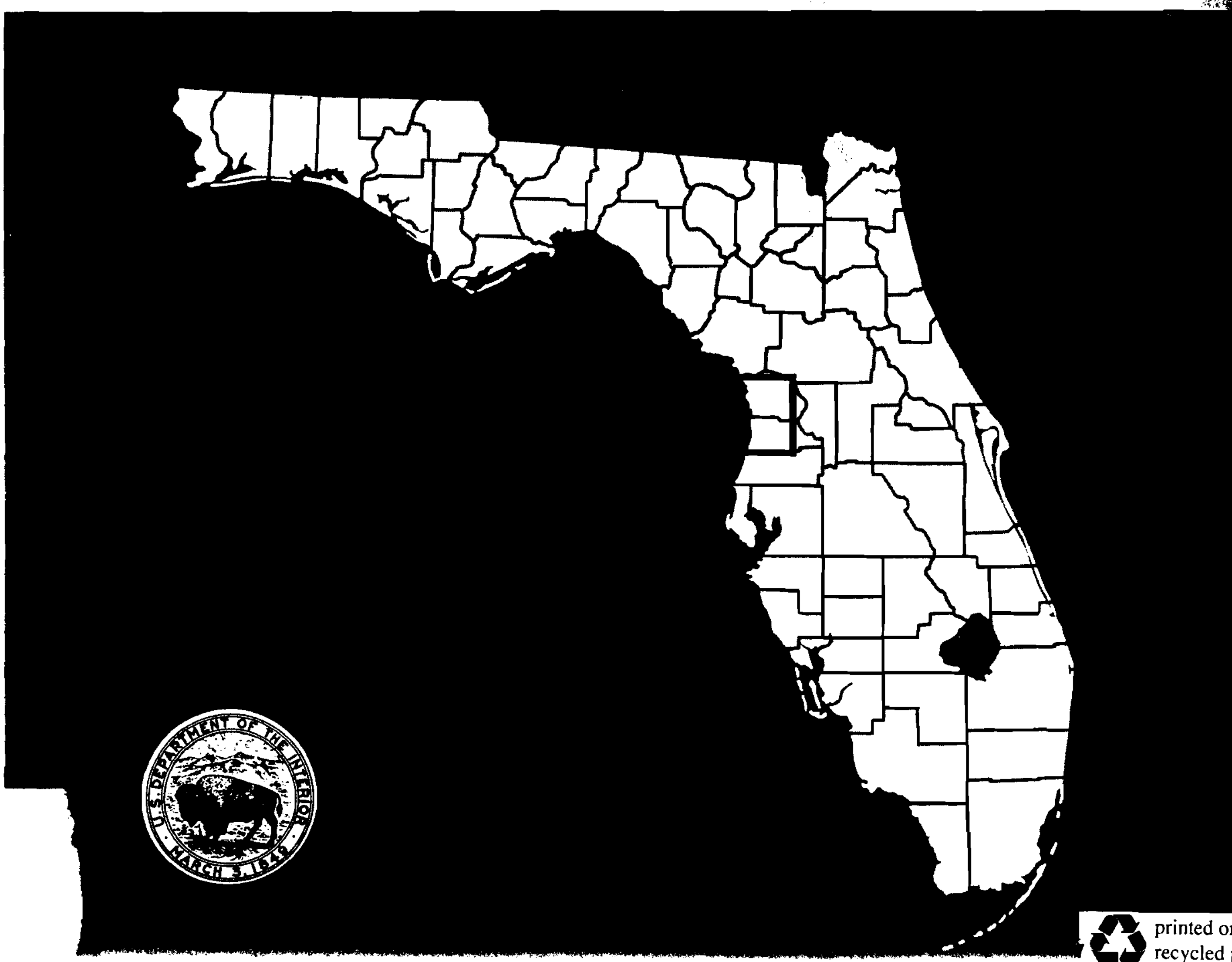
SIMULATION OF STEADY-STATE GROUND WATER AND SPRING FLOW IN THE UPPER FLORIDAN AQUIFER OF COASTAL CITRUS AND HERNANDO COUNTIES, FLORIDA

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 88-4036

Prepared in cooperation with the

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT



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DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For use of readers who prefer to use metric units (International System), conversion factors for inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
square mile (mi^2)	2.590	square kilometer (km^2)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.0438	cubic meter per second (m^3/s)

* * * * * * * * * * * *

Sea level: In this report, "sea level" refers to the 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 "Sea Level Datum of 1929."

* * * * * * * * * * * *

ADDITIONAL ABBREVIATIONS

evapotranspiration	ET
milligrams per liter	mg/L

SIMULATION OF STEADY-STATE GROUND WATER AND SPRING FLOW IN THE UPPER FLORIDAN AQUIFER OF COASTAL CITRUS AND HERNANDO COUNTIES, FLORIDA

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ABSTRACT

A digital ground-water flow model was developed to approximate steady-state, predevelopment flow conditions in the Upper Floridan aquifer of coastal west-central Florida. The aquifer is the major source of public water supply and natural spring flow in the area. The aquifer was simulated as a one-layer system with constant vertical recharge and discharge rates. A head-dependent drain function was used to simulate spring flow.

Model calibration consisted of adjustments of aquifer transmissivities and recharge-discharge rates until the average absolute error per grid block was less than 3 feet and computed spring discharge was within 10 percent of measured or estimated discharges. Calibration transmissivities ranged from 8,640 feet squared per day in the northern part of the area to nearly 13,000,000 feet squared per day near large springs. Calibration inflows were about 2,700 cubic feet per second. Of this, about 2,567 cubic feet per second discharges as natural spring flow and 137 cubic feet per second discharges as upward leakage along the coast. A sensitivity analysis indicated that the model was most sensitive to changes in transmissivity and least sensitive to changes in upward leakage.

The model was used to demonstrate aquifer response to large manmade stresses. Withdrawing 116 cubic feet per second from hypothetical regional well fields resulted in potentiometric-surface drawdowns ranging from 0.1 to 1.7 feet and a drawdown of generally less than 0.2 foot along the coast. Total spring flow decreased about 5 percent, and the change to individual spring discharge varied from 0.1 to 8.0 percent of predevelopment discharge. Withdrawing 62 cubic feet per second from each of the 4-square-mile spring nodes resulted in six of the seven springs to the south of Chassahowitzka River contributing 50 percent of their flow to pumpage and three contributed 100 percent of their flow to pumpage. Springs located north of Chassahowitzka River contributed as much as 18 percent of their flow to pumpage.

INTRODUCTION

The coastal springs basin includes about 600 mi^2 along the west-central gulf coast of Florida (fig. 1). The area contains 4 first-order magnitude springs (springs that discharge 100 ft^3/s or more) and at least 23 smaller

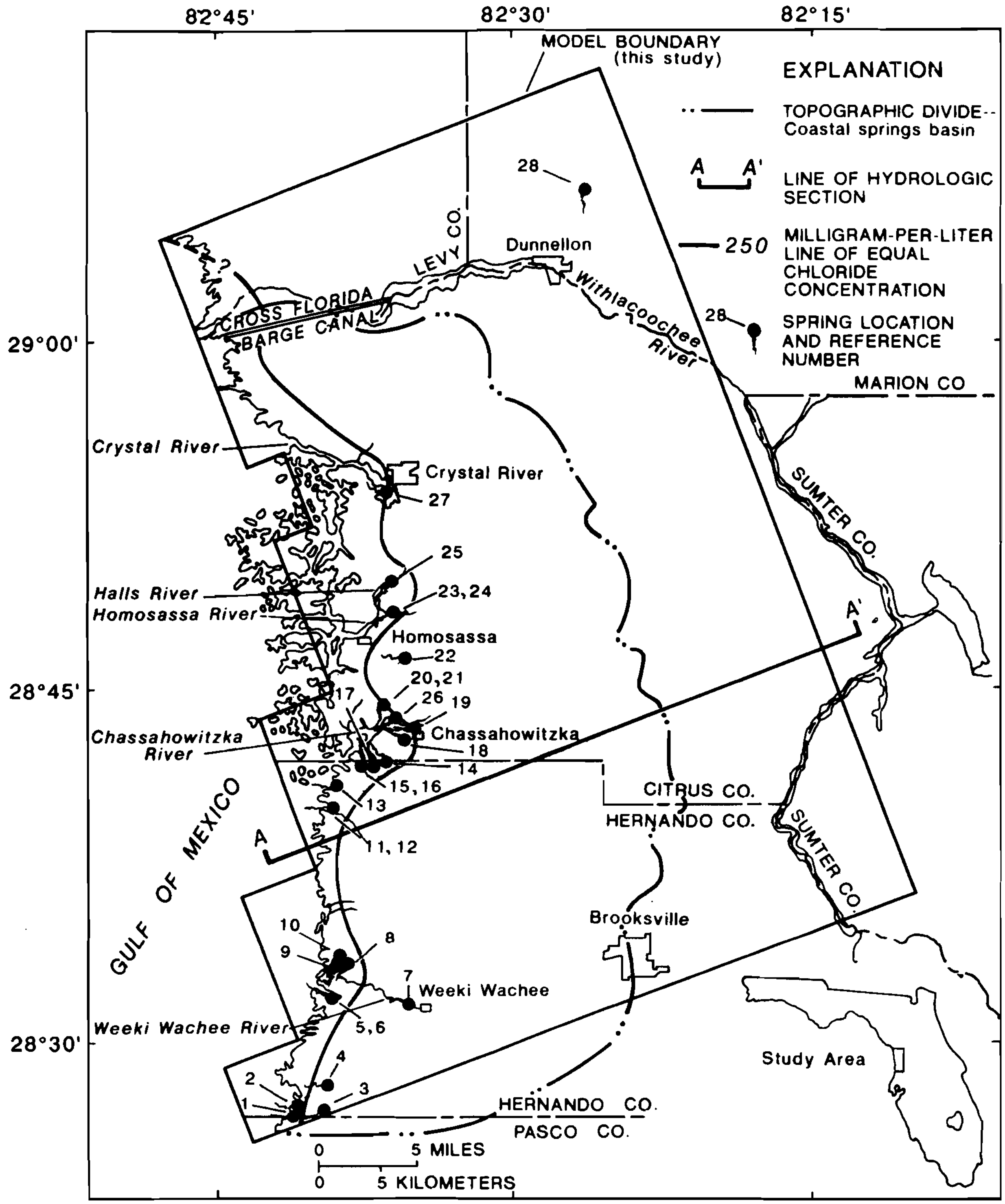


Figure 1.--Location of study area and position of 250-milligram-per-liter line of equal chloride concentration at 100 feet below sea level. (From Mills and Ryder, 1975.)

springs. The springs discharge a combined total of about 2,690 ft^3/s of water to coastal rivers, salt marshes, and swamps along the Gulf of Mexico. The area is undergoing rapid growth, and proposals are being considered to develop some of the water resources for regional water supply. Of interest and concern is the quantity of coastal spring water that may be diverted and the environmental effect of flow reduction to estuarine resources of the area.

This report describes part of a larger study that examines salinity changes that may occur in estuarine zones of the study area if freshwater inflow is reduced through spring flow or aquifer pumpage. This report describes the calibration of a computer model for simulating steady-state, predevelopment flow in the Upper Floridan aquifer in the coastal springs basin of Citrus and Hernando Counties and the use of that model to simulate the effects of future pumping on spring discharge and aquifer heads.

DESCRIPTION OF THE AREA

The coastal springs basin primarily includes the coastal drainage of Citrus and Hernando Counties (fig. 1). It is bounded on the north and east by the western topographic divide of the Withlacoochee River drainage basin, on the south by a topographic divide near the Hernando-Pasco County line, and on the west by the Gulf of Mexico. The largest municipality in the area is Brooksville with an estimated 1984 population of 6,390.

