharge, sluggish flow, and diffuse upward leakage generally have lower transmissivity than the areas of high recharge, rapid flow, and spring discharge, with the exception of the southeast-Georgia area west and northwest of Brunswick. Lower transmissivity in areas of low-flow activity would be expected, since high transmissivity in limestone is the result of solution associated with vigorous ground-water circulation. Stringfield and LeGrand (1966) attribute the development of relatively high transmissivity in thickly confined southeast Georgia to Pleistocene time when sea level was lower than at present. Freshwater occupied more of the limestone system then; recharge probably occurred through sinkholes that are now buried and below present sea level; points of freshwater discharge were farther offshore. The net result was more active circulation and more aggressive solution of the limestone then than now.

The discussion thus far in this section has been about the characteristics of the flow system in the upper permeable zone. This is because little specific data are available pertaining to flow characteristics in the lower permeable zone. In the past there has been no need to obtain these data on a regional basis as the upper permeable zone has served ground-water needs in nearly all areas. Limited head data from the lower permeable zone indicate a downward gradient from overlying strata inland and an upward gradient to overlying strata along the coast. Predevelopment head difference between the two permeable zones is estimated to be on the order of 1 to 5 feet.

Preliminary results from the flow model and sensitivity analyses showed that the influence of the lower permeable zone on the overall predevelopment flow system was small. For this reason, and as lack of data precluded a hydrologic basis for parameter changes, no serious attempt to calibrate this layer was made. Likewise, the parameters in the model that represent the low-permeability zone between the two permeable zones were left largely unchanged from initial estimates during model calibration of the upper permeable zone.

The estimated predevelopment potentiometric surface of the upper permeable zone of the limestone aquifer is shown by figure 7 (modified from Johnston and others, 1980). This illustration was placed last in the discussion of the predevelopment flow system because the potentiometric surface can be considered as an integration of all the properties and characteristics that influence the flow system; it is an "illustrated summary" of the interaction of geologic structure, transmissivity, recharge, discharge, and boundary conditions.

The salient features of the potentiometric surface map (fig. 7) indicate the major characteristics of the flow system. The general direction of flow, perpendicular to contour lines, is shown to be from inland areas to coastal areas. The low gradients in south Florida and southeast Georgia, denoted by the widely spaced contours, suggest not much flow-through; and the model confirms this to be true in both areas. The distortion of contour lines around rivers, particularly in areas 2 and 4, indicate appreciable ground-water discharge to rivers in these areas. Low heads along the coast in areas 2 through 6 and in the northeast corner of area 8 coincide with the unconfined and thinly confined coastal areas delineated on figure 4. Conversely, higher heads occur in coastal areas where the aquifer is thickly confined. Heads would be expected to adjust to lower equilibrium altitudes in thinly confined areas where water can more easily flow out of the limestone. In coastal areas where heads are relatively low (for example, west-central Florida north of Tampa Bay) saltwater has established an equilibrium position closer to shore than in areas where heads are relatively high (for example, southeast Georgia).

Some major characteristics of the flow system are not readily apparent from the potentiometric surface map. Refer again to the widely spaced contours in south Florida and in southeast Georgia: a rule-of-thumb that can be erroneously applied is that widely spaced contours indicate high transmissivity. However, the contrast in transmissivity of about 20 to 1 between these two areas (fig. 6) shows that contour spacing in this flow system is not a reliable indicator of transmissivity. A combination of low gradients coupled with low transmissivity (south Florida) is as likely an occurrence as low gradients with high transmissivity (southeast Georgia) if ground-water flow is nearly stagnant, as it is in both of these areas.

The generalization that closed-contour domes on a potentiometric surface map identify areas of high rates of recharge does not universally apply to the potentiometric map of the limestone aquifer. Comparison of figures 5 and 7 shows that closed-contour domes may or may not represent recharge areas, depending upon hydrologic conditions at the particular closed-contour dome. For example, in the vicinity of the closed-contour potentiometric high in central peninsular Florida (on the boundary between areas 5 and 6, fig. 7), recharge ranges from 1 to 5 in/yr. Recharge to the limestone aquifer is relatively low primarily because the potentiometric surface is about at the same altitude as the water table in the thin surficial aquifer. Both the potentiometric surface and the water table are close to land surface. Thus, little vertical gradient exists to move water downward, and little storage space exists in the surficial aquifer for much of the rainfall. Potential limestone-aquifer recharge thus is lost to runoff or evapotranspiration (Grubb, 1978). In contrast, the closed-contour potentiometric high around Valdosta in south-central Georgia (confluence of areas 3, 4, and 8, fig. 7) is in an area where recharge to the principal artesian aquifer is estimated to range from 10 to 20 in/yr. The Withlacoochee River and sinkhole lakes provide direct links between rainfall and the aquifer system in this area (Krause, 1979).

In general, rates of recharge are higher in the downgradient areas than in the potentiometric high areas. For example, highest recharge rates are 15 to 20 in/yr in the Tallahassee area along the path of flow toward springs near the coast. Similar rates occur along the karstic high-flow paths to springs on the Suwannee and Santa Fe Rivers in north Florida.

To again emphasize the contrast in flow activity among different areas of the regional flow system, discharge from each of eight major ground-water basins, or subregional flow systems, is shown on figure 7 as a percentage of the total steady-state flow through the system (20,600 ft^3/s), and also in cubic feet per second. Subregional discharge is an excellent indicator of flow activity; high steady-state discharge from a ground-water basin implies correspondingly high recharge, which in turn implies rapid flow from points of recharge to points of discharge. Ninety-one percent of the regional-system discharge is from the subregional areas that are predominantly unconfined and thinly confined (basins 2 through 6 on fig. 7). In contrast the thickly confined south Florida and southeast Georgia basins (7 and 8), which together occupy nearly 50 percent of the limestone aquifer, account for only about 3 percent of the regional limestone discharge.

MODELING THE GROUND-WATER FLOW SYSTEM

The only practical way to determine the areal distribution of parameters controlling ground-water flow, and the areal distribution of flow itself, in a reasonably complex aquifer is with a digital computer model. For this application, the U.S. Geological Survey's three-dimensional finite difference model was chosen for two reasons: (1) it allows the simulation of flow in a layered aquifer where major permeable zones are separated by confining units, and (2) it is both documented and tested in numerous applications. In the model, the differential equations of ground-water flow are simulated by finite-difference equations, which are solved by an iterative numerical technique known as the strongly implicit procedure. No attempt is made here to describe the solution algorithm, as it is explained in Trescott's model documentation (Trescott, 1975; Trescott and Larson, 1976).

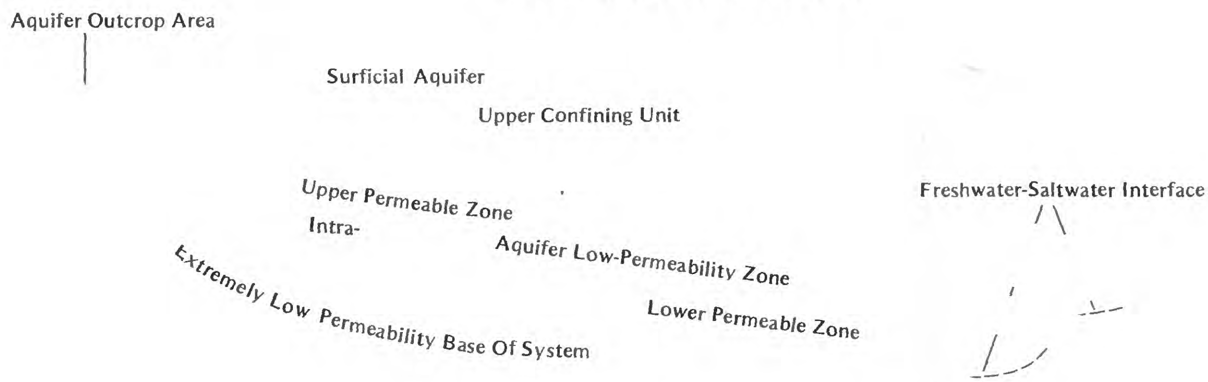
The goal of this phase of the modeling was to adjust hydraulic parameters to: (1) reproduce the steady-state predevelopment potentiometric surface of the upper permeable zone as closely as possible (that is, minimize the difference between the estimated predevelopment potentiometric surface and the computer-generated predevelopment potentiometric surface), and (2) to reproduce measured or estimated spring discharges. Accordingly, this section documents the initial data input requirements, the calibration procedure, and presents the simulation results.

Model Requirements

Idealized Model

Any model requires a series of compromises, or idealizations, to bridge the gap between the complexities of the real ground-water flow system and the simplifications necessary to fit the system into the model. Figure 8 shows the conceptual model of the aquifer system in typical section, and the corresponding idealization of that section for modeling. The section in figure 8 is patterned after the real-world section B'-B' of figure 3, but extends farther southeast, offshore. A typical section across central Florida would have a freshwater-saltwater interface on both sides; a typical section through the northwest Florida unconfined area would show little or no surficial aquifer.

CONCEPTUAL CROSS SECTION



IDEALIZED CROSS SECTION FOR MODELING

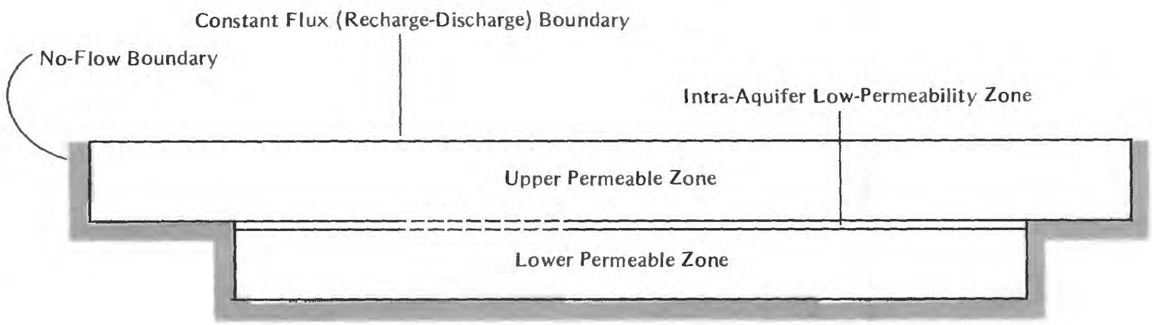


Figure 8. Conceptual representation of the aquifer and idealized representation in the model.

However, common to all typical sections as shown in figure 8 are two aquifer layers separated by an intra-aquifer low-permeablility zone.

