Hydrogeology and Simulation of the Effects of Reclaimed-Water Application in West Orange and Southeast Lake Counties, Florida

By Andrew M. O'Reilly

U.S. Geological Survey

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Leakance	
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

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.

**Transmissivity:* The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [($ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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Acronyms and additional abbreviations used in report		
AAS	=	Alternate Application Site
ET	=	Evapotranspiration
MODFLOW	=	U.S. Geological Survey Modular Three-Dimensional Ground-Water Flow Model
NOAA	=	National Oceanic and Atmospheric Administration
PVC	=	Polyvinyl chloride
RCID	=	Reedy Creek Improvement District
RIB	=	Rapid Infiltration Basin
USGS	=	U.S. Geological Survey

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Abstract

Wastewater reclamation and reuse has become increasingly popular as water agencies search for alternative water-supply and wastewater-disposal options. Several governmental agencies in central Florida currently use the land-based application of reclaimed water (wastewater that has been treated beyond secondary treatment) as a management alternative to surface-water disposal of wastewater. Water Conserv II, a water reuse project developed jointly by Orange County and the City of Orlando, began operation in December 1986. In 1995, the Water Conserv II facility distributed approximately 28 Mgal/d of reclaimed water for discharge to rapid-infiltration basins (RIBs) and for use as agricultural irrigation. The Reedy Creek Improvement District (RCID) began operation of RIBs in September 1990, and in 1995 these RIBs received approximately 6.7 Mgal/d of reclaimed water. Analyses of existing data and data collected during the course of this study were combined with ground-water flow modeling and particle-tracking analyses to develop a process-oriented evaluation of the regional effects of reclaimed water applied by Water Conserv II and the RCID RIBs on the hydrology of west Orange and southeast Lake Counties.

The ground-water flow system beneath the study area is a multi-aquifer system that consists of a thick sequence of highly permeable carbonate rocks overlain by unconsolidated sediments. The hydrogeologic units are the unconfined surficial aquifer system, the intermediate confining unit, and the confined Floridan aquifer system, which consists of two major permeable zones, the Upper and Lower Floridan aquifers, separated by the less permeable middle semiconfining unit. Flow in the surficial aquifer system is dominated regionally by diffuse downward leakage to the Floridan aquifer system and is affected locally by lateral flow systems produced by streams, lakes, and spatial variations in recharge. Ground water generally flows laterally through the Upper Floridan aquifer aquifer to the north and east. Many of the lakes in the study area are landlocked because the mantled karst environment precludes a well developed network of surface-water drainage.

The USGS three-dimensional ground-water flow model MODFLOW was used to simulate ground-water flow in the surficial and Floridan aquifer systems. A steady-state calibration to average 1995 conditions was performed by using a parameter estimation program to vary values of surficial aquifer system hydraulic conductivity, intermediate confining unit leakance, and Upper Floridan aquifer transmissivity. The calibrated model generally produced simulated water levels in close agreement with measured water levels and was used to simulate the hydrologic effects of reclaimed-water application under current (1995) and proposed future conditions.

In 1995, increases of up to about 40 ft in the water table and less than 5 ft in the Upper Floridan aquifer potentiometric surface had occurred as a result of reclaimed-water application. The largest increases were under RIB sites. An average travel-time of 10 years at Water Conserv II and 7 years at the RCID RIBs was required for reclaimed water to move from the water table to the top of the Upper Floridan aquifer. Approximately 67 percent of the reclaimed water applied at the RCID RIB site recharged the Floridan aquifer system, whereas 33 percent discharged from the surficial aquifer system to surface-water features; 99 percent of the reclaimed water applied at Water Conserv II recharged the Floridan aquifer system, whereas only 1 percent discharged from the surficial aquifer system to surface-water features. The majority of reclaimed water applied at both facilities probably will ultimately discharge from the Floridan aquifer system outside the model boundaries.

Proposed future conditions were assumed to consist of an additional 11.7 Mgal/d of reclaimed water distributed by the Water Conserv II and RCID facilities. Increases of up to about 20 ft in the water table and 2 ft in the potentiometric surface of the Upper Floridan aquifer were simulated. The directions of reclaimed water movement through the ground-water system generally were similar to those under 1995 conditions. However, the greater reclaimed-water application rate at the RCID RIBs caused approximately half of the RCID reclaimed water to discharge to surface-water features and half to recharge the Floridan aquifer system.

INTRODUCTION

Wastewater reclamation and reuse has become increasingly popular as water agencies search for alternative water-supply and wastewater-disposal options. Land-based application of reclaimed water (wastewater that has been treated beyond secondary treatment) is being used as an alternative to the discharge of treated wastewater to lakes or streams (Metcalf & Eddy, Inc. 1991). Reclaimed water can be used in place of freshwater previously withdrawn for nonpotable uses, such as agricultural or landscape irrigation. The conservation of valuable freshwater resources makes the application of reclaimed water an attractive management choice. Several governmental agencies (Orange County, City of Orlando, and the Reedy Creek Improvement District (RCID)) in central Florida currently use the land-based application of reclaimed water as a management alternative to surface-water disposal of wastewater.

Operation of Water Conserv II, a water reuse project developed jointly by Orange County and the City of Orlando, began in December 1986. In 1995, the Water Conserv II facility distributed approximately 28 Mgal/d of reclaimed water received from two wastewater-treatment plants serving the Orlando metropolitan area. About 40 percent of the reclaimed water was used for agricultural irrigation and 60 percent was discharged to rapid-infiltration basins (RIBs). Areas where several RIBs are concentrated are referred to as RIB sites in this report.

The RCID began discharging reclaimed water to RIBs in September 1990. In 1995, these RIBs received approximately 6.7 Mgal/d of reclaimed water from a wastewater-treatment plant serving the Walt Disney World theme parks and resorts. The combined flow of the Water Conserv II and RCID facilities in 1995 was 34.7 Mgal/d, but based on design capacities as much as 65 Mgal/d might be directed to these facilities in the future.

The Water Conserv II and RCID reclaimed-water application sites are located in west Orange and southeast Lake Counties, Florida (fig. 1). Reclaimed water applied to the land surface is either lost to the atmosphere through evapotranspiration or percolates to the water table of the surficial aquifer system. Once within the surficial aquifer system, water can move laterally and discharge at an adjacent stream, lake, or wetland or be extracted by evapotranspiration where the water table is near land surface; or water can move downward to recharge the underlying Floridan aquifer system, a very transmissive limestone aquifer and the major source of freshwater in central Florida.

The Water Conserv II and RCID facilities have extensive programs for monitoring the effects of reclaimed-water application on the local ground-water levels and water quality; however, a process-oriented evaluation of the ground-water system was required for a more comprehensive and regional appraisal of these effects. In 1993, the U.S. Geological Survey (USGS) in cooperation with the RCID, Orange County, and the City of Orlando, began a 4-year study of the combined effects of Water Conserv II and the RCID RIBs on the hydrology of west Orange and southeast Lake Counties.

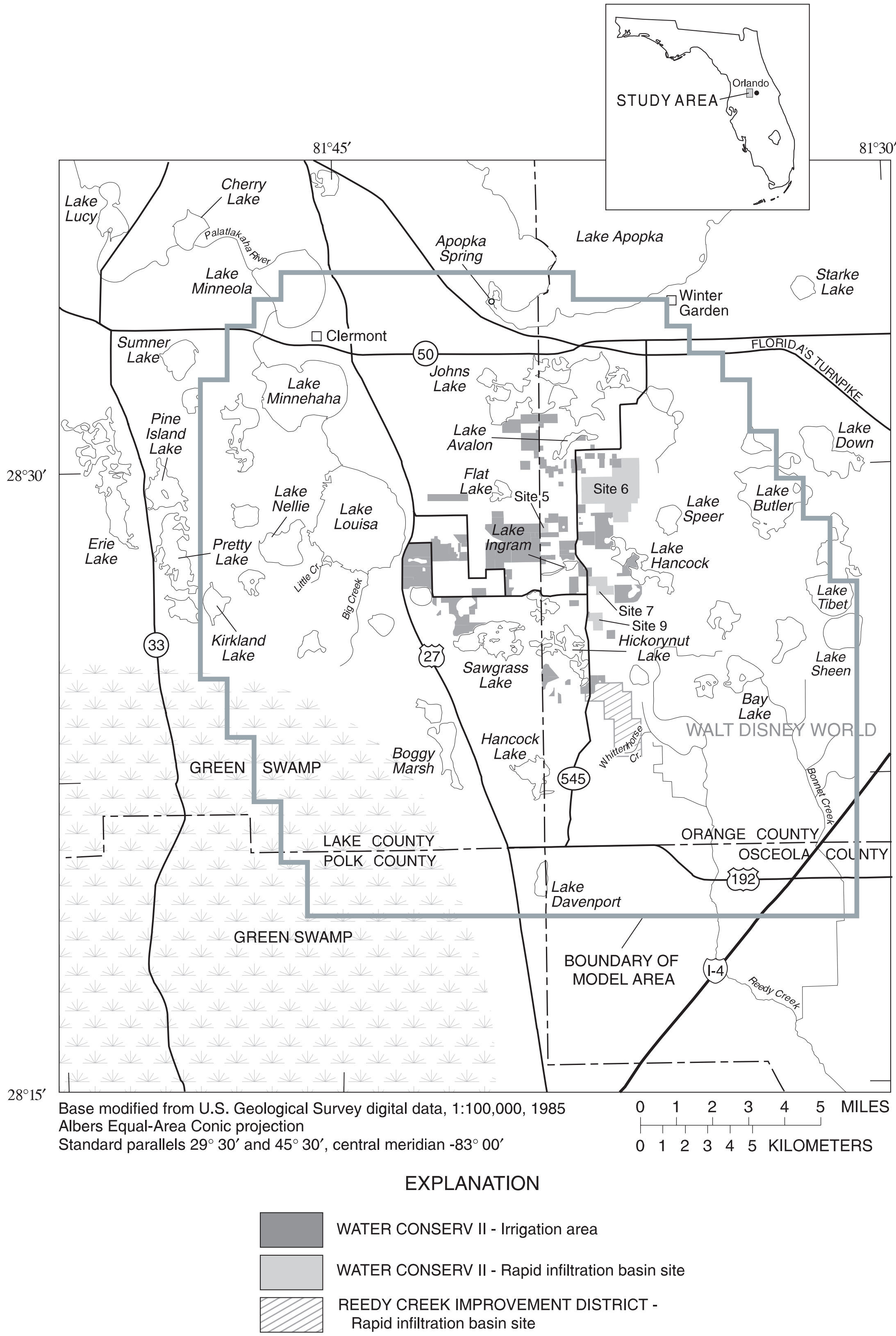


Figure 1. Location of study area, model area, and reclaimed-water application sites.

Purpose and Scope

This report presents the results of a ground-water flow model of west Orange and southeast Lake Counties that includes areas where reclaimed water is used for irrigation and also is directed to RIBs (fig. 1). The model addresses the more regional effects of reclaimed-water application and not the local effects of an individual RIB or small irrigation site. Data collected during the course of the study are described and analyzed in the report to help characterize the hydrogeology of the study area. A hydrologic budget for the surficial aquifer system is presented that includes estimated rates of evapotranspiration from the study area, recharge to the Floridan aquifer system, and surface-water outflow. Hydrologic effects resulting from current (1995) and proposed future reclaimed-water application rates are quantified based on results of the ground-water flow model and particle-tracking analyses.

Data Collection

Data-collection sites were inventoried based on a review of existing data in the study area. Additional data-collection sites were installed to further define the characteristics of the hydrologic system. Data collection included rainfall, evaporation, lake stage, stream stage and discharge, and ground-water levels (figs. 2 and 3, tables 1 and 2). Most data were collected from August 1994 through February 1996.

A standard U.S. Class A evaporation pan was installed at the RCID RIB site in January 1995 and operated through January 1996 (fig. 2). Pan water level, pan water temperature (0.25 in. below water surface), air temperature (3.3 ft above land surface), windspeed (1.6 ft above land surface), and relative humidity (3.3 ft above land surface) were measured at 20-minute intervals. These data were used for estimation of evapotranspiration.

Seven staff gages and 16 surficial aquifer system monitoring wells were installed in areas where existing water-level data were not available. The wells were constructed by the mud-rotary technique, to the depth typically required to place the bottom of the well at least 20 ft below the water table. Each well consisted of 2.5 ft of polyvinyl chloride (PVC) slotted screen and 2- or 4-in. diameter threaded flush-joint PVC casing from the screen to approximately 3 ft above land surface. The borehole annulus was backfilled with clean sand to at least 3 ft above the screen, followed by cement grout to the land surface. Each well was developed with compressed air after installation.

Lithologic data were also collected and analyzed. Split-spoon cores were collected at 5-ft intervals during construction of four of the new wells to provide additional data on surficial aquifer system lithology. Geophysical logs (caliper and natural gamma) were collected at 16 wells to supplement existing data on the altitude of the top of the intermediate confining unit and the top of the Upper Floridan aquifer.

Description of Reclaimed-Water Application

Water Conserv II is the largest water reuse project in the world that combines agricultural irrigation and RIBs (Estow, 1996). Reclaimed water is provided free-of-charge to privately owned citrus groves and commercial nurseries based on a 20-year agreement among the grower, Orange County, and the City of Orlando. In 1995, approximately 4,800 acres of citrus and 100 acres of nursery were being served.

Water beyond that required for irrigation typically is directed to 46 RIBs. Clusters of 3 to 35 RIBs are located at four separate RIB sites numbered 5, 6, 7, and 9 (fig. 1). The RIBs were excavated in native sands with no soil profile modification. Each RIB consists of up to five adjacent cells that are connected with buried pipes. The average RIB cell bottom surface area is 1.3 acres; the interior side-slopes are covered with geotextile liner and the exterior slopes are grass-covered. Water is discharged to the RIB through a vertical pipe in the center of each cell and allowed to fill no more than 2- to 3-ft deep. RIBs typically are loaded for 1 week and allowed to rest for 1 to 2 weeks while the local ground-water mound dissipates. RIBs are loaded on a rotating basis: while one set of RIBs is in its resting period, another set is being loaded. RIB bottoms are tilled periodically to disrupt the thin algal layer that commonly forms after extended loading periods and to destroy any weeds.

Alternate application sites (AASs) are used during extreme and prolonged wet periods when irrigation demand is minimal and the RIBs are operating at full capacity. Most AASs are natural land depressions where reclaimed water can be directed and allowed to infiltrate in a manner similar to a RIB. Some AASs utilize overhead sprinkler irrigation of natural herbaceous vegetation.

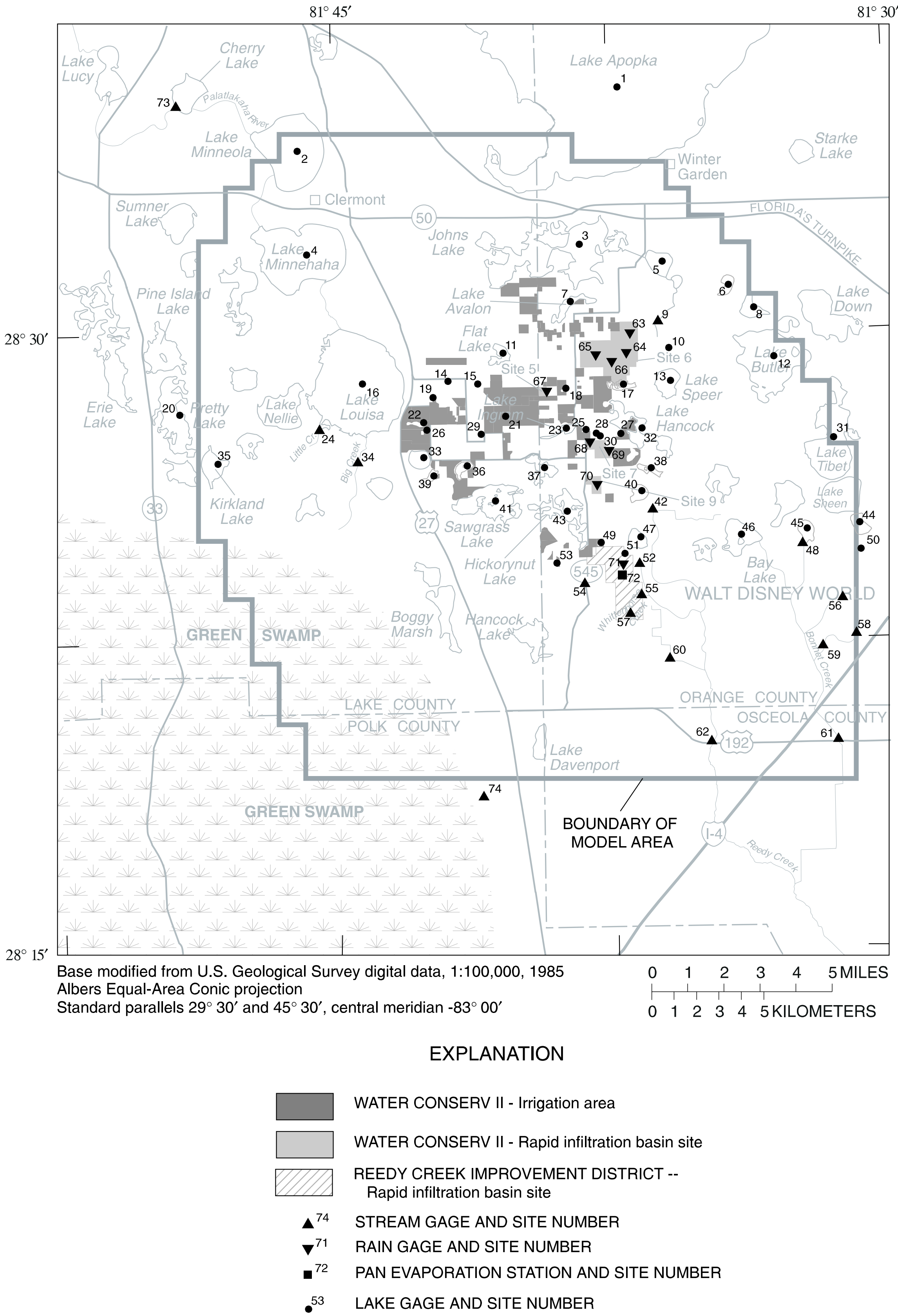


Figure 2. Locations of surface-water and climatological data-collection sites (site information in table 1).

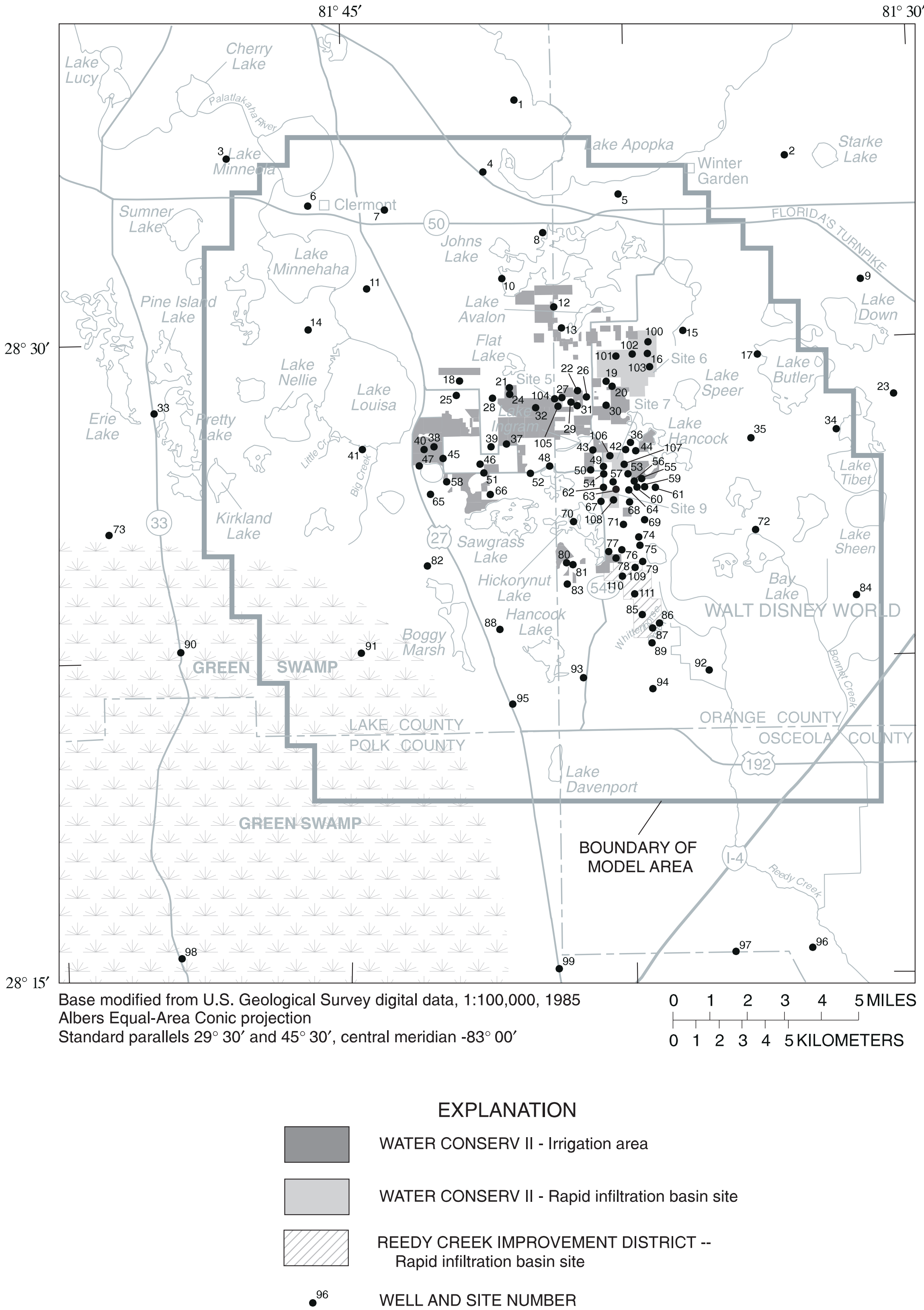


Figure 3. Locations of ground-water data-collection sites (site information in table 2).