The basin lies within the coastal lowlands and the central highlands topographic regions (Cooke, 1939) and is characterized by a series of karst ridges and marine terraces that parallel the coast. The terraces are low and nearly flat, whereas the ridges are high and undulating. Land altitudes vary from sea level at the gulf coast to about 240 feet above sea level near Brooksville. Numerous swamps, lakes, and intermittent ponds occur in the area. The coastline is broad and flat and dotted with many small islands separated by shallows.

The coastal springs basin is underlain by a thick sequence of honeycombed and fractured limestone and dolomite of Tertiary age (table 1). The carbonate rocks are at or near land surface and covered by unconsolidated, porous sands that range in thickness from less than 5 feet near the coast to over 100 feet in the central Highlands.

HYDROLOGIC CONDITIONS

Surface drainage in the study area is minimal and most water movement is through the Upper Floridan aquifer (Miller, 1986). The few perennial streams that occur are supplied almost entirely from spring discharge. The Upper Floridan aquifer is the source of these springs, as well as virtually all water used in the area. The aquifer is composed of several geologic formations that function as a single hydrologic unit, from top to bottom, the Suwannee and Ocala Limestones and the Avon Park Formation (table 1). The top of the aquifer is about 80 feet below land surface in the ridges of the Central Highlands but is at or near land surface near the coast. The base of the Upper Floridan aquifer in the study area is considered to be at the first

Table 1.--Lithologic descriptions and chart showing correlation of major geologic and geohydrologic units

[Modified from Ryder, 1982, table 1 and Miller, 1984, table 5]

System	Series	Stratigraphic unit	General lithology	Major lithologic unit	Geohydrologic unit
Quaternary	Holocene, Pleistocene	Surficial sand, terrace sand, phosphorite	Predominantly fine sand; interbedded clay, marl, shell, limestone, phosphorite.	Sand	Surficial aquifer
Tertiary	Pliocene	Undifferentiated deposits	Clayey and pebbly sand; clay, marl, shell, phosphatic.	Clastic deposits	Upper confining unit
	Miocene	Hawthorn Formation	Dolomite, sand, clay, and limestone; silty, phosphatic.	Carbonate and clastic deposits	
	Oligocene	Suwannee Limestone	Limestone, sandy limestone, fossiliferous.	Carbonate deposits	Upper Floridan aquifer
	Eocene	Ocala Limestone	Limestone, chalky, foraminiferal, dolomitic near bottom.		
		Avon Park Formation	Limestone and hard brown dolomite; intergranular evaporite in lower part in some areas.	Carbonate with intergranular evaporite deposits	Middle confining unit
		Oldsmar Formation	Dolomite and chalky limestone, with intergranular gypsum and anhydrite in most areas.		Lower Floridan aquifer

occurrence of vertically persistent evaporites, which generally occur about 600 feet below sea level in the lower part of the Avon Park Formation. Saltwater is present in the upper part of the aquifer near the coast and is present at a depth of 100 feet, 1 to 5 miles inland (fig. 1).

The estimated predevelopment potentiometric surface of the Upper Floridan aquifer and the ground-water drainage area tributary to the coastal springs basin are shown in figure 2. The area extends 30 to 40 miles beyond the eastern edge of the coastal springs topographic divide to the eastern topographic divide of the Withlacoochee River and encompasses an area of about 3,400 mi^2. Arrows on the map indicate the general direction of flow in the aquifer within the area. Water moves generally northwesterly from the interior of the area toward the Gulf of Mexico and from areas of high potential to areas of low potential normal to the contour lines. The potentiometric-surface map is a composite of potentiometric-surface maps made for the area from mid-1970 through 1979 (Johnston and others, 1980). The contours are considered to represent average annual (steady-state) water levels and to have been affected little by development.

Rainfall averages 55 in/yr in the area and is the source of recharge for the Upper Floridan aquifer. Recharge occurs as percolation through surficial deposits and drainage into sinkholes that breach the surficial aquifer. Very little water runs off, and the topography west of the western topographic divide of the Withlacoochee River is almost devoid of a surface-drainage pattern. Most of the ground-water outflow from the area occurs as discharge at the major coastal springs.

A surficial sand aquifer, separate from the Upper Floridan aquifer, does not occur as a continuous unit within the coastal springs basin (Fretwell, 1983). Some perched water-table aquifers of limited extent occur locally in these sands. The surficial deposits, however, are generally too thin or clayey to comprise an important aquifer.

The principal rivers that drain the coastal springs basin are, from north to south, the Crystal, Homosassa, Chassahowitzka, and Weeki Wachee Rivers. Each of these rivers originates from a spring or group of springs that provide almost the entire freshwater flow of the rivers. Numerous other small springs and spring-fed streams dot the coastal fringe of the study area (fig. 1). Names and discharge rates for springs and spring-fed rivers are listed in table 2.

CONCEPTUAL FLOW MODEL OF THE UPPER FLORIDAN AQUIFER

A generalized conceptual model of predevelopment ground-water flow and sources of recharge to and discharge from the Upper Floridan aquifer is shown in figure 3. The geohydrologic section is made from known and generalized data along column 7. The Upper Floridan aquifer in the coastal springs basin receives water by downward percolation of rainfall through the surficial deposits and by lateral flow across basin boundaries from the east. Ground water generally flows westward toward the gulf and vertically upward to discharge as springs or diffuse upward leakage into low-lying coastal swamps. No-flow boundaries are assumed to occur at the freshwater-saltwater interface and at the aquifer base.

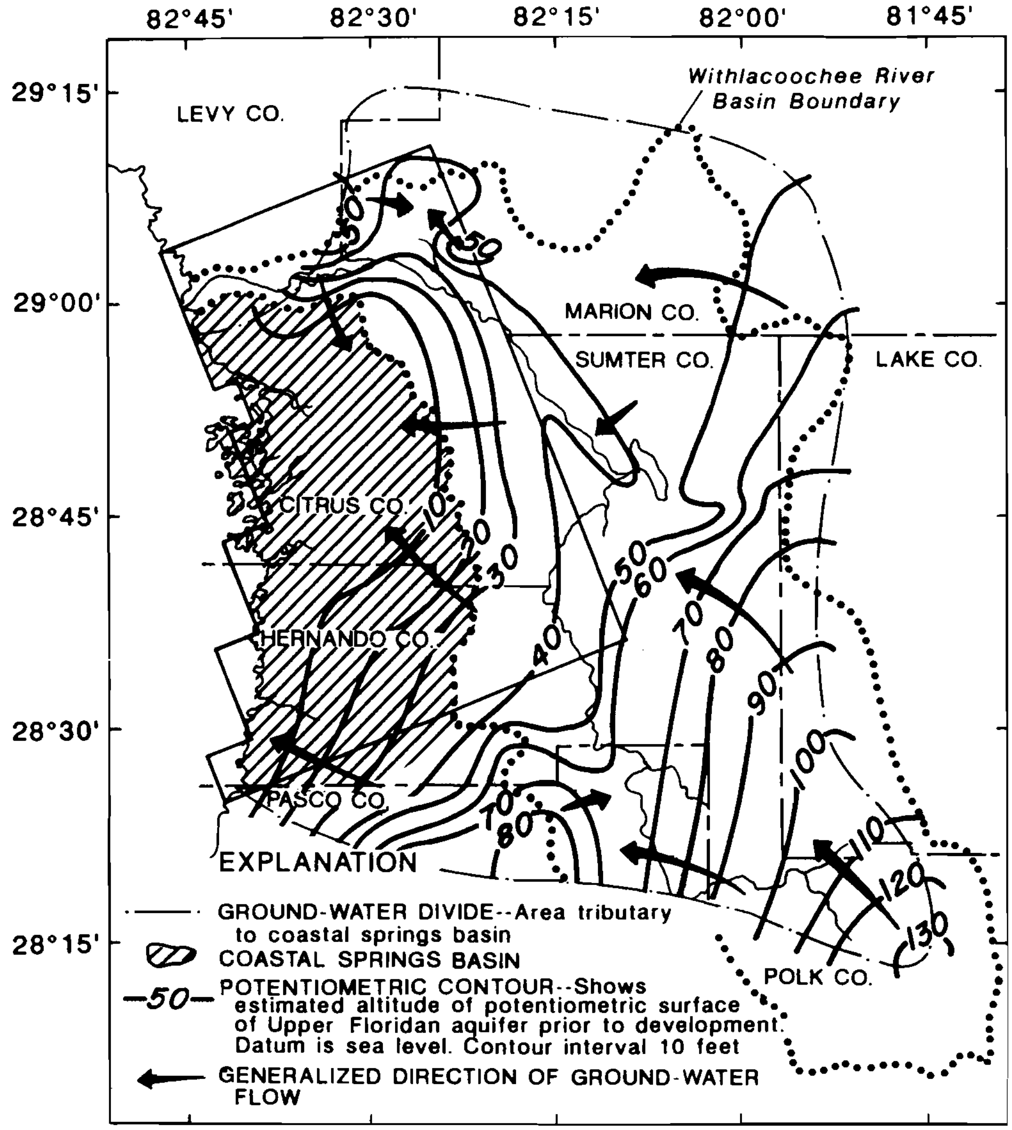


Figure 2.--Ground-water drainage area tributary to the coastal springs basin and related average potentiometric surface of the Upper Floridan aquifer prior to development.

Table 2.--Hydrologic data for coastal springs

[ft³/s, cubic feet per second; mg/L, milligrams per liter]

Spring No. (fig. 1)	Spring name	Period of record	Number of discharge measurements	Instantaneous discharge (ft^3/s) Average	Instantaneous discharge (ft^3/s) Range	Average chloride concentration (mg/L)
1	Unnamed spring no. 1	1964-65	6	8.7	5-11.0	391
2	Boat Spring	1962-64	2	3.8	1.5-6.0	17
3	Bobhill Springs	1961-72	6	3.3	2.0-4.4	5
4	Unnamed spring no. 2	1960	1	1	---	5
5	Unnamed spring no. 4	1962	1	10.0	---	1,600
6	Unnamed spring no. 5	1962	1	12.5	---	1,500
7	Weeki Wachee Springs	1917-74	364	176	101-27.5	5
8	Salt Spring	1961-75	11	30.6	24.7-38.9	912
9	Mud Spring	1961-75	6	52.0	0-128	8,000
10	Unnamed spring no. 6	1960	1	[1]5	---	2,700
11	Unnamed spring no. 7	1961	1	[1]50	---	--
12	839-238-7	1961	1	50.3	---	4,600
13	Unnamed spring no. 8	1961	1	[1]10	---	6,400
14	Unnamed spring no. 9	1961-64	3	28.8	20.9-35.4	136
15	Unnamed spring no. 10	1961	1	5	---	4,300
16	Unnamed spring no. 11	1961-64	2	15.6	5-26.2	3,800
17	Unnamed spring no. 12	1961-65	6	28.6	9.1-39.9	2,100
18	Baird Creek Springs	1964-65	5	31.1	11.1-53.1	2,350
19	Chassahowitzka Springs	1930-72	81	139	31.8-197	127
20	Ruth Spring	1961-72	6	8.8	8.0-11.8	460
21	Potter Spring	1961-65	6	6.5	0-22.0	460
22	Hidden River Springs	1964-65	5	26.5	7.0-65.6	1,300
23	Homosassa Springs	1931-74	90	106	80-165	812
24	Southeast Fork Homosassa Springs	1931-74	89	69.1	33-129	54
25	Halls River Springs	1964-66	12	162	95.7-291	1,020
26	Salt Creek Springs	1961	0	--	---	1,900
27	Crystal River Springs	1964-75	-[2]	916	-1,520-4,320	820
28	Rainbow Springs	1899-1974	-[3]	763	487-1,230	3

[1]Estimated.
[2]Daily discharge, tidally affected.
[3]Daily discharge.