Confining layers in the model may be represented by active layers of nodes with components of flow in three dimensions. An alternative approach is to represent only the aquifers by nodes and to use only the confining-bed permeabilities to control the vertical flow between adjacent aquifers. The latter approach was used because it simplifies the model input requirements; and because the contrast in the values of horizontal permeability of aquifers to vertical permeability of the confining bed is large enough so that the simpler approach may be used without loss of accuracy in model results. Thus the intra-aquifer low-permeability zone in the aquifer system is idealized in the model only as an impediment to the vertical exchange of water between producing zones, and not as a model layer with a potentiometric surface and the potential for horizontal flow.

Two options are available for supplying and removing water vertically to (or from) the limestone aquifer in the steady-state model: (1) Leakage from the surficial aquifer (recharge) and to the surficial aquifer (discharge) through the upper confining bed can be simulated by adding a third aquifer layer on top of the two limestone layers and a vertical-flow-retarding confining bed between the second and newly added third aquifer layer. Heads in the third layer (water-table heads) are held constant during a simulation period; this allows rates of recharge and discharge, which vary in direct proportion to vertical gradients across the upper confining bed, to change as heads in the upper permeable zone change. (2) The second option is to enter areal recharge and discharge rates, which remain constant during a simulation period, directly into the model as input data. The input requirements for this method are simpler than the first one because water-table heads, and leakance values for the upper confining layer, need not be provided. It is also easier to calibrate a model using this option because recharge (or discharge), the parameter of interest, can be adjusted directly rather than indirectly by adjusting heads (actually, head difference) and leakance. The latter option was used here; that is why no confining unit and surficial aquifer are shown above the upper permeable zone on the idealized cross section in figure 8.

Either of these two options can be used when the object of a simulation, as in this case, is to reproduce the initial-condition heads at the end of the simulation period; but only the first option can be used in a simulation of pumping stresses. This is because heads at the end of the pumping simulation will be different from initial-condition heads; and initial condition recharge rates will change in response to changes in vertical head gradients. Thus, before the regional limestone aquifer model can be used to generate a modern-day potentiometric surface, head differences and upper-confining-layer leakance values that (when used in Darcy's law) yield initial leakage rates equivalent to direct-input leakage rates must be computed.

The no-flow boundary shown on the idealized cross section in figure 8 is consistent with the conceptual model of the system. As discussed in the ground-water hydrology section, the freshwater-saltwater interface represents the limiting coastward flow line. This flow line rises to intersect the top of each aquifer layer, as shown in the conceptual cross section of figure 8;

therefore no lateral flow occurs at the coastward boundary of the system. As conceptualized, the limestone thins and pinches out entirely at the updip limit of the system, implying that the nearly impermeable base rises to land surface. In reality, some water moves laterally into the limestone from adjacent sandy deposits at its updip limit; but whether recharge enters the system there vertically from above (or from below) or laterally makes little difference--the net result is the same. Thus all water enters or leaves vertically from above in the idealized model.

Grid

The regional-model grid defines a 65-row by 80-column matrix of blocks, each block 8 miles on a side. Figure 9 shows the area of active blocks within the rectangular matrix; that is, the limits of the modeled area. Superimposed on the modeled area are the approximate limits of the active area of each of the three subregional models noted at the beginning of this report. Each subregional-model grid is aligned the same as the regional-model grid; each block of a subregional grid is 4 miles on a side; thus each regional-grid block exactly overlies four subregional-grid blocks in areas where the regional and subregional models are coincident.

The regional grid was aligned parallel to the major axis of Florida primarily to minimize the number of inactive nodes. Transmissivity did not influence grid alignment because there is no regional preferred direction of transmissivity.

Coastal Boundary Location

The assumption that a stable freshwater-saltwater interface exists and defines the seaward extent of the freshwater predevelopment flow system has been stated in the ground-water hydrology section. This assumption is supported in one location by head and salinity data obtained during recent hydrologic testing in an offshore oil well (Tenneco Oil Company) 55 miles east of Fernandina Beach, Fla. (Johnston and others, 1982). These data in conjunction with data from a previous offshore drilling program (Wait and Leve, 1967) suggest the existence of an interface. At the Tenneco site the position of the interface (about 1,100 feet below sea level) is nearly compatible with the predevelopment head (about 30 feet).

The method used to estimate the seaward extent of freshwater flow, and thus the limit of the active model area, is based on the Hubbert interface equation (Hubbert, 1940; G. D. Bennett, written commun., 1979). The interface equation states that the depth below sea level to the base of freshwater is 40 times the altitude of the freshwater head on the interface. The factor "40" comes from the density difference between seawater and freshwater, as shown below. The interface equation is:

$$Z = \left[\frac{\rho f}{\rho f - \rho s}\right] \cdot h_f$$

where Z = depth below sea level to the base of freshwater
h_f = altitude of freshwater head on the interface
ρf = density of freshwater
ρs = density of saltwater

Taking $\rho f = 1.000$ g/cm^3 and $\rho s = 1.025$ g/cm^3, the factor

$$\left[\frac{\rho f}{\rho f - \rho s}\right] = -40.$$

Predevelopment potentiometric contour lines of the upper permeable zone were linearly extrapolated seaward to altitudes near sea level. This exercise provided a coastal contour map of the theoretical base of freshwater, after the altitude of each contour was multiplied by 40. The predevelopment potentiometric surface map was constructed from heads measured or estimated at points above the interface, rather than on the interface, as required in the Hubbert equation. It was assumed that the head at the interface was equal to the head of the potentiometric surface as measured or estimated vertically above. This condition is not precisely met because freshwater flow above the interface necessitates lines of equal head that are curved, not vertical. However, because of high aquifer permeabilities, the interface has a very low slope. The existence of a very low slope has been verified between the coast and the Tenneco site 55 miles offshore (Johnston and others, 1982). Therefore, freshwater flow lines near the interface must be nearly horizontal. This in turn suggests that the lines of equal head near the interface are nearly vertical. Thus an estimate of the interface position based on heads obtained higher in the section is acceptable. Errors associated with the linear extrapolation of contours are probably greater than those caused by differences between heads on the interface and those vertically above.

Next, contour lines of the top of the limestone aquifer (Miller, 1982d) were extended offshore like the potentiometric surface contours. The two maps were then overlain, and points where the altitude of the interface was equal to the altitude of the top of the limestone were plotted. A line connecting these points indicated the seaward extent of freshwater in the aquifer.

If available water-quality data showed high chloride concentrations (greater than 10,000 mg/L) in unstressed areas landward of the seaward limit of freshwater as determined above, the limit was modified accordingly.

Location of the seaward limit of freshwater in the lower permeable zone could only be approximated because no potentiometric surface and top-of-the-aquifer maps are available for the lower zone. Because heads and tops of the upper zone extended offshore are only approximations, the upper zone potentiometric surface and the map of the base of the upper zone (Miller, 1982c) were used in the procedure described above to locate a seaward limit of freshwater flow in the lower permeable zone.

Input Data

To simulate the steady-state predevelopment flow system as shown in the idealized section of figure 8, the following data is input to the model, in matrix form (that is, one value per active grid block):

Parameters associated with the upper permeable zone[1/]

head	(FT)
transmissivity	(FT^2/D)
recharge and discharge	(IN/YR)
spring-pool head	(FT)
spring vertical hydraulic conductance	(FT^3/S)/FT

Parameters associated with the lower permeable zone[1/]

head	(FT)
transmissivity	(FT^2/D)

Parameters associated with intra-aquifer low-permeability zone[1/]

leakance	(IN/YR)/FT

An initial areal distribution of each of these parameters is therefore required. Methods of obtaining initial model input data, and the time and effort expended in doing so, vary widely. Some ground-water modelers believe the best approach is to spend little time on initial input, get the model running early in a study, and rely on the model to improve upon the rough initial areal distributions of parameters during calibration. Other modelers spend a great deal of time obtaining the best possible distributions of parameters prior to running the model, believing that calibration will therefore go quickly and smoothly, requiring only minor adjustments to the initial input parameters. The approach taken here to obtain starting matrices of input parameters is somewhere between these two extremes.

The starting head matrix for the upper permeable zone was generated by overlaying the grid on the predevelopment potentiometric surface (fig. 7) and estimating the areal average head within each active grid block.

A preliminary regional areal distribution of transmissivity for the upper permeable zone was prepared in a format similar to that of figure 6, so it too could be overlain by the grid, and block values obtained. To do this, all available historical aquifer-test and specific-capacity test data from the limestone aquifer in the region was gathered and evaluated. The "good" test data were plotted and an areal breakdown by different ranges of transmissivity delineated. In offshore areas, transmissivities of adjacent land areas were extended toward the model boundary. Near the seaward model boundary, transmissivity was reduced to reflect the assumed decrease in thickness of the freshwater flow section caused by the sloping interface.

Initial intra-aquifer low-permeability zone leakance values were of necessity rough estimates based on qualitative judgment of vertical permeability by J. A. Miller (oral commun., 1980), thicknesses from lithologic and geophysical logs, and head gradients across the zone at a limited number of points.

[1/]Parameters used by the model must be in consistent units; units shown are those used prior to model application.

The key parameters of the regional limestone-aquifer flow system are recharge and discharge. An accurate areal distribution of recharge and discharge is the basis for understanding the range and areal variation of all other parameters associated with the flow system. Accordingly, more time and effort was spent preparing initial estimates of recharge and discharge than any other parameter.

To estimate recharge rates for model input, a series of steady-state water-balance calculations for surface-water basins (or groups of basins) was made. To do the water-balance calculations, it was necessary to estimate long-term average basin runoff, rainfall, and evapotranspiration. A description of the procedure for estimating these parameters follows:

Runoff: A composite regional surface-water basin map was prepared from existing maps. The locations of stations with at least 10 years of record and gaged basins of at least 100 square miles (with a few exceptions in areas of sparse control) were plotted on the map. If runoff in adjacent basins was the same (within an inch or two per year), basins were combined; if runoff between gages within basins was variable, subbasins consisting of areas between gages were delineated. Basin areas were taken from published records or planimetered maps as necessary, and runoff for each basin was determined.

In south Florida surface-water basins cannot be delineated; therefore no runoff values were calculated there. Runoff in coastal areas downstream of the lowermost gages was assumed to be the same as that in adjacent basins; therefore adjacent basins were extended to include coastal areas.

Rainfall: The locations of 154 rainfall stations in and adjacent to the project area with 30 or more years of record were plotted on a regional base map. Thiessen polygons (Linsley and others, 1975) were constructed to distribute long-term average rainfall over the regional area. The surface-water basin map was overlain on the map of distributed rainfall; basin rainfall estimates were obtained by planimetering the segments of rainfall polygons within each basin and calculating weighted averages based on proportional areas.