Table 1. Surface-water and climatological data-collection sites

[Sites are located by site numbers in figure 2. Sites in close proximity to each other have the same site number. Abbreviation for data type: R, rainfall; E, evaporation; S, surface-water stage; D, stream stage and discharge. Abbreviation for frequency: M, data collected monthly; W, data collected weekly; C, data collected at least daily but typically hourly. Abbreviation for source of data: M&E, Metcalf & Eddy Services, Inc.; OCSMD, Orange County Stormwater Management Department; RCES, Reedy Creek Energy Services, Inc.; SJRWMD, St. Johns River Water Management District; USGS, U.S. Geological Survey. --, not applicable]

Site number	Station number	Station name	Data type	Frequency	Source of data
1	--	Lake Apopka	S	C	SJRWMD
2	--	Lake Minneola	S	C	SJRWMD
3	--	Johns Lake	S	M	OCSMD
4	02236840	Lake Minnehaha	S	C	USGS
5	--	Black Lake	S	M	OCSMD
6	--	Lake Roberts	S	M	OCSMD
7	--	Lake Avalon	S	M	OCSMD
8	--	Crescent Lake	S	M	OCSMD
9	283013081360800	Stream at Tilden Road	S	M	USGS
10	--	Cawood Pond West	S	M	OCSMD
11	--	Flat Lake	S	M	OCSMD
12	--	Lake Butler	S	M	OCSMD
13	--	Lake Speer	S	M	OCSMD
14	--	Water Conserv II HA-5	S	W	M&E
15	--	Water Conserv II HA-1	S	W	M&E
16	02236820	Lake Louisa	S	W	USGS
17	--	Lake Hartley	S	M	OCSMD
18	--	Water Conserv II JR-2	S	W	M&E
19	282826081423000	Hi-Acres pond near Shell Pond Road	S	M	USGS
20	--	Pretty Lake	S	C	SJRWMD
21	282754081402700	Hi-Acres pond near Five Mile Road	S	M	USGS
22	--	Water Conserv II HA-3	S	W	M&E
23	--	Lake Ingram	S	M	OCSMD
24	02236700	Little Creek	D	C	USGS
25	--	Water Conserv II JR-3	S	W	M&E
26	--	Water Conserv II HA-6	S	W	M&E
27	--	Water Conserv II SP-5	S	W	M&E
28	--	Water Conserv II SP-2	S	W	M&E
29	--	Water Conserv II HA-4	S	W	M&E
30	--	Water Conserv II DM-1	S	W	M&E
31	--	Lake Tibet	S	M	OCSMD
32	--	Lake Hancock	S	M	OCSMD
33	02266239	Trout Lake	S	W	USGS
34	02236500	Big Creek	D	C	USGS
35	--	Kirkland Lake	S	W	SJRWMD
36	--	Island Lake, Water Conserv II HA-2	S	W	M&E
37	--	Lake Needham	S	M	OCSMD
38	--	Lake Sawgrass	S	M	OCSMD
39	--	Pike Lake, Water Conserv II HA-8	S	W	M&E
40	--	Huckleberry Lake	S	M	OCSMD
41	282616081405500	Sawgrass Lake	S	M	USGS
42	02266291	L-405 above S-405A	D	C	USGS
42	02266292	L-405 below S-405A	S	C	USGS
43	--	Hickorynut Lake	S	M	OCSMD
44	--	Pocket Lake	S	M	OCSMD
45	02263868	South Lake	S	C	USGS
46	02263850	Bay Lake	S	C	USGS
47	282452081370200	Reedy Lake	S	M	USGS
48	02263870	South Lake outlet below S-15	S	C	USGS
48	02263869	South Lake outlet above S-15	D	C	USGS
49	--	Water Conserv II CH-1	S	W	M&E
50	--	Little Fish Lake	S	M	OCSMD
51	282431081371400	RCID pond near Hartzog Road	S	M	USGS
52	02266026	Reedy Creek below S-46	S	C	USGS
52	02266025	Reedy Creek above S-46	D	C	USGS
53	--	Water Conserv II AT-1	S	W	M&E
54	282351081381600	Bear Bay at SR 545	S	M	USGS
55	02266205	Whittenhorse Creek above S-411	D	C	USGS
56	02264000	Cypress Creek	D	C	USGS
57	02266200	Whittenhorse Creek near Vineland	D	C	USGS
58	02264051	Black Lake outlet above S-101A	D	C	USGS
59	02264060	L-101 above S-101	D	C	USGS
60	02266295	L-410 above S-410	D	C	USGS
60	02266296	L-410 below S-410	S	C	USGS

Table 1. Surface-water and climatological data-collection sites--Continued

Site number	Station number	Station name	Data type	Frequency	Source of data
61	02264100	Bonnet Creek	D	C	USGS
62	02266300	Reedy Creek near Vineland	D	C	USGS
63	--	Water Conserv II Rain Gage 6-1	R	C	M&E
64	--	Water Conserv II Rain Gage 6-2	R	C	M&E
65	--	Water Conserv II Rain Gage 6-4	R	C	M&E
66	--	Water Conserv II Rain Gage 6-3	R	C	M&E
67	--	Water Conserv II Rain Gage 5-1	R	C	M&E
68	--	Water Conserv II Rain Gage 7-1	R	C	M&E
69	--	Water Conserv II Rain Gage 7-2	R	C	M&E
70	--	Water Conserv II Rain Gage 9-1	R	C	M&E
71	--	Rain Gage at RCID RIB site	R	C	RCES
72	--	Class A Pan Evaporation Station	E	C	USGS
73	02236900	Palatlakaha River at Cherry Lake outlet	D	C	USGS
74	02236350	Green Swamp Run near Eva	D	C	USGS

Table 2. Ground-water data-collection sites

[Sites are located by site numbers in figure 3. Sites in close proximity to each other have the same site number. Abbreviation for data type: Gs, surficial aquifer system ground-water level; Gf, Floridan aquifer system ground-water level. Abbreviation for frequency: B, data collected bimonthly; M, data collected monthly; W, data collected weekly; C, data collected at least daily but typically hourly. Abbreviation for source of data: M&E, Metcalf & Eddy Services, Inc.; RCES, Reedy Creek Energy Services, Inc.; USGS, U.S. Geological Survey. --, not applicable]

Site number	Station number	Station name	Data type	Frequency	Source of data
1	283540081402401	LK031	Gf	B	USGS
2	283417081331401	OR059 Ocoee Drain Well	Gf	B	USGS
3	283422081480401	LK028 Sand Mine	Gf	B	USGS
4	283359081411501	LK027 FDAWPC Well	Gf	B	USGS
5	283325081374001	OR053 City of Oakland #2	Gf	B	USGS
6	283314081455501	LK025 Clermont Deep Replacement	Gf	C	USGS
7	283307081435301	LK024 Jacks Lake Well	Gf	B	USGS
8	283232081394101	LK023 Edgewater Beach	Gf	B	USGS
9	283121081311601	OR043 Lake Olivia Drain Well	Gf	B	USGS
10	283128081404701	LK020 L-0052 Johns Lake	Gf	B	USGS
11	283116081442301	LK019 Rings Pond	Gf	B	USGS
12	283047081392401	SW-9 Fischer Marsh Road	Gs	C	USGS
13	283017081391301	OR040 Davenport Road	Gf	B	USGS
14	283019081455701	LK101 LCFD District 9 Station 1	Gf	B	USGS
15	283011081360002	OR038 West Orange Country Club	Gf	B	USGS
16	--	Water Conserv II 6-IW	Gf	W	M&E
16	282939081365701	Water Conserv II 6-F1	Gf	C	USGS
16	282939081365702	Water Conserv II P-40	Gs	C	USGS
17	282936081340201	OR036 Ross Home Well	Gf	B	USGS
18	282904081415701	SW-1 Hi-Acres Summit	Gs	M	USGS
19	--	Water Conserv II MW11-01	Gs	W	M&E
19	282901081380301	Water Conserv II EW11-04	Gs	C	USGS
20	--	Water Conserv II MW11-02	Gs	W	M&E
21	282853081403801	Water Conserv II HA7-F	Gf	B	USGS
21	282854081403701	Water Conserv II HA7-2	Gs	M	USGS
22	282848081384901	SW-10 Ross Grove on Rex Road	Gs	M	USGS
23	282835081305201	OR028 Palm Lake Drive	Gf	C	USGS
24	282844081403701	Water Conserv II HA7-1	Gs	M	USGS
25	282844081420201	Water Conserv II HA5-1	Gs	M	USGS
25	282848081420101	Water Conserv II HA5-F	Gf	B	USG5
26	282839081383501	Water Conserv II JR2-F	Gf	B	USGS
27	--	Water Conserv II 5-F1A	Gf	W	M&E
28	282839081410501	Water Conserv II HA1-F	Gf	B	USGS
29	--	Water Conserv II EW12-03	Gs	W	M&E
29	--	Water Conserv II EW12-04	Gs	W	M&E
29	--	Water Conserv II MW12-01	Gs	W	M&E
29	--	Water Conserv II EW12-02	Gs	W	M&E
30	282827081380401	SW-11 Phillips Grove	Gs	M	USGS
31	282827081385001	Water Conserv II JR2-1	Gs	M	USGS
31	282835081384901	Water Conserv II JR2-3	Gs	M	USGS

Table 2. Ground-water data-collection sites--Continued

Site number	Station number	Station name	Data type	Frequency	Source of data
32	282825081395601	SW-2 Fabry Grove	Gs	M	USGS
33	282823081500401	LK014 D D Gaffney	Gf	B	USGS
34	282749081315801	OR027 Butler Groves	Gf	B	USGS
35	282738081341401	OR025 Lake Sawyer Well	Gf	C	USGS
36	282733081372501	Water Conserv II 2W-1	Gf	B	USGS
37	282734081404301	SW-3 Hi-Acres Five Mile Road	Gs	M	USGS
38	282732081423901	Water Conserv II HA6-1	Gs	M	USGS
38	282738081423702	Water Conserv II HA6-3	Gs	M	USGS
38	282738081423801	Water Conserv II HA6-F	Gf	B	USGS
39	282731081410801	Water Conserv II HA4-F	Gf	B	USGS
40	282728081425501	SW-5 Clonts Grove	Gs	C	USGS
41	282729081443301	LK013 L-0053 Lake Louisa State Park	Gf	B	USGS
42	282724081373401	Water Conserv II DM2-2	Gs	M	USGS
43	282724081382601	SW-13 Ross Grove on SR 545	Gs	M	USGS
43	282730081381701	Water Conserv II JR3-1	Gs	M	USGS
44	282722081371701	Water Conserv II SP5-1	Gs	M	USGS
45	282715081422501	RCID 4-inch PVC #1	Gs	M	USGS
46	282706081412601	RCID 12-inch Irrigation	Gf	C	USGS
46	282706081412602	SW-4 RCID Shell Pond Road	Gs	C	USGS
47	282705081430701	LK103 Trout Lake Well	Gf	B	USGS
48	282702081393501	RCID 4-inch PVC #4	Gs	M	USGS
49	--	Water Conserv II EW16-04	Gs	W	M&E
49	--	Water Conserv II EW16-01	Gs	W	M&E
49	--	Water Conserv II GC-10	Gs	W	M&E
50	282656081383001	SW-12 Ford Avalon Grove	Gs	M	USGS
51	282654081412002	Water Conserv II HA2-5	Gs	M	USGS
51	282654081412401	Water Conserv II HA2-F	Gf	B	USGS
52	282652081400601	RCID 4-inch PVC #3	Gs	M	USGS
53	--	Water Conserv II GC-01	Gs	W	M&E
53	--	Water Conserv II EW13-16	Gs	W	M&E
54	--	Water Conserv II GC-09	Gs	W	M&E
54	--	Water Conserv II EW16-02	Gs	W	M&E
55	--	Water Conserv II EW14-01	Gs	W	M&E
55	--	Water Conserv II EW14-07	Gs	W	M&E
56	--	Water Conserv II GC-02	Gs	W	M&E
56	--	Water Conserv II EW14-02	Gs	W	M&E
57	--	Water Conserv II EW13-06	Gs	W	M&E
57	--	Water Conserv II EW13-08	Gs	W	M&E
58	282642081421901	Water Conserv II HA8-F	Gf	B	USGS
59	--	Water Conserv II EW14-06	Gs	W	M&E
59	--	Water Conserv II EW14-08	Gs	W	M&E
60	--	Water Conserv II GC-04	Gs	W	M&E
60	--	Water Conserv II EW14-04	Gs	W	M&E
61	--	Water Conserv II GC-03	Gs	W	M&E
62	--	Water Conserv II EW13-20	Gs	W	M&E
62	--	Water Conserv II GC-08	Gs	W	M&E
63	282628081375001	Water Conserv II 9-F1	Gf	C	USGS
63	282628081375002	SW-6 at Water Conserv II RIB site 9	Gs	C	USGS
64	--	Water Conserv II GC-05	Gs	W	M&E
64	--	Water Conserv II EW15-01	Gs	W	M&E
65	282624081424601	Water Conserv II HA8-FB	Gf	B	USGS
65	282624081424602	Water Conserv II HA8-1	Gs	M	USGS
66	282623081411001	RCID 4-inch PVC #2	Gs	M	USGS
66	282626081411101	SW-7 RCID Cook Road	Gs	M	USGS
67	282611081381401	SR 545 at Old YMCA Road	Gs	M	USGS
68	--	Water Conserv II GC-06	Gs	W	M&E
68	--	Water Conserv II EW15-04	Gs	W	M&E
69	282544081370501	RCID LW-18	Gs	M	USGS
70	282543081385801	OR019 Hickorynut Lake Well	Gf	B	USGS
71	--	Water Conserv II GC-07	Gs	W	M&E
72	282528081340901	OR016 Bay Lake Deep	Gf	C	USGS
73	282532081511801	LK008 Jack Barry	Gf	B	USGS
74	282520081371501	RCID LW-17	Gs	M	USGS
75	282508081371301	RCID LW-16	Gs	M	USGS
76	282502081374201	RCID LW-15	Gs	M	USGS
77	282500081380301	RCID LW-14	Gs	M	USGS
78	282451081375201	Water Conserv II CH1-F	Gf	B	USGS
79	282445081370901	SW-17 RCID Reedy Lake	Gs	M	USGS
80	282445081391001	Water Conserv II 3W-4	Gf	B	USGS
81	262442081390001	SW-14 Austin Grove	Gs	M	USGS

Table 2. Ground-water data-collection sites--Continued

Site number	Station number	Station name	Data type	Frequency	Source of data
82	282443081425201	LK007 Lykes Groves	Gf	B	USGS
83	282415081391001	Water Conserv II AT1-1	Gs	M	USGS
84	282354081313001	OR012 Disney World	Gf	B	USGS
85	282330081371101	SW-15 Hartzog Road Shallow	Gs	C	USGS
85	282331081370801	OR009 Hartzog Road Deep	Gf	C	USGS
86	282317081364601	RCID 2-inch PVC #3	Gs	M	USGS
86	282318081364401	RCID 2-inch PVC #2	Gs	M	USGS
87	282311081365501	RCID TW-1	Gs	M	USGS
88	282312081405801	Citrus Valley #2	Gf	B	USGS
89	282249081365601	SW-16 Fischer Grove on Hartzog Road	Gs	C	USGS
90	282245081492601	LK003 Eva Deep	Gf	C	USGS
91	282241081443901	L-0051 Sand Mine Deep	Gf	M	USGS
91	282241081443902	L-0050 Sand Mine Shallow	Gs	M	USGS
92	282210081352601	RCID Tree Farm	Gs	C	USGS
93	282202081384601	OR005 Lake Oliver Deep	Gf	C	USGS
93	282202081384602	Lake Oliver Shallow	Gs	C	USGS
94	282145081365601	OR003 Britt Groves	Gf	B	USGS
95	282126081403901	LK002	Gf	B	USGS
96	281536081324801	OS026 FPC Well	Gf	B	USGS
97	281532081345001	PK033 Loughman Deep	Gf	B	USGS
98	281532081493001	PK034 near Polk City	Gf	B	USGS
99	281511081393101	PK032	Gf	B	USGS
100	--	Water Conserv II P-085	Gs	W	M&E
101	--	Water Conserv II MW6-28	Gs	W	M&E
102	--	Water Conserv II P-062	Gs	W	M&E
103	--	Water Conserv II P-104	Gs	W	M&E
104	--	Water Conserv II MW5-1	Gs	W	M&E
105	--	Water Conserv II MW5-4	Gs	W	M&E
106	--	Water Conserv II MW7-9	Gs	W	M&E
107	--	Water Conserv II MW7-8	Gs	W	M&E
108	--	Water Conserv II MW9-7	Gs	W	M&E
109	--	RCID P8-2D	Gs	C	RCES
110	--	RCID P10-3D	Gs	C	RCES
111	--	RCID P6-4D	Gs	C	RCES

The 85 RCID RIBs are similar in construction and operation to the Water Conserv II RIBs, except that each RCID RIB consists of only one cell with approximately 1 acre of bottom surface area. In addition, the RCID RIBs are all located at one RIB site (fig. 1) and typically operate on a rotating 1-week loading period followed by a 4-week resting period.

Monthly reclaimed water application rates vary significantly at both facilities. For example, the highest application rates in 1995 occurred during the July through October rainy season (fig. 4). Wet weather and the subsequent increase in ground-water levels can cause significant inflow and infiltration into wastewater collection systems that produce higher flow rates at the wastewater treatment plant (Metcalf & Eddy, Inc., 1991). The higher flow rates at the wastewater treatment plants serving the Water Conserv II and RCID facilities correspond to the higher reclaimed water application rates. The variation of irrigation rates relative to RIB application rates at Water Conserv II (fig. 4) is due to variable crop water requirements as influenced by rainfall and crop growth characteristics.

Previous Studies

Numerous reports on investigations of the hydrology and geology of the general study area are available. Cooke (1945) and White (1958, 1970) described the geology and geomorphology of central Florida. A detailed description of the hydrology of the Green Swamp area in central Florida is presented in Pride and others (1966); Grubb and others (1978) presented numerous lithologic and geophysical data within the Green Swamp area, and Grubb and Rutledge (1979) modeled ground-water flow in the area. Lichtler and others (1968) described the hydrology of Orange County, and Knochenmus and Hughes (1976) described the hydrology of Lake County. Johnson (1979) described the geology of the Ocklawaha River basin. Putnam (1975) and German (1986) investigated and summarized the hydrologic conditions and effects of development within the entire RCID. German (1990) described the lithology and hydrology of the surficial aquifer system as a part of a larger study to determine the water quality effects of spray irrigation of treated wastewater in the RCID. Ground-water flow models of the Floridan aquifer

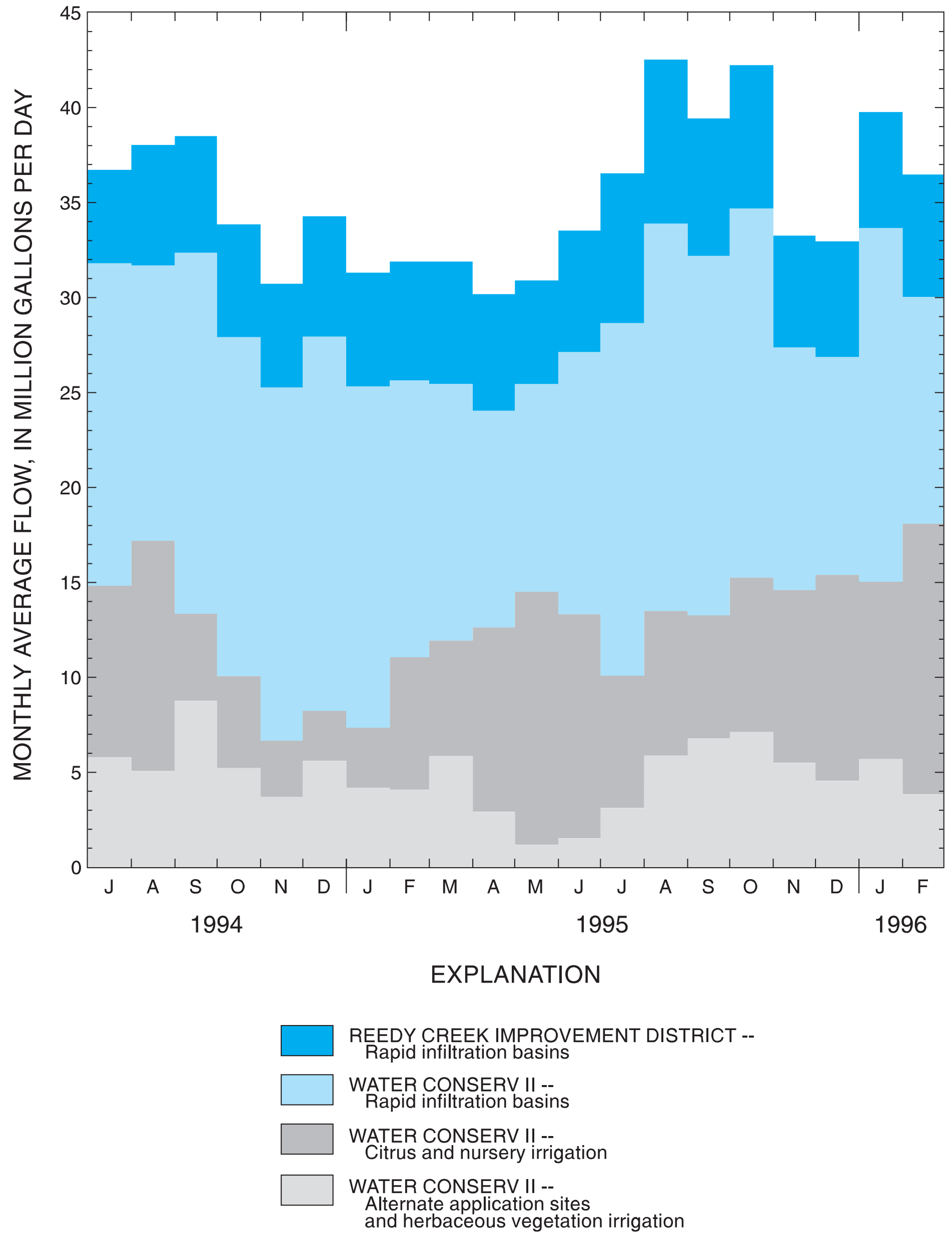


Figure 4. Monthly average reclaimed-water application rates, July 1994 through February 1996.

system were constructed for parts of Osceola, Orange, and Brevard Counties by Planert and Aucott (1985); for east-central Florida by Tibbals (1990); and for the greater metropolitan Orlando area by Murray and Halford (1996). Sumner (1996) measured and modeled evapotranspiration from successional vegetation in a deforested area in west Orange County.

Several studies specifically addressed the Water Conserv II or RCID RIBs. A description of the hydrogeology of the four Water Conserv II RIB sites was presented by Camp Dresser and McKee, Inc. (1984) and included ground-water flow modeling of both the local and regional impacts of RIB operation on the hydrologic system. CH2M Hill (1989) described the hydrogeology of the RCID RIB site and presented the results of a ground-water flow model simulating the impact of the RIBs on the local surficial aquifer system. A description of the hydrogeology of a site adjacent to and north of the present RCID RIB site was presented by CH2M Hill (1993). Sumner and Bradner (1996) examined the unsaturated and saturated zone hydraulics and nutrient transport and fate at the individual RIB scale at the RCID RIB site.

Acknowledgments

The author expresses his appreciation to Preston Merrick, Reedy Creek Improvement District, for providing information on the RCID RIBs; Ted W. McKim, Reedy Creek Energy Services, Inc., and his staff for their maintenance of the pan evaporation station and contribution of data on the RCID RIBs; Gabor L. Delneky, Orange County Public Utilities Division, and Thomas L. Lothrop, City of Orlando Environmental Services Department, for providing information on the Water Conserv II facility; Phillip F. Cross, Metcalf & Eddy Services, Inc., and his staff for their assistance with field data collection and contribution of data on the Water Conserv II facility; David F. MacIntyre, PB Water, and his staff for providing data on the Water Conserv II facility; and the numerous landowners who granted permission for the construction of wells or staff gages on their property.

HYDROLOGIC SETTING

The majority of the study area lies within three physiographic regions: Lake Wales Ridge, Lake Upland, and Osceola Plain (fig. 5). However, nearly all of the Water Conserv II and RCID reclaimed-water application sites are within the Lake Wales Ridge physiographic region, which is characterized by relatively high altitudes (exceeding 200 ft in some areas), large hills, numerous sinkholes, deep water table (greater than 100 ft below land surface in some areas), and internal drainage. The karst topography of the Lake Wales Ridge precludes significant surface-drainage features in many areas. The Lake Upland, which includes the Green Swamp west of the Lake Wales Ridge, and the Osceola Plain to the east of the ridge are relatively flat with numerous wetlands separated by low ridges and hills. The water table is at or near land surface throughout most of the Lake Upland and Osceola Plain except beneath isolated ridges and hills.

Much of the study area was planted with citrus that was killed or severely damaged during a series of freezes in the 1980s; as a result, many citrus groves were abandoned. At the time of the study, many of the abandoned groves remained uncultivated and had been succeeded by natural herbaceous vegetation; however, some citrus groves were present along with a few areas of scrub oaks and pines.

Climate

Long-term average annual rainfall in central Florida is 51 in., based on 80 years of record (1913–92) for Orlando and Sanford (Murray and Halford, 1996). However, annual rainfall varies from year to year; for example, at rain gage site 67 (fig. 2), annual rainfall was 80 percent higher in 1994 (70 in.) than in 1993 (39 in.). Annual rainfall also varies spatially within the study area, but the spatial differences generally are less significant than are the temporal differences. For example, 1994 annual rainfall at rain gage site 70 was 60 in., about 15 percent less than rain gage site 67.

Rainfall in central Florida follows seasonal trends. Plots of cumulative daily rainfall for 1994 and 1995 indicate that 69 and 77 percent of the total annual rainfall, respectively, occurred during the 5-month period from June through October (fig. 6). This seasonal variation is corroborated by long-term monthly rainfall data and leads to significant seasonal trends in surface- and ground-water levels and stream discharge.

Although rainfall represents the largest input of water to the study area, the largest water loss is through evapotranspiration (ET). Conceptually, evapotranspiration is a combination of two processes: evaporation of water directly from surface-water bodies, plants, and soil; and the transpiration of water extracted from soil moisture by plant roots. In practice it is difficult to separate the two processes; consequently, they are typically treated as the one quantity of ET. In the context of this report, ET is meant to represent actual ET, not potential ET, which is the amount of water loss which occurs when there is sufficient water available to meet plant needs. Potential ET represents an upper limit; a lesser amount of water is evaporated or transpired as limited by the actual water available. ET varies considerably across the study area. This spatial variation is primarily the result of differences in vegetation (citrus compared to herbaceous vegetation) and water availability (wetland compared to nonirrigated upland). A strong temporal variation in ET is due primarily to plant growth characteristics and climatological variables such as rainfall, solar radiation, windspeed, and humidity.