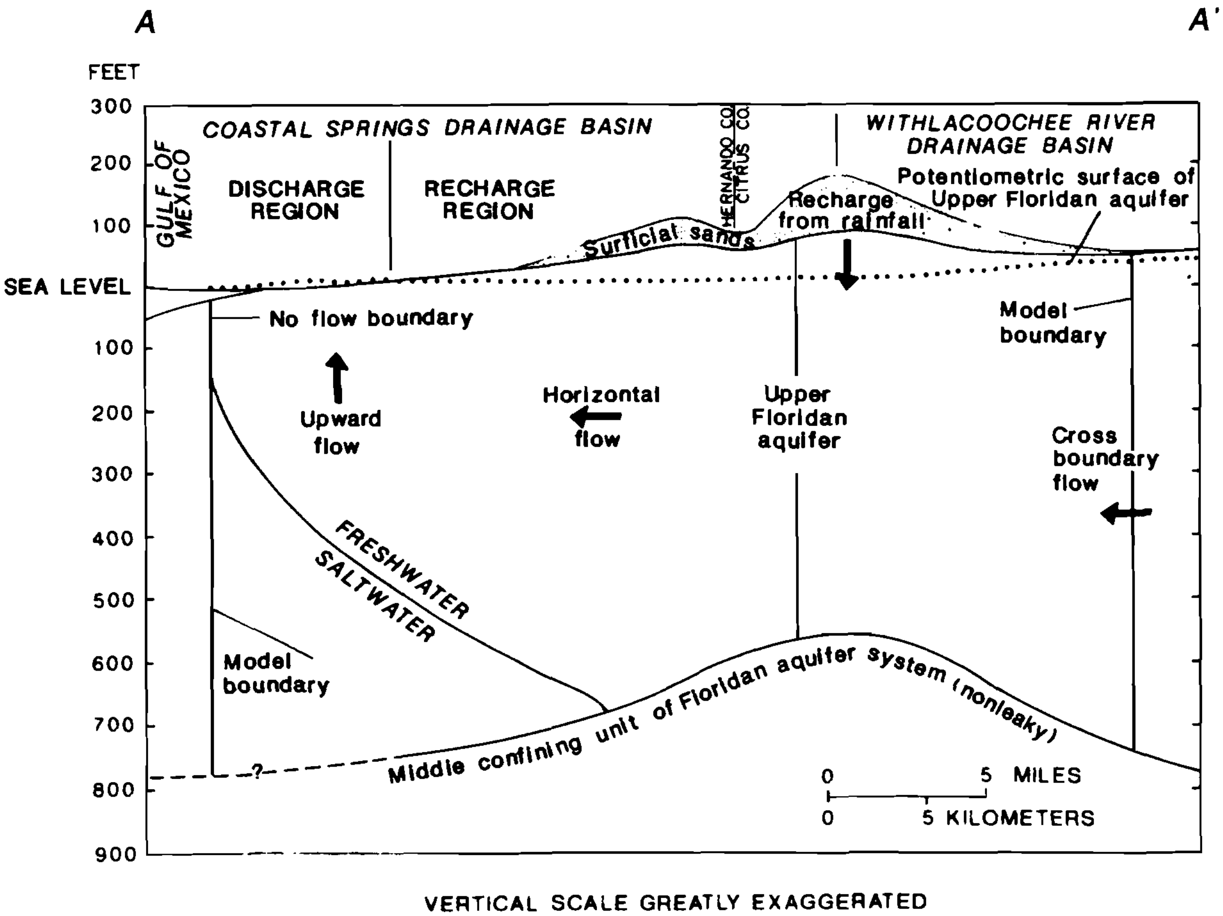


Figure 3.--Generalized geohydrologic section A-A' showing major components and directions of predevelopment ground-water flow.

The position of the freshwater-saltwater interface was estimated by applying the Hubbert (1940) interface relation to predevelopment hydraulic head data. The relation basically states that, under hydrodynamic equilibrium, for every foot of freshwater head above sea level measured at the interface, the interface is depressed 40 feet below sea level.

A hydrologic budget was used to account for inflows, outflows, and changes in storage in the study area. Predevelopment conditions represent long-term average and are considered steady-state. Accordingly, change in storage is zero, and aquifer inflows and outflows are equal. The steady-state hydrologic budget of the coastal springs basin area may be expressed in inches per year as follows:

$$\underline{\text{Inflow}} = \underline{\text{Outflow}}$$

$$(RF + BI) = (ETRO + QDI + BO), \qquad (1)$$

where RF = rainfall,
BI = boundary inflow,
ETRO = evapotranspiration plus surface runoff,
QDI = spring discharge and upward seepage, and
BO = boundary outflow.

Under average annual conditions, inflows to the study area are equal to about 70 in/yr and consist of 55 in/yr of rainfall (Mann and Cherry, 1969) and 15 in/yr of subsurface boundary flow from outside the study area. Outflows from the study area consist of 31 in/yr from known spring flow (table 2), 1 in/yr as upward seepage along the coast and subsurface boundary outflow, and a minimum ET (evapotranspiration) rate of 25 in/yr. Upward seepage and boundary flows were computed from simulations of predevelopment conditions by a large scale ground-water flow model developed as a part of the Floridan Aquifer Regional Aquifer Systems Analysis (Ryder, 1982). The minimum rate of ET is determined by evaporation and transpiration losses that take place before rainfall infiltrates to the water table, regardless of the depth to the water table (Tibbals, 1978). The remaining 13 in/yr is considered a loss to ET from the water table and surface runoff.

Direct ground-water recharge to the Upper Floridan aquifer by downward leakage is calculated as the difference between aquifer outflow and inflow. Total aquifer outflow to other than ET is 32 in/yr from spring flow, upward leakage, and boundary outflow. Subtracting boundary inflow of 15 in/yr from total outflow of 32 in/yr yields 17 in/yr of total recharge from rainfall.

COMPUTER SIMULATION OF GROUND WATER AND SPRING FLOW

Regional Model

As part of the Regional Aquifer System Analysis program (RASA), the U.S. Geological Survey developed a regional finite-difference ground-water flow model of the Upper Floridan aquifer in the southeastern United States (Bush, 1982). In Florida, modeling efforts included development of several subregional models, each of which is based on ground-water flow in the respective subregional areas. The subregional models are designed to be interfaced with each other to simulate regional flows.

The subregional model of west-central Florida (Ryder, 1982) covers the western half of central Florida from Levy County to southern Charlotte County and includes the coastal springs area (fig. 4). The model was calibrated to approximate steady-state predevelopment flow conditions in the multilayered aquifer system of west-central Florida. Application of the model, however, is limited to assessment of regional ground-water problems because of the large grid-block size (16 mi^2). To provide detailed information on effects of stress in individual springs, a smaller, more detailed model was selected to simulate the flow system in the coastal springs basin.

Coastal Springs Basin Model

A small-scale model with 4-mi^2 grid-block size was designed for the study area using boundary conditions from the west-central Florida subregional RASA model. The strongly implicit solution procedure (SIP) of the digital ground-water flow model developed by McDonald and Harbaugh (1984) was used to simulate ground water and spring flow in the one-layer aquifer system. The following assumptions are applied to use of the model: (1) flow within the aquifer is horizontal, (2) only freshwater flow occurs in the part of the aquifer being simulated (chloride less than 5 mg/L), and (3) the estimated saltwater-freshwater interface is constant in time and space.

The steady-state model requires initial estimates of hydraulic parameters and conditions that describe the hydrologic system in each grid block. For the one-layer aquifer system in the coastal springs basin, the hydrologic input parameters are:

1. Boundary flows, in cubic feet per second;
2. Altitude of the unstressed potentiometric surface of the Upper Floridan aquifer, in feet;
3. Transmissivity of the Upper Floridan aquifer, in feet squared per second;
4. Recharge-discharge rates to the Upper Floridan aquifer, in inches per second;
5. Spring-pool altitudes, in feet; and
6. Spring vertical hydraulic conductances, in feet squared per second.

Grid and Boundary Conditions

The ground-water flow system tributary to the coastal springs basin extends many miles beyond the modeled area. Model boundaries encompass a large enough area, however, that simulated pumpage from the Upper Floridan aquifer within the coastal springs basin should not cause significant head changes at the model boundaries. Ryder (1982) indicated that a withdrawal

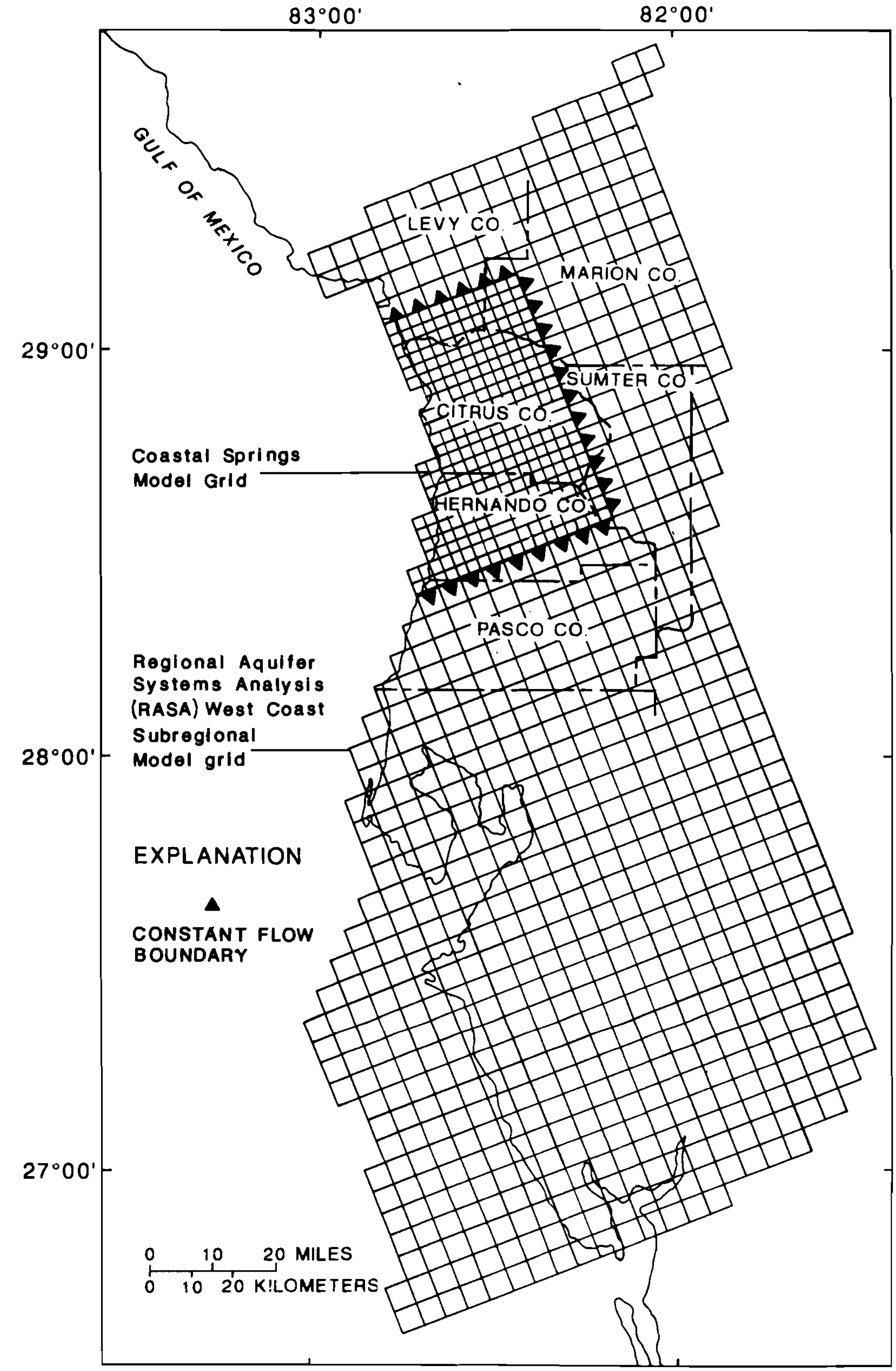


Figure 4.--Coastal springs model grid and relation to west-central Florida Regional Aquifer Systems Analysis subregional model grid.

rate of 46.4 ft^3/s (30 Mgal/d) from a hypothetical well field near the coast at the Citrus-Hernando County line would have a cone of depression with a radius of about 4 miles. Based upon the limits indicated by Ryder's simulation, a rectangular area 36 by 44 miles was selected within an area where the surficial aquifer generally is absent. The resulting finite-difference grid is 18 rows by 22 columns and is comprised of uniform 2-mile by 2-mile nodes or nodal cells. A total of 298 nodes are active (fig. 5). Where the aquifer is filled with saltwater, such as beneath the Gulf of Mexico, nodes are inactive.