Evapotranspiration: The basis for estimating actual evapotranspiration rates over the regional area was a method using temperature and precipitation developed by Holdridge (1967) and later described and used in Florida by Dohrenwend (1977). The central variable for the estimation of evapotranspiration by this method is "biotemperature," defined as the annual sum of hourly temperatures between 0°C and 30°C divided by the number of hours in the year, with temperatures below 0°C and above 30°C added in as 0°C. Holdridge first linearly relates the biotemperature for a given site to potential evapotranspiration, which he defines as the quantity of water (expressed as a depth) that would be given up to the atmosphere within a zonal climate and upon a zonal soil by the natural vegetation of the area, if sufficient but not excessive water were available during the growing season. (Thus actual evapotranspiration estimates are for losses from land surface only.) Estimated actual evapotranspiration can then be obtained by the use of a nomogram that relates the potential evapotranspiration ratio (potential evapotranspiration divided by precipitation) with a ratio of actual evapotranspiration to potential evapotranspiration. Dohrenwend computed biotemperatures for 21 stations in Florida from 5 years of temperature record.

To begin the procedure for estimating actual evapotranspiration over the regional area, the method of least squares was used to obtain a linear statistical relation between the mean annual temperature and the biotemperature for the 21 stations. Two tests were made on the linear correlation model thus determined in order to verify that the relation between mean annual temperature and biotemperature was indeed linear. The tests justified a linear relation.

Because the linear statistical relation between mean annual temperature and biotemperature seemed adequate, biotemperatures were calculated for as many of the rainfall stations for which mean annual temperature data was available; this was about two-thirds of the 154 rainfall stations. Using the calculated biotemperatures in the method outlined above, estimates of actual evapotranspiration from land surface at 96 stations in the regional area were determined. The values were plotted on a regional base map and lines of equal evapotranspiration were drawn.

Lines of equal lake evaporation over the regional area were available from Kohler and others (1959).

The surface-water basin map was overlain on both the regional evapotranspiration map and the regional evaporation map, and a land-surface evapotranspiration estimate and an open-water evaporation estimate made for each basin. The fraction of each basin's surface area that is land and the fraction that is open water and the fraction that is swamp were then estimated. The final basin evapotranspiration estimates used in the water-balance calculations were weighted averages of the land, open-water, and swamp values; evapotranspiration from swamps was assumed to be 90 percent of the open-water value.

No rigorous technical justification for using this method for estimating regional evapotranspiration can be offered. It provided estimates for central Florida that are similar to some determined in previous studies (Parker and others, 1955; Pride and others, 1966). But more important, the method provided a means to develop estimates in a consistent manner over the entire project area. It is not simply a series of interpolations between sites for which evapotranspiration data have been gathered in various ways.

With estimates of rainfall, runoff, and evapotranspiration available, the water-balance calculations for each basin were made as follows: First the general equation

$$\text{RAINFALL} - \text{RUNOFF} - \text{ET} = \text{NET INTERBASIN TRANSFER}$$

was applied to each basin, where

RUNOFF = Streamflow that originates from direct surface runoff, from discharge from the material above the limestone aquifer, and from the limestone aquifer as spring flow or other discharge.

ET = Evapotranspiration of water from the surface, from the surficial material above the limestone aquifer, and from the limestone aquifer.

NET INTERBASIN TRANSFER = Basin boundary outflow in the limestone aquifer minus basin boundary inflow in the limestone aquifer (net interbasin transfer is negative in basins where boundary inflow exceeds outflow).

In those basins in which runoff includes no spring flow or other direct discharge from the limestone aquifer, net interbasin transfer is equivalent to recharge to the limestone aquifer. This can be demonstrated by considering basin control volumes around the surficial material and around the limestone aquifer as shown in figure 10A. Inputs to and outputs from both control volumes in figure 10A are necessarily balanced by the limestone aquifer recharge. Thus

LIMESTONE RECHARGE = NET INTERBASIN TRANSFER

In basins where runoff includes water from the limestone aquifer, an additional component is added to the control volume concept as shown in figure 10B. The general equation

RAINFALL - RUNOFF - ET = NET INTERBASIN TRANSFER

still applies, but the specific equations for each control volume have changed as shown in figure 10B. Thus, in basins where runoff includes discharge from the limestone aquifer, an estimate of the fraction of runoff that is from the limestone had to be made to obtain limestone recharge. From figure 10B,

LIMESTONE RECHARGE = NET INTERBASIN TRANSFER + LIMESTONE DISCHARGE

where limestone discharge is a part of the runoff. The term "base flow" is not applied here, because base flow usually refers to total ground-water runoff, which could include the surficial aquifer as well as the limestone aquifer; whereas here, only the component of runoff that is from the limestone is desired.

Estimating the fraction of runoff that is discharge from the limestone aquifer was difficult, and hydrologic judgment was relied upon to make the estimates. The basins for which estimates were made most easily were those receiving substantial (at least 10 in/yr) interbasin transfer. This was typical of basins in the northwest Florida area where large springs occur and the limestone is close to land surface and relatively unconfined. In these areas actual "surface" runoff is minimal and a high percentage of gaged streamflow is water from the limestone aquifer. In other areas estimates were made on the basis of topography, nature of terrain (karstic or sand plain), thickness of surficial material, direction and magnitude of vertical gradients, chemical characteristics of the streamflow, configuration of the predevelopment potentiometric surface, and magnitude of the average total runoff estimate. No attempt was made at this point to use more sophisticated hydrologic techniques, such as hydrograph separation, to estimate the limestone-aquifer component of runoff. Once again, the purpose of estimating initial recharge for model input is not to obtain extremely accurate figures that are unlikely to change,

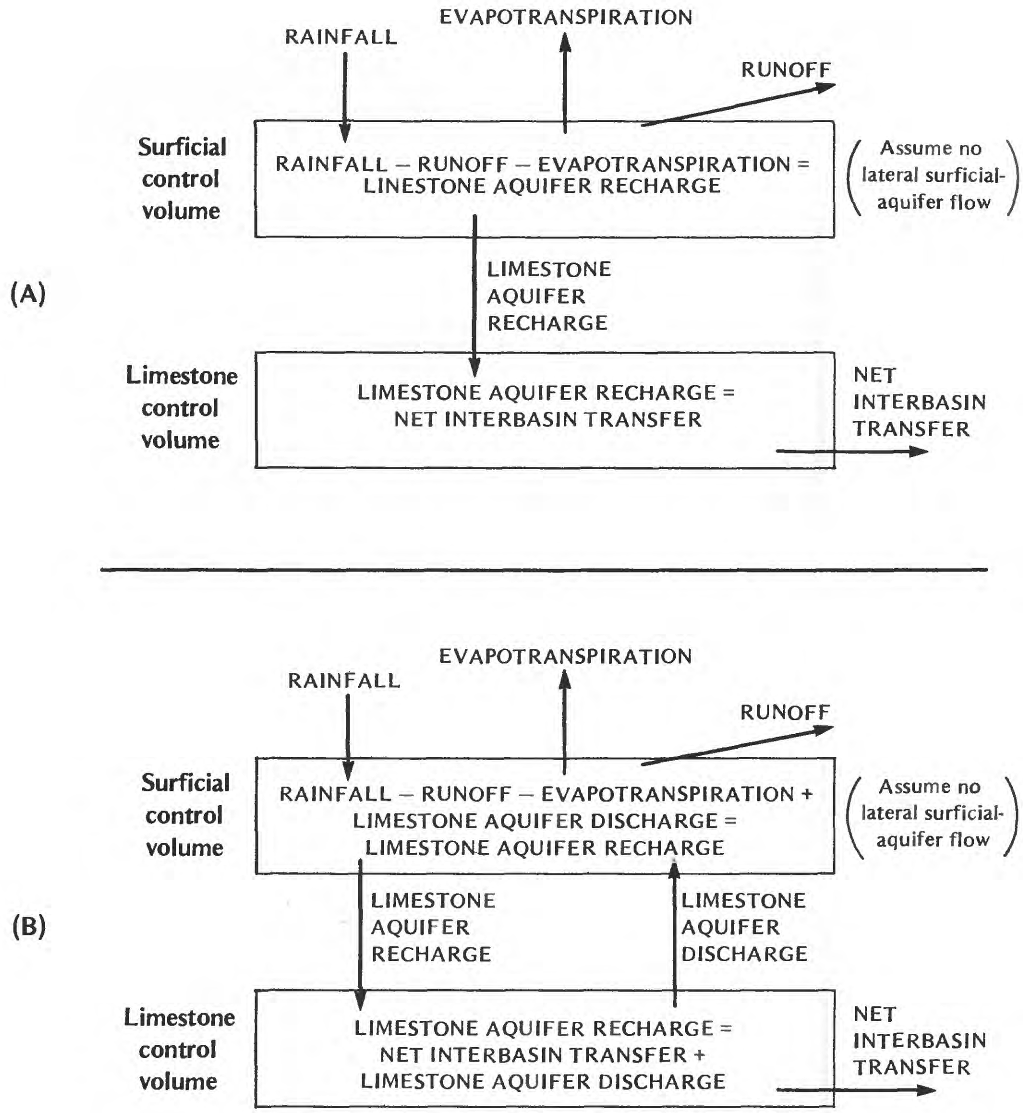


Figure 10. Diagrams showing control-volume water-balance technique to obtain limestone aquifer recharge in (A) surface-water basins where the runoff contains no discharge from the limestone aquifer; and (B) surface-water basins where the runoff includes discharge from the limestone aquifer.

but to provide initial estimates, a reasonably accurate set of values that will undoubtedly need adjustment during model calibration.

The method described above has limitations, especially in basins where the net interbasin transfer is close to zero, and is therefore less than the potential error in the estimates of rainfall, runoff, and evapotranspiration. This situation occurs in basins where limestone-aquifer recharge is naturally low, and in coastal areas where much of a basin is discharge area but the limestone is confined under an appreciable thickness of surficial material. Because discharge rates over these areas are very low, typical water-balance calculations may result in small positive or small negative recharge values, which in themselves provide no "new" information. Also, basins that are fairly evenly divided between recharge area and area of diffuse upward leakage pose problems for this method--hydrologic judgment is again necessary.

To get recharge and discharge areally distributed and into the model, the method described above was used where it worked best--the recharge areas. Basin recharge estimates were refined and enhanced by overlay and comparison with qualitative recharge maps (in Florida; Lichtler, 1972; Stewart, 1980), the regional top-of-the-aquifer map (Miller, 1982b), spring locations and discharges, and the predevelopment potentiometric surface map (Johnston and others, 1980). The total amount of recharge to the regional limestone aquifer was calculated; from this was subtracted the sum of all known spring discharges and estimated spring like discharges from the limestone aquifer. The difference was assumed to be discharge by diffuse upward leakage (as opposed to point discharge through spring vents) that occurred in coastal and offshore areas of the region. This discharge was areally distributed over the model discharge area primarily on the basis of qualitative estimates of the leakance of the surficial materials and the upward vertical gradients.