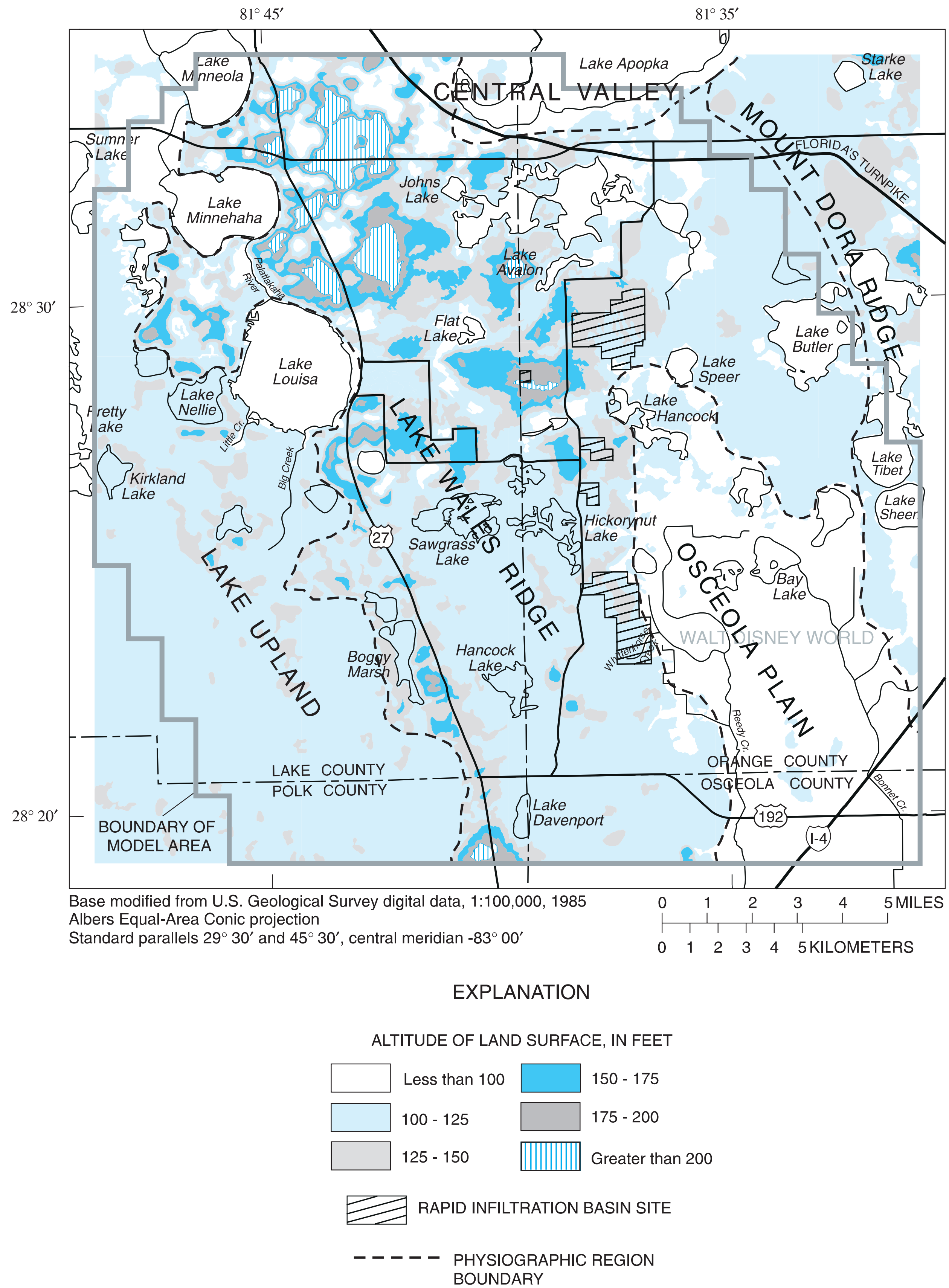


Figure 5. Generalized topography and physiographic regions in the study area (physiographic regions modified from White (1970) and Knochenmus and Hughes (1976)).

Hydrogeologic Framework

The ground-water flow system beneath the study area is a multi-aquifer system that consists of a thick sequence of carbonate rocks overlain by unconsolidated deposits of sand, silt, and clay. The hydrogeologic units are the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system (fig. 7). Beneath the Floridan aquifer system is marine dolomite that contains considerable gypsum and anhydrite of low permeability and defines the bottom of the freshwater flow system in the study area. Selected hydrogeologic sections are shown in figure 8.

The surficial aquifer system is the uppermost water-bearing unit in the study area. The system is unconfined and consists mainly of undifferentiated deposits of marine sand, silt, clay, and crushed shell of late Pliocene to Recent age (fig. 7). The upper boundary of the system is defined by the water table, which in most areas is a subdued reflection of land-surface topography. The base of the surficial aquifer system is defined by the first persistent bed containing a significant increase in silt and clay of Miocene or Pliocene age. Thickness of the system averages about 50 ft but ranges from less than 25 ft in low-lying areas around Reedy Creek and the Palatlakaha River to greater than 200 ft at and near collapse features located along karstic ridge areas.

The fine- to medium-grained sand that characterizes much of the surficial aquifer system contains relatively small amounts of fine-grained sediments and is quite permeable. Grain-size analyses of core samples collected during drilling operations indicate

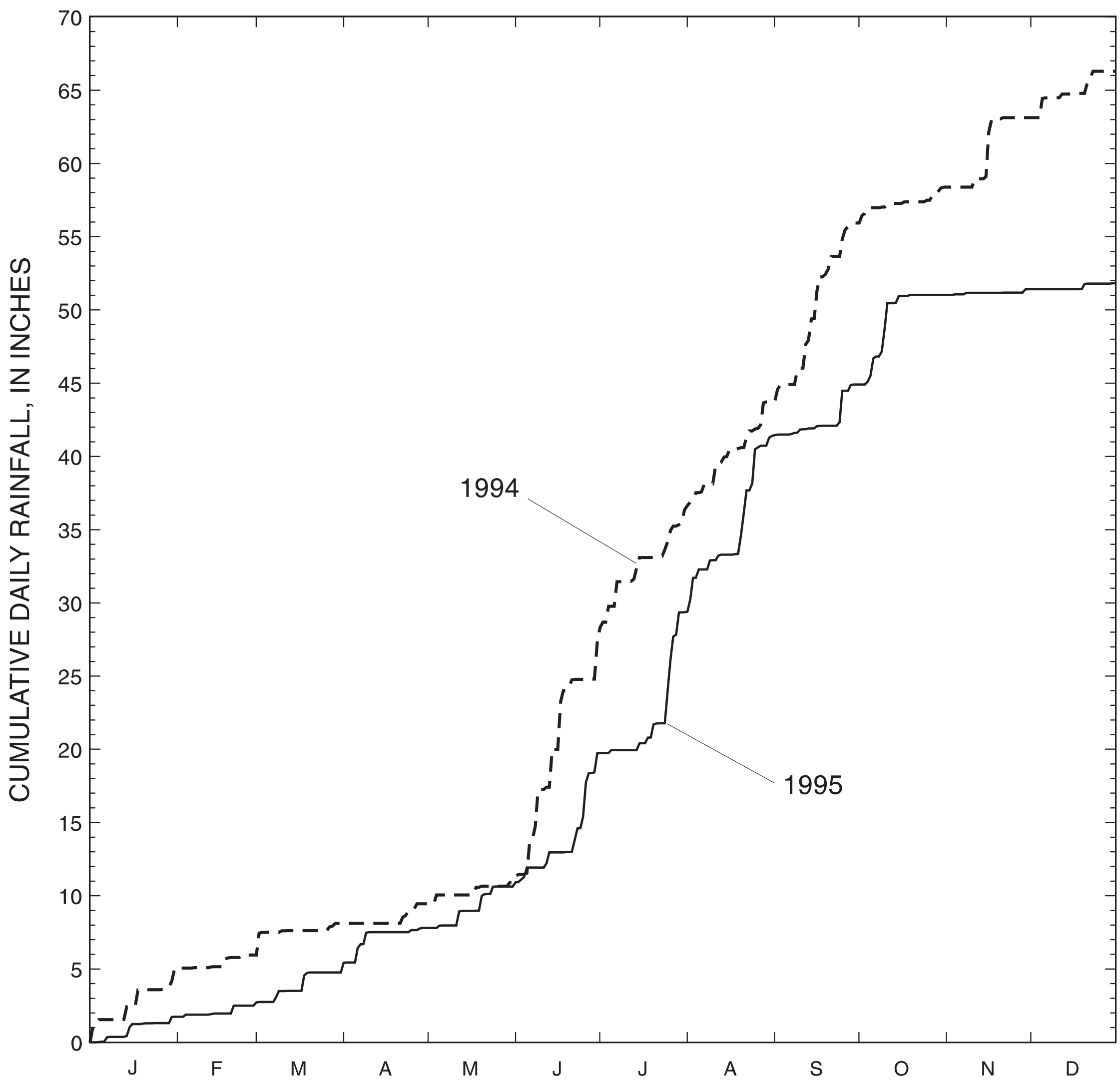


Figure 6. Cumulative daily rainfall, 1994 and 1995 (from average of rainfall measured at site numbers 63 through 70, fig. 2).

GEOLOGIC UNITS

SYSTEM	SERIES		STRATIGRAPHIC UNIT	THICKNESS (feet)	LITHOLOGY	AQUIFER
QUATERNARY	RECENT		UNDIFFERENTIATED DEPOSITS	0-150	Alluvium, freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand.	SURFICIAL AQUIFER SYSTEM
QUATERNARY	PLEISTOCENE		UNDIFFERENTIATED DEPOSITS	0-150	Mostly marine quartz sand, unconsolidated and generally poorly graded. Also, some fluviatile and lacustrine sand, clay and marl.	SURFICIAL AQUIFER SYSTEM
TERTIARY	PLIOCENE		UNDIFFERENTIATED DEPOSITS	0 - 50	Interbedded deposits of sand, shell fragments, and sandy clay; base characterized by phosphatic clay and rubble.	SURFICIAL AQUIFER SYSTEM
TERTIARY	MIOCENE		HAWTHORN GROUP	0 - 100	Cream to light green to greenish-gray clayey quartz sand, silt, shell fragments and sandy clay; often contains phosphatic sands and clays; phosphatic limestone often found at base of formation.	
TERTIARY	EOCENE	UPPER	OCALA LIMESTONE	0-200	Marine foraminiferal limestone, white to cream to tan, soft to hard, granular, highly porous, sometimes dolomitic.	FLORIDAN AQUIFER SYSTEM
TERTIARY	EOCENE	MIDDLE	AVON PARK FORMATION	600-1,600	Marine limestone, light brown to brown, fragmental, poor to good porosity, highly fossiliferous, slightly carbonaceous; and dolomite, brown to dark brown, crystalline.	FLORIDAN AQUIFER SYSTEM
TERTIARY	EOCENE	LOWER	OLDSMAR FORMATION	300-1,350	Marine limestone, light brown to white, chalky, porous, fossiliferous with interbedded brown crystalline dolomite.	FLORIDAN AQUIFER SYSTEM
TERTIARY	PALEOCENE		CEDAR KEYS FORMATION	500-2,200	Marine dolomite, light gray, hard, slightly porous to porous, crystalline, in part fossiliferous, with considerable anhydrite and gypsum, some limestone.	

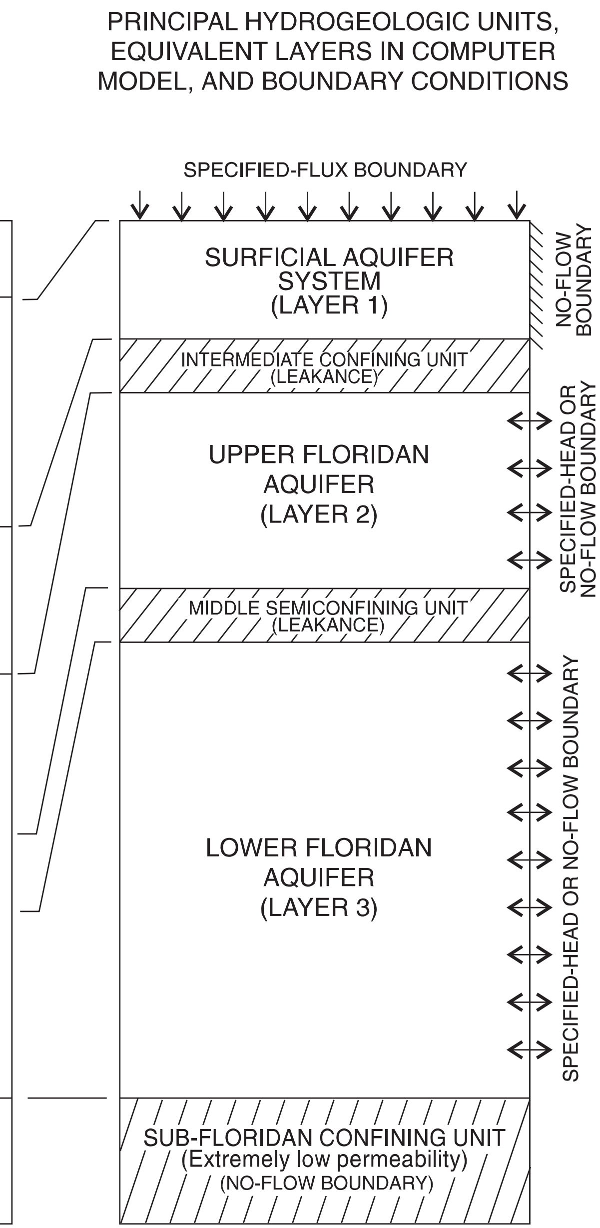


Figure 7. Geologic units, hydrogeologic units, and equivalent layers and boundary conditions used in ground-water flow model (modified from Murray and Halford, 1996, fig. 4).

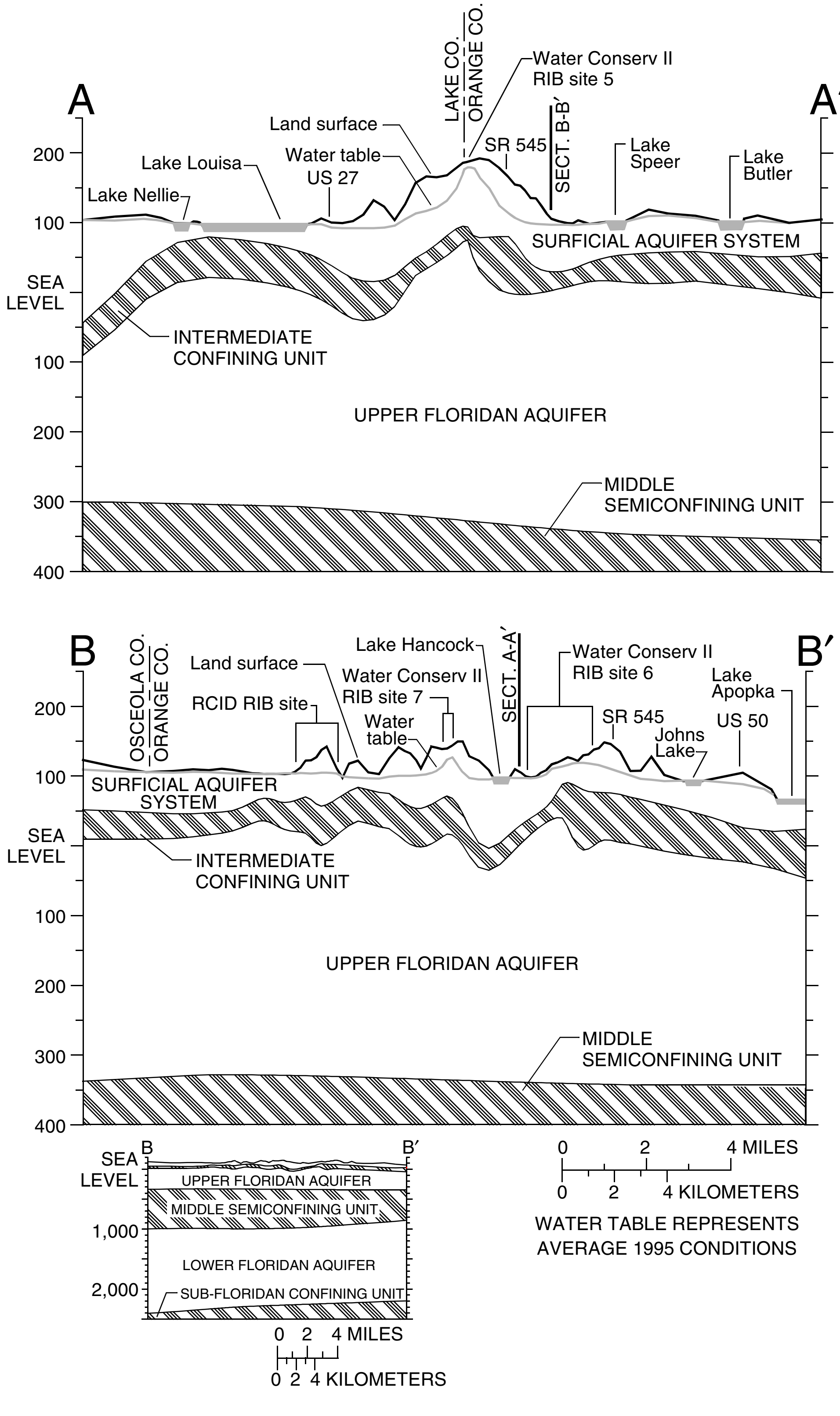


Figure 8. Hydrogeologic sections A-A′ and B-B′ (location of sections shown in fig. 9). Based on interpolation of data shown in figs. 9 and 10 and Miller (1986).

that the upper half of the surficial sediments generally are poorly graded and contain less than 10 percent (by weight) silt- and clay-sized particles. Finer-grained cores generally contained 10 to 30 percent (by weight) silt- and clay-sized particles. Most of the finer-grained sediments are near the base of the system, although isolated beds of clayey to silty sand are present in upper parts as well. However, these shallower beds tend to be thin, discontinuous, and only locally affect the ground-water flow system.

The intermediate confining unit separates the surficial and Floridan aquifer systems throughout the study area, except where breached by sinkholes, and retards the vertical exchange of water between these systems (fig. 8). The unit consists of bedded clay, silt, sand, crushed shell, and phosphatic limestone of Miocene age (Hawthorn Group) and, locally, low permeability beds of early Pliocene age (fig. 7). Strata of these various lithologies are not present in all areas and where present they usually occur in varying proportions; therefore, the overall lithology of the intermediate confining unit is quite variable. Beds of basal Hawthorn limestone that are in direct contact with the limestone of the Upper Floridan aquifer generally are not considered to be part of the Floridan aquifer system because the beds occur locally and the hydraulic conductivity of the Hawthorn limestone is at least an order of magnitude less than that of the Floridan limestone (Murray and Halford, 1996). However, in the vicinity of Water Conserv II RIB site 5, Camp Dresser and McKee, Inc. (1984) reported that the Hawthorn limestone is 100- to 200-ft thick and contains a major cavernous zone. In addition, water levels in a monitoring well (site number 27, fig. 3) open only to this unit reflect a potentiometric surface in agreement with that of the regional Upper Floridan aquifer. Therefore, the Hawthorn limestone was included as part of the Upper Floridan aquifer in this area.

The altitude of the top and thickness of the intermediate confining unit are highly variable, owing to the effects of past erosional processes and sinkhole formation. Where present, the top of the unit generally ranges from less than 50 ft below to greater than 75 ft above sea level across the study area (fig. 9). Intermediate confining unit thickness ranges from less than 25 ft in the southwestern part of the study area and localized areas in the center of the study area, to greater than 150 ft in the northeastern part (fig. 10). The unit is relatively thin or absent within many of the sinkhole chimneys present across west Orange and southeast Lake Counties. These chimneys were often backfilled with more permeable surficial sand shortly after collapse and provide avenues for water from the surficial aquifer system to recharge the underlying Floridan aquifer system. The contours for the top and thickness of the unit (figs. 9 and 10) are highly generalized and are based on lithologic and geophysical data collected at the indicated sites. Actual tops and thicknesses can vary considerably from those shown in figures 9 and 10 because of the presence of local erosional and collapse features in the underlying limestone.

The Floridan aquifer system is composed of a sequence of highly permeable Tertiary carbonate rocks of Eocene age that average about 2,300 ft in thickness across the study area (Tibbals, 1990, fig. 10). The top of the system is defined by the porous Ocala limestone of upper Eocene age and the base of the system is defined by the first occurrence of relatively impermeable, persistent beds of anhydrite associated with the Cedar Keys Formation of Paleocene age (fig. 7). The system has been subdivided into two major permeable zones, the Upper and Lower Floridan aquifers, separated by the less permeable middle semiconfining unit (Miller, 1986). The Upper Floridan aquifer consists of the Ocala limestone, where present, and the dolomitic limestone of about the upper one-third of the Avon Park Formation and ranges in thickness from about 200 to 400 ft across the study area (fig. 8). The Ocala limestone is absent in some areas as a result of past erosional processes (Lichtler and others, 1968). Because of past erosional and dissolution processes, the top of the Upper Floridan aquifer is highly irregular but generally ranges from an altitude of about 50 ft in northern Polk County to about -50 ft just southeast of Lake Apopka.

The middle semiconfining unit underlies the Upper Floridan aquifer and consists of the less permeable, micritic limestone and dense dolomitic limestone found in about the middle one-third of the Avon Park Formation. The lithologic character of the Avon Park limestone varies considerably with depth and spatially across the study area. The top of the middle semiconfining unit slopes from west to east, from an altitude of about -300 to -350 ft. The thickness of the unit beneath the study area averages about 600 ft (Miller, 1986). The Lower Floridan aquifer underlies the middle semiconfining unit and includes about the bottom one-third of the Avon Park Formation and all of the Oldsmar Formation. The Lower Floridan aquifer dips from north to south across the study area and averages 1,300 ft in thickness (Miller, 1986).

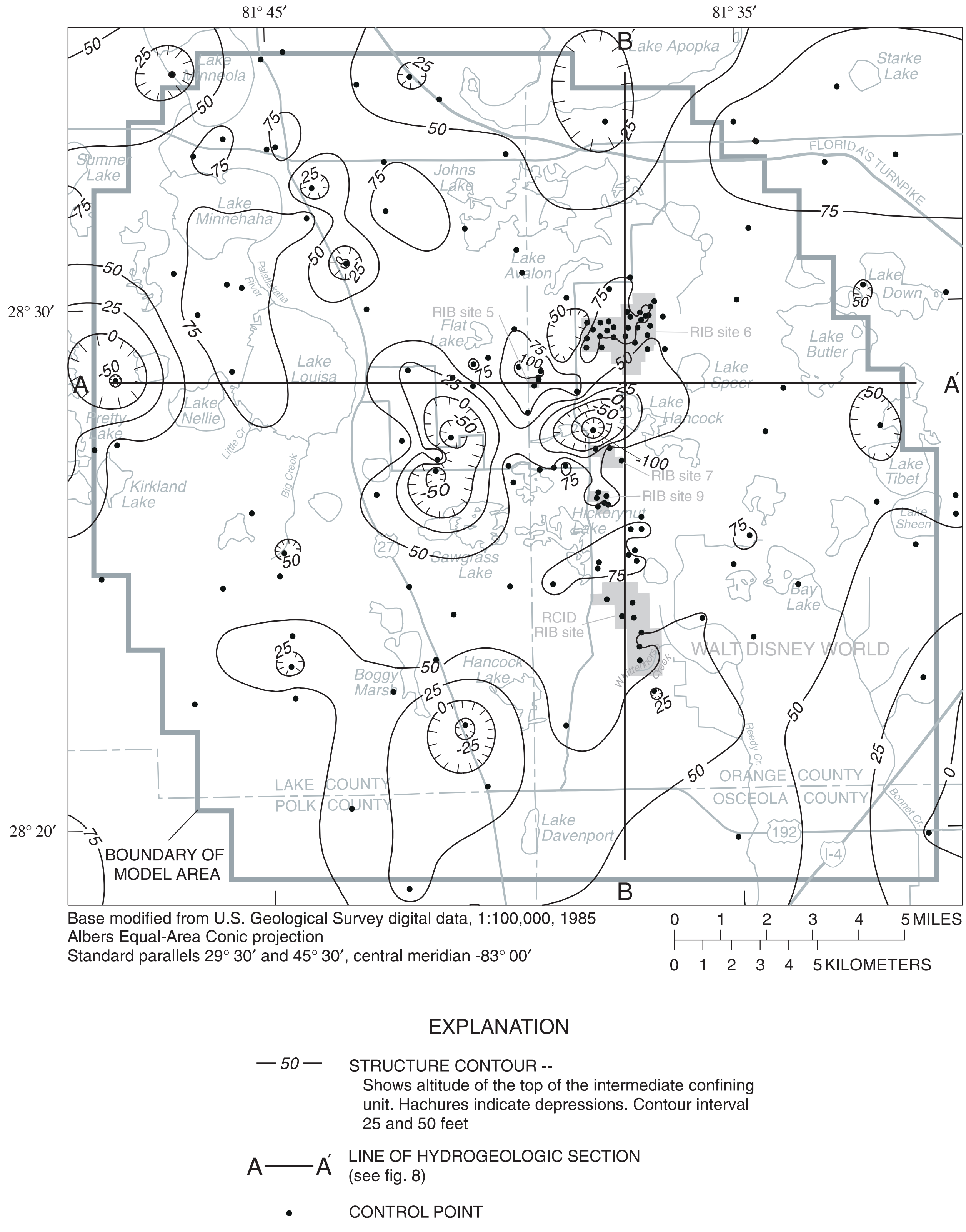
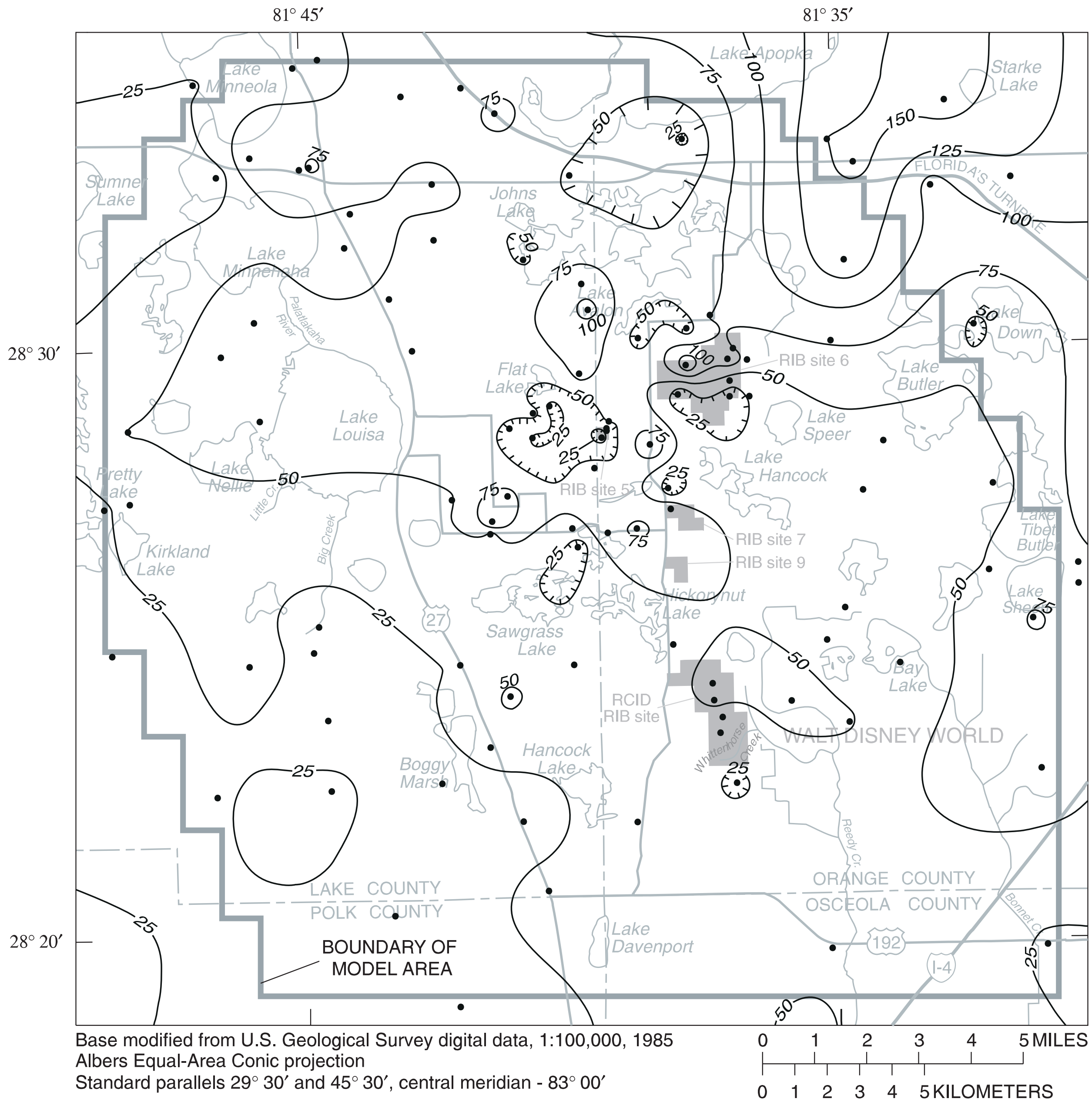


Figure 9. Altitude of the top of the intermediate confining unit and locations of hydrogeologic sections.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Albers Equal-Area Conic projection
Standard parallels 29° 30′ and 45° 30′, central meridian - 83° 00′

EXPLANATION

— 25 — LINE OF EQUAL THICKNESS -- Shows thickness of the intermediate confining unit. Hachures indicate lesser confining unit thickness. Contour interval 25 feet

• CONTROL POINT

Figure 10. Thickness of the intermediate confining unit.