The grid was oriented within the subregional RASA model grid (fig. 4) so that the grids could be interfaced and predevelopment boundary flows would be spatially coincident with flow at nodal boundaries computed internal to the RASA subregional model. This technique allows the model area to be relatively small and still accurately simulate the effects of regional flow tributary to the coastal springs basin.

Accordingly, along the northern, eastern, and southern boundaries, a constant-flow boundary was used with predevelopment flows determined from the RASA subregional model. A no-flow boundary was used along the Gulf of Mexico at the interface between saltwater and freshwater. The base of the aquifer was considered to be impermeable and a no-flow boundary.

Flows at the eastern, northern, and southern boundaries of the model were derived from the west-central Florida subregional RASA model. Flows were computed across grid-block faces that coincided with the coastal springs basin model boundaries and were apportioned to coincident grid blocks. Boundary outflow occurred along the northern border of the model and totaled 6 ft^3/s. Boundary inflow was relatively large and occurred along the northern, eastern, and southern boundaries of the model. Total boundary inflow was 1,349 ft^3/s. Boundary flows ranged from -1.9 ft^3/s at grid block 11,22 to 249 ft^3/s at grid block 18,22 (fig. 5).

The estimated predevelopment potentiometric surface was used to obtain starting head values (fig. 2). The model grid was superimposed on this surface, and average heads were determined at the center of each active node within the model grid.

Hydraulic Parameters

Transmissivities were based on estimates from aquifer tests, specific-capacity tests of wells, and flow-net analysis. The transmissivity matrix that was developed during calibration of the west-central Florida subregional RASA model was used to provide initial values in this model.

The Upper Floridan aquifer is characterized by an overall high transmissivity caused by solution of limestone and dolomite. Transmissivities are highest in areas immediately surrounding large springs and decrease away from the springs. Transmissivities commonly exceed 500,000 ft^2/d and may exceed 13,000,000 ft^2/d near springs where water moves through open solution channels many feet in diameter. Even though transmissivity values are relatively large, Hickey (1984) was able to confirm that flow in the aquifer is Darcian.

The areal variation in transmissivity is controlled primarily by the occurrence of solution channels, fractures, and cavern systems (Wolansky and

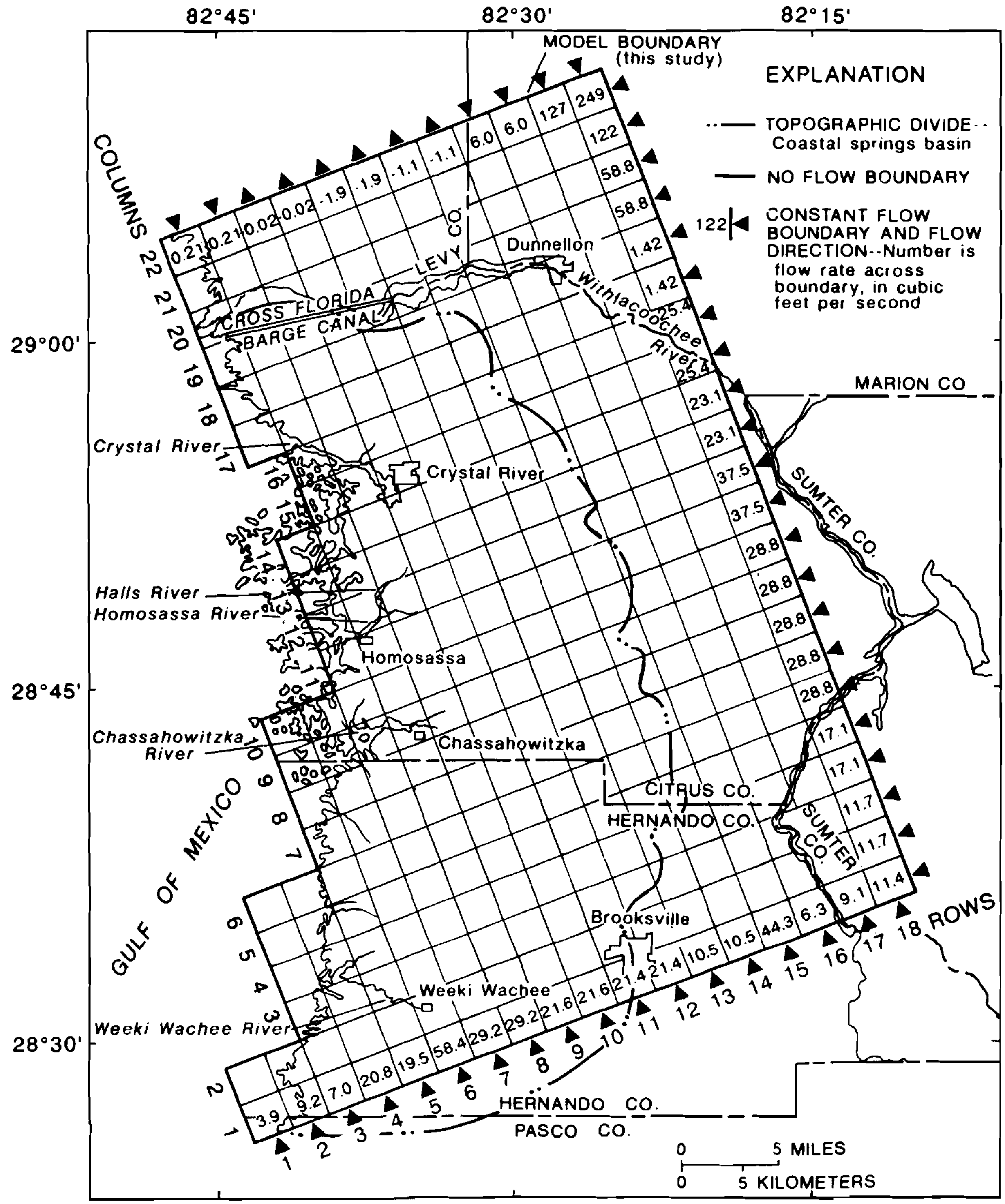


Figure 5.--Coastal springs model grid and boundary conditions.

Corral, 1985). Higher transmissivities around springs are due to greater dissolution and enlargement of fractures in the rock caused by convergence of ground-water flow. At springs, turbulent flow probably occurs, and application of the flow equations that assume laminar flow through porous medium may not be valid.

Specified Recharge and Discharge

Recharge and discharge rates from the calibrated west-central Florida RASA model also were used to provide initial values to the coastal springs basin model. Those rates were initially estimated from steady-state water-balance calculations completed for the regional RASA model (Bush, 1982). The procedure involved balancing long-term average basin runoff, rainfall, and evapotranspiration and, where necessary, the component of runoff from the aquifer.

Recharge to the Upper Floridan aquifer is high because much of the area is internally drained and most surface runoff flows directly to the aquifer through sinkholes or flows to lakes where it eventually leaks downward to the aquifer. Recharge is highest in internally drained sand hill ridges where infiltration rates are high and water levels are deep. Evapotranspiration probably occurs at or near minimum rates in these areas. Recharge is lowest in marsh and swamp areas along the coast where the potentiometric surface lies at or above land surface.

Discharge that is not measured spring flow occurs as diffuse upward leakage along the coast. Rates also include any unmeasured spring flow as well as any offshore submarine springs.

Spring Discharge

Spring discharge was simulated by a head-dependent drain function where steady-state discharge was linearly related to head difference between the spring pool and the potentiometric surface. The equation governing discharge is:

$$Q = CD\,(h-d), \tag{2}$$

where Q = rate of spring flow, in cubic feet per second;
CD = spring vertical conductance, in square feet per second;
h = aquifer head, in feet; and
d = spring-pool head, in feet.

Pool altitudes were determined by instrument level or were estimated from 1:24,000 topographic maps. In cells where multiple springs occur, a weighted-average composite pool elevation was determined based on the magnitude of individual spring discharges in the cell. With spring flow, spring-pool heads, and predevelopment aquifer heads available, conductance was then calculated using equation 2. When the simulated head in the upper Floridan aquifer dropped below the spring-pool head, spring flow ceased.

The calibrated coastal springs model includes several spring groups that were not included in the subregional RASA model. The three spring groups of most significance are Halls River, Hidden River, and Baird Creek that discharge 162, 26, and 31 ft^3/s, respectively. The improved estimate of spring flow is due to spring-flow measurements that were not recognized in the RASA subregional model effort.

Many springs in the study area discharge a mixture of saltwater and freshwater, as indicated by the average chloride concentration (table 2). Because the model assumes that no flow occurs across the saltwater-freshwater interface, a correction factor was used to compute the freshwater component of flow for the coastal springs. The correction factor is modified from a simplified solute-balance equation from Hem (1985):

$$CL_o = (F_{fw})\ (CL_{fw}) + (1 - F_{fw})\ CL_{sw}, \tag{3}$$

where CL_o = observed chloride concentration, in milligrams per liter;
F_{fw} = fraction of freshwater component, in percent;
CL_{fw} = chloride concentration of freshwater, in milligrams per liter; and
CL_{sw} = chloride concentration of saltwater, in milligrams per liter.

Assuming a chloride concentration of 0 mg/L for freshwater and 19,000 mg/L for saltwater, the equation reduces to

$$F_{fw} = 1.0 - \frac{CL_o}{19,000}. \tag{4}$$

The freshwater component of measured spring flow is shown in table 3. Total estimated spring flow was reduced about 4 percent, from about 2,700 to 2,580 ft^3/s, and the correction for individual spring flows ranged from zero at several springs to about 42 percent (22 ft^3/s) at Mud Springs.

Steady-State Model Calibration and Results

One of the main objectives of model calibration is to minimize differences between observed data and model-computed values. A model is calibrated by adjusting input parameters until the model reproduces historical data within acceptable limits. Calibration of the coastal springs basin model was achieved when steady-state flow through the aquifer resulted in a potentiometric surface that closely matched the estimated predevelopment potentiometric surface and when spring discharges computed by the model were in general agreement with estimated predevelopment spring discharges.