Springs in the model are simulated by a generalized head-dependent source-sink function. This is a modification to the Trescott source code written by J. V. Tracy (written commun., 1979) that can be used to simulate any process where steady-state discharge is a linear function of head gradient; that is, discharge can be expressed in the form

$$Q = C \cdot (H-h) \quad \text{for } h > H$$
$$Q = 0 \quad \text{for } h \leq H$$

Applied to spring simulation,

Q = discharge
H = spring-pool head
h = limestone aquifer head (grid-block head)
C = spring vertical hydraulic conductance

As previously stated, two matrices, one consisting of spring pool heads and the other, spring conductances, must be input. In each matrix, values of H and C are entered only for those grid blocks containing springs. Pool altitudes were determined by instrument level or estimated from 1:24,000 topographic maps. If more than one spring occurred in a grid block (frequently the case), a composite pool altitude was calculated as a weighted-average based on spring discharge rates in the block. With pool altitudes calculated, and predevelopment aquifer heads and spring discharges available, conductance could then be solved for using the equation above.

As discussed on page 19, very little head and transmissivity data exist for the lower major permeable zone. Initial lower-zone heads were arbitrarily assigned values 1 or 2 feet lower than upper-permeable-zone heads in recharge areas (as delineated on fig. 5) and 1 or 2 feet higher than upper-zone heads in discharge areas.

Initial lower-zone transmissivity values were rough estimates for the most part, based on thickness of section, upper-zone transmissivity, and qualitative assessment of the permeability of the aquifer material based on lithologic types by J. A. Miller (oral commun., 1980).

Calibration

Purpose and Procedure

The main purpose of calibrating the model, that is, adjusting input parameters to reproduce the predevelopment potentiometric surface with a physically realistic mass balance, is really the same as the main reason for making the model--to refine or improve the conceptual model, and thus to better understand the predevelopment flow system.

A secondary reason for a calibrated regional model is to provide boundary flows to the subregional models if the effects of pumping stresses simulated in the second phase of modeling reach the subregional model boundaries. For this reason, the regional model must be a "model of the subregional models" in addition to a model of the regional flow system. Consequently, in this application the calibration process was a series of simulations in which adjustments to input parameters in successive runs were based on the results of previous runs, and also on the results of subregional calibration runs.

The approach to calibration of the regional model, and subregional models also, was to consider predevelopment potentiometric heads of the upper permeable zone, and spring pool heads and discharges (and therefore conductances) as known parameters; therefore these data were not changed during calibration. These known data influence the criteria that define a calibrated model. That is, the predevelopment potentiometric surface represents estimated heads in most areas. Spring discharges are subject to a measurement error of several percent, and discharge may have changed slightly since development began. It is therefore impractical to try to eliminate all differences between "known" and computed potentiometric heads and spring discharges. Accordingly, it was decided that if the average absolute error per block (defined as the sum of the absolute differences between estimated and computed grid-block heads divided by the number of active blocks) could be made less than 5 feet, and all input parameters were within realistic ranges, the steady-state model would be considered calibrated. No criterion for matching spring discharges was chosen. Because of the way spring discharge is computed, if aquifer head is accurately reproduced at the end of a simulation, then spring discharge will also be correct.

The parameters adjusted continuously and in detail between calibration simulations were recharge and discharge rates, and transmissivity of the upper permeable zone. Other parameters were changed only incidentally because they have less influence on the flow system and because there is less hydrologic justification for making changes when little data exist (although the range of potential parameter change may be greater when data are sparse).

Calibration of the regional model and the three subregional models took place concurrently. Each regional-model grid block coincides with four subregional-model grid blocks over large parts of the project area. Both the regional and subregional models must have equivalent parameters in coincident areas after calibration. Parameters defined in more detail, on a finer grid, should be used to generate equivalent regional-grid parameters. The results of regional-model simulation should be used as a guide to the subregional modelers in parameter adjustment, particularly near subregional boundaries, but to ensure compatible results from both models, the calibration should proceed from a subregional scale to a regional scale.

Thus the question arose as to how best calculate regional-grid parameters from subregional-grid parameters. A simple arithmetic average seemed appropriate for each parameter except transmissivity; transmissivity has directional properties. Because of the analogy between ground-water flow and electrical-current flow, a sequence of hydraulic conductances in series can be reduced to a single equivalent conductance in the same way that electrical conductances in series can be converted to an equivalent conductance (G. D. Bennett, written commun., 1979). The equivalent hydraulic (or electrical) conductance obtained from this exercise is the harmonic mean conductance. From the electrical analogy and Darcy's law, in models with uniformly spaced grids, hydraulic conductance is equal to transmissivity. Thus, to rigorously make subregional and regional models compatible, some method involving harmonic mean transmissivity of subregional grid blocks should be used to obtain equivalent regional-block transmissivity values. A method devised by G. D. Bennett (written commun., 1980) was used to incorporate harmonic-mean-based equivalent transmissivities into the model's solution routine. However, the results of comparable model runs using harmonic-mean-based equivalent transmissivities and equivalent transmissivities obtained from arithmetic averaging were essentially the same. Arithmetic averaging does not yield transmissivities significantly different than the theoretically-based harmonic-mean calculation. Thus, for simplicity, arithmetic averaging of subregional-block values was used for transmissivity as well as the rest of the input parameters to obtain regional-block values.

Results and Sensitivity of Calibration

When calibration of the steady-state regional model was achieved, the average absolute error per block of the upper permeable zone was 4.7 feet; and the average error per block was -0.1 feet, with a standard deviation of 6.7 feet. For the lower permeable zone, the average absolute error per block was 4.2 feet; and the average error per block was -1.0 feet, with a standard deviation of 6.0 feet. The total regional model-computed spring discharge was 97 percent of the total regional measured or estimated spring discharge. The weighted average absolute error between simulated and actual measured or estimated spring discharge was 8.7 percent. The weighted average absolute error is defined as

$$\frac{\displaystyle\sum_{n=1}^{108}\left\{\left[\left(\frac{\text{actual spring discharge minus simulated spring discharge}}{\text{actual spring discharge}}\right)\cdot 100\right]\cdot \text{actual spring discharge}\right\}}{\displaystyle\sum_{n=1}^{108}\left(\text{actual spring discharge}\right)}$$

Simulated spring discharges are listed in table 2 adjacent to corresponding actual spring discharges.

Figures 11 and 12 graphically show the sensitivity of the calibrated predevelopment model to the parameters that control flow in the limestone aquifer. A series of simulations was made in which recharge and discharge, upper zone transmissivity, lower zone transmissivity, and intra-aquifer low-permeability zone leakance were varied over ranges within which the parameters might vary from their respective "calibrated" values. The insensitivity of heads in both the upper and lower permeable zones to lower zone transmissivity and intra-aquifer leakance values is demonstrated. This insensitivity means that the model is less useful in defining a regional distribution of each of these parameters. As was expected, heads in both aquifer zones are considerably more responsive to changes in recharge and upper zone transmissivity (figs. 11 and 12).

No clear pattern of relative sensitivity variation between areas of high and low flow activity emerged. That is, heads in areas of large springs, and high recharge and transmissivity were not necessarily more or less sensitive to parameter changes than heads in areas of very sluggish flow.

SUMMARY

The Tertiary limestone aquifer in the southeastern United States underlies all of Florida, south Georgia, and adjacent parts of Alabama and South Carolina. The rock units that comprise the aquifer generally range in age from Paleocene to early Miocene. They are collectively known as the Floridan aquifer in Florida and the principal artesian aquifer in Georgia, Alabama, and South Carolina. The limestone aquifer in general consists of either one vertically continuous permeable zone, or two major permeable zones separated by a less-permeable zone of highly variable water-transmitting characteristics.

A basic assumption about the predevelopment limestone-aquifer flow system in and near coastal areas is that a stable freshwater-saltwater interface exists at depth, rising seaward toward and ultimately intersecting the top of

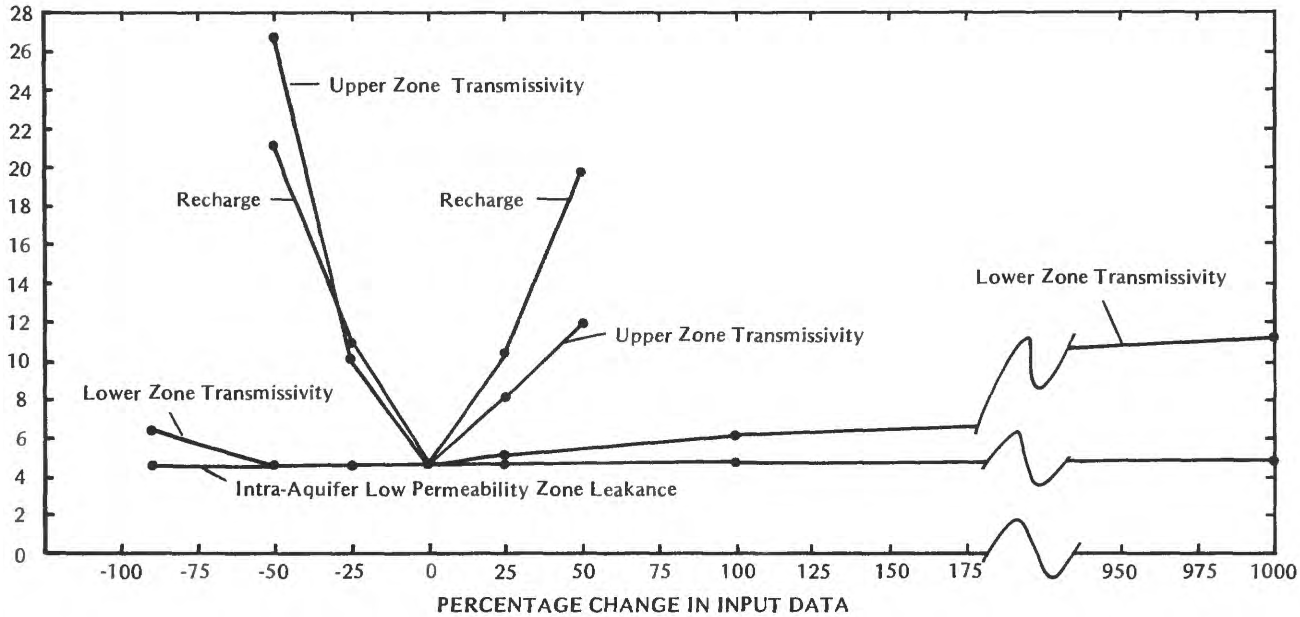


Figure 11. Relation between changes in magnitude of input parameters and average absolute error per grid block of the upper permeable zone.