Ground-Water Flow-System Characteristics

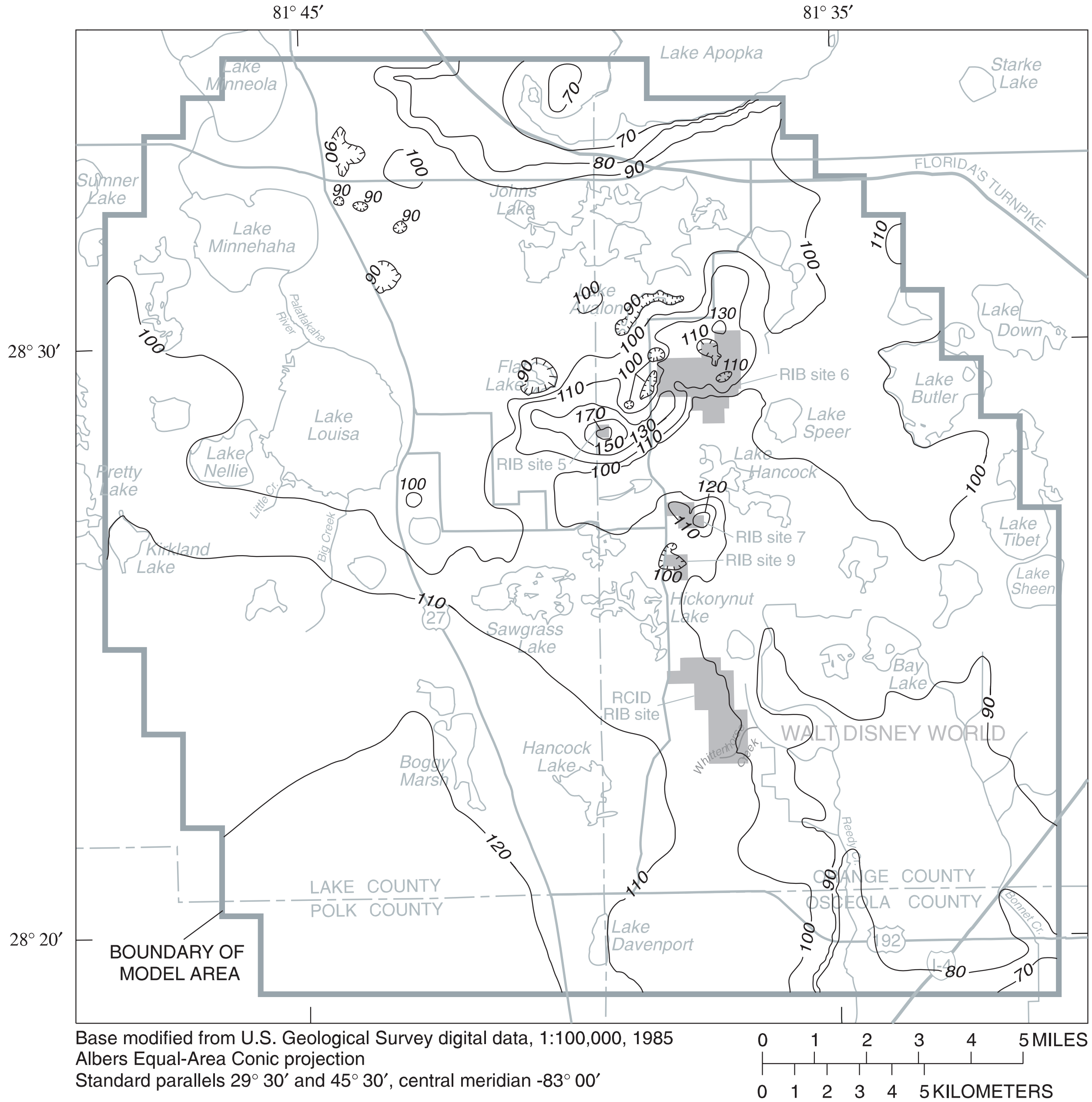
The surficial aquifer system is recharged by rainfall, irrigation, septic-tank effluent, reclaimed water and, in areas where the water table is below the potentiometric surface of the underlying Upper Floridan aquifer, by diffuse upward leakage from the Floridan aquifer system. Water is discharged from the surficial aquifer system through ET in areas with relatively shallow water tables, by lateral seepage to lakes and streams, and by downward leakage to the Floridan aquifer system in areas where the potentiometric surface of the Upper Floridan aquifer is below the water table. Little water is pumped from the surficial aquifer system, because well yields are typically low (compared to the Floridan aquifer system) and the water often contains high concentrations of dissolved iron and can be highly colored (Tibbals, 1990).

Water levels measured monthly (or more frequently) during 1995 at selected surficial aquifer system monitoring wells and lakes (figs. 2 and 3, tables 1 and 2) were averaged to construct a water-table contour map (fig. 11). The localized effects of reclaimed-water application were greatest at Water Conserv II RIB site 5 where the altitude of the mounded water table was greater than 170 ft, or about 40 ft greater than the levels prior to reclaimed-water application. However, the water table is relatively flat throughout most of the model area. Where there is little relief in the water table, the 10-ft contour interval depicted in figure 11 limits the inferences that can be made about lateral flow in the surficial aquifer system. Numerous local flow systems produced by streams, lakes, and spatial variations in recharge probably would be apparent if data were available that allowed a finer resolution of water-table contours. The thin saturated thickness of the surficial aquifer system and the relatively high rates of leakage through the intermediate confining unit also reduce the possibility of regional lateral flow in the system.

The water table does not always represent a subdued reflection of land-surface topography. A comparison of figures 5 and 11 illustrates this to be especially true under many hills in the Lake Wales Ridge, excluding areas near RIB sites. Pride and others (1966) and Knochenmus and Hughes (1976) reported similar findings in the Lake Wales Ridge in Polk and central Lake Counties, respectively. This probably is a combination of the effects of a relatively high surficial aquifer system hydraulic conductivity and a very leaky intermediate confining unit.

Seasonal changes in water-table altitude measured during 1995 were typically 2 to 6 ft in areas outside the vicinity of reclaimed-water application sites and up to about 15 ft at Water Conserv II RIB site 5. However, given the same recharge flux exiting the rooting zone (that is, beneath the depth that plants can extract water) the water table will respond differently depending primarily upon the thickness and lithology of the unsaturated zone. The unsaturated zone ranges in thickness from 0 ft at lakes to greater than 100 ft under many hills. Where the unsaturated zone is very thick, the water table varies smoothly in response to monthly or longer term trends in rainfall; although where the unsaturated zone is thinner, the water table responds more abruptly to daily rainfall events (fig. 12). The times of hydrograph minima and maxima also differ significantly, and can be delayed up to a month or more at a deep water table (fig. 12). Local beds of clay and silt in the unsaturated zone can cause an even more muted and delayed response to recharge. Where such great variability exists in unsaturated thickness, the spatial distribution of recharge to the water table is not uniform (Winter, 1983). For example, the rise in water table under hills where the depth to the water table is great is caused not only by vertical infiltration through the unsaturated zone, but also by lateral flow from water-table mounds that appear earlier at the toe of the hill where the water table is near land surface (Winter, 1983).

The Upper Floridan aquifer is recharged by downward leakage from the surficial aquifer system and upward leakage from the Lower Floridan aquifer in areas where the potentiometric surface of the Upper Floridan aquifer is below that of the Lower Floridan aquifer. Excluding recharge from reclaimed water, recharge rates from the surficial aquifer system to the Upper Floridan aquifer have been estimated to range from 3 to 20 in/yr across most of the study area (Murray and Halford, 1996). The aquifer is discharged by pumping wells, Apopka Spring, diffuse upward leakage to the surficial aquifer system (primarily beneath Reedy Creek and Lake Apopka), and by downward leakage to the Lower Floridan aquifer in any areas where the potentiometric surface of the Upper Floridan aquifer is above that of the Lower Floridan aquifer. Nearly all of the water withdrawn by wells in the study area is from the Upper Floridan aquifer.



EXPLANATION

— 120 — WATER TABLE CONTOUR -- Shows average altitude of water table in 1995. Hachures indicate depression. Contour interval 10 and 20 feet

Figure 11. Water table in the surficial aquifer system, average 1995 conditions.

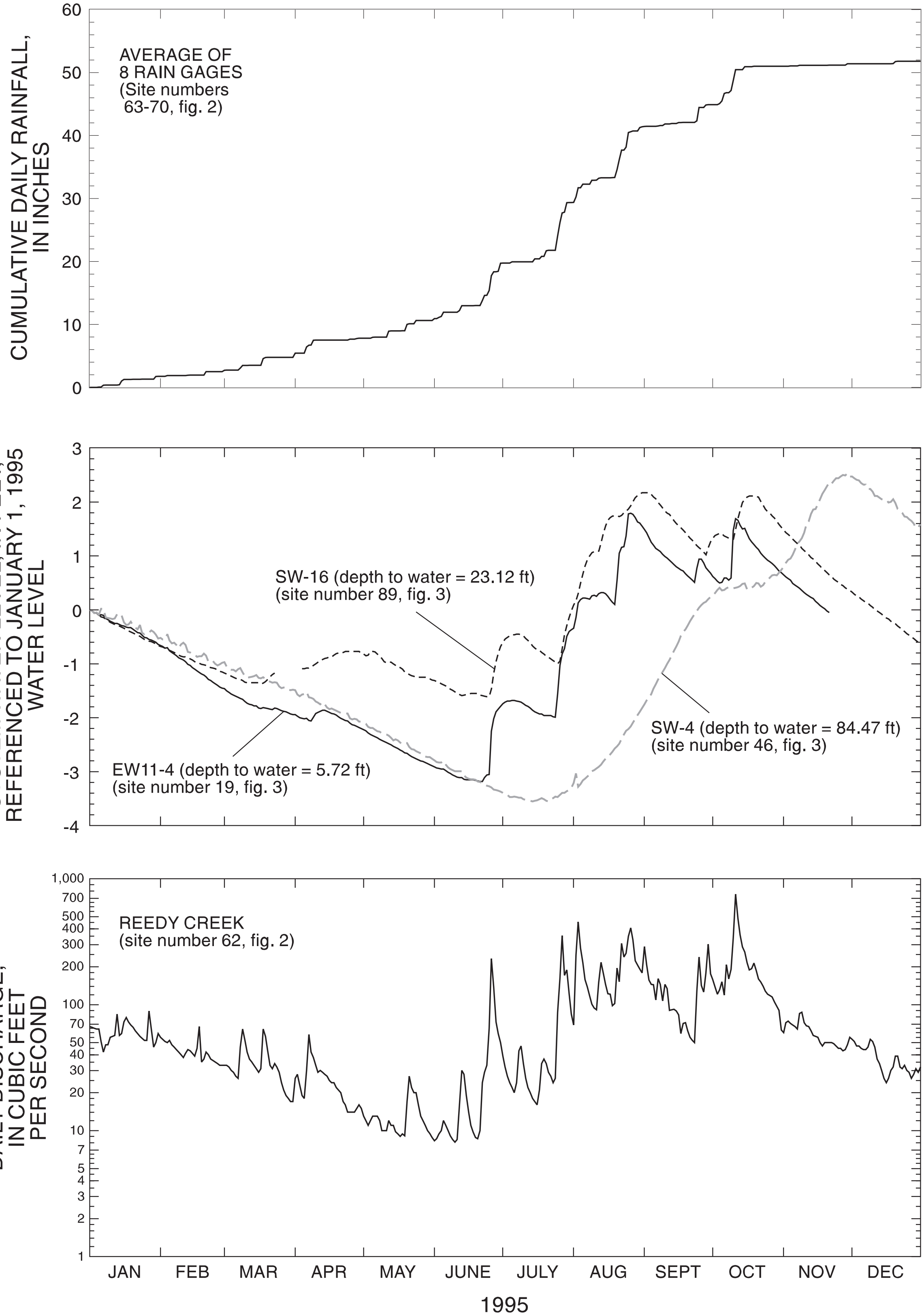


Figure 12. Cumulative rainfall, surficial aquifer system water levels, and discharge at Reedy Creek, 1995 (depth to water indicates depth of the surficial aquifer system water table below land surface on January 1, 1995).

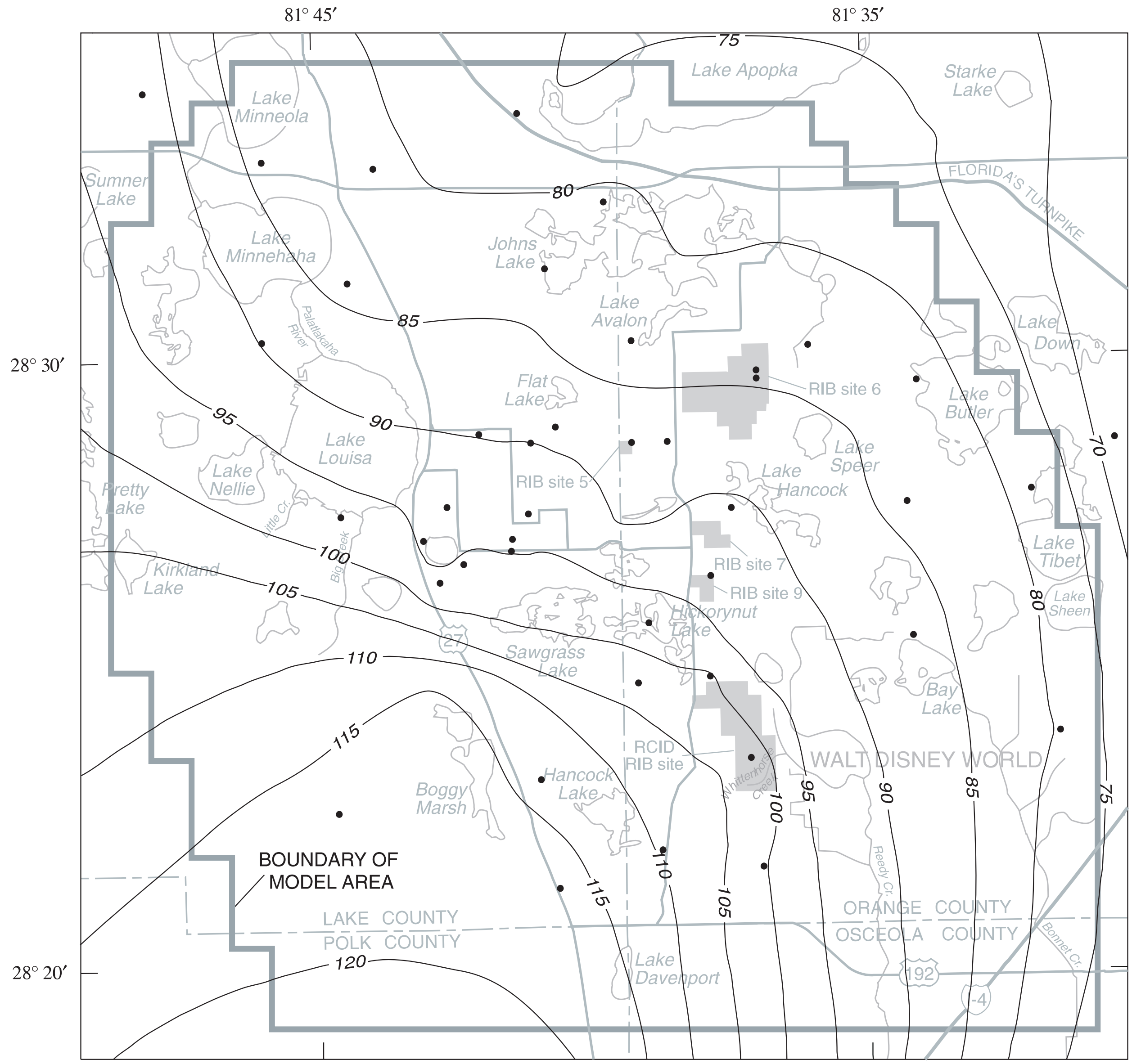
Water levels in Upper Floridan aquifer monitoring wells that were measured bimonthly (or more frequently) during 1995 were averaged to construct a potentiometric-surface map (fig. 13). Flow in the Upper Floridan aquifer primarily is regional because the high transmissivity of the Upper Floridan aquifer precludes the formation of significant mounds or depressions in the potentiometric surface that would induce local flow systems. Accordingly, mounds in the potentiometric surface from reclaimed-water application are not apparent. In contrast to the surficial aquifer system water table, a 10-ft contour interval probably accurately represents all the significant variations in the Upper Floridan aquifer potentiometric surface. Consequently, referring to figure 13 and noting that ground water moves from high-to-low head and generally perpendicular to potentiometric contours, regional flow in the Upper Floridan aquifer can be inferred to occur from northern Polk County, where water levels exceed 120 ft, to the north and east, where altitudes as low as 70 ft were measured.

Seasonal changes in the Upper Floridan aquifer potentiometric surface that were measured during 1995 were typically 3 to 5 ft. Variations in potentiometric surface generally are similar to those in the surficial aquifer system water table, but usually are of lesser magnitude (fig 14). Pumpage from the Upper Floridan aquifer causes short-term changes in the potentiometric surface that usually are not reflected by the water table. Fluctuations that more closely mimic those in the water table generally indicate a better connection between the surficial and Upper Floridan aquifers.

No data exist within the study area on the potentiometric surface of the Lower Floridan aquifer, although what little data exist elsewhere indicate that the potentiometric surface generally is similar to that of the Upper Floridan aquifer. Murray and Halford (1996) reported model simulated head differences between the Upper and Lower Floridan aquifers of 1 to 3 ft downward in central Orange County. In September 1996, measured potentiometric surfaces of the Upper and Lower Floridan aquifers indicated downward head differences of 1 ft near Polk City and 0.5 ft near Orlando (G.G. Phelps, USGS, oral commun., 1996). A few pumping wells in the study area may withdraw water from both the Upper and Lower Floridan aquifers; however, insufficient data were available regarding well construction or aquifer lithology to make this distinction.

Hydraulic conductivity of the surficial aquifer system has been estimated by previous investigators. Slug tests performed at the RCID RIB site yielded horizontal hydraulic conductivity values between 25 and 160 ft/d (CH2M Hill, 1989); additional tests conducted just north of the RCID RIB site yielded values of 35 to 67 ft/d (CH2M Hill, 1993). Sumner and Bradner (1996) reported that a horizontal hydraulic conductivity of 150 ft/d was required to calibrate a numerical flow model designed to analyze a loading test conducted at one of the RCID RIBs. Camp Dresser and McKee, Inc. (1984) reported hydraulic conductivity values generally between 20 and 80 ft/d based on laboratory analyses of numerous cores collected at each of the Water Conserv II RIB sites. This range of values was consistent with those used to calibrate a ground-water flow model of the Water Conserv II area (Camp Dresser and McKee, Inc., 1984).

The leakance of the intermediate confining unit is highly variable across the study area and depends on the vertical hydraulic conductivities and thicknesses of the individual strata of the unit from one location to the next. The leakance of any vertically homogeneous geologic unit is equal to its vertical hydraulic conductivity divided by its thickness. Field-derived estimates of leakance are sparse; however, two Upper Floridan aquifer tests conducted in the Water Conserv II project area yielded leakance values of $2x10^{-4}$ to $9x10^{-4}$ (ft/d)/ft (Camp Dresser and McKee, Inc., 1984). Leakance values calibrated in a more regional flow model ranged from $4x10^{-5}$ to $8x10^{-4}$ (ft/d)/ft (Murray and Halford, 1996). Results from this calibrated model indicate that the highest leakance values are in the southwestern part of the study area where the confining unit is thinnest. Lowest leakance values are in the northeastern part, just southeast of Lake Apopka, where the unit is thickest. Fewer similarities in fluctuations of the surficial aquifer system water table and the Upper Floridan aquifer potentiometric surface in adjacent wells as well as increasing head differences between the two aquifers also indicate that intermediate confining unit leakance decreases from south to north across the study area (fig. 14). However, the extremely variable lithology and thickness of strata in mantled karst environments, such as is characteristic of much of the study area, make inferring leakance values (except in a very general manner) from unit thicknesses unreliable. It would be very difficult to collect data at such a fine resolution as to represent this variability in its true complexity. Yet it is the very local variations (for example, where the unit is breached by sinkholes or composed primarily of silty



Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Albers Equal-Area Conic projection
Standard parallels 29° 30′ and 45° 30′, central meridian -83° 00′

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

EXPLANATION

—120— POTENTIOMETRIC CONTOUR --
Shows the average altitude at which water level would have stood in tightly cased wells tapping the Upper Floridan aquifer in 1995. Contour interval 5 feet

• OBSERVATION WELL

Figure 13. Potentiometric surface of the Upper Floridan aquifer, average 1995 conditions.