A trial and error approach was used to calibrate the coastal springs model. Predevelopment heads, spring-pool heads, spring discharges, and boundary flows were considered the more accurately known parameters and were not adjusted during calibration. Adjustments of aquifer transmissivities and recharge-discharge rates were made until the average absolute error over 298

Table 3.--Observed and simulated spring flows

[ft^3/s, cubic feet per second]

Grid block		Spring No.	Spring name	Estimated flow (ft^3/s)		Adjusted cell flow[1] (ft^3/s)		Simulated flow (ft^3/s)	
Row	Column	(fig. 1)		Uncorrected	Corrected				
2	1	1	Unnamed spring no. 1	9	9	13		11.8	
		2	Boat Spring	4	4				
3	1	3	Bobhill Springs	3	3	4		4.8	
		4	Unnamed spring no. 2	1	1				
4	3	5	Unnamed spring no. 4	10	9	20		34.7	
		6	Unnamed spring no. 5	12	11				
4	4	8	Salt Spring	31	29	63		73.9	
		9	Mud Spring	32	30				
		10	Unnamed spring no. 6	5	4				
6	2	7	Weeki Wachee Springs[2]	176	176	176		173	
6	8	11,12	Blind Creek Springs[3]	80	61	68		32	
		13	Unnamed spring no. 8	10	7				
7	8	14	Unnamed spring no. 9	29	29	72		45.6	
		15	Unnamed spring no. 10	5	4				
		16	Unnamed spring no. 11	16	13				
		17	Unnamed spring no. 12	29	26				
8	9	18	Baird Creek Springs[2]	31	26	164		177	
		19	Chassahowitzka Springs[2]	139	138				
8	10	20	Ruth Spring	9	9	16		34.3	
		21	Potter Spring	7	7				
9	11	22	Hidden River Springs	26	24	24		34.7	
9	12	23	Homosassa Springs	106	101	323		338	
		24	Southeast Fork Homosassa Springs[2]	69	69				
		25	Halls River Springs[2]	162	153				
9	14	27	Crystal River Springs[2]	229	219	219	816	200	874
9	15	27	Crystal River Springs[2]	229	219	219		177	
10	14	27	Crystal River Springs[2]	229	219	219		268	
10	15	27	Crystal River Springs[2]	229	219	219		229	
17	20	28	Rainbow Springs	763	763	763		733	
			Totals			2,582		2,567	

[1]Freshwater component of total observed flow using equation 3.
[2]Major spring used to evaluate model calibration.
[3]Includes unnamed spring no. 7, 839-238-7, and other springs not inventoried.

active grid blocks was less than 3 feet, total spring discharge was within 10 percent of measured or estimated discharge, and all model parameter values were within the range of expected values.

Model runs, with initial estimates of input parameters based on the west-central Florida subregional RASA model, resulted in simulated aquifer hydraulic heads above the estimated predevelopment levels in much of the area, except along the eastern and northern areas of the model where substantial head declines occurred. Head declines also initially occurred in most nodal cells where major springs were located and in nodal cells were additional springs were added to the new model. In addition, total simulated spring flow was about 16 percent less than observed spring flow. Accordingly, significant adjustments of the initial subregional RASA model input data were made, including (1) decreased transmissivity in drawdown areas near the boundaries, (2) increased transmissivity in areas around selected springs where drawdowns occurred, (3) increased recharge to balance spring flow, and (4) increased discharge along coastal areas.

Calibration of this model was then centered on adjusting transmissivity and recharge-discharge rates. As will be shown in the sensitivity analysis section of this report, the model is sensitive to adjustments to both parameters.

The distribution of transmissivity derived from model calibration is shown in figure 6. Calibrated transmissivities ranged from about 8,600 ft^2/d in the northern part of the model area to nearly 13,000,000 ft^2/d in the grid blocks around the Crystal River springs group. At select grid blocks in which new springs were added, transmissivities were increased by as much as nine times the original RASA values. However, in about 60 percent of the remaining model area, transmissivities were unchanged, and overall transmissivity, not including grid blocks where new springs were added, was increased by less than 5 percent. Transmissivity at the boundary was increased by an average of about 6 percent. Most transmissivity values in the calibrated model are greater than 500,000 ft^2/d and agree well with values derived from field aquifer tests and specific capacity, flow-net analysis, and model-simulated values reported by Ryder (1982).

The simulated distribution of recharge to and discharge from the Upper Floridan aquifer, excluding spring flow, is shown in figure 7. Recharge is highest along the sand hill ridge that forms the topographic divide between the coastal springs and Withlacoochee River basins and decreases eastward toward the Withlacoochee River and westward toward the gulf coast. Recharge rates vary from 0 to 30 in/yr and average 19.2 inches for recharging nodal cells. Discharge by upward leakage occurs along the coastal margins and varies from 0 to 21 in/yr. Average discharge is 7.3 in/yr.

Recharge was increased about 50 percent above the initial input values of Ryder (1982). The increase was needed to balance about 410 ft^3/s of spring flow that was not simulated by the RASA model. Calibrated rates compare well with those reported by Hutchinson (1984) in the coastal area bordering the coastal springs basin to the south. On the basis of computer simulations, Hutchinson reports recharge to the surficial aquifer that varies from near 0 in coastal marsh areas to 30 in/yr in sand hill ridge area.

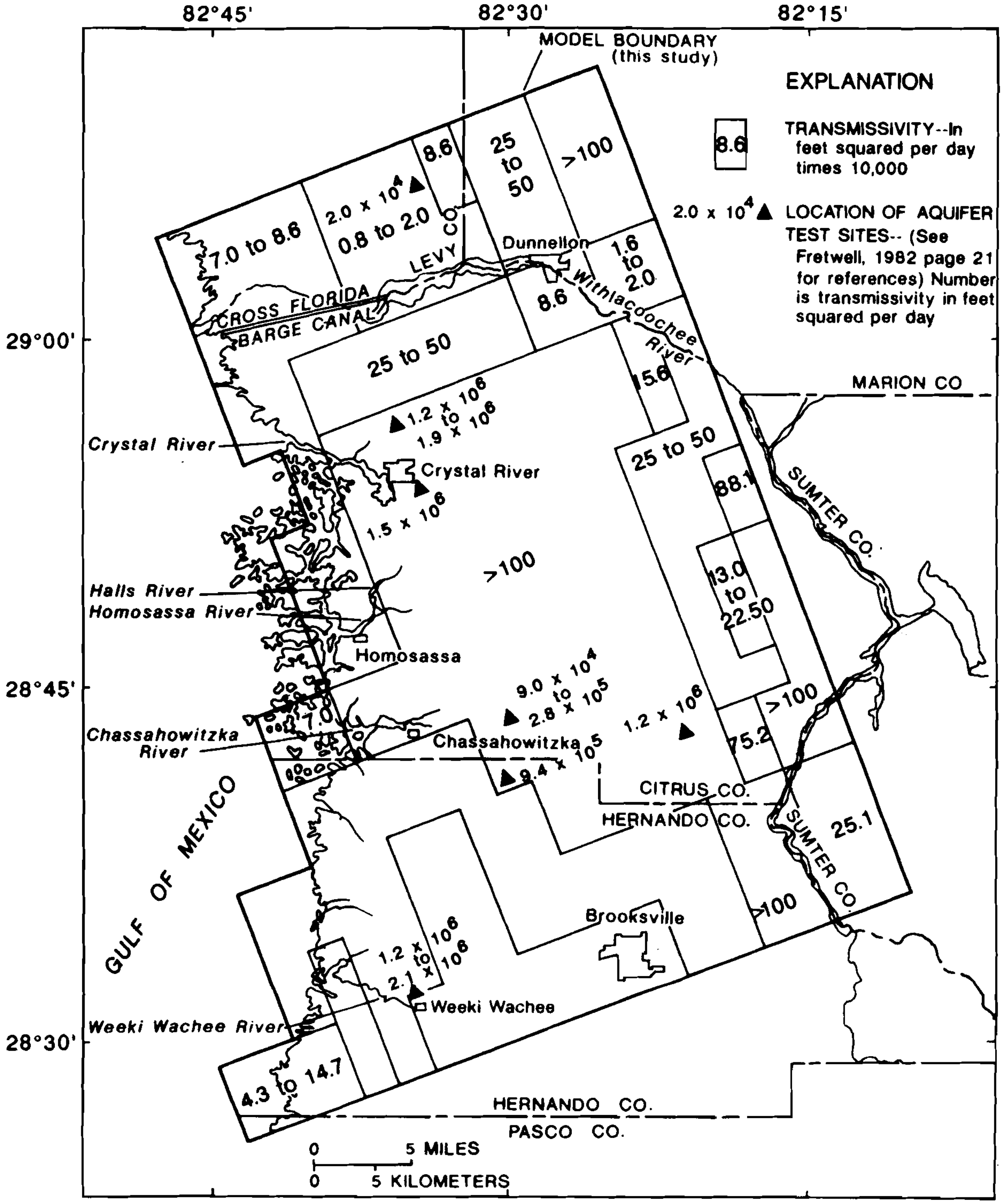


Figure 6.--Distribution of Upper Floridan aquifer transmissivity in the calibrated model.

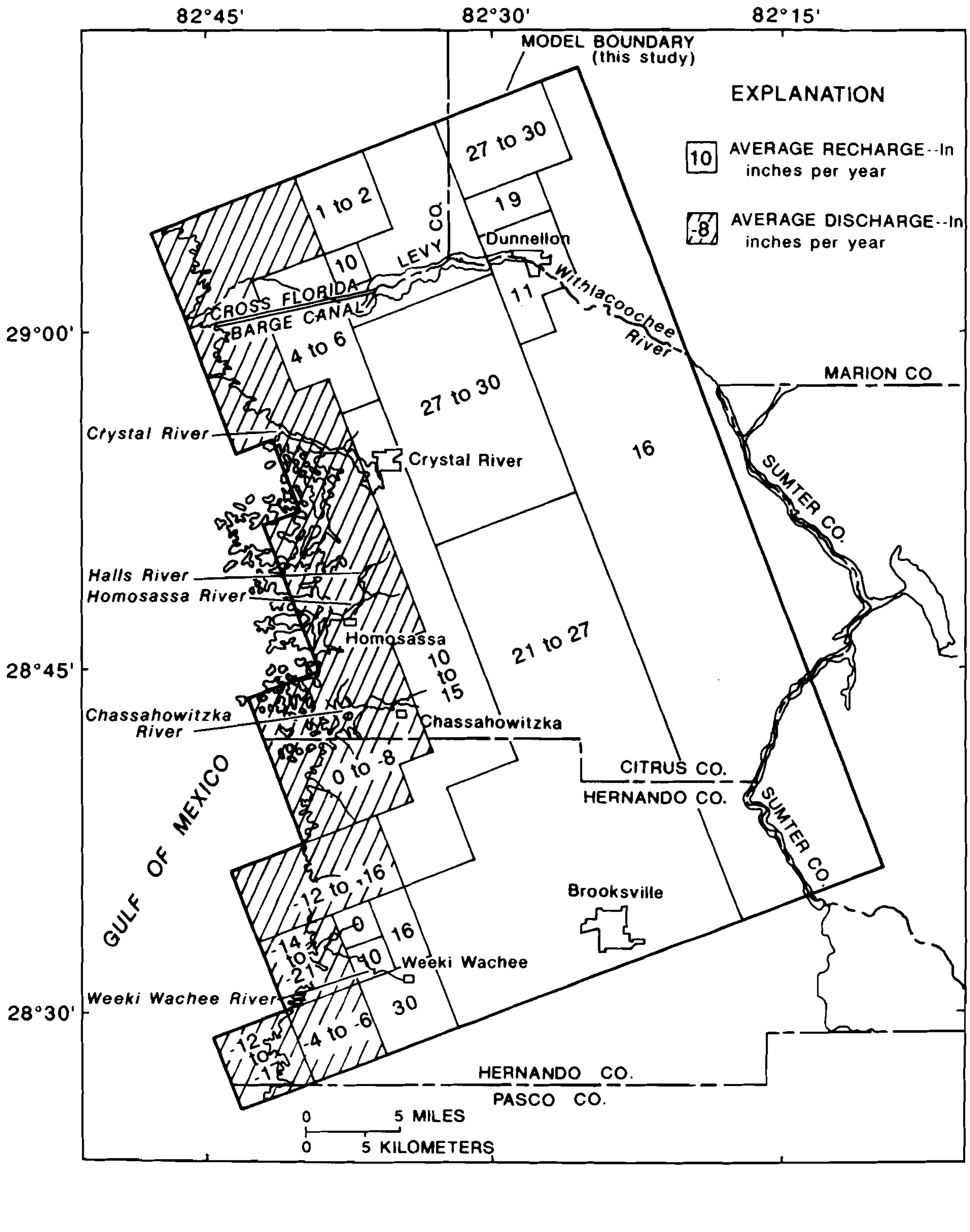


Figure 7.--Distribution of Upper Floridan aquifer recharge and discharge (upward leakage) in the calibrated model.