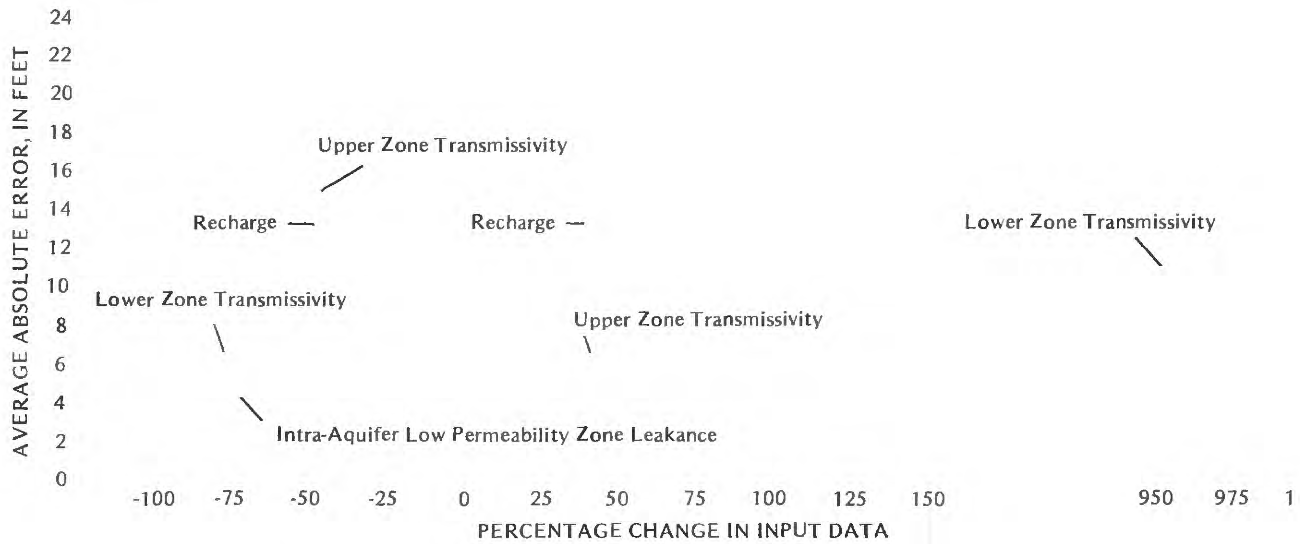


Figure 12. Relation between changes in magnitude of input parameters and average absolute error per grid block of the lower permeable zone.

the aquifer as distance from inland areas increases seaward. Flowing freshwater occurs above the interface; static saltwater exists below the interface. Thus the predevelopment flow system is exclusively freshwater.

Overlying much of the aquifer system is a confining unit of clayey Miocene and younger rocks. Where it exists, this confining unit separates the limestone aquifer from a surficial aquifer that contains water under water-table conditions. The limestone aquifer is under water-table conditions where the overlying material has been eroded to a minimal thickness or removed altogether.

The lateral and vertical boundary of freshwater flow in the limestone aquifer in and near coastal areas is the freshwater-saltwater interface; inland, the lateral and vertical boundaries consist of rocks of varying age and lithology that are much less permeable than the limestone above or adjacent to them.

Most of the flow activity in the aquifer occurs in the unconfined and thinly confined areas of northwest and central Florida and southwest Georgia. Springs in these areas are visible evidence of major flow activity. Springs and spring like discharge to streams account for about 90 percent of the predevelopment total annual average discharge from the regional aquifer system. About 18,100 ft^3/s leaves the predevelopment limestone aquifer as spring flow. By contrast, only about 2,500 ft^3/s discharge occurs through diffuse upward leakage in areas where the vertical head gradient is upward. Most of the 20,600 ft^3/s recharge necessary to balance total discharge enters the limestone aquifer in the unconfined and thinly confined spring areas. Because the areas of greatest recharge before development are near the areas of highest discharge, flow paths are relatively short. Much water goes into and out of the limestone quickly. A very active shallow flow system at the expense of deep circulation has evolved in unconfined and thinly confined parts of the limestone.

Solution of limestone is responsible for high transmissivity in the aquifer. Transmissivity is therefore highest in the unconfined and thinly confined areas where natural recharge and discharge are highest. Transmissivity commonly exceeds 1,000,000 ft^2/d in these areas.

In contrast, predevelopment flow in the aquifer in southeast and coastal Georgia, far west Florida, and in south Florida was extremely sluggish. In these areas the aquifer is overlain by several hundred feet of sand and clay, except for the outcrop areas along the updip limit of the aquifer. This thick overburden severely retards discharge from the aquifer, causing lethargic flow in these three areas. Large-discharge springs are nonexistent.

The south Florida and southeast Georgia segments of the flow system (areas 7 and 8 on fig. 7), which taken together occupy about 50 percent of the regional system, only accounted for slightly more than 3 percent of the predevelopment regional limestone discharge.

The U.S. Geological Survey's three-dimensional finite difference model was used to simulate the steady-state predevelopment flow system. The goal of the modeling was to adjust input data to reproduce the steady-state predevelopment potentiometric surface of the upper permeable zone and to compute spring discharges that match measured or estimated spring discharges.

The flow system was simulated as two aquifer layers separated by a low-permeability zone. Recharge and discharge were input directly into the upper layer. Discharge by springs was simulated by a generalized head-dependent source-sink function. A no-flow boundary surrounded the entire model. The model grid defined a 65-row by 80-column matrix of blocks, each block 8 miles on a side.

Calibration primarily consisted of adjusting recharge and discharge and transmissivity of the upper permeable zone to minimize the average absolute error per grid block, defined as the sum of the absolute differences between estimated and computed grid-block heads divided by the number of active blocks. After calibration the average absolute error per block of the upper permeable zone was 4.7 feet; and the average error per block was -0.1 feet, with a standard deviation of 6.7 feet. For the lower permeable zone, the average absolute error per block was 4.2 feet; and the average error per block was -1.0 feet, with a standard deviation of 6.0 feet. The total model-computed spring discharge was 97 percent of the total measured or estimated spring discharge. The weighted average absolute error between simulated and actual measured or estimated spring discharge was 8.7 percent.

Among the input parameters, the model was most sensitive to recharge and discharge and transmissivity of the upper permeable zone.

SELECTED REFERENCES

Dohrenwend, R. E., 1977, Evapotranspiration patterns in Florida: Florida Academy of Sciences, Journal of Florida Scientist, v. 40, no. 2, p. 184-192.

Faulkner, G. L., 1973, Geohydrology of the Cross-Florida Barge Canal area with special reference to the Ocala vicinity: U.S. Geological Survey Water-Resources Investigations 73-1, 117 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 603 p.

Grubb, H. F., 1978, Potential for downward leakage, to the Floridan aquifer, Green Swamp area, Central Florida: U.S. Geological Survey Water-Resources Investigations 77-71, 1 map sheet.

Holdridge, L. R., 1967, Life Zone Ecology: Tropical Science Center, San Jose, Costa Rica.

Hubbert, M. K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, p. 785-944.

Johnston, R. H., Bush, P. W., Krause, R. E., Miller, J. A., and Sprinkle, C. L., 1982, Summary of hydrologic testing in Tertiary limestone aquifer, Tenneco offshore exploratory well--Atlantic OCS, lease-block 427 (Jacksonville NH 17-5): U.S. Geological Survey Water-Supply Paper 2180, 15 p.

Johnston, R. H., Healy, H. G., and Hayes, L. R., 1981, Potentiometric surface of the Tertiary limestone aquifer system, southeastern United States, May 1980: U.S. Geological Survey Open-File Report 81-486, 1 map sheet.

Johnston, R. H., Krause, R. E., Meyer, R. W., Ryder, P. D., Tibbals, C. H., and Hunn, J. D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development: U.S. Geological Survey Open-File Report 80-406, 1 map sheet.

Kohler, M. A., Nordenson, T. V., and Baker, D. R., 1959, Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37, 13 p.

Krause, R. E., 1979, Geohydrology of Brooks, Lowndes, and western Echols Counties, Georgia: U.S. Geological Survey Water-Resources Investigations 78-117, 48 p.

______1982, Digital model evaluation of the predevelopment flow system of the Tertiary limestone aquifer, southeast Georgia, northeast Florida, and southern South Carolina: U.S. Geological Survey Water-Resources Investigations 82-173, 27 p.

Lichtler, W. F., 1972, Appraisal of water resources in the east-central Florida region: Florida Department of Natural Resources, Division of Interior Resources, Bureau of Geology Report of Investigations No. 61, 52 p.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1975, Hydrology for engineers: New York, New York, McGraw-Hill, 482 p.

Miller, J. A., 1982a, Thickness of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1124, 1 map sheet.

______1982b, Geology and configuration of the base of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1176, 1 map sheet.

______1982c, Configuration of the base of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1177, 1 map sheet.

______1982d, Geology and configuration of the top of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1178, 1 map sheet.

______1982e, Thickness of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1179, 1 map sheet.

Musgrove, R. H., Barraclough, J. T., and Grantham, R. G., 1965, Water resources of Escambia and Santa Rosa Counties, Florida: Florida Geological Survey Report of Investigations No. 40, 102 p.

Parker, G. G., Ferguson, G. E., and Love, S. K., 1955, Water resources of southeastern Florida, with special reference to the geology and ground water of the Miami area: U.S. Geological Survey Water-Supply Paper 1255, 965 p.

Pride, R. W., Meyer, F. W., and Cherry, R. N., 1966, Hydrology of Green Swamp area in central Florida: Florida Geological Survey Report of Investigations No. 42, 137 p.

Rhoades, Roger, and Sinacori, M. N., 1941, Pattern of ground-water flow and solution: Journal of Geology, v. 49, no. 8, p. 785-794.

Rosenau, J. C., Faulkner, G. L, Hendry, C. W., and Hull, R. W., 1977, Springs of Florida: Florida Department of Natural Resources, Division of Resource Managment, Bureau of Geology Bulletin No. 31, 461 p.

Ryder, P. D., 1982, Digital model of predevelopment flow in the Tertiary limestone aquifer system in west-central Florida: U.S. Geological Survey Water-Resources Investigations 81-54, 61 p.

Sprinkle, C. L., 1982a, Sulfate concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1101, 1 map sheet.

______1982b, Total hardness of water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1102, 1 map sheet.

______1982c, Chloride concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 81-1103, 1 map sheet.

______1982d, Dissolved-solids concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Open-File Report 82-94, 1 map sheet.

Stewart, J. W., 1980, Areas of natural recharge to the Floridan aquifer in Florida: Florida Department of Environmental Regulation, Bureau of Water Resources Management Map Series No. 98, 1 map sheet.

Stringfield, V. T., 1966, Artesian water in Tertiary limestone in the Southeastern States: U.S. Geological Survey Professional Paper 517, 226 p.

Stringfield, V. T., and LeGrand, H. E., 1966, Hydrology of limestone terranes in the coastal plain of the southeastern United States: Geological Society of America Special Paper 93, 46 p.