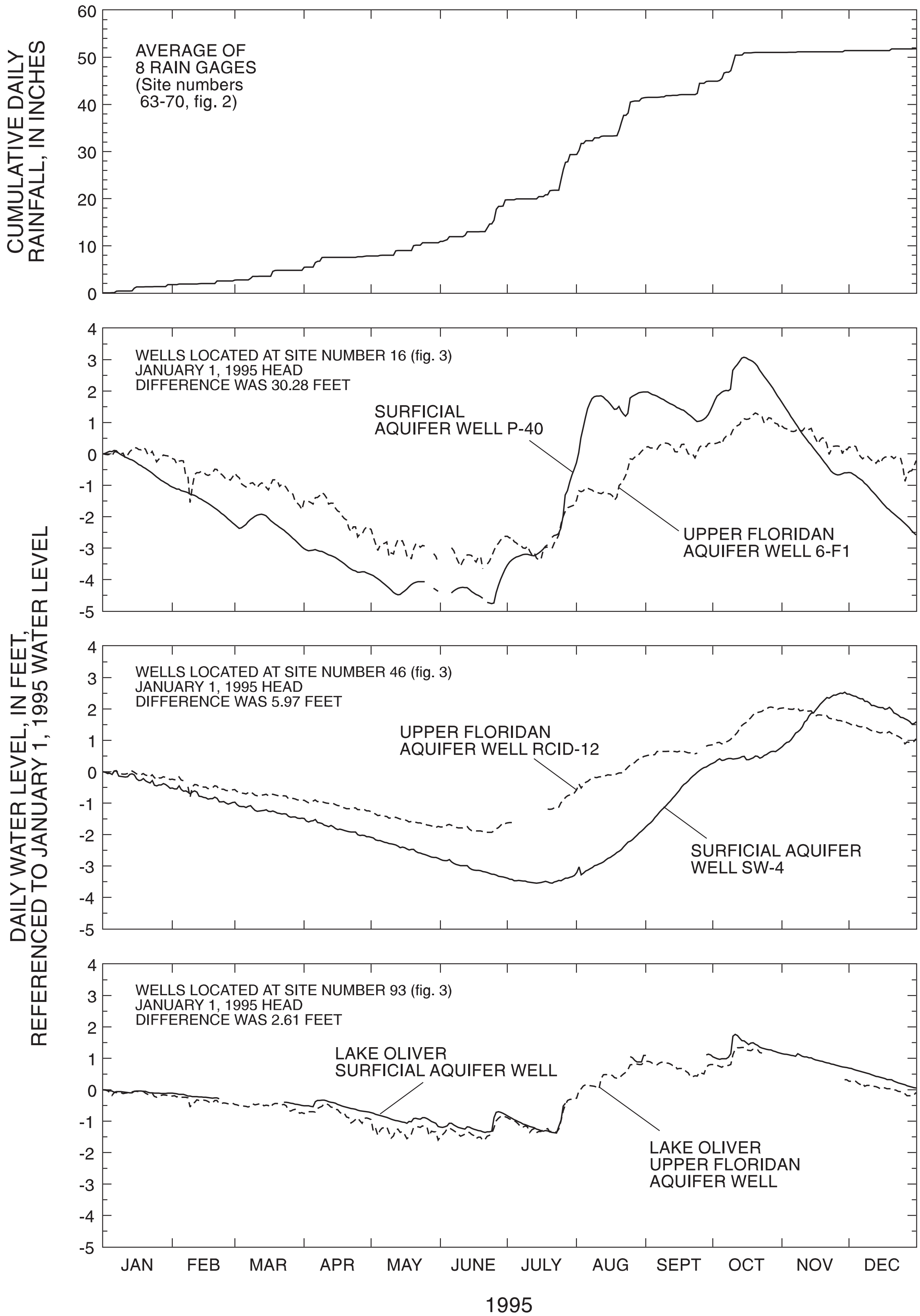


Figure 14. Changes observed in surficial aquifer system and Upper Floridan aquifer water levels at selected monitoring wells, 1995. Water levels have been offset for each well by a constant value equal to the water-level altitude for the respective well on January 1, 1995.

sand) that control the leakage rate between the surficial and Floridan aquifer systems. Therefore, the areal average leakance of the intermediate confining unit could be high in an area where it is breached by several sinkholes, even though the confining unit is composed of thick clay.

Results of aquifer tests indicate that the transmissivity of the Upper Floridan aquifer generally is lowest in the Green Swamp and increases toward the northeast with values of between 3,400 and 130,000 ft^2/d (Pride and others, 1966; Grubb and Rutledge, 1979; Camp Dresser and McKee, Inc., 1984). Preferential flow zones occur in the Upper Floridan aquifer as a result of variations in lithology and solution-enlarged cavities in the limestone. Likewise, zones of reduced transmissivity exist where sinkhole collapses have caused the filling of cavities with a mixture of overlying sand and clay.

No data exist within the study area concerning the leakance of the middle semiconfining unit and transmissivity of the Lower Floridan aquifer. Based on regional ground-water flow models, Tibbals (1990) and Murray and Halford (1996) reported a value of $5x10^{-5}$ (ft/d)/ft for leakance of the middle semiconfining unit and 30,000 to 130,000 ft^2/d for transmissivity of the Lower Floridan aquifer in the study area.

Surface Water

Approximately 16 percent of the surface area of the model consists of lakes (fig. 15). The few lakes for which bathymetry data are available indicate that these lakes are relatively shallow. Based on data by Kenner (1964), average depth is approximately 6 ft for Lake Apopka, 10 ft for Lakes Louisa and Minnehaha, and 15 ft for Lake Butler. Many lakes in the study area are internally drained and even more have surface-water inflow or outflow only during prolonged wet periods. Lake level represents a surface expression of the water table and the lakes generally are gaining water from the surficial aquifer system (for example, Flat Lake and Lake Ingram, fig. 11). However, it is not unusual for the water table to be sloping away from a lake and inducing the flow of lake water into the surficial aquifer system. A comparison of the water levels in well HA2-5 and Island Lake shows that flow probably is out of the lake and into the surficial aquifer system (fig. 16), at least along the northern shore.

Ground- and surface-water interaction can be largely dependent on the water-table configuration near a lakeshore. Winter (1983) reported that transient ground-water mounds can occur near a lakeshore due to rapid recharge to a shallow water table. Lee and others (1991) observed this phenomenon at Lake Lucerne in Polk County, a lake which probably is hydrologically similar to many lakes in the study area. Where these transient water-table mounds exist, they could induce a significant amount of ground-water inflow to the lake or prevent a significant amount of ground-water outflow from the lake, consequently having a direct effect on lake level.

The majority of the lakes are within the Lake Wales Ridge physiographic region; the mantled karst environment of this region is prone to sinkhole development which probably formed most of these lakes. Using high resolution seismic-reflection data, Tihansky and others (1996) confirmed the sinkhole origin of four lakes along the Lake Wales Ridge in Polk and Highlands Counties and concluded that the lithology and distribution of geologic materials under and in the immediate vicinity of a lake is highly variable, yet it is very important in determining the response of the lake to changes in stress. Most of the lakes in the study area probably are similar to these; therefore, the effects on lake level of reclaimed-water application can differ considerably, even between lakes in close proximity to each other.

A comparison of the water levels in well SW-4 and Island Lake (fig. 16) indicates that there might be an area of high intermediate confining unit leakance north of the lakeshore which could induce the movement of ground water northward from Island Lake and southward from SW-4. These data illustrate the effect that leakance of the intermediate confining unit can have on the movement of ground water near lakes and in the surficial aquifer system in general.

Approximately 18 percent of the surface area of the model consists of wetlands (fig. 15). The majority of the wetlands are located in the Lake Upland and Osceola Plain physiographic regions because the water table generally is near land surface in these areas. Within the wetlands, the water table is often at or above land surface. Fluctuations in wetland water levels are generally small. For example, the water level at site 54, which is located at the edge of a wetland (fig. 2), rose only 1.92 ft from May to October 1994 even though this was an unusually wet year (fig. 6). An ET rate often equal to potential ET and drainage by overland flow and streams preclude large fluctuations in water levels. Most of the wetlands are drained by streams in the Reedy Creek and Palatlakaha River basins (fig. 15).

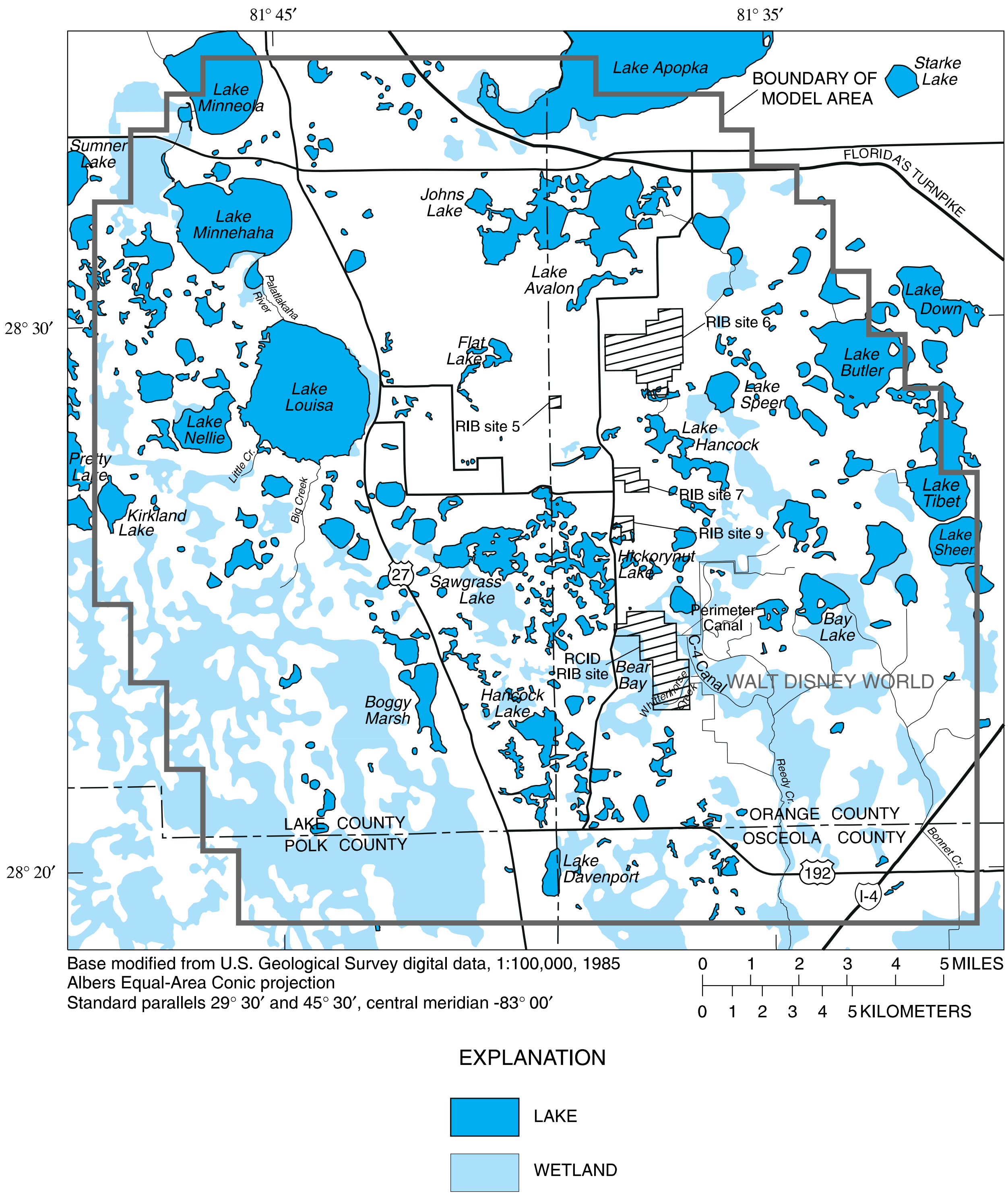


Figure 15. Surface-water features in the study area.

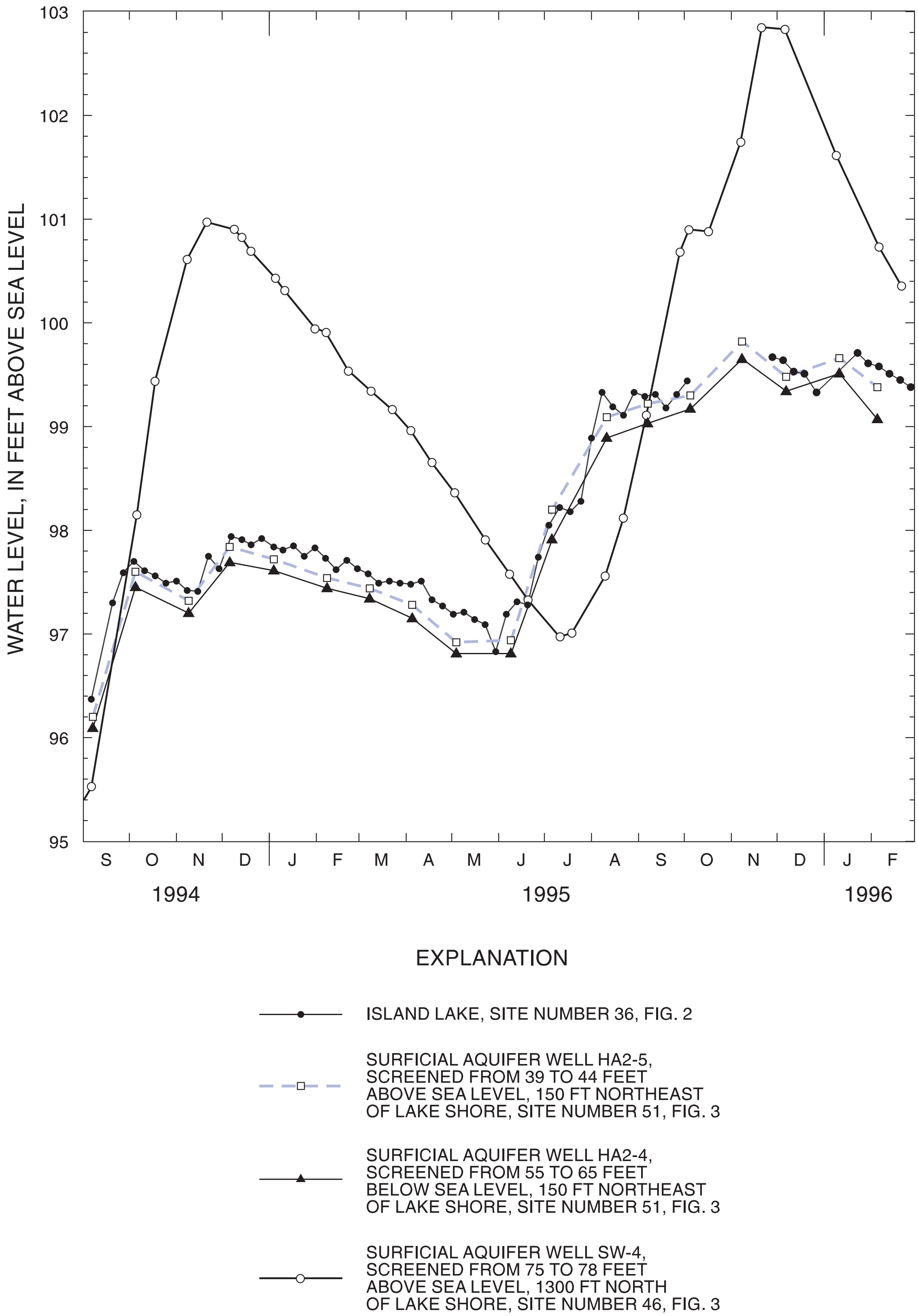


Figure 16. Water levels in Island Lake and nearby surficial aquifer system monitoring wells, September 1994 through February 1996.

As a result of the karst topography, much of the study area is internally drained, especially along the Lake Wales Ridge. Therefore, nearly all of the well-developed streams are within the Lake Upland and Osceola Plain physiographic regions. Whittenhorse, Cypress, Bonnet, and Reedy Creeks are part of the headwaters of the Kissimmee River; and Big Creek, Little Creek, and the Palatlakaha River are part of the headwaters of the Ocklawaha River (fig. 15). Annual 1995 stream discharge was calculated for each major stream flowing across a model boundary (table 3). The net annual average 1995 stream discharge out of the model area was approximately 5.4 in/yr.

Stream discharge is greatly influenced by surficial aquifer system water levels and rainfall (fig. 12). As rainfall increases in frequency and intensity during the summer, stream discharge and shallow water levels increase accordingly. The greater rainfall increases the amount of overland runoff to streams as indicated by sharp, discharge hydrograph peaks. If a hypothetical stream discharge hydrograph were compiled with these peaks removed, it would look similar in shape to the hydrographs of wells EW11-4 and SW-16 in the shallow surficial aquifer system (fig. 12). This represents the base-flow contribution of this system to stream discharge.

There are few streams or wetlands near reclaimed-water application sites, with the exception of the RCID RIB site. This site is surrounded by wetlands to the west, northeast, and east; Whittenhorse Creek to the south; and the RCID Perimeter and C-4 Canals to the east (fig. 15). Chloride concentrations have increased significantly in Whittenhorse Creek since the start of RCID RIB operation, even as discharge appears to have increased slightly (fig. 17). Typical chloride concentration of RCID reclaimed water is approximately 100 mg/L (J. Hubbard, Reedy Creek Energy Services, Inc., oral commun., 1993). A plot of chloride concentration and daily discharge indicates that water samples taken at periods of low flow (that is, when discharge was assumed to be primarily base flow) had significantly greater chloride concentration after RIB operation began than before (fig. 17). No other significant changes in land use have taken place in the stream basin since 1990; therefore, some reclaimed water probably discharges from the surficial aquifer system to Whittenhorse Creek and Bear Bay (an area of wetlands immediately to the west of the RCID RIB site that drains into Whittenhorse Creek, fig. 15).

Chloride concentration also has increased significantly in the Perimeter Canal, which runs along much of the eastern boundary of the RCID RIB site (fig. 15). Water samples collected from the canal and analyzed by RCID since 1980 (near site 52, fig. 2) show an abrupt increase in chloride concentration of approximately 25 mg/L from October 1991 to January 1992. The minimum, maximum, and average chloride concentrations were 10, 28, and 19 mg/L, respectively, for the period 1980-91 and 33, 89, and 57 mg/L, respectively, for the period 1992-96. Therefore, reclaimed water probably discharges from the surficial aquifer system to the Perimeter Canal.

Water Budget

A water budget for the surficial aquifer system within the model area was used to estimate leakage to the Floridan aquifer system. The water budget was compiled for the 1995 calendar year (fig. 18) using the following equations:

$$P + R_a - ET - L_f - Q = \Delta S, \qquad (1)$$

$$\Delta S = S_y \, \Delta H_s, \qquad (2)$$

where

- P is precipitation, [L/T];
- R_a is artificial recharge, [L/T], which is the sum of RIB recharge (R_{RIB}), reclaimed-water irrigation and AAS recharge (R_{ri}), and nonreclaimed-water irrigation (R_{nri});
- L_f is net leakage between the surficial and Floridan aquifer systems, [L/T];
- Q is stream discharge, [L/T], which is the sum of surface runoff (Q_S), and base flow (Q_B);
- ET is evapotranspiration, [L/T];
- ΔS is change in storage in the surficial aquifer system, [L/T];
- S_y is specific yield of the surficial aquifer system, [dimensionless]; and
- ΔH_s is time rate of change of the water level in the surficial aquifer system, [L/T].

All components of the water budget were based on measured or estimated data with the exception of leakage to the Floridan aquifer system, which was set equal to the value required to balance the water budget. Flow crossing model boundaries was assumed to be negligible because, as previously explained, there probably is little lateral flow in the surficial aquifer system. P was calculated as an average of data collected at eight rain gages

Table 3. Average annual stream discharge into and out of model area, 1995

[Sites are located by site numbers in figure 2. ft^3/s, cubic foot per second; in/yr, inch per year averaged over model area. Abbreviation for flow direction: I, stream flows into model area; O, stream flows out of model area]

Site number	Station number	Station name	Flow direction	Gaged discharge (ft^3/s)	Estimated discharge crossing model boundary	
					ft^3/s	in/yr
74	02236350	Green Swamp Run near Eva	I	21.5	21.5	1.0
56	02264000	Cypress Creek at Vineland	I	13.5	7.5[1]	.4
73	02236900	Palatlakaha River at Cherry Lake outlet near Groveland	O	24.5	24.5	1.2
61	02264100	Bonnet Creek near Vineland	O	44.7	44.7	2.1
62	02266300	Reedy Creek near Vineland	O	74.3	74.3	3.5

[1]Approximately 55 percent of stream basin lies outside model area.

(fig. 6). R_a was based on measured values for R_{RIB} and R_{ri} and an estimated value for R_{nri}. R_{nri} was assumed to only consist of citrus grove irrigation water that was pumped from the Upper Floridan aquifer. An irrigation rate of 9.3 in/yr was calculated from measured data for other citrus groves in Lake, Orange, and Polk Counties (citrus irrigation rate data provided by V. Singleton, St. Johns River Water Management District, written commun., 1996). Q was based on measured discharge of streams crossing model boundaries (table 3). Measured data indicated that there was a change in surficial aquifer system storage for 1995. That is, a rise in the water table for 1995 represented an increase in water stored in the pore spaces of the surficial aquifer system; similarly, a drop in the water table represented a decrease in storage. ΔH_s was interpolated from point values of net change in water level measured at wells and lakes yielding an average value representing a rise of 0.39 ft in 1995. A uniform value of 0.35 was used for S_y throughout the model area (including lakes and wetlands). Because no data were available on S_y in the model area, S_y was estimated based on reported values of the total porosity of surficial sediments of 0.36 to 0.51 (Camp Dresser and McKee, Inc., 1984; Sumner and Bradner, 1996) minus a specific retention of poorly graded surficial sand of 0.06 cm^3/cm^3 (Sumner and Bradner, 1996). ET was evaluated in detail because it is the largest loss in the water budget and one of the most difficult to estimate accurately. In addition, ET is an important process in determining the fraction of P and R_a that reaches the water table to recharge the surficial aquifer system.

In order to more accurately estimate the spatial variability of ET, the study area was divided into five regions having similar ET characteristics (fig. 19 and table 4). These regions were defined considering both the characteristics of the local vegetation and the amount of water available to that vegetation. Areas considered to have a sufficient supply of water to meet the needs of the local vegetation (regions 1 and 2) were assigned maximum ET rates characteristic of that vegetation. Lowland areas (region 1) were defined where the water table was 5 ft or less below land surface, which included lakes and wetlands. Depth to the water table below land surface was estimated based on measured surficial aquifer system water levels and a digital elevation model interpolated from 5-ft topographic contours from USGS 7.5-minute quadrangles. Cultivated citrus groves (region 2) were located by field reconnaissance. Regions 3, 4, and 5 (also located by field reconnaissance) were assumed to be moisture deficient for a significant part of the year as a result of having a deep water table (greater than 5 ft below land surface) and not being irrigated. In addition, the sandy, rapidly drained soils typical in the study area often do not provide a residual moisture content great enough to prevent plant moisture stress.

Table 4. Characteristics of evapotranspiration regions delineated in figure 19

[≤, less than or equal to; >, greater than]

Region number	Dominant land cover	Fraction of model area	Depth to water table, in feet	Average 1995 evapotranspiration, in inches
1	Lake, wetland, and various vegetation	0.55	≤ 5	47
2	Cultivated citrus	.03	> 5	45
3	Upland woodland, primarily oaks and pines	.01	> 5	38
4	Uncultivated citrus	.01	> 5	36
5	Herbaceous vegetation	.40	> 5	27

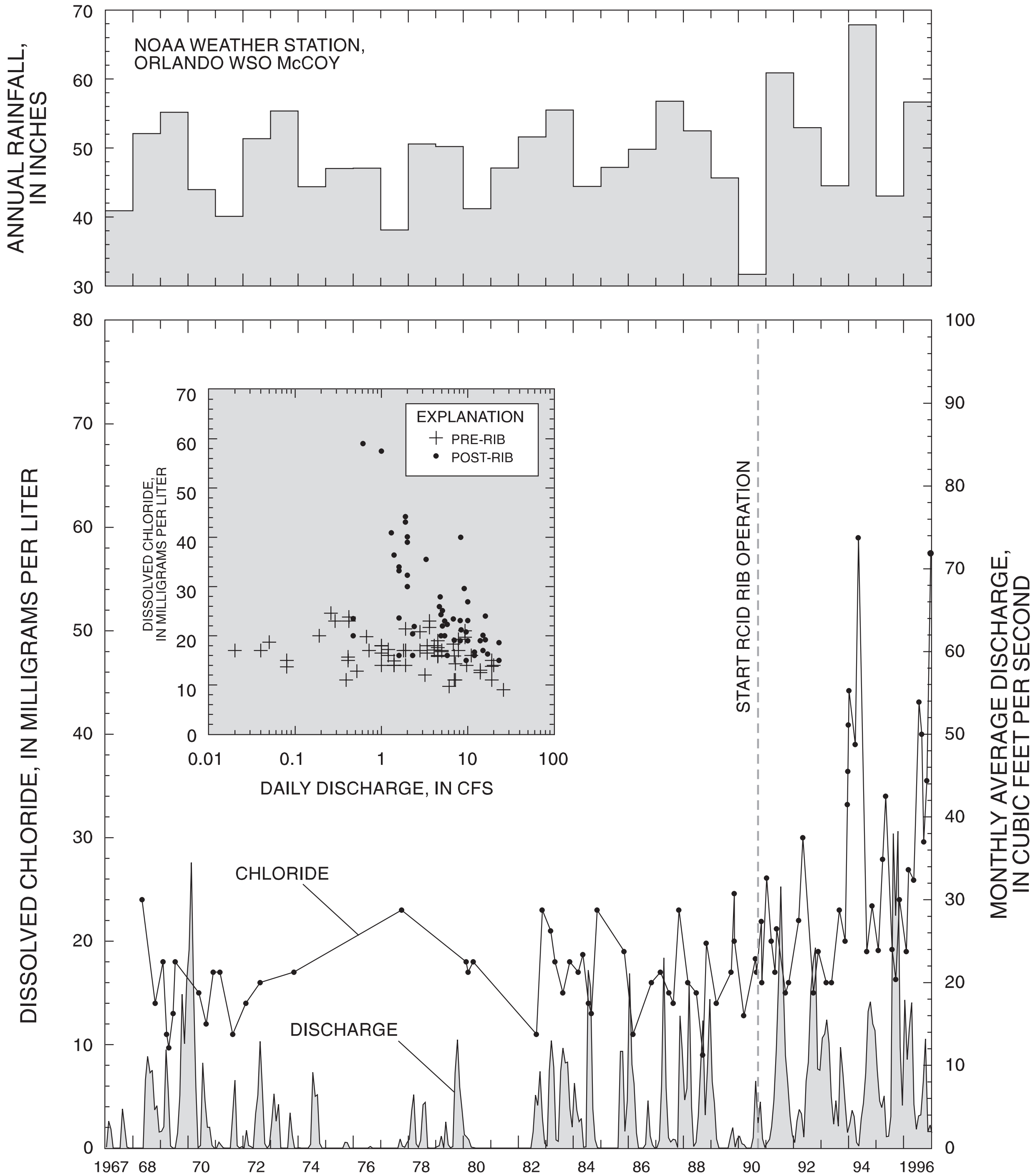


Figure 17. Discharge and chloride concentrations in water sampled from Whittenhorse Creek (site number 57, fig. 2), January 1967 through January 1997.