The difference between observed and computed potentiometric surfaces of the Upper Floridan aquifer are shown in figure 8. A statistical summary of changes between estimated and simulated heads and spring flow is as follows:

Statistic	Estimated versus model-simulated potentiometric surface
Number of active grid blocks -----------	298
Mean of residuals (feet) ---------------	-0.9
Mean of absolute residuals (feet) -------	2.0
Maximum buildup (feet) -----------------	8
Maximum drawdown (feet) ----------------	8
Percent of estimated spring flow --------	99

Observed and simulated spring flows are compared in table 3. Total model-simulated spring flow is 2,567 ft^3/s, which is 99 percent of the total estimated spring flow. In comparison, only about 84 percent (2,170 ft^3/s) of total spring flow was simulated by the RASA model. Simulated flows of the larger spring groups, representing 89 percent of total estimated spring flow, compared closely with observed flows. Simulated flows from some of the smaller spring groups, however, differed substantially from estimated flows. Errors may be related to inadequate estimates of flow or hydraulic parameters.

Model Sensitivity

Sensitivity tests were made to assess responses of the calibrated model to changes in input parameters. The test procedure was to uniformly change input parameters over a reasonable range of values, run the model, and observe the magnitude and direction of changes in head and spring flow. Results of nine sensitivity tests are summarized in table 4. Changes in head along row 11 and columns 5 and 15 are shown in figures 9 and 10.

Varying transmissivity significantly affected head values in the model from north to south and from east to west. The model was relatively insensitive to changes in transmissivity in the model's interior (fig. 9). Calibrated transmissivities were very large in the interior of the model, varying between $1x10^6$ to $13x10^6$ ft^2/d, whereas calibrated transmissivities around the perimeter of the model were relatively less, varying between about $2x10^4$ to $1.5x10^6$ ft^2/d. Simulated heads were more sensitive to a decrease in transmissivity than to an increase. Decreasing transmissivity by 50 percent increased the average absolute error per grid block by 6.2 times, whereas increasing transmissivity by 50 percent increased the average absolute error per grid block by 2 times.

Varying transmissivity had little effect on total spring flow but had a prominent effect on individual spring flows because of the variability of transmissivity between springs (table 4). The most significant effect occurred in the flow of Weeki Wachee Springs. Reducing transmissivity by 50 percent resulted in a 39 percent increase in flow of Weeki Wachee Springs,

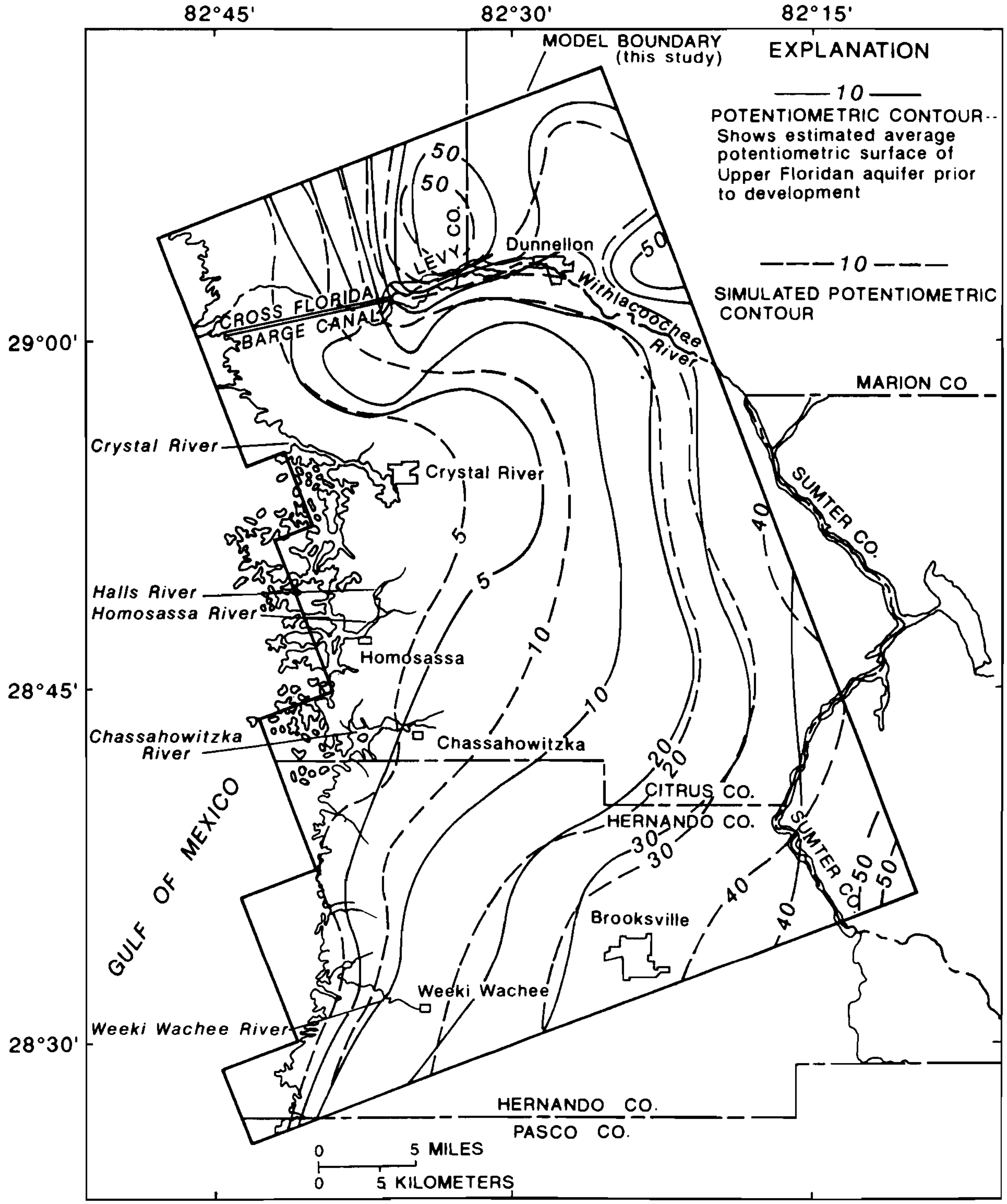
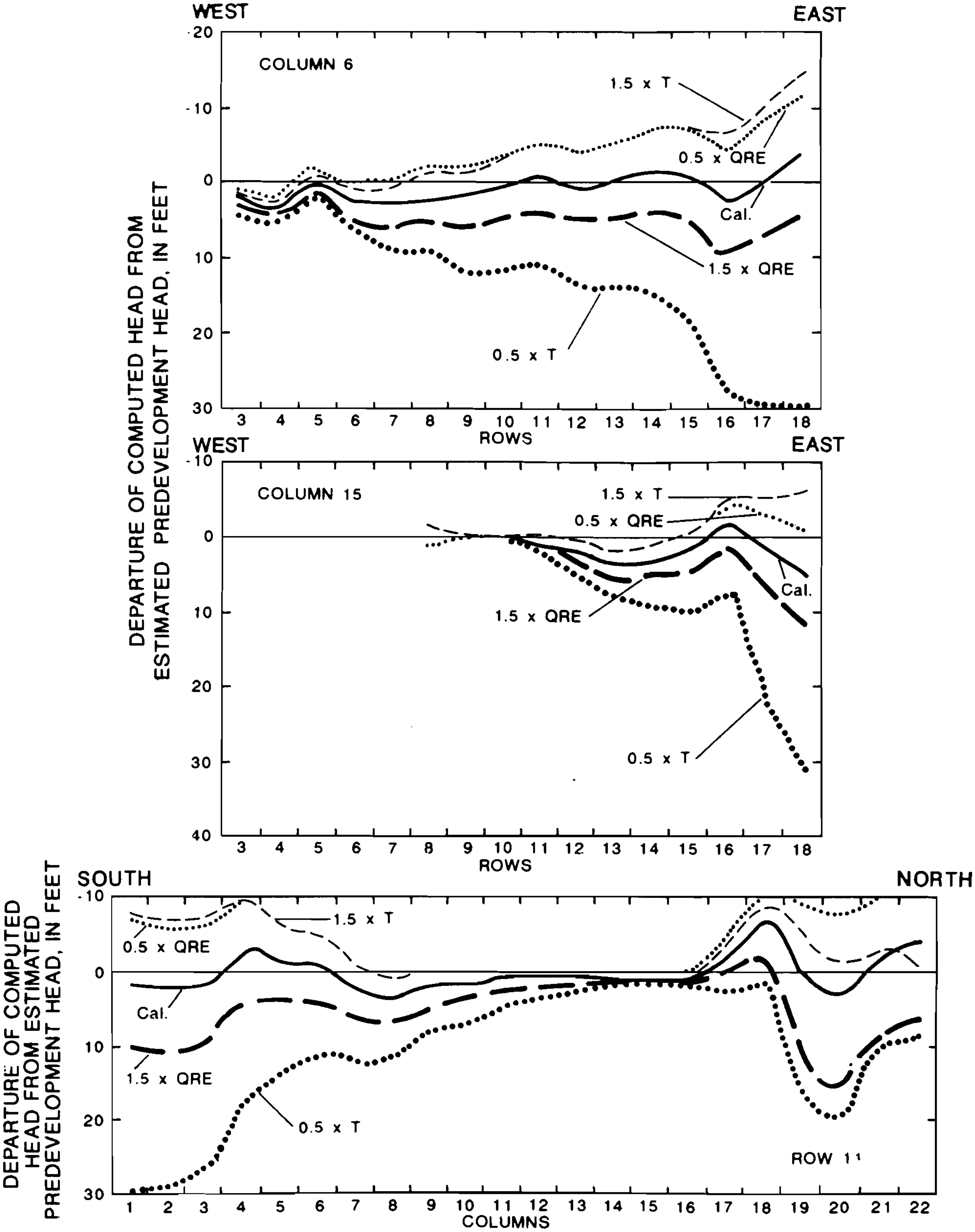


Figure 8.--Comparison between estimated predevelopment and simulated potentiometric surfaces.

Table 4.--Changes in average absolute error of simulated potentiometric head and simulated spring flow caused by uniformly varying calibrated values of transmissivity, recharge, discharge, and boundary flows

[T, calibrated transmissivity; R, calibrated recharge rate; D, calibrated discharge rate; BF, calibrated boundary flow; C head, constant head boundary flow]

	Input change									
	Calibration run	Tx0.5	Tx1.5	Rx0.5	Rx1.5	Dx0.0	Dx1.5	BFx0.5	BFx1.5	C head
Average absolute error in head per cell, in feet ---	2.0	13.2	4.0	4.1	5.5	3.1	2.3	3.3	4.4	1.8
Maximum buildup, in feet --	8	48	5	3	18	16	7	6	15	7
Maximum drawdown, in feet -	8	9	15	18	5	8	10	14	7	8
Simulated spring flow, in cubic feet per second										
Unnamed spring no. 1, Boat Spring -----------	12	8	14	10	14	24	5	4	20	0
Unnamed spring no. 2, Bobhill Springs --------	5	8	3	3	6	7	4	1	9	0
Unnamed spring no. 4, unnamed spring no. 5 ---	35	32	36	28	42	43	30	26	43	36
Unnamed spring no. 6, Salt Spring, Mud Spring ----------------	74	44	94	55	93	104	58	54	93	74
Weeki Wachee Springs ----	173	241	124	110	236	185	166	103	243	166
Unnamed spring no. 8, Blind Creek Springs ----	32	22	39	20	44	45	25	24	40	31
Unnamed spring no. 9, unnamed spring no. 10, unnamed spring no. 11, unnamed spring no. 12 --	46	44	47	31	60	51	43	37	54	47
Chassahowitzka Springs, Baird Creek Springs ----	177	209	156	120	234	183	174	145	209	175
Ruth Spring, Potter Spring ----------------	34	44	29	23	45	36	34	28	40	34
Hidden River Springs ----	35	49	29	24	46	35	34	29	41	34
Homosassa Springs, Southeast Fork Homosassa Springs, Halls River Springs ----	338	325	338	226	451	346	335	277	399	333
Crystal River Springs ---	874	782	925	597	1,162	907	860	743	1,004	854
Rainbow Springs ---------	733	746	692	651	819	735	732	422	1,043	575
Totals --------------	2,568	2,551	2,526	1,898	3,252	2,701	2,500	1,893	3,238	2,359



EXPLANATION

T - Transmissivity of Upper Floridan aquifer, in feet squared per day

QRE - Recharge, inches per year

Cal. - Calibration head, in feet

Figure 9.--Simulated changes to selected predevelopment heads caused by uniformly varying model transmissivity and recharge.