Tibbals, C. H., 1981, Computer simulation of the steady-state flow system of the Tertiary (Floridan) limestone aquifer system in east-central Florida: U.S. Geological Survey Water-Resources Investigations 81-681, 31 p.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 103 p.

Trescott, P. C., and Larson, S. P., 1976, Supplement to Open-File Report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow, U.S. Geological Survey Open-File Report 76-591, 21 p.

Wait, R. L., and Leve, G. W., 1967, Ground water from JOIDES core hole J-1, in Geological Survey Research 1967: U.S. Geological Survey Professional Paper 575-A, p. A127.

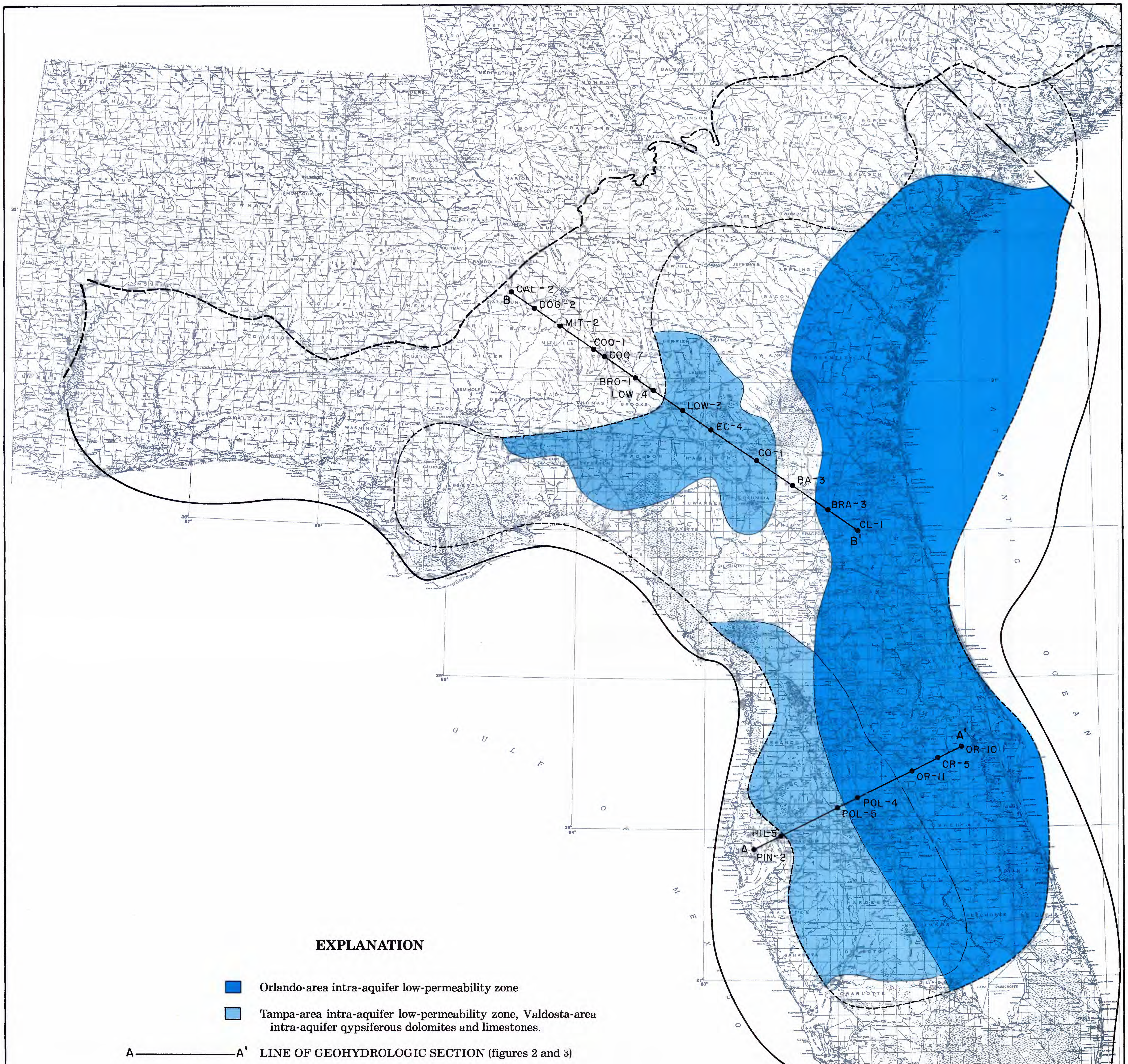


Figure 1.—Estimated lateral limit of the predevelopment freshwater flow system of the two major permeable zones of the Tertiary limestone aquifer.

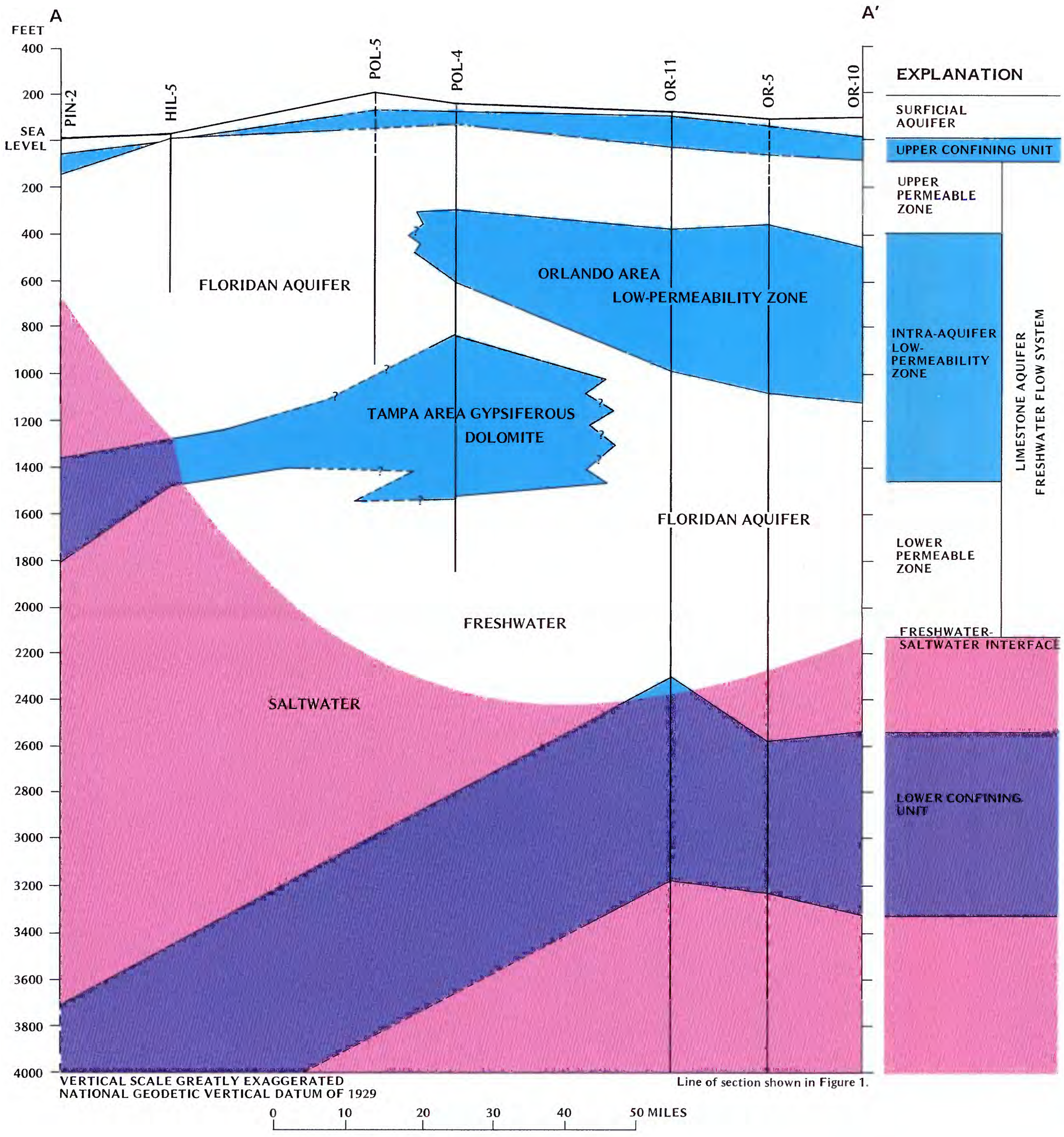


Figure 2. Geohydrologic section A - A'; west to east through central Florida (modified from J.A. Miller, written commun., 1980).