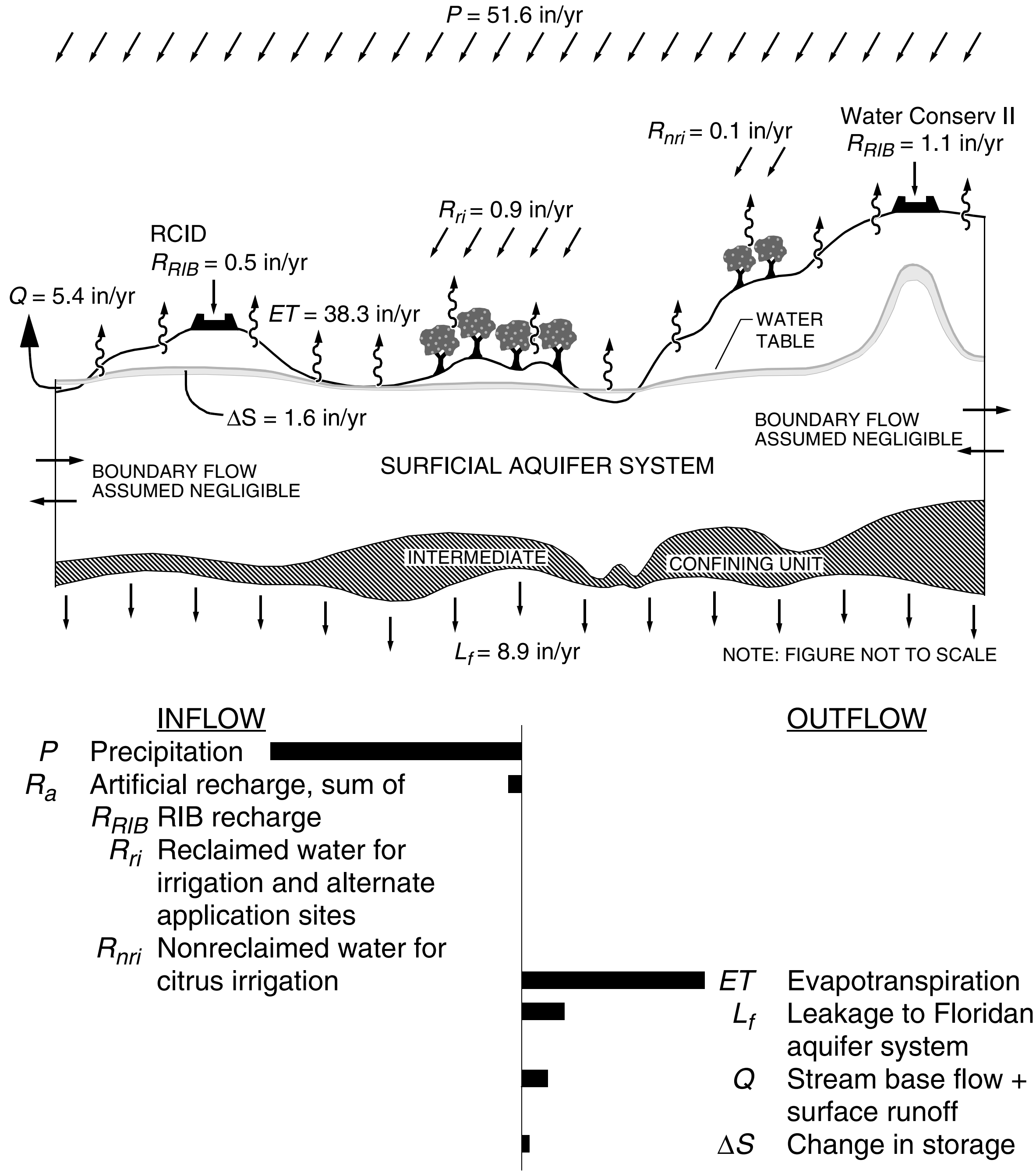


Figure 18. Hydrologic budget of the surficial aquifer system within the model area, 1995. All values are fluxes averaged over the model area.

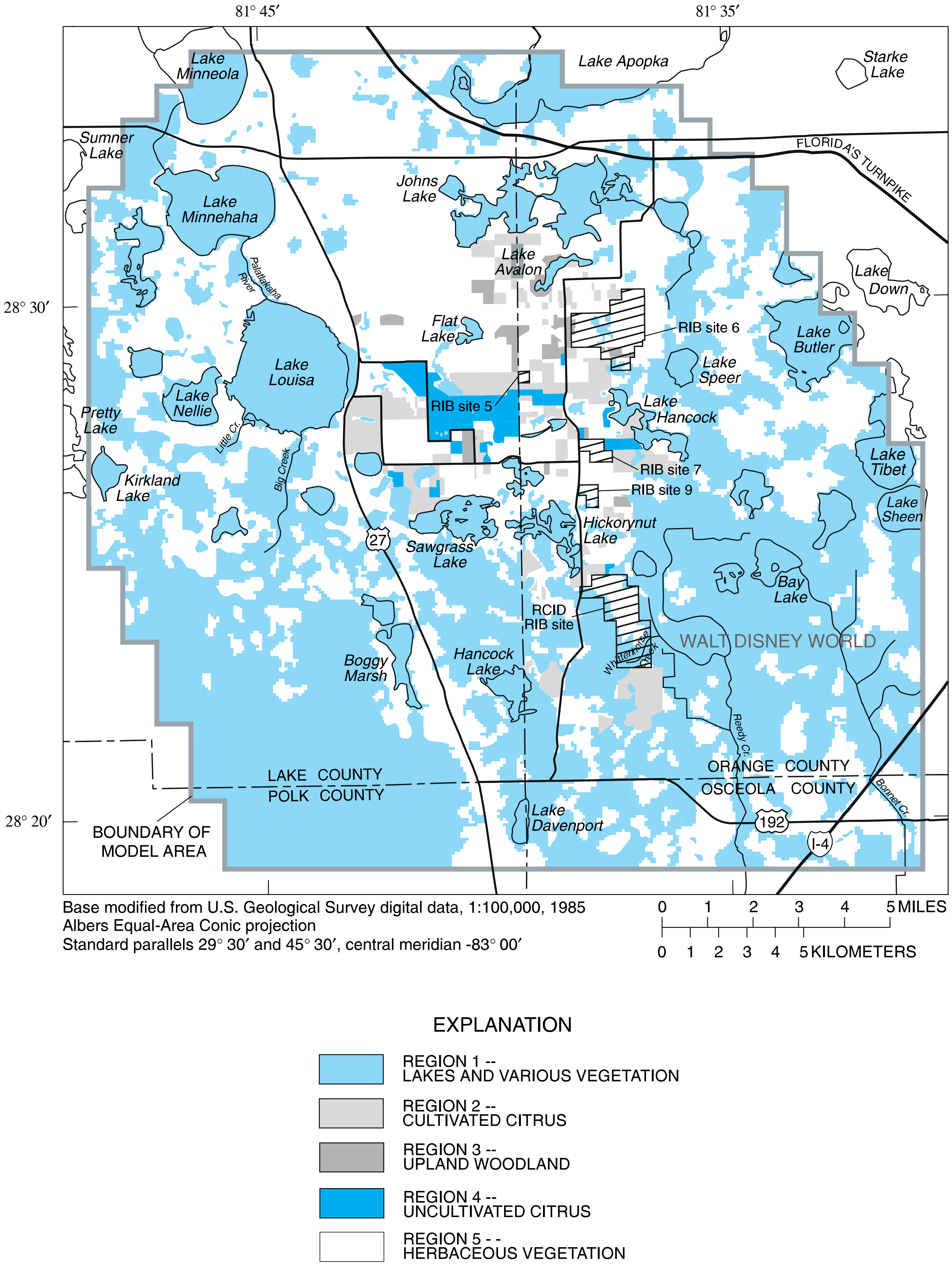


Figure 19. Distribution of evapotranspiration regions in the model area.

Fetter (1988) indicated that 0.05 cm^3/cm^3 is a typical wilting point moisture content for sand. Sumner and Bradner (1996) reported a residual moisture content of 0.06 cm^3/cm^3 for a poorly graded sand at the RCID RIB site. At a site near Water Conserv II RIB site 6, Sumner (1996) reported moisture content in the upper 1-ft rooting zone of herbaceous vegetation can be as low as 0.02 cm^3/cm^3 during dry periods and often drops rapidly to below 0.05 cm^3/cm^3 after summer rainfall events.

ET was quantified for each region based on a combination of field data and literature values. Using data collected at the Class A pan evaporation station, monthly average free-water surface evaporation (assumed equal to lake evaporation and used for region 1) was calculated using the following equation from Kohler and others (1955):

$$E_{fws} = 0.7[E_p + 0.00051P\alpha_p(0.37 + 0.0041U_p)\,(T_0 - T_a)^{0.88}]\,, \quad (3)$$

where

E_{fws} is free-water surface evaporation, in inches per day;
E_p is pan evaporation, in inches per day;
P is barometric pressure, in inches of mercury;
α_p is ratio of advected energy used in evaporation to total energy advected from the pan, [dimensionless];
U_p is wind movement over pan measured 6 in. above rim of pan, in miles per day;
T_0 is average pan water temperature, in degrees Fahrenheit; and
T_a is average air temperature, in degrees Fahrenheit.

Free-water surface evaporation is the maximum rate of evaporation from a shallow water body that does not store an appreciable amount of heat. Lake evaporation may be assumed to be equal to free-water surface evaporation if energy advected into the lake is equal to a corresponding change in energy storage and the pan exposure is similar to that of the lake. Based on data collected at Lake Lucerne in Polk County, Lee and Swancar (1997) reported that annual E_{fws} was about 6 percent less than annual evaporation calculated from an energy budget analysis and it might be a reasonable predictor of actual lake evaporation for periods of at least a month. The climatological and hydrologic variables affecting Lake Lucerne are probably similar to those in the study area. Barometric pressure was assumed to be constant at 30.11 inches of mercury (1995 annual mean as measured at the NOAA Orlando WSO McCoy weather station). The ratio α_p was taken from a plot of α_p in relation to pan water temperature and daily wind movement (Kohler and others, 1955, fig. 5). For comparison to previous studies, monthly pan coefficients (k_p) were also calculated:

$$k_p = \frac{E_{fws}}{E_p}\,. \quad (4)$$

Farnsworth and others (1982) determined a k_p for central Florida for the period May through October to be 0.75; Lee and Swancar (1997) reported an average k_p of 0.73 for a 1-year period starting October 1985 at Lake Lucerne. These compare well with the calculated values of 0.72 to 0.75 obtained during this study.

Cultivated citrus ET was estimated based on E_{fws} as calculated above and monthly crop coefficients reported by Rogers and others (1983) for well-irrigated citrus with grass cover:

$$ET_{cit} = k_c E_{fws}\,, \quad (5)$$

where

ET_{cit} is citrus evapotranspiration, [L/T]; and
k_c is crop coefficient, [dimensionless].

Sumner (1996) reported daily ET for nonirrigated, herbaceous vegetation in a deforested area near Water Conserv II RIB site 6 for the 1-year period starting September 15, 1993. The daily data were based on a model calibrated to micrometeorological measurements of ET. Monthly average ET was estimated from data reported by Sumner (1996) and used as estimates of herbaceous vegetation ET (ET_{hbv}) for region 5.

ET for region 3 (upland woodland) and region 4 (uncultivated citrus) is not well known. Upland woodland ET probably is somewhat greater than that of uncultivated citrus as a result of a deeper root system and the typically poor condition of the uncultivated citrus. ET rates for both these regions were assumed to fall between those values for citrus and nonirrigated, herbaceous vegetation:

$$ET_{ucc} = 0.5(ET_{cit} - ET_{hbv}) + ET_{hbv}\,, \quad (6)$$

$$ET_{upw} = 0.6(ET_{cit} - ET_{hbv}) + ET_{hbv}\,, \quad (7)$$

where

ET_{ucc} is uncultivated citrus evapotranspiration, [L/T]; and
ET_{upw} is upland woodland evapotranspiration, [L/T].

ET as calculated above has been summarized for 1995 in table 5 and figure 20. The January 1995 value of E_{fws} was assumed equal to that measured in January 1996. As expected during the wet period of June through October, all ET values were nearer E_{fws} than during drier months.

The uncertainty associated with ET data depends on the method used to collect and analyze the data. Sumner (1996) reported an error of ±10 percent among three models calibrated to ET measured with micrometeorological methods; the pan evaporation method has a typical error of ±15 percent, depending on pan location (Doorenbos and Pruitt, 1977). Error may also be introduced in the application of these data to an inappropriate area. As described earlier, ET varies with plant growth characteristics and water availability; therefore, incorrect estimation of these can be another source of error.

Based on the data discussed above and application of equations 1 and 2, leakage to the Floridan aquifer system was 8.9 in/yr in 1995 (fig. 18). It was the second largest outflow from the surficial aquifer system and represented about 16 percent of the total flow through the hydrologic system. Leakage between the surficial and Floridan aquifer systems is variable and depends upon the thickness and vertical hydraulic conductivity of the intermediate confining unit and the head difference between the two aquifer systems.

DESCRIPTION OF MODEL

The conceptual model and hydrologic data discussed in the previous section were used to construct a numerical ground-water flow model of the surficial and Floridan aquifer systems. The model simulates steady-state, ground-water flow as affected by both current (average 1995) and proposed future reclaimed-water application conditions. Particle-tracking analyses were used to identify rates and directions of reclaimed water movement as well as to locate points where reclaimed water might exit the ground-water system.

The USGS three-dimensional ground-water flow model code MODFLOW (McDonald and Harbaugh, 1988) was used to simulate the flow system. MODFLOW uses a set of simultaneous finite-difference equations to approximate the partial differential equation that describes the response of ground-water flow to hydrologic stresses and boundary conditions. This requires vertical and horizontal discretization of the total model volume into cells delineated by layers, rows, and columns. Therefore, values of aquifer and confining-unit hydraulic properties and hydrologic stresses can be assigned to the center of each cell, defined as a node.

Table 5. Monthly average pan evaporation, evapotranspiration, pan coefficients, and citrus crop coefficients during 1995

[in/d, inch per day; E_p, pan evaporation; k_p, pan coefficient; E_{fws}, free-water surface evaporation; k_c, citrus crop coefficient; ET_{cit}, cultivated citrus evapotranspiration; ET_{upw}, upland woodland evapotranspiration; ET_{ucc}, uncultivated citrus evapotranspiration. k_c from data reported by Rogers and others (1983)]

Month	E_p (in/d)	k_p	E_{fws} (in/d)	k_c	ET_{cit} (in/d)	ET_{upw} (in/d)	ET_{ucc} (in/d)
January[1]	0.128	0.74	0.095	0.90	0.086	0.061	0.055
February	.152	.75	.114	.90	.103	.074	.067
March	.188	.74	.139	.90	.125	.095	.088
April	.222	.73	.162	.90	.146	.118	.112
May	.299	.72	.215	.95	.204	.163	.153
June	.209	.73	.153	1.00	.153	.139	.136
July	.237	.73	.172	1.00	.172	.153	.148
August	.157	.74	.116	1.00	.116	.116	.116
September	.138	.74	.102	1.00	.102	.099	.099
October	.121	.74	.089	1.00	.089	.081	.079
November	.138	.74	.102	1.00	.102	.079	.073
December	.098	.75	.073	1.00	.073	.055	.050

[1]Data for January 1995 assumed equal to that measured in January 1996.

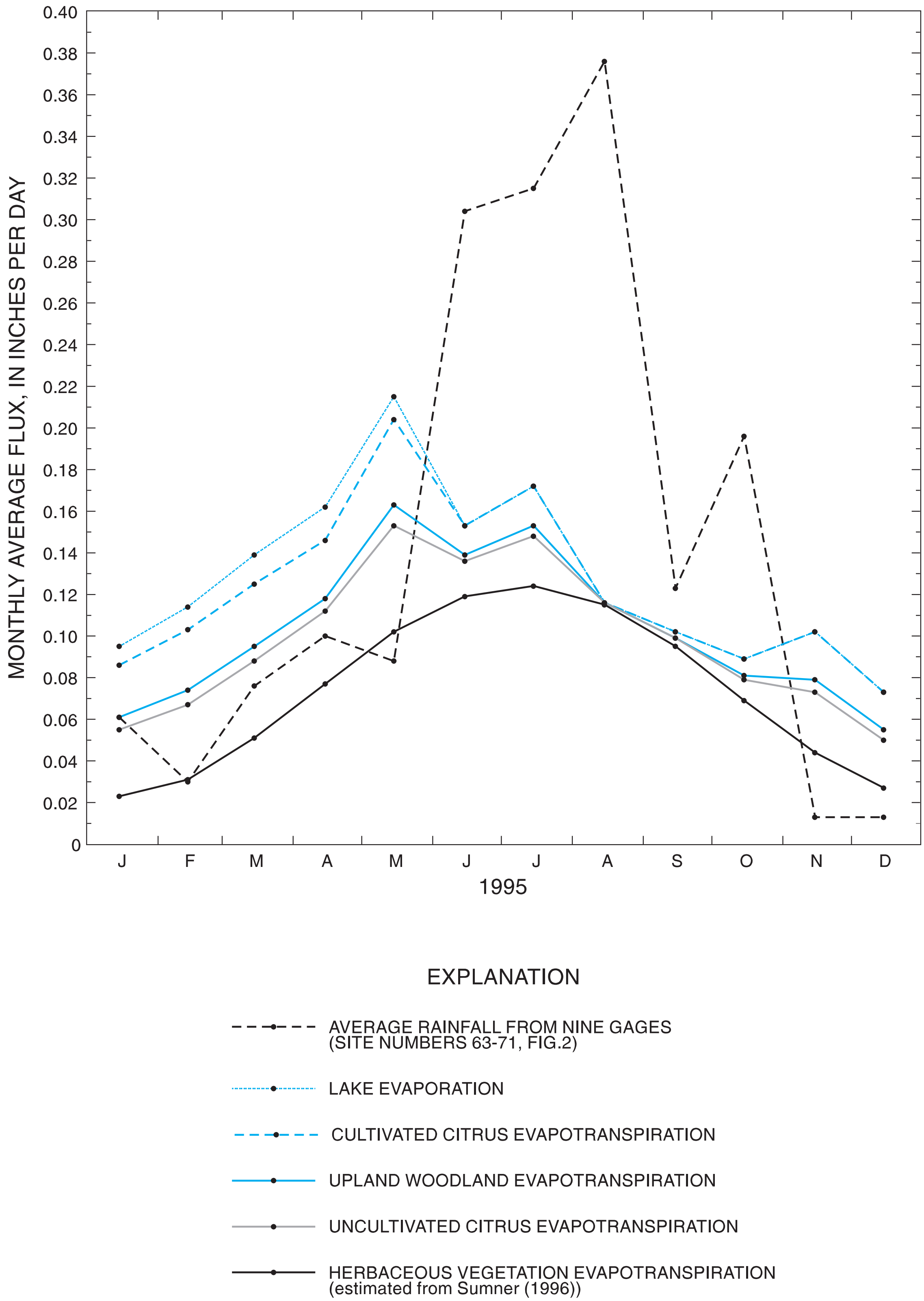


Figure 20. Rainfall and estimated rates of evapotranspiration in the study area, 1995.

Ground-water flow was simulated by the model by using three layers to represent the surficial, Upper Floridan, and Lower Floridan aquifers (fig. 7). The resistance to flow between adjacent layers was assumed to be controlled by the leakance of the intervening intermediate confining unit or middle semiconfining unit (fig. 7). The leakance is calculated as the harmonic mean of the vertical hydraulic conductivities of the aquifer or confining unit material between nodes (weighted by aquifer or confining unit thickness between nodes) divided by the vertical distance between corresponding nodes in adjacent model layers. The large contrast in hydraulic conductivity between the confining units and adjacent aquifers, typically at least 100 times less in the confining unit, indicates that the flow is nearly vertical in the confining units. Therefore, the confining units were simulated using leakance values, not as separate layers. The model implicitly assumed vertically isotropic conditions, because each aquifer was simulated by only one layer. Because of the absence of any hydrologic data concerning the middle semiconfining unit and Lower Floridan aquifer in the model area, it might be more appropriate to consider these units collectively as representing a leaky lower boundary condition.

Horizontal discretization of each layer consisted of 79 rows and 57 columns with variable cell sizes ranging from 656 by 656 ft to 3,936 by 3,936 ft (fig. 21). Smaller cells were used in areas of interest with significant stresses, such as RIB sites; larger cells were used in areas of less interest and relatively small hydrologic stresses, such as near model boundaries. Of the 13,509 cells, 12,996 were active and represented an area of approximately 285 mi^2.

Boundary Conditions

Vertical and lateral boundaries were chosen where possible to coincide with physical hydrologic barriers. The upper boundary condition, located at the water table, was a specified flux represented by an effective recharge array that is described in more detail in the following section. The very low permeability sub-Floridan confining unit served as the no-flow lower boundary condition (fig. 7). Lateral boundaries for all three layers were coincident but varied in type. These boundaries were located far enough away from reclaimed-water application areas so as to minimize their effects in these areas. Lateral boundaries generally coincided with a topographic low or lake where a local minimum in the water table would most likely exist. Therefore, in the surficial aquifer system a no-flow condition was specified along all lateral boundaries (fig. 22). This condition is especially appropriate because lateral movement of ground water in the surficial aquifer system typically is minimal, except in very localized flow systems. In the Upper Floridan aquifer, a no-flow condition was established where potentiometric contour lines (fig. 13) were perpendicular to model boundaries; a specified head condition was applied elsewhere (fig. 23). Specified- head values were interpolated from an arithmetic average of Upper Floridan aquifer water-level data measured during 1995 (fig. 13). Lower Floridan aquifer lateral boundary conditions were assumed identical to those of the Upper Floridan aquifer. Specified-head values were set uniformly 0.75 ft below those used for the overlying Upper Floridan aquifer boundary, based on an average of previously described data collected outside the study area.