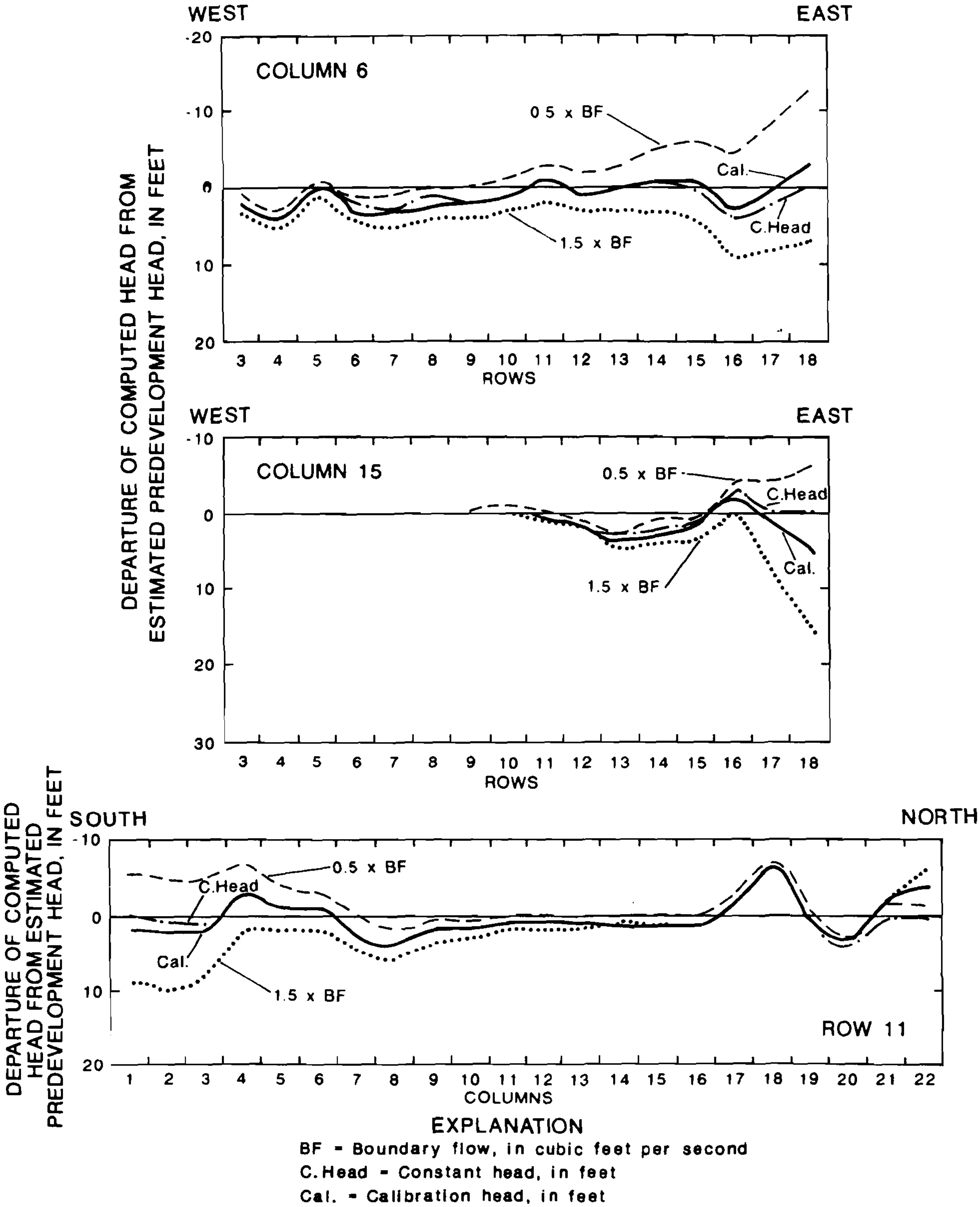


Figure 10.--Simulated changes to selected predevelopment heads caused by uniformly varying boundary flows.

whereas increasing transmissivity by 50 percent resulted in a 28-percent decrease in flow of Weeki Wachee Springs. A similar effect occurred at the spring groups of Chassahowitzka-Baird Creek, Ruth-Potter, and Hidden River, but the impact was much less. The other spring groups showed an opposite effect. When transmissivity was increased, spring flow increased, and conversely, when transmissivity was decreased, spring flow decreased.

The sensitivity of the model to changes in recharge was generally less than to changes in transmissivities, but it also increased toward the boundaries (fig. 9). The highest residuals occurred near the northern, southern, and eastern boundaries where transmissivity and recharge have a wide range in value. Decreasing recharge by 50 percent increased the average absolute error per grid block by about 2 times and resulted in simulated heads generally lower than calibrated heads. Increasing recharge by 50 percent increased the average absolute error per grid block by about 2.7 times and resulted in simulated heads generally higher than calibrated values.

Changes in recharge had significant effects on total and individual spring flows (table 4). Under steady-state conditions, any adjustments in recharge resulted in an equal volume change in total spring flow, but because of variations in transmissivities from one spring to another, impacts on individual springs varied. When recharge was changed by a factor of 50 percent, total spring flow increased or decreased by about 25 percent. Of the major spring groups (flow greater than 100 ft^3/s), Weeki Wachee Springs showed the most significant effect to changes in recharge. A 50-percent change in recharge resulted in a change of about 36 percent in spring flow of Weeki Wachee Springs. The percentage of change was slightly smaller at the other major spring groups. Overall, when recharge was increased, total and individual spring flows increased. Conversely, when recharge was decreased, total and individual spring flows also decreased.

Along with recharge and transmissivity, the sensitivity of the model to changes in boundary flows increased toward the northern, southern, and eastern boundaries of the model (fig. 10). Increasing boundary flows by 50 percent increased the average absolute error per grid block by 2.2 times, whereas decreasing boundary flows by 50 percent increased the average absolute error per grid block by about 1.6 times. Increases in boundary flows caused the residuals to become more positive (buildup), whereas decreasing boundary flows caused residuals to become more negative (drawdown).

Any change in the amount of boundary flows resulted in similar changes in total spring flow, whereas effects on individual springs varied (table 4). Increasing boundary flows by 50 percent (672 ft^3/s) resulted in about a 25-percent change (from 2,567 to 3,238 ft^3/s) in total spring flow. The effect was greatest in flow from springs located near the constant-flow boundaries. The largest change in flow occurred at Rainbow Springs, near the northeast boundaries, where a 50-percent change in boundary flow resulted in a 42-percent change in spring flow.

Changes in discharge (upward leakage) had less effect on the model results than changes in recharge. The most significant effect occurred in discharging grid blocks along the Gulf of Mexico. Increasing discharge by 50 percent increased the average absolute error in head per grid block by 0.9 times, whereas reducing discharge to zero increased the average absolute error per grid block by 1.6 times. Moving easterly away from the gulf, the model was very insensitive to changes in discharge.

Variations in discharge had little effect on total or individual spring flows (table 4) because the quantity of upward leakage was small in comparison to total spring flow. Increasing discharge by 50 percent decreased total spring flow by about 2 percent, whereas reducing discharge by 100 percent increased spring flow by about 5 percent.

A test of the model's sensitivity to boundary conditions was made during the predictive-modeling phase of the study. Five well fields were pumped at a combined rate of 116 ft^3/s under constant-head and constant-flow boundary conditions. Under constant-head boundary conditions, drawdown at the boundary, by definition, was zero. Average drawdown over the modeled area was less than 0.1 foot. Total simulated spring flow decreased from 2,567 to 2,522 ft^3/s (1.6 percent). Under constant-flow boundary conditions, drawdown at the boundary was about 0.4 foot and average drawdown over the modeled area was about 0.3 foot. Total simulated spring flow decreased from 2,567 to 2,449 ft^3/s (4.5 percent).

In summary, sensitivity tests indicated the following:

1. The sensitivity of the model to changes in input parameters increased toward northern, southern, and eastern boundaries;
2. The model was relatively insensitive to changes in input parameters in the interior of the model;
3. Increases in input parameters had less of an impact on the model than an equal percentage decrease in the same parameter.
4. The model was most sensitive to changes in transmissivity and least sensitive to changes in discharge, but relatively sensitive to changes in both parameters;
5. Any change in inflow caused an equivalent change in outflow; and
6. Effects on individual springs varied widely with changes in input parameters.

Simulation of Ground-Water Withdrawals

The model can be used to show how water levels and spring flows might respond to large manmade stresses in the system, with reservations and qualifications. Because no appreciable ground-water development has occurred in the study area, the distributions of aquifer properties derived from simulating predevelopment flow conditions have not been verified. Therefore, the results of predictive pumpage simulations need to be regarded as speculative. Model-derived aquifer properties, however, result from extensive calibration simulations and are within realistic limits, based on available field data. With this deficiency, the model is still the best available tool at present for predicting drawdowns.

The stresses include two separate hypothetical pumpage scenarios. The first scenario included five pumpage centers aligned with the coast that withdraw a total of 116 ft^3/s (75 Mgal/d). The distribution of pumpage was patterned after one of 17 alternatives proposed by the Corps of Engineers to meet anticipated future water needs by the year 2035 in central and southwest Florida (U.S. Army Corps of Engineers, 1980). The simulation was conducted to evaluate the extent of the areal drawdown and its impact on individual springs. The second scenario was designed to show the impact on spring flow where 62 ft^3/s (40 Mgal/d) is pumped alternately from grid blocks that contain springs. A pumping rate of 62 ft^3/s was selected because this is generally the maximum permitted average daily pumpage from a well field within the Southwest Florida Water Management District (Fretwell, 1983). For purposes of simulation, the following assumptions are made:

1. The aquifer remains confined throughout the model area for all predictive scenarios;
2. Head declines at the boundaries are insignificant; and
3. Recharge, discharge, and boundary-flow rates remain constant.

Withdrawal of 116 cubic feet per second

The calibration heads were used for initial conditions in the model. Pumpage was distributed evenly among five pumping centers (fig. 11), and recharge and discharge rates (upward leakage) were held at calibration levels. The maximum drawdown was 1.6 feet at grid block 9,7 and occurred where transmissivity was relatively low (500,000 ft^2/d). Drawdowns of 0.5 foot or more occurred in 30 of the 298 active grid blocks. Drawdowns in coastal areas were less than 0.2 foot. Although the impact on water levels was small, a reduction in head near the saltwater-freshwater interface could cause upconing or lateral intrusion of saltwater.

Effects of well-field pumpage on spring flow at 13 spring groups are shown in table 5. The effect on individual springs varied from 8.0 percent (27 ft^3/s) at the springs group comprised of Homosassa Springs and Halls River to 0.1 percent (1 ft^3/s) at Rainbow Springs. Because upward leakage, recharge rates, and boundary flows were held constant in the model, all water pumped by wells was captured from individual spring discharges.