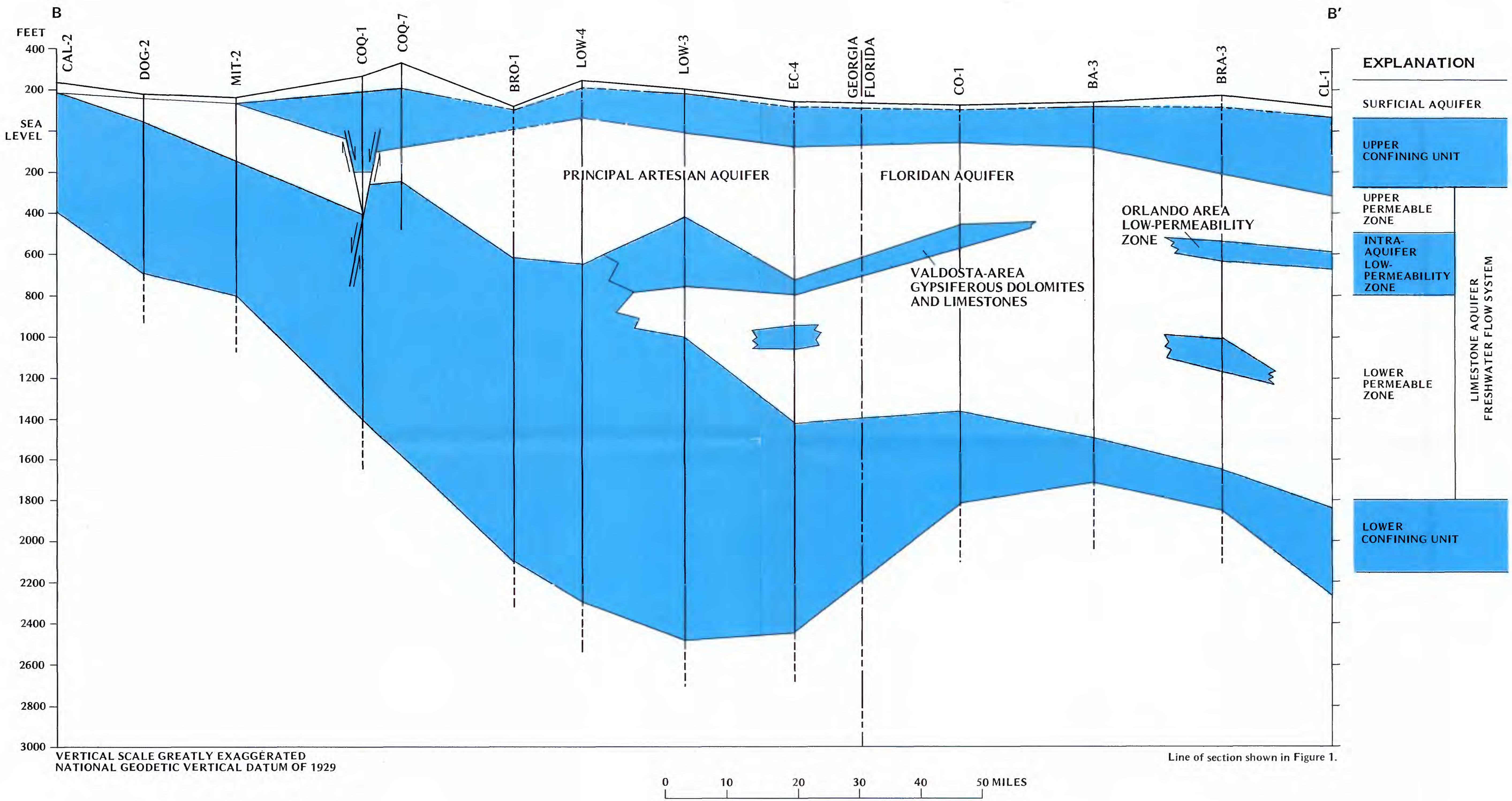


Figure 3. Geohydrologic section B - B'; northwest to southeast through south Georgia and northeast Florida (J.A. Miller, written commun., 1980).

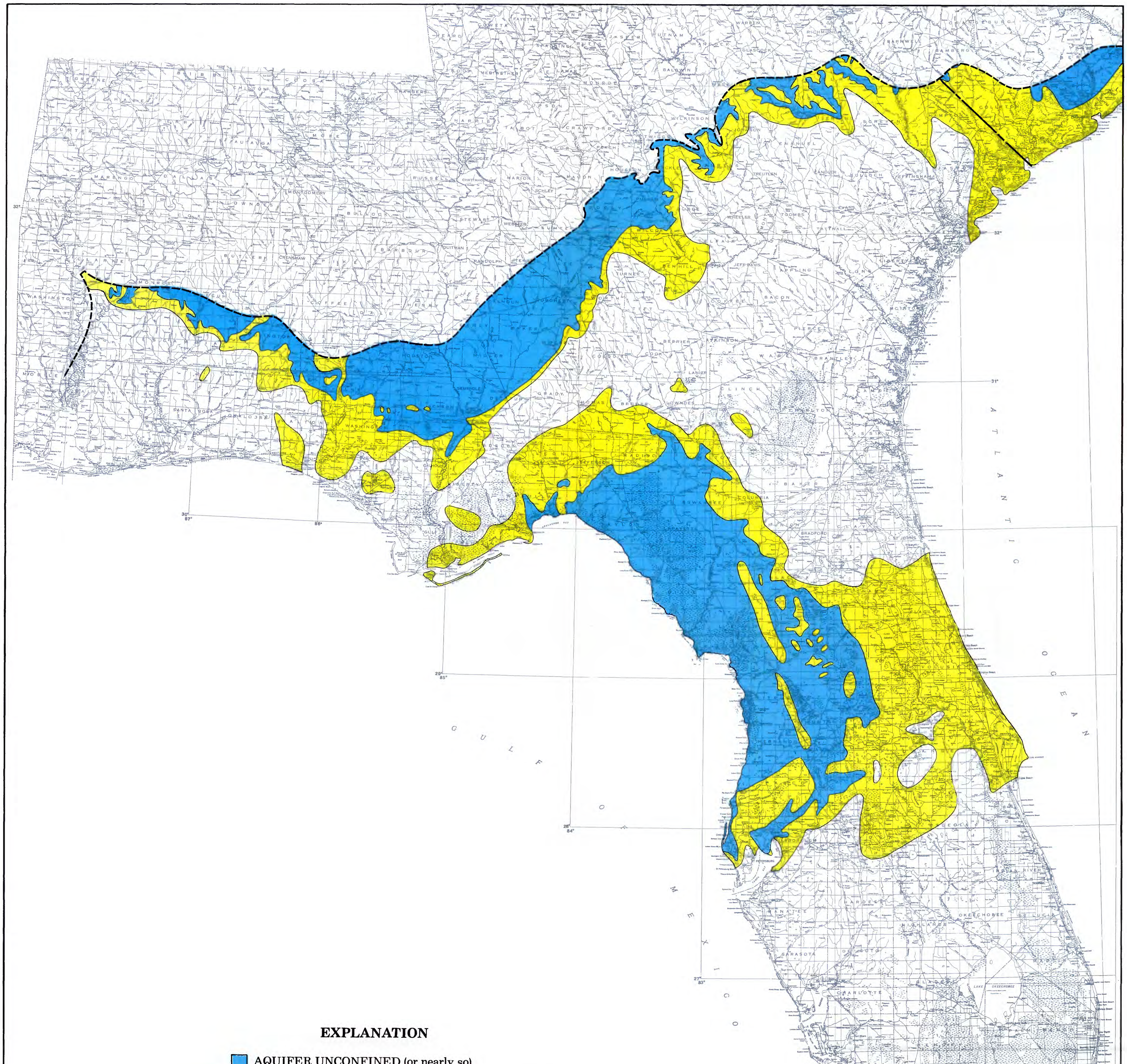


Figure 4.—Confined-unconfined conditions for the Tertiary limestone aquifer (Modified from J.A. Miller, written commun., 1980).

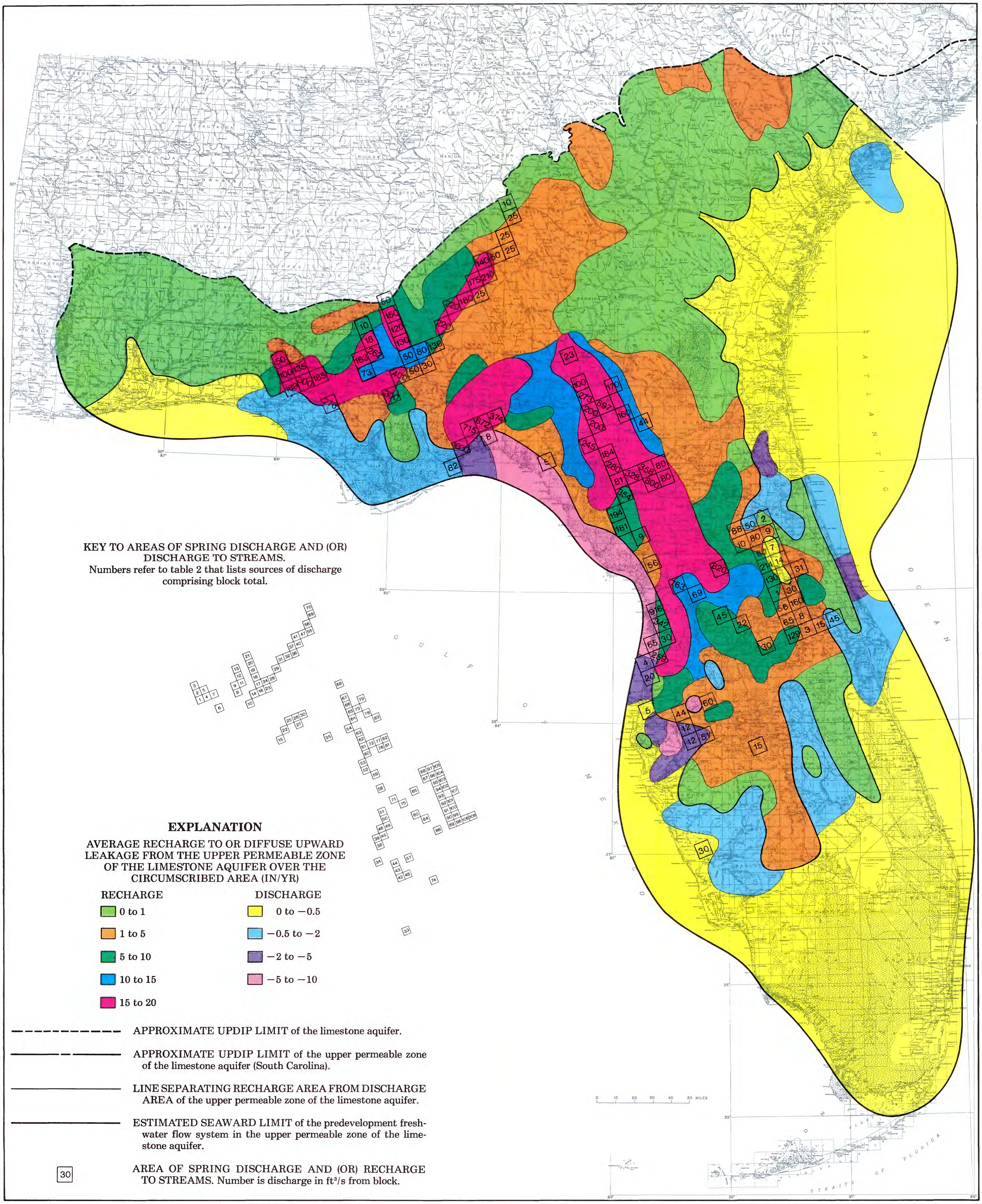


Figure 5.—Predevelopment distribution of recharge to and discharge from the upper permeable zone of the Tertiary limestone aquifer.