Internal boundaries were established at streams, wetlands, lakes, and Apopka Spring, because MODFLOW does not simulate surface-water flow (figs. 22 and 23). Streams and wetlands were modeled with the MODFLOW River and Drain Packages, as described in more detail in the following section. Lakes affected by stream inflow or outflow were represented by specified-head cells. Specified-head values were based on measured lake-level data where available (fig. 2), otherwise values were estimated from USGS 7.5-minute topographic quadrangles. Lake-level data estimated from topographic maps were adjusted to reflect trends indicated by measured data in nearby lakes. Landlocked lakes (lakes lacking stream inflow or outflow) were simulated as variable-head cells. In order to effectively represent the absence of aquifer materials in these lakes, the hydraulic conductivity was specified at 1,000 times that of the surrounding aquifer. Even though landlocked lakes are surface-water features, MODFLOW was able to simulate them because of the lack of surface-water flow. The upper boundary condition of specified effective recharge accounted for the effects of precipitation and evaporation, and the variable-head cells allowed the simulation of ground-water flow into or out of the lake. Apopka Spring was simulated by the Well Package (fig. 23). Discharge at Apopka Spring varies considerably depending upon the head difference between the potentiometric surface of the Upper Floridan aquifer and the stage of Lake Apopka. No discharge data were available during the study;

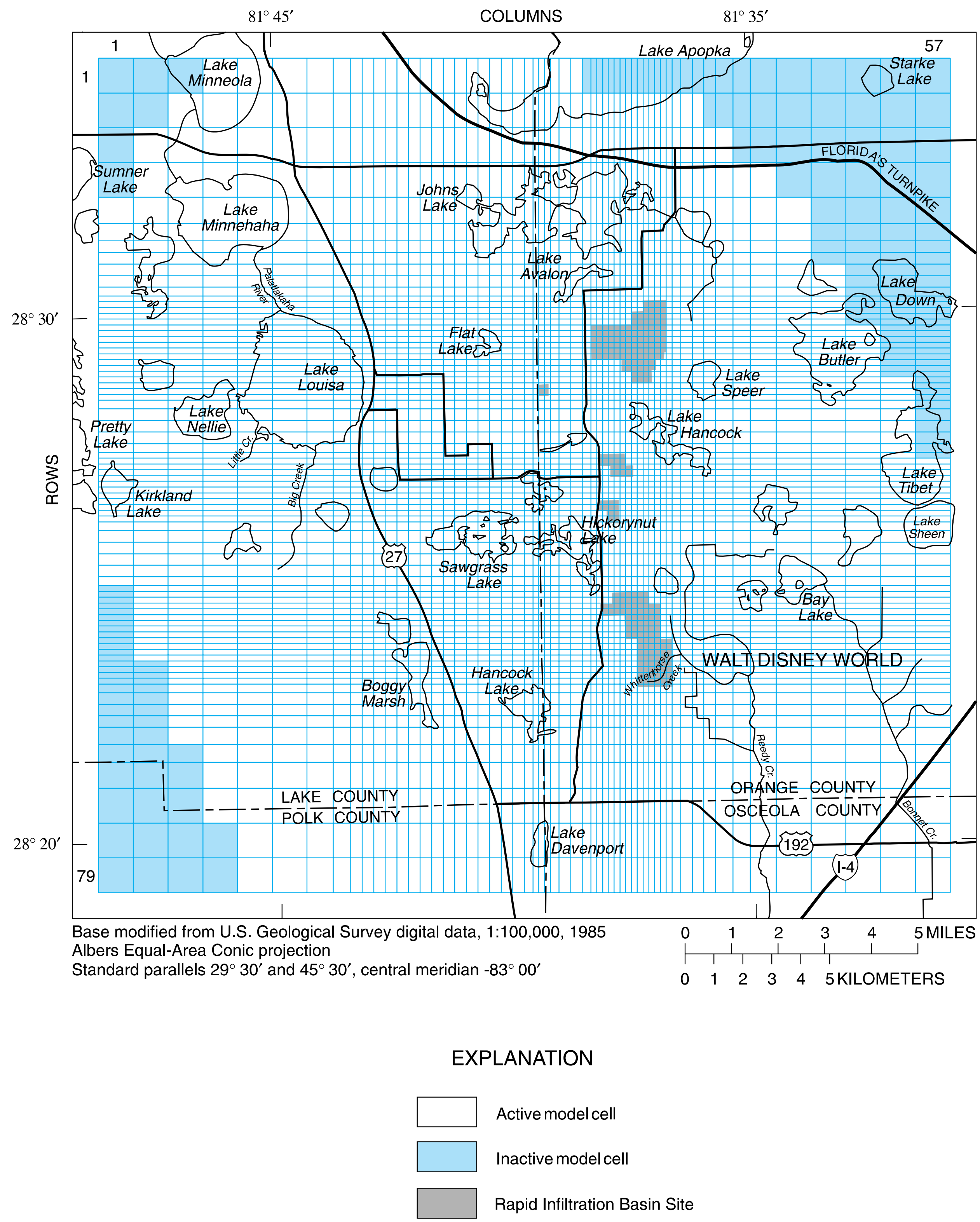
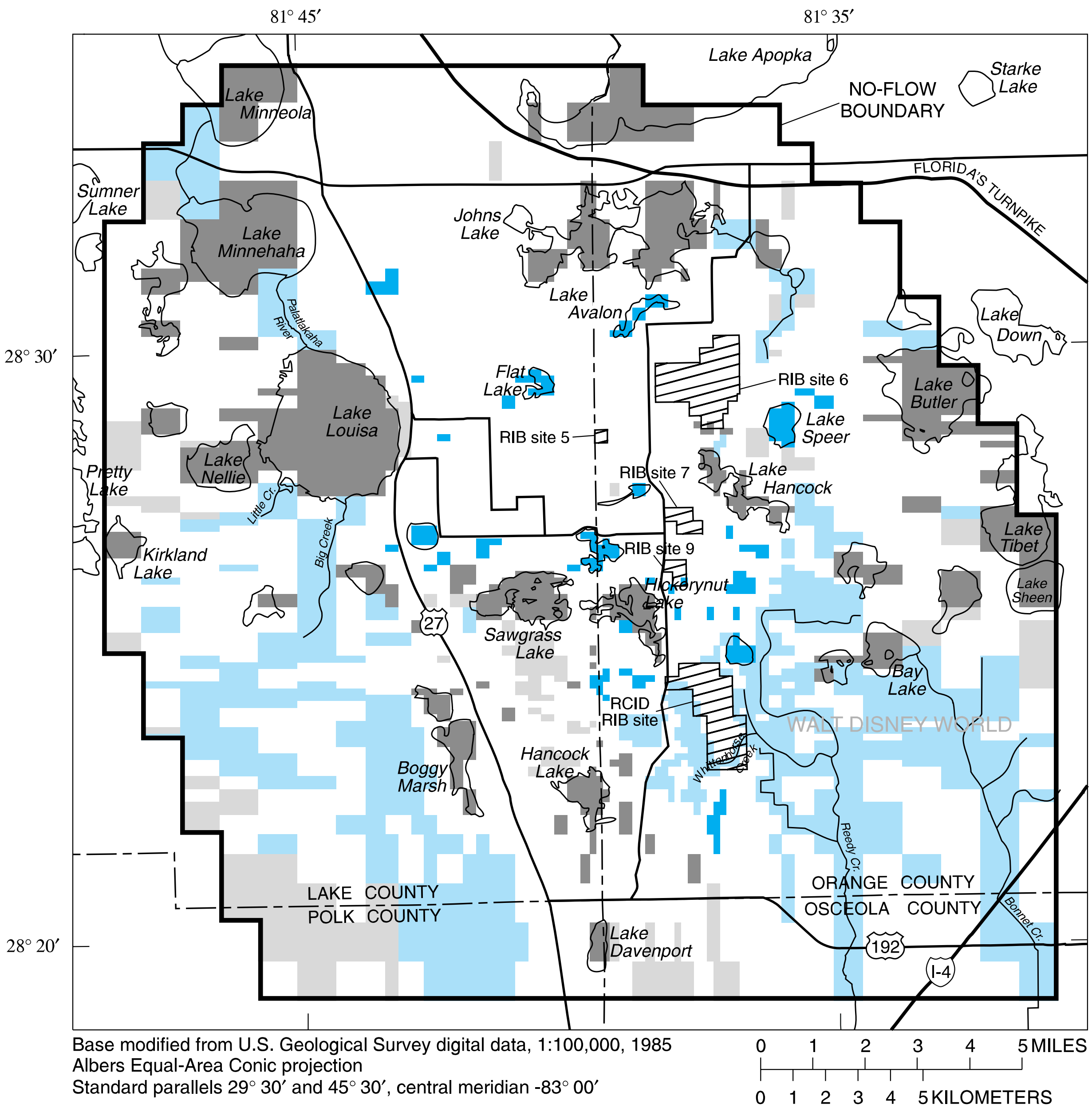


Figure 21. Finite-difference grid showing active and inactive model cells in each layer.



EXPLANATION

BOUNDARY CONDITIONS

- Cell representing a wetland which drains to a key gaging station and/or a stream. Simulated by the MODFLOW River Package
- Cell representing a wetland which does not drain to key gaging station. Simulated by the MODFLOW Drain Package
- Cell representing a landlocked lake. Simulated by a variable-head cell with very high hydraulic conductivity
- Cell representing a lake affected by surface-water inflow and/or outflow. Represented by a specified-head cell

Figure 22. Boundary conditions for the surficial aquifer system (model layer 1).

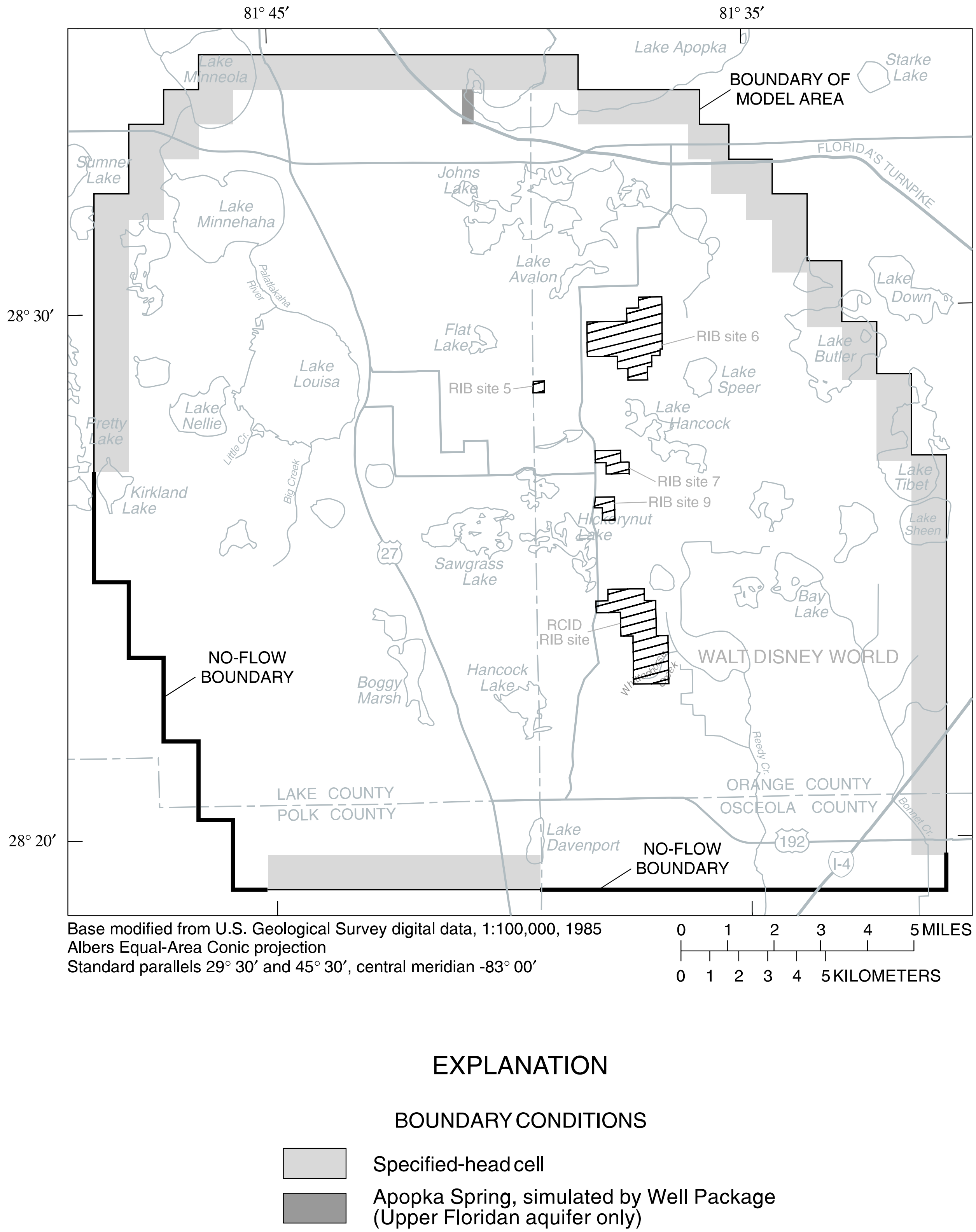


Figure 23. Boundary conditions for the Upper and Lower Floridan aquifers (model layers 2 and 3, respectively).

therefore, discharge was estimated based on historical head difference and discharge data. The head difference between the potentiometric surface of the Upper Floridan aquifer (measured at site 4, fig. 3) and the stage of Lake Apopka was approximately 8.1 ft in 1995. Data collected during 1988 indicated a discharge of approximately 42 Mgal/d (65 ft^3/s) and a head difference of about 8 ft. Apopka Spring was simulated by an Upper Floridan aquifer well discharging 42 Mgal/d at the spring location.

All specified-head cells were simulated by the MODFLOW Time-Variant Specified-Head Package (Leake and Prudic, 1991). Starting head values were set equal to ending head values to comply with the steady-state assumption used in the model.

Hydrologic Input Data

Aquifer and confining unit properties and hydrologic stresses were initially estimated for calibration of a steady-state model to simulate average 1995 conditions. Average annual 1995 values of time-variant data (specified-head values, effective recharge, stream stage, and well pumpage) were calculated as an arithmetic average of data collected monthly or more frequently.

Aquifer and Confining Unit Properties

Aquifer properties required for calibration of the model included hydraulic conductivity and base altitude of the surficial aquifer system, transmissivity of both the Upper and Lower Floridan aquifers, and lateral anisotropy of all three aquifers. All cells in the surficial aquifer system initially were assigned a hydraulic conductivity value of 50 ft/d with the exception of cells representing landlocked lakes, which were assigned a value of 50,000 ft/d. Surficial aquifer system base altitude was established at the top of the intermediate confining unit and interpolated from measured point values (fig. 9). Using these data, MODFLOW calculated surficial aquifer system transmissivity as the difference between the altitudes of the simulated water table and aquifer base multiplied by hydraulic conductivity. Model-calibrated values of transmissivity for both the Upper and Lower Floridan aquifers reported by Murray and Halford (1996) were used as initial estimates for these parameters. Approximately the western one-fifth of the model area was outside of the area modeled by Murray and Halford (1996); transmissivity values for these cells were extrapolated by continuing the trend of adjacent cells. The transmissivity of the Lower Floridan aquifer was not changed from its initial values (fig. 24) during model calibration, because no field data exist on the hydrologic properties of the Lower Floridan aquifer in the model area. All three aquifers were assigned a lateral anisotropy of 1; that is, aquifer hydraulic properties were assumed to be equal in the model row and column directions. No data exist within the model area on lateral anisotropy, and the assumption of isotropic conditions is consistent with previous models (Grubb and Rutledge, 1979; Camp Dresser and McKee, Inc., 1984; Planert and Aucott, 1985; Tibbals, 1990; CH2M Hill, 1993; Murray and Halford, 1996)

Leakance values were required for the intermediate confining unit and the middle semiconfining unit. A uniform leakance of 1×10^{-4} (ft/d)/ft was used as an initial value for the intermediate confining unit (approximate average of values from Murray and Halford (1996)). Middle semiconfining unit leakance was assigned a uniform value of 5×10^{-5} (ft/d)/ft (Tibbals, 1990; Murray and Halford, 1996).

Recharge to the Surficial Aquifer System

The surficial aquifer system is recharged when sufficient water is applied to overcome evapotranspirative losses and capillary effects in the unsaturated zone and remaining water percolates across the water table. When precipitation or artificial recharge rates exceed the infiltration capacity of the soil, some water continues to move downward while excess water is rejected and becomes surface runoff. Of the water that crosses the water table, recharge is the fraction not immediately extracted by ET and that moves downgradient. In addition, water released from storage in the surficial aquifer system pore spaces as a result of a falling water table can be mathematically represented as a flux occurring over the time period during which the drop in water table was measured. Considering all these factors, except surface runoff, surficial aquifer system recharge was simulated as an effective recharge. Surface runoff was assumed to be negligibly small because of the karst environment and highly permeable surficial sand characteristic in the model area. Surface runoff may be significant where the water table is near land surface, such as wetlands, as will be addressed in a later section. Effective recharge (N) represented the net

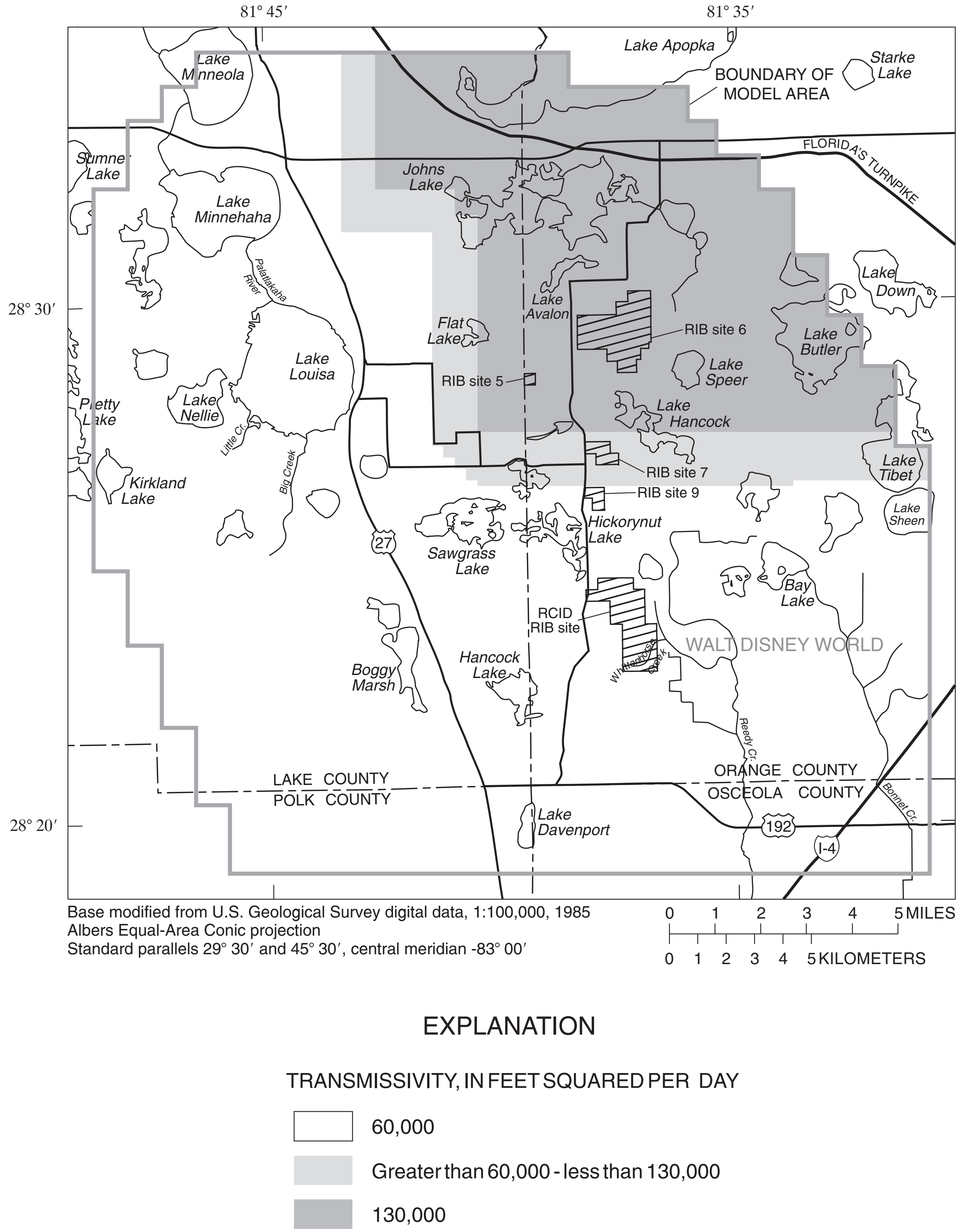


Figure 24. Transmissivity of the Lower Floridan aquifer specified in the model.

effects of precipitation, artificial recharge, evapotranspiration, and change in surficial aquifer system storage as described by

$$N = P + R_a - ET - \Delta S, \quad (8)$$

The components of N in equation 8 are identical to those defined for equations 1 and 2 for the surficial aquifer system water budget and were calculated as previously explained. However, equation 8 was applied at every active model cell; therefore, N consisted of an array of values that varied spatially. P was assumed to be a uniform value (fig. 18). The array of values used for R_a are shown in figure 25. ET was based on area-weighted averages of data from figure 19 and table 4. Because steady-state conditions assume zero change in aquifer storage, a correction was made to account for the change in surficial aquifer system storage measured in 1995 by reducing the estimated recharge by ΔS where there was a rise in the water table and increasing the estimated recharge by ΔS where there was a drop in water table. Conceptually, this representation of ΔS can be interpreted as follows: (1) an increase in storage is equivalent to a reduction in recharge, because a rise in water-table altitude is produced by recharge that otherwise would have been available to move downgradient; or (2) a decrease in storage is equivalent to an increase in recharge, because a drop in water-table altitude releases water that otherwise would not have been available to move downgradient. Because of the small storage coefficients typical of confined aquifers, the change in storage in the Floridan aquifer system during 1995 was assumed negligible; therefore, a correction for storage changes was not made for the Upper and Lower Floridan aquifers.

Effective recharge was calculated exterior to MODFLOW and input to the model using the MODFLOW Well and Recharge Packages. At artificial recharge sites the subcomponent of effective recharge, ($P+R_a-ET$), was simulated by the Well Package by specifying surficial aquifer system wells injecting a volume rate of water equal to the product of ($P+R_a-ET$) and recharge site area (RIB bottom area or irrigated area). ΔS at artificial recharge sites and N in all other areas not containing artificial recharge sites were simulated by the Recharge Package as a flux array. Figure 26 shows the effective recharge rates specified in the model.

Stream Leakage

Leakage of water from the surficial aquifer system to streams, or from streams to the aquifer, was simulated by the MODFLOW River Package (fig. 22). Flow between the aquifer and the stream is controlled by the conductance of the streambed and the hydraulic gradient between stream stage and aquifer head. Streambed conductance was based on a streambed material hydraulic conductivity of 10 ft/d, total stream length in the model cell, streambed width measured during discharge measurements, and streambed thickness of 1 ft. Using these values yields a streambed conductance of such magnitude that the hydraulic conductivity of the adjacent surficial aquifer system primarily controls stream leakage. Values of stream stage and stream bottom altitude were assigned by linear interpolation based on measured values at gaging stations.

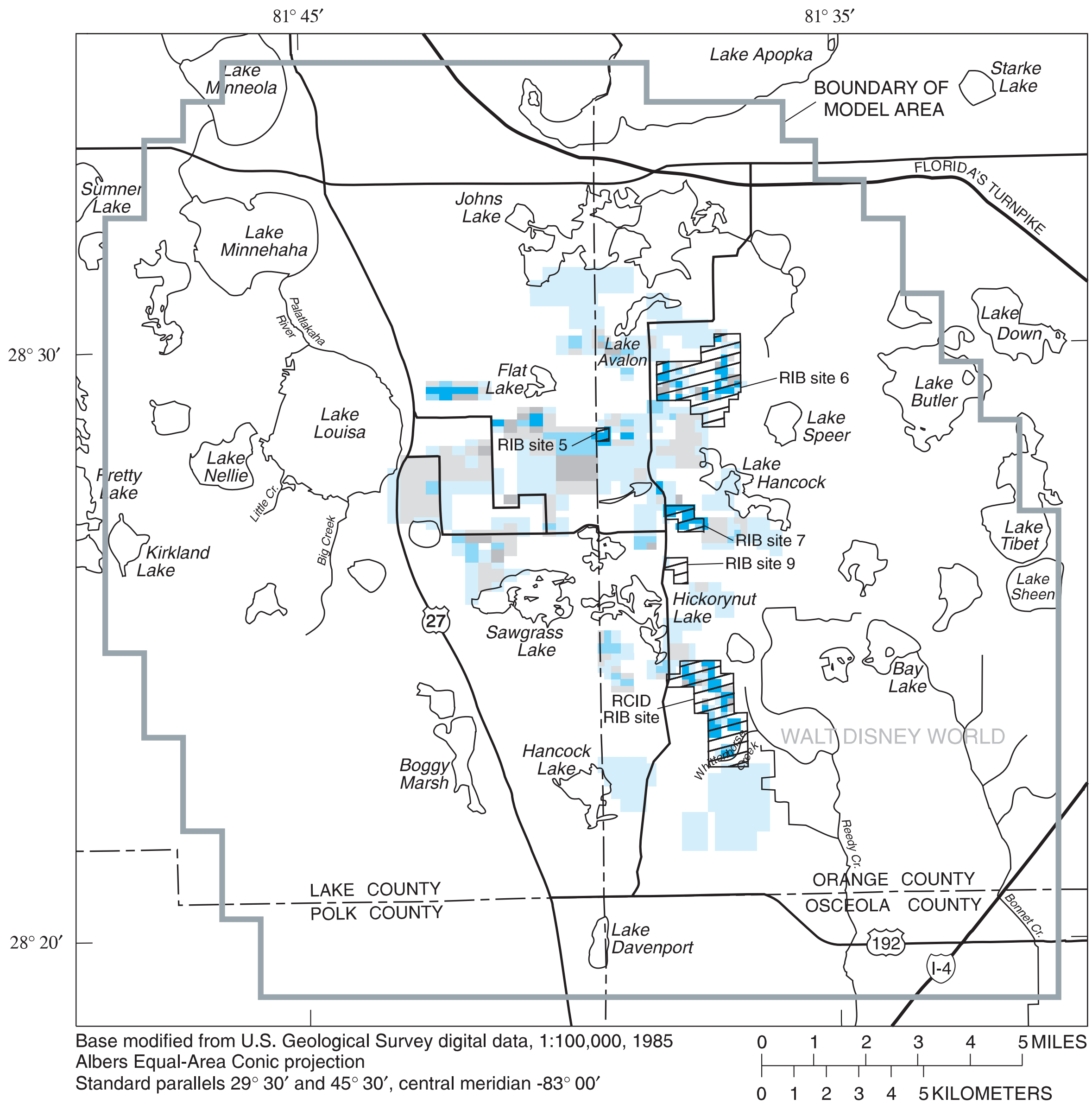
Wetland Discharge

The numerous wetlands within the model area typically have perennial water levels that are above land surface or are less than 2 ft below land surface. For convenience of extracting model-simulated leakage to streams, wetlands which drained into streams upstream from key gaging stations (site numbers 24, 34, 57, and 62, fig. 2) were simulated by the MODFLOW River Package (fig. 22). In these areas, an arbitrarily high conductance of 10,000 ft^2/d was used and stream stage was set equal to land-surface altitude. The stream bottom altitude was set equal to stream stage so the river nodes representing wetlands would never be recharging the surficial aquifer system. All other wetlands were simulated by the MODFLOW Drain Package (fig. 22). Drain conductance was specified at an arbitrarily high value of 10,000 ft^2/d and drain altitude was set equal to land-surface altitude.

Both of these representations of wetlands are mathematically identical. Conceptually, where the water level of the surficial aquifer system is higher than land-surface altitude, the river and drain nodes represent the effects of higher surface runoff rates in these areas. Where the aquifer's water level is lower than or equal to land-surface altitude, the river and drain nodes have no effect.

Ground-Water Withdrawals

Average 1995 ground-water withdrawals from wells within the model area totaled approximately 23 Mgal/d (about 1.7 in/yr averaged over the model area). All water withdrawn for municipal, commercial, industrial, or agricultural use was assumed to be pumped from wells tapping only the Upper Floridan aquifer.