The simulation shows that the cone is shallow and of small areal extent. The results are representative of an area of high transmissivities and recharge and where pumpage is derived from spring flow.

Withdrawal of 62 cubic feet per second at individual spring nodes

Sixteen computer runs were made, one at a time, with a total pumpage of 62 ft^3/s (40 Mgal/d) during each run from a single well in the center of each grid block of the spring groups (table 3). Initial conditions were the same as the 116-ft^3/s withdrawal simulation. The purpose of the simulations was to show extremes in spring-flow reductions due to ground-water withdrawals. Because it is unlikely that a well field would be located adjacent to a spring and that 62 ft^3/s per node is an exaggeration of present demand and that natural discharge would remain constant, simulation results represent a worst-case situation. A summary of the simulations are shown in table 6.

Results of the computer runs indicated pumpage had a significant effect upon flow of individual springs. Six of the seven springs to the south of Chassahowitzka River contributed at least 50 percent of their flow to pumping and three contributed 100 percent of their flow to pumping and were completely shut off. To the north of Chassahowitzka River, springs contributed up to 18 percent of their flow to pumping. The major factor affecting the impact of pumping on spring flow was the variation in transmissivity. Although overall

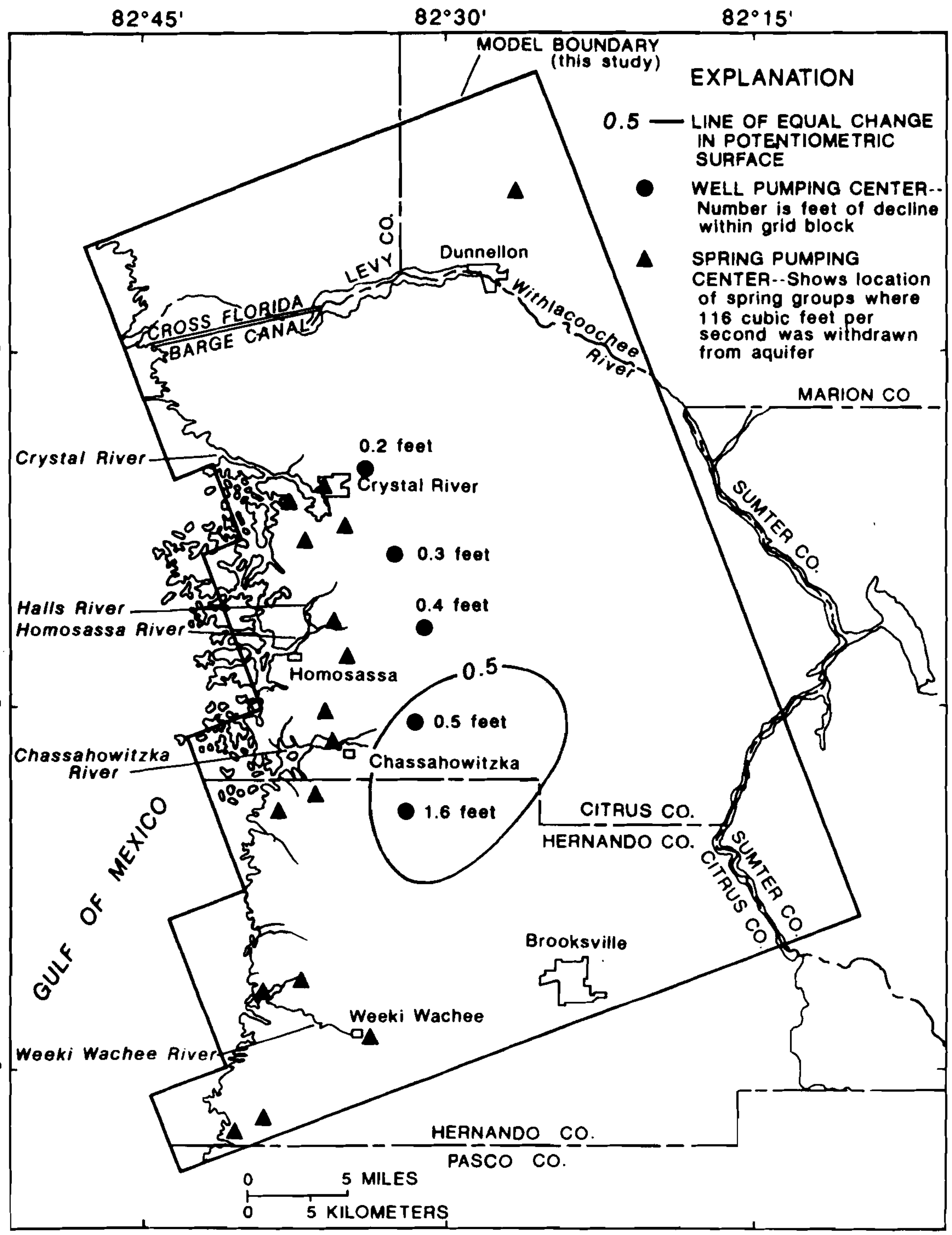


Figure 11.--Simulated change in predevelopment potentiometric surface under 116-cubic-foot-per-second withdrawal scenario.

Table 5.--Simulated changes in spring discharge caused by future withdrawals of 116 cubic feet per second

[ft^3/s, cubic feet per second]

Spring name	Simulated spring flow (ft^3/s)		Impact due to pumpage	
	Calibrated, no pumpage	116-ft^3/s pumpage	ft^3/s	Percent reduction
Unnamed spring no. 1, Boat Spring	11.8	11.7	0.1	0.8
Unnamed spring no. 2, Bobhill Springs	4.8	4.7	0.1	2.1
Unnamed springs no. 4 and no. 5	34.7	34.4	0.3	0.9
Salt Spring, Mud Spring, unnamed spring no. 6	73.9	72.7	1.2	1.6
Weeki Wachee Springs	173	170	3	1.7
839-238-7, unnamed springs no. 7 and no. 8	32.0	30.1	1.9	3.1
Unnamed springs no. 9, no. 10, no. 11, and no. 12	45.6	42.5	3.1	6.8
Chassahowitzka Springs, Baird Creek Springs	177	163	14	7.9
Ruth Spring, Potter Spring	34.3	31.7	2.6	7.6
Hidden River Springs	34.7	32.1	2.6	7.5
Homosassa Springs, Southeast Fork Homosassa Springs, Halls River Springs	338	311	27	8.0
Crystal River Springs	874	812	62	7.1
Rainbow Springs	733	732	1	0.1

transmissivity is high in the area, transmissivity in the spring area south of Chassahowitzka River is relatively low (less than $2x10^6$ ft^2/d) in comparison with transmissivities in the spring area in the north (greater than $9x10^6$ ft^2/d). Consequently, smaller spring-flow impacts occurred in the north as compared with effects in the south. It is important to note that a 34.3-ft^3/s spring (Hidden River) in the north is reduced by about 6 ft^3/s when a 62-ft^3/s well is added, whereas a 32-ft^3/s spring group (839-238-7, No. 7, and No. 8) in the south is completely shutoff under the same conditions.

SUMMARY AND CONCLUSIONS

The coastal springs basin is underlain by the Upper Floridan aquifer, a thick sequence of freshwater-bearing carbonate strata considered as a single hydrologic unit. The aquifer is the major source of virtually all ground

Table 6.--Simulated changes in spring discharge caused by future withdrawals of 62 cubic feet per second

[ft³/s, cubic feet per second]

Spring name	Simulated spring flow (ft^3/s)		Impact due to pumpage	
	Calibrated, no pumpage	62-ft^3/s pumpage at spring node	ft^3/s	Percent reduction
Unnamed spring no. 1, Boat Spring	11.8	0	11.8	100
Unnamed spring no. 2, Bobhill Springs	4.8	0	4.8	100
Unnamed springs no. 4 and no. 5	34.7	17	17.7	51
Salt Spring, Mud Spring, unnamed spring no. 6	73.9	26	47.9	65
Weeki Wachee Springs	173	130	43	25
839-238-7, unnamed springs no. 7 and no. 8	32.0	0	32	100
Unnamed springs no. 9, no. 10, no. 11, and no. 12	45.6	10	35.6	78
Chassahowitzka Springs, Baird Creek Springs	177	150	27	15
Ruth Spring, Potter Spring	34.3	28	6.3	18
Hidden River Springs	34.7	30	4.7	14
Homosassa Springs, Southeast Fork Homosassa Springs, Halls River Springs	338	294	44	13
Crystal River Springs[1]	874	813	61	7
Rainbow Springs	733	671	62	8

[1]Well located in grid block 9,15. Simulated flows for grid blocks 10,14, 10,15, and 9,15 are 816, 814, and 816 ft^3/s, respectively.

water used in the area. Some of the largest freshwater springs in the world discharge from the aquifer. In the coastal area along the Gulf of Mexico, the aquifer discharges are estimated to be about 2,567 ft^3/s by spring flow and about 137 ft^3/s by diffuse upward leakage.

A finite-difference model was used to simulate the steady-state ground-water flow system in the coastal springs basin. The main objectives of the modeling effort were to simulate the predevelopment potentiometric surface of the Upper Floridan aquifer and to compare model-computed spring discharge with measured or estimated spring flow. The model was also developed as a tool for evaluating the effects of development on the hydrologic system.

The flow system was simulated as two-dimensional horizontal flow in a one-layer aquifer system where constant vertical recharge or discharge rates and constant horizontal boundary fluxes were applied to the aquifer. A head-dependent drain function was used to simulate spring flow.

Model calibration consisted of adjustments of aquifer transmissivities and recharge-discharge rates. Adjustments were made to minimize the difference between the predevelopment potentiometric surface and simulated heads over 298 active grid blocks. The mean of absolute values of residuals between the estimated and simulated predevelopment potentiometric surface was 2.0 feet, and total computed spring discharge was 99 percent of total measured or estimated spring flow.

Sensitivity tests were made to assess responses of the calibrated model to changes in input parameters. The sensitivity tests showed the following results:

1. The sensitivity of the model to changes in input parameters increased toward northern, southern, and eastern boundaries;
2. The model was relatively insensitive to changes in input parameters in the interior of the model;
3. Increases in input parameters had less of an effect on the model than an equal decrease in the same parameter;
4. The model was most sensitive to changes in transmissivity and least sensitive to changes in discharge, but relatively sensitive to changes in both parameters;
5. Any change in inflow caused an equivalent change in outflow; and
6. Effects on flow rates of individual springs were significantly variable with changes in input parameters.

The model was tested to show how the system might respond to large man-made stresses. Withdrawing a total of 116 ft^3/s from five regional pumping centers resulted in potentiometric-surface drawdowns ranging from 0.1 foot to 1.7 feet. Drawdowns of 1 foot or more occurred in 13 of the 298 active nodes; drawdowns of less than 0.2 foot occurred along the coast. Total spring flow decreased about 5 percent, and the impact on individual springs varied from 0.1 percent (1 ft^3/s) at Rainbow Springs to 8.0 percent (27 ft^3/s) at the spring group comprised of Homosassa Springs, southeast fork of Homosassa Springs, and Halls River. A worst-case situation also was tested where 62 ft^3/s was pumped individually, one at a time, at each of the 16 spring nodes. Results of the simulation showed a significant effect on the flow of springs. Of the 13 spring groups simulated, 6 contributed at least 50 percent of their flow to pumpage. All small springs south of the Chassahowitzka River ceased flowing and Weeki Wachee Springs contributed 25 percent of its flow to pumpage. Flow from Hidden River spring (34.3 ft^3/s) was reduced by about 6 ft^3/s when a 62-ft^3/s well that discharged 62 ft^3/s was added. The spring group, which consisted of 839-238-7, No. 7, and No. 8, ceased to flow under the same conditions.

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