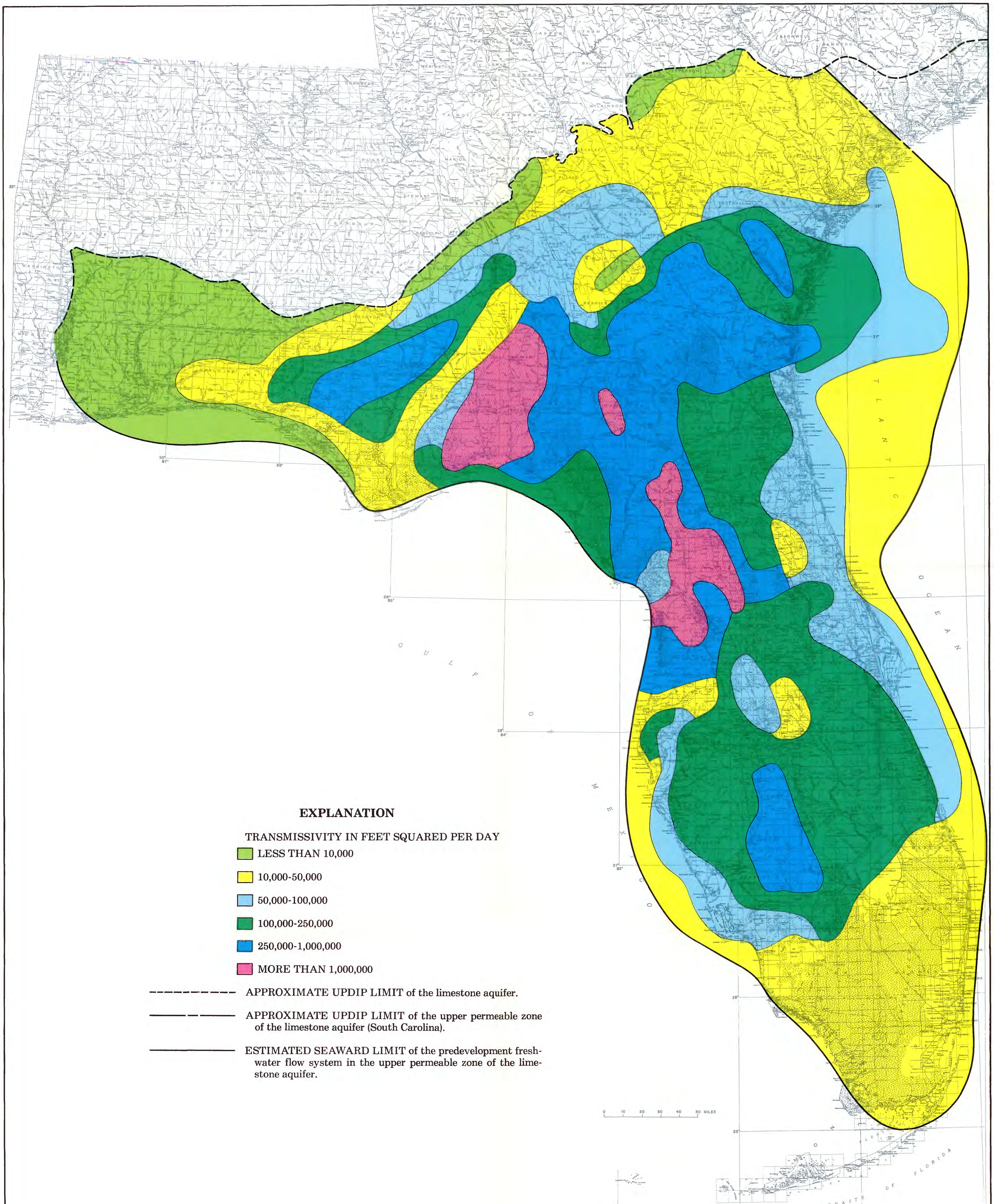


Figure 6.—Estimated transmissivity of the upper permeable zone of the Tertiary limestone aquifer.

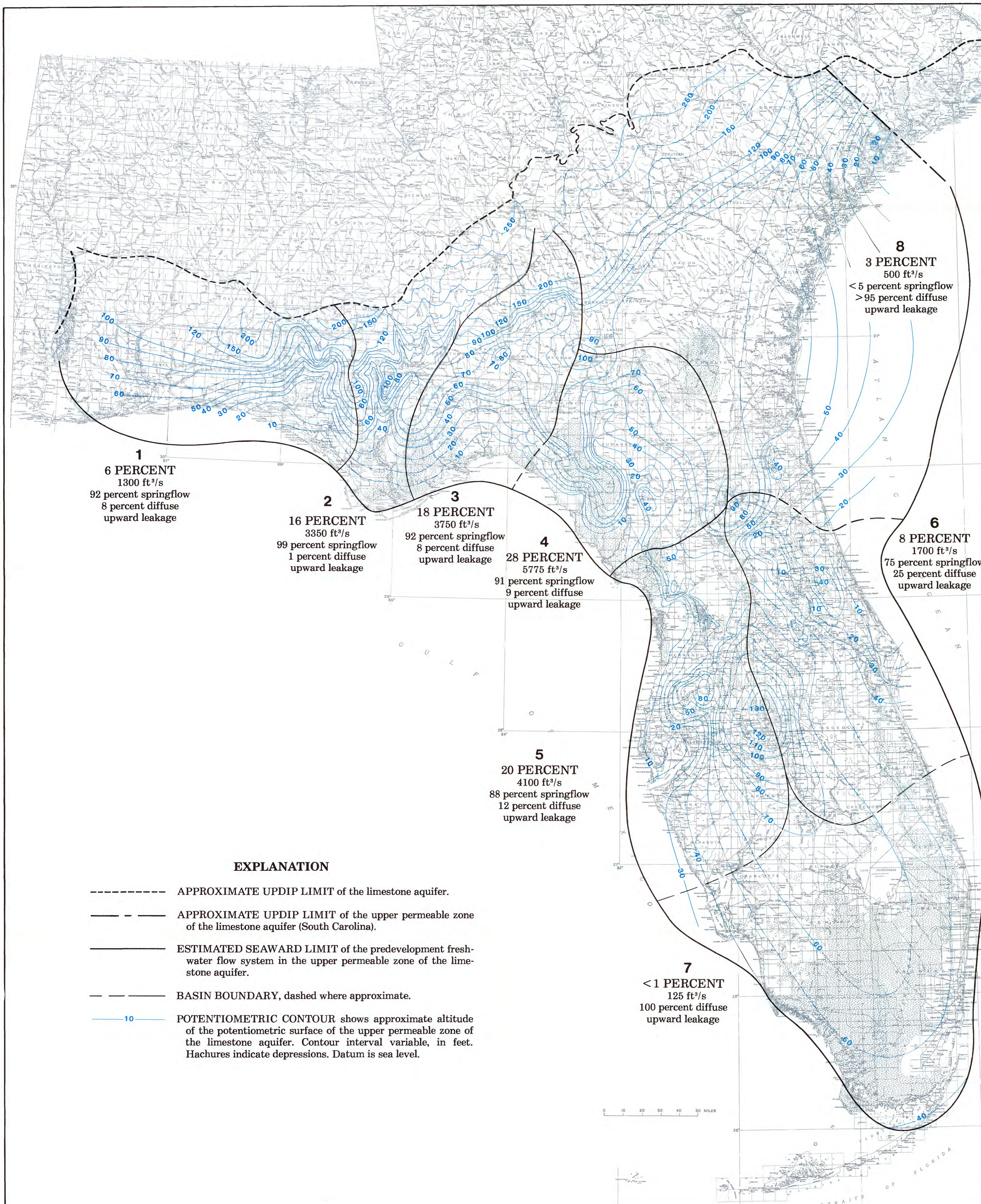


Figure 7.—Estimated potentiometric surface of the upper permeable zone of the Limestone aquifer prior to development, showing the percentage of total system flow that discharges from each numbered basin (modified from Johnston and others, 1980).

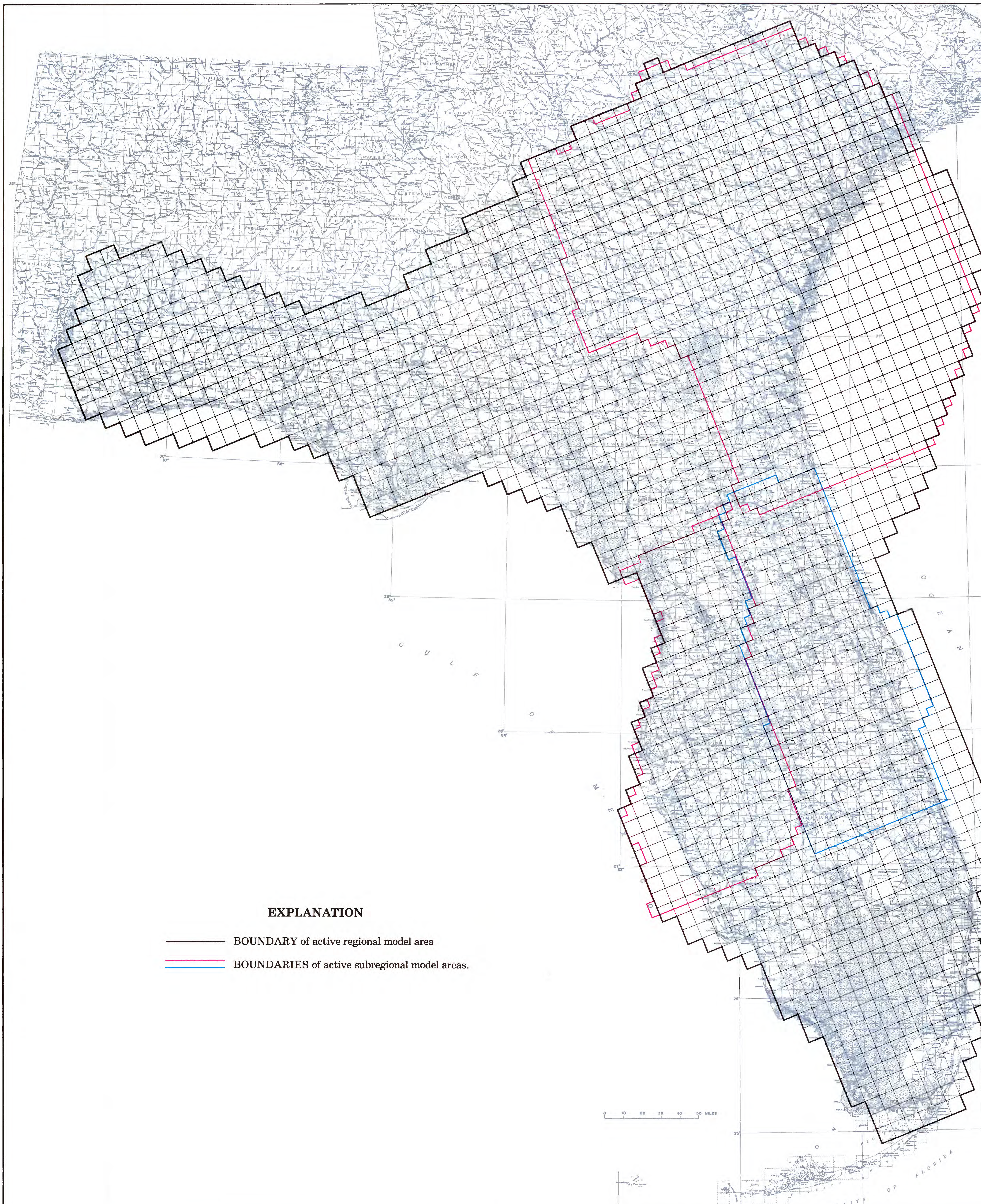


Figure 9.—Regional model grid with active regional and subregional model areas delineated.