EXPLANATION

ARTIFICIAL RECHARGE RATES, IN INCHES PER YEAR

- No artificial recharge
- 0 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- Greater than 100

Figure 25. Artificial recharge rates used to calculate effective recharge, average 1995 conditions.

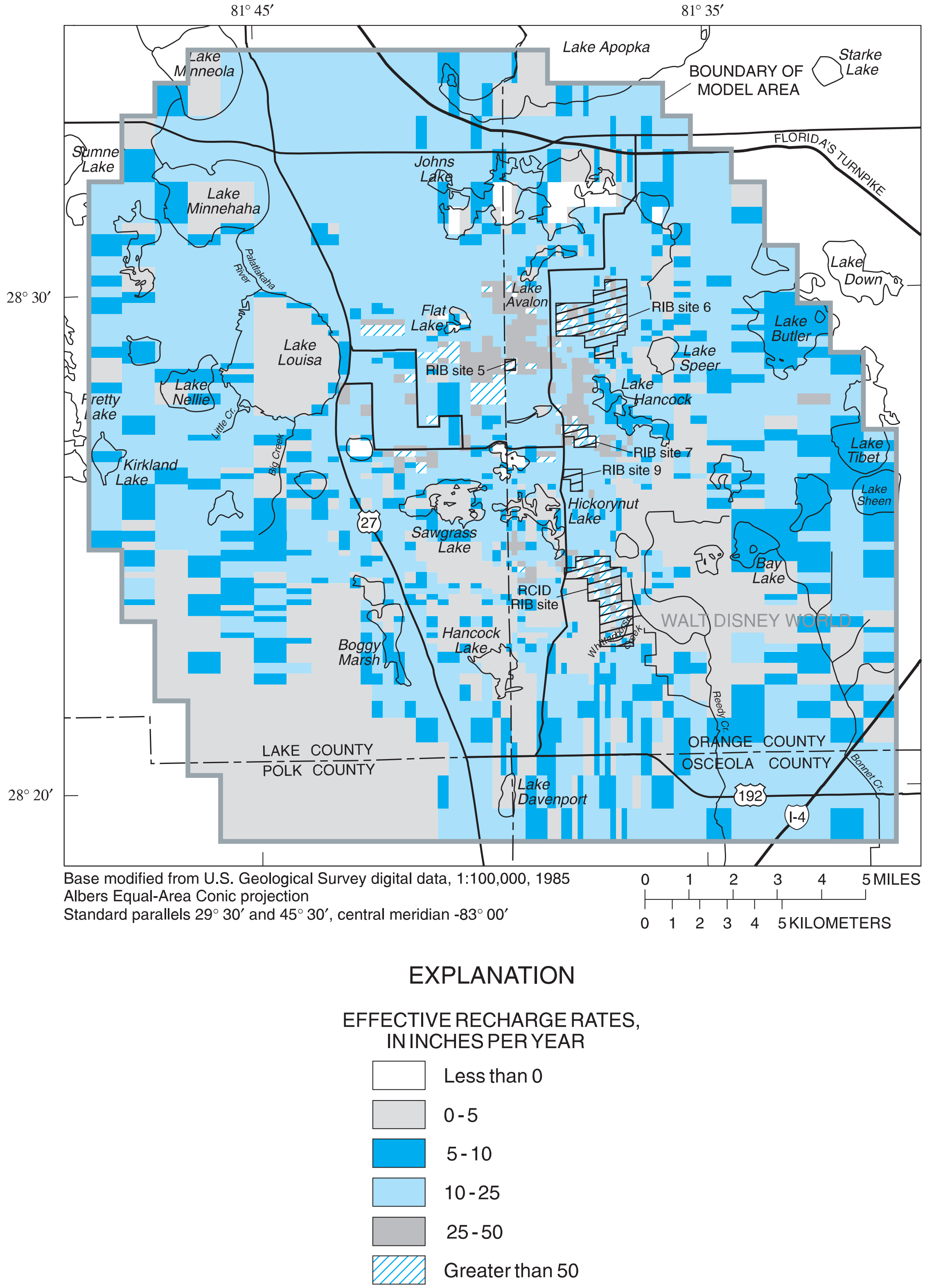


Figure 26. Effective recharge rates specified in the model, average 1995 conditions.

Well locations and ground-water withdrawal rates for municipal, commercial, and industrial users were obtained from Consumptive Use Permits and monthly operating reports compiled by St. Johns River Water Management District and South Florida Water Management District. Additional data were obtained from R.L. Marella (USGS, written commun., 1996), Reedy Creek Energy Services, Inc., and the Florida Department of Environmental Protection. Agricultural water use, which consisted solely of citrus irrigation, was estimated based on an irrigation rate of approximately 9.3 in/yr (as described in an earlier section) and irrigated acreage (estimated from field reconnaissance). Ground-water withdrawals were simulated by the MODFLOW Well Package (fig. 27).

Calibration

Calibration is the attempt to reduce the difference between model results and measured data by adjusting model hydrologic parameters within reasonable ranges. A reduction in the differences between simulated and measured ground-water levels and flows indicates improvement of the calibration. The process of running the model, evaluating improvement of the model calibration, and adjusting model parameters accordingly is continued iteratively until an acceptable calibration criterion is met. Simulated water levels and stream discharges usually depart from measured values, even after a diligent calibration effort. The differences between model results and measurements (model error) usually result from the simplifications inherent in the conceptual model, grid scale, and the difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydrologic properties and stresses throughout the model area.

The steady-state ground-water flow model was calibrated to average water-level data collected during 1995 by adjusting values of surficial aquifer system hydraulic conductivity, intermediate confining unit leakance, and Upper Floridan aquifer transmissivity. A steady-state calibration to average 1995 conditions was considered suitable for several reasons:

1. Model results will be used to ascertain the long-term hydrologic effects of reclaimed-water application, not the relatively short-term transient variations that may occur as a result of, for example, a year of unusually heavy rainfall.
2. The surficial aquifer system is strongly influenced by temporal variations in precipitation, evapotranspiration, and movement of water in the unsaturated zone. Sufficient data does not exist to even grossly simulate unsaturated zone hydraulics on a regional scale. In addition, a transient simulation would have introduced at least two more unknowns, Upper and Lower Floridan aquifer storage coefficients, which are not well known.
3. The 1995 calendar year was the longest period during the 19 months of data collection for this study that the surficial and Floridan aquifer systems were considered reasonably near steady-state based on measured water levels.
4. Measured annual precipitation and potential evapotranspiration in 1995 were very close to long-term average values. Consequently, natural hydrologic stresses (all stresses excluding artificial recharge and well pumpage) were probably near long-term values and can be used as representative values for predictive simulations.
5. The frequency of data collection was sufficient for calculation of representative annual average values.

Calibration improvement was determined by decreases in sum-of-squares error (*SS*) which is defined by

$$SS = \sum_{k=1}^{n} (\hat{h}_k - h_k)^2 , \qquad (9)$$

where

$\hat{h}_k$ is $k^{\underline{th}}$ simulated water level, [L];
h_k is $k^{\underline{th}}$ measured water level, [L]; and
n is number of water-level comparisons.

Although the sum-of-squares error serves as the objective function, root-mean-square error (*RMSE*) is reported because *RMSE* is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. Root-mean-square error is related to the sum-of-squares error by

$$\mathrm{RMSE} = \sqrt{\frac{SS}{\mathrm{n}}} . \qquad (10)$$

Because locations of measured water levels rarely coincide with cell nodes, simulated water levels were interpolated laterally to points of measurement from the nodes of surrounding cells. Simulated water levels were interpolated because they were assumed to be part of a continuous distribution. Vertical interpolation was not considered because of the discontinuity and associated refraction of potential fields from an aquifer across a confining unit.

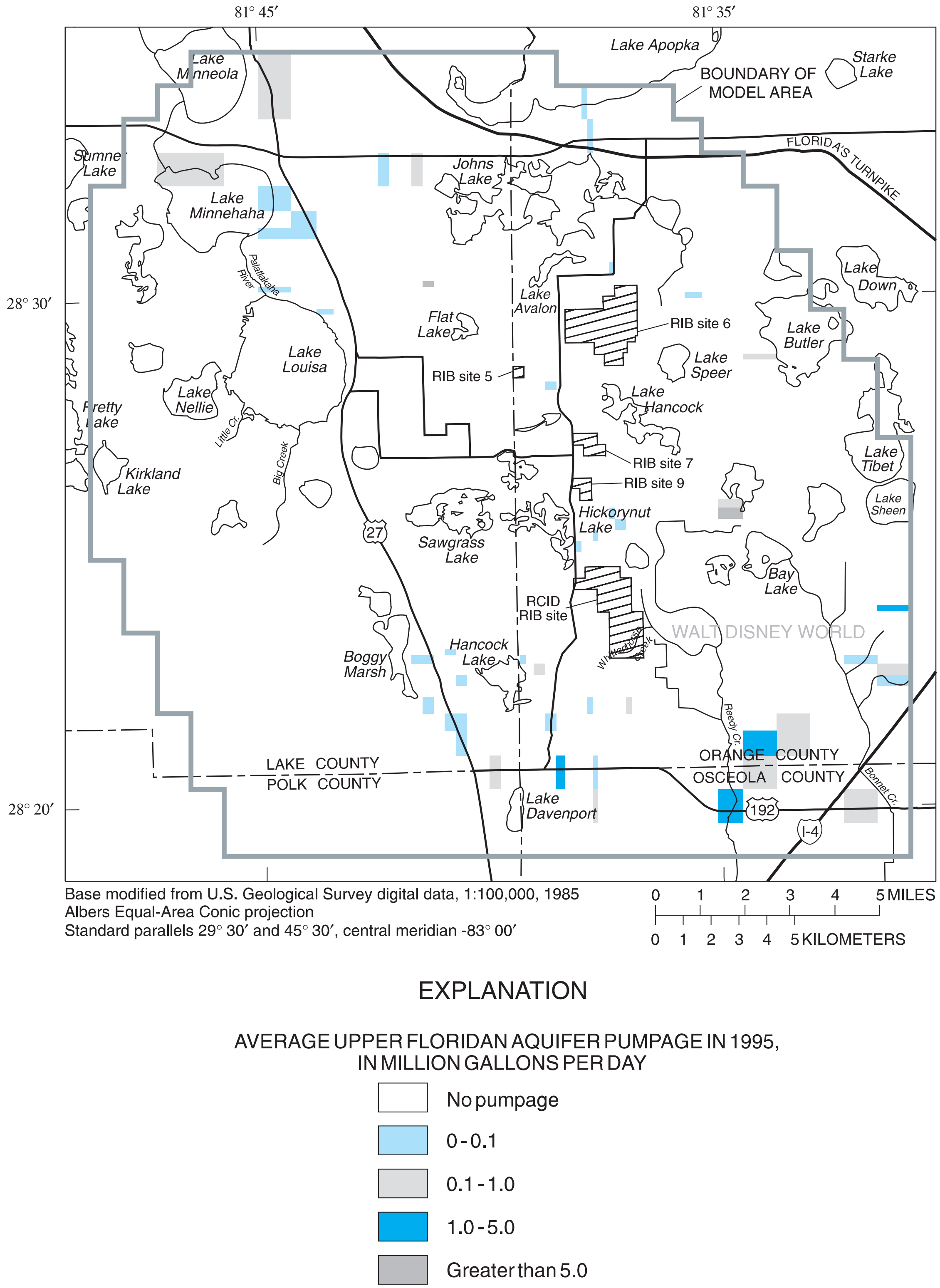


Figure 27. Ground-water withdrawal rates for the Upper Floridan aquifer specified in the model, average 1995 conditions.

The model was calibrated using water-level measurements from 21 landlocked lakes, 65 surficial aquifer system wells, and 36 Upper Floridan aquifer wells. The calibration criterion was to minimize the objective function (eq. 9). Multiple measurements for a well or lake were reduced to a single representative 1995 water-level measurement by calculating a time-weighted arithmetic average. Water-level measurements from additional wells were available but were not used for calibration, because these measurements were affected by factors that the model did not simulate, such as a transient ground-water mound in the immediate vicinity of a heavily loaded individual RIB or AAS. Therefore, only water-level measurements representative of the regional flow field were used. In addition, where dense clusters of wells were present at a RIB site, only a few wells representative of the RIB site as a whole were used so as not to overly bias the *SS*, and consequently the model calibration, toward these areas.

Stream discharge measurements were not formally used during model calibration because of the difficulties of accurately determining the base flow, or ground-water discharge, component of total gaged stream discharge. The upper limit of base flow is equal to the gaged stream discharge, although annual average base flow probably is less than the gaged discharge. Another problem is determining which wetlands contribute discharge to which streams. Ground-water that discharges into wetlands and subsequently flows into a stream is measured as stream discharge at the gaging station. If the simulated wetland discharge is not attributed to the appropriate stream, the total stream discharge simulated by the model as a whole would be correct but the relative fraction attributed to each stream would be incorrect. Simulated ground-water discharge to streams was only considered to assure that it was less than gaged stream discharge.

Parameter Estimation

Model calibration was facilitated by a parameter estimation program (Halford, 1992). The parameter estimation process is initialized by using the model to establish the initial differences between simulated and measured water levels. These differences, or residuals, are then minimized by the parameter estimation program. To implement parameter estimation, the sensitivity coefficients (derivatives of simulated water-level change with respect to parameter change) are calculated by the influence coefficient method (Yeh, 1986) using the initial model results. Each parameter is changed a small amount and MODFLOW is used to compute new water levels for each perturbed parameter. The current arrays of sensitivity coefficients and residuals are used by a quasi-Newton procedure (Gill and others, 1981, p. 137) to compute the parameter changes that should improve the model. The model is updated to reflect the latest parameter estimates and a new set of residuals is calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter is continued iteratively until model error or model-error change is reduced to a specified level or until a specified number of iterations are made (Halford, 1992). Additional details on the theory and application of parameter estimation techniques to ground-water flow modeling are presented by Yeh (1986), Hill (1992), and Poeter and Hill (1997).

Twenty-eight parameters (table 6) were used as multipliers that modified the value of surficial aquifer system hydraulic conductivity, intermediate confining unit leakance, or Upper Floridan aquifer transmissivity by a fixed amount in the zone assigned to each parameter. Zonation of the model into areas of homogeneous hydrologic properties (each zone characterized by one constant parameter value) is a way to reduce the number of parameters estimated and minimize the nonuniqueness problems associated with overparameterization. A nonunique solution is not desirable because it is dependent on the initial estimates of parameters.

The zonation method of parameter identification was used for parameterizing surficial aquifer system hydraulic conductivity (parameters K_{s1} and K_{s2}) which yielded the calibrated distribution of hydraulic conductivity (fig. 28). Initially, one parameter was used for hydraulic conductivity. However, this resulted in the simulation of water-table gradients at the RCID RIB site that were too steep. After examining other possible explanations (such as a transmissivity that was too low resulting from an aquifer base altitude that was too high), the surficial aquifer system hydraulic conductivity was assumed to be different in the vicinity of the RCID RIB site (see K_{s2} zone, fig. 28). Addition of the K_{s2} parameter produced a much better fit to measured water levels. The relatively high value of 150 ft/d is substantiated by independent estimates of hydraulic conductivity at the RCID RIB site made by CH2M Hill (1989) and Sumner and Bradner (1996). The calibrated value of K_{s1} of 30 ft/d (fig. 28) is within the range of values reported by Camp Dresser and McKee, Inc. (1984) and CH2M Hill (1989, 1993).

Table 6. Initial and calibrated values of parameters estimated to calibrate the model

[Parameter units shown in parentheses; in/yr, inch per year; ft/d, foot per day; ft/d/ft, foot per day per foot; ft^2/d, foot squared per day; --, not applicable]

Parameter description	Parameter symbol	Initial value	Calibrated value
Effective recharge to surficial aquifer system[a] (in/yr)	N	1[b]	--
Surficial aquifer system hydraulic conductivity (ft/d):			
Zone 1	K_{s1}	50	30
Zone 2	K_{s2}	50	150
Intermediate confining unit leakance (ft/d/ft):			
Zone 1	V_1	$1x10^{-4}$	$4.1x10^{-4}$
Zone 2	V_2	$1x10^{-4}$	$13x10^{-4}$
Zone 3	V_3	$1x10^{-4}$	$47x10^{-4}$
Zone 4	V_4	$1x10^{-4}$	$42x10^{-4}$
Zone 5	V_5	$1x10^{-4}$	$53x10^{-4}$
Zone 6	V_6	$1x10^{-4}$	$21x10^{-4}$
Zone 7	V_7	$1x10^{-4}$	$6.9x10^{-4}$
Zone 8	V_8	$1x10^{-4}$	$0.55x10^{-4}$
Zone 9	V_9	$1x10^{-4}$	$72x10^{-4}$
Zone 10	V_{10}	$1x10^{-4}$	$18x10^{-4}$
Zone 11	V_{11}	$1x10^{-4}$	$69x10^{-4}$
Zone 12	V_{12}	$1x10^{-4}$	$54x10^{-4}$
Zone 13	V_{13}	$1x10^{-4}$	$1.0x10^{-4}$
Zone 14	V_{14}	$1x10^{-4}$	$1.2x10^{-4}$
Zone 15	V_{15}	$1x10^{-4}$	$2.3x10^{-4}$
Zone 16	V_{16}	$1x10^{-4}$	$8.3x10^{-4}$
Zone 17	V_{17}	$1x10^{-4}$	$38x10^{-4}$
Zone 18	V_{18}	$1x10^{-4}$	$0.66x10^{-4}$
Zone 19	V_{19}	$1x10^{-4}$	$0.32x10^{-4}$
Zone 20	V_{20}	$1x10^{-4}$	$2.1x10^{-4}$
Zone 21	V_{21}	$1x10^{-4}$	$2.0x10^{-4}$
Zone 22	V_{22}	$1x10^{-4}$	$1.0x10^{-4}$
Zone 23	V_{23}	$1x10^{-4}$	$4.1x10^{-4}$
Zone 99	V_{99}	$1x10^{-4}$	$40x10^{-4}$
Upper Floridan aquifer transmissivity (ft^2/d):			
Zone 1	T_{u1}	1[b]	0.30[b]
Zone 2	T_{u2}	1[b]	2.0[b]
Middle semiconfining unit leakance[a] (ft/d/ft)	V_{ms}	$5x10^{-5}$	--
Lower Floridan aquifer transmissivity[a] (ft^2/d)	T_{lf}	1[b]	--

[a] This parameter was specified and not varied during model calibration.
[b] This value is a multiplier for the spatially variable parameter values.

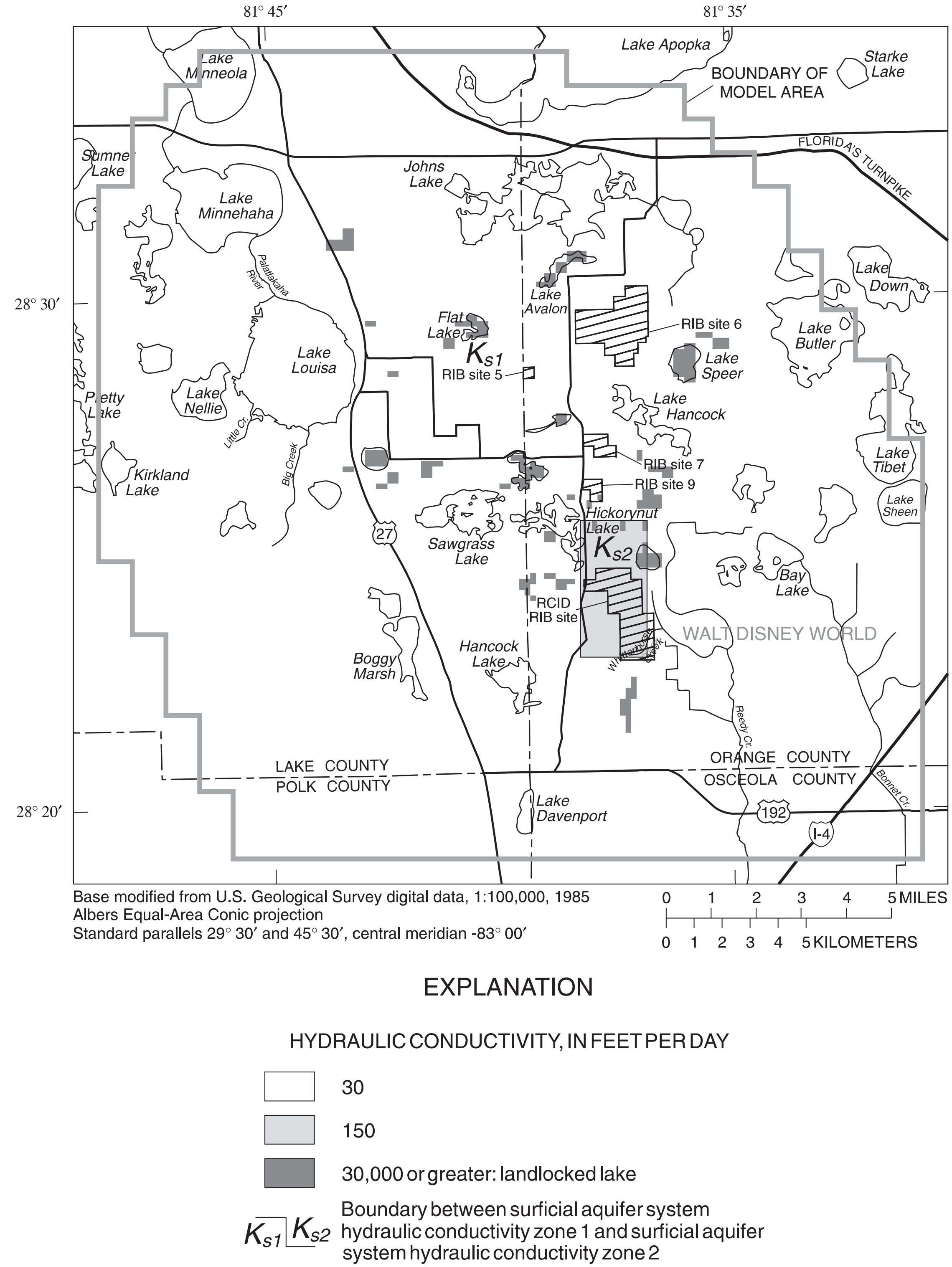


Figure 28. Calibrated hydraulic conductivity of the surficial aquifer system and delineation of zones used for parameter estimation.

The zonation method of parameter identification was also used for parameterizing Upper Floridan aquifer transmissivity (parameters T_{u1} and T_{u2}) which yielded the calibrated distribution (fig. 29). T_{u1} and T_{u2} served as multipliers for the initial Upper Floridan aquifer transmissivity distribution. Two parameters were required because the use of one global Upper Floridan aquifer transmissivity parameter produced an Upper Floridan aquifer potentiometric surface that was too low in the southwestern part of the model area. Inclusion of the T_{u1} parameter (fig 29) produced a much better match to measured water-level data. Low Upper Floridan aquifer transmissivity values in the southwestern part of the model area (fig. 29) generally are in agreement with previously reported data from aquifer tests and model simulations (Pride and others, 1966; Grubb and Rutledge, 1979; Planert and Aucott, 1985; and Tibbals, 1990). High transmissivity values in the north and northeastern parts of the model area (fig. 29) generally are higher than those from previous models of the study area (Grubb and Rutledge, 1979; Camp Dresser and McKee, Inc., 1984; Planert and Aucott, 1985; Tibbals, 1990; and Murray and Halford, 1996). This might result from a higher rate of leakage from the surficial aquifer system to the Upper Floridan aquifer because, as will be discussed later, the calibrated leakance of the intermediate confining unit generally is higher than in previous models. Consequently, with a greater amount of water flowing through the Upper Floridan aquifer, a higher transmissivity is required to maintain approximately the same potentiometric surface.

It should be emphasized that the calibrated values of Upper Floridan aquifer transmissivity are dependent on the assumed properties of the middle semiconfining unit and Lower Floridan aquifer. Future hydraulic testing of the Floridan aquifer system could determine aquifer or confining unit properties that differ from those modeled. For example, if the leakance of the middle semiconfining unit is increased, the Upper Floridan aquifer transmissivity would decrease because less water would be flowing through the aquifer and more would move through the middle semiconfining unit and into the Lower Floridan aquifer. If the middle semiconfining unit were very leaky, the Floridan aquifer system would function more as one vertically continuous aquifer rather than as separate upper and lower permeable zones. Because transmissivity is a function of aquifer hydraulic conductivity and thickness, the high Upper Floridan aquifer transmissivity in the northern half of the model area may be indicative of a much thicker aquifer. In this case, these high transmissivities might seem more reasonable for an aquifer 2,300-ft thick rather than 300-ft thick.

A slight variation of the zonation method was used for parameterizing intermediate confining unit leakance (parameters V_1 through V_{23} and V_{99}, table 6). As a result of the highly variable lithology and thickness of the intermediate confining unit, zones of uniform leakance could not be accurately delineated based only on lithologic and thickness data. An attempt was made to weight the leakance distribution by intermediate confining unit thickness (fig. 10); that is, leakance would be greater where the unit is thinner and less where the unit is thicker. However, this weighting approach did not yield satisfactory results. An attempt to weight the leakance distribution on sinkhole density also proved unsatisfactory. Sinkhole locations were inferred from land-surface depressions with the aid of a digital elevation model; leakance was assumed to be greater where there were a greater number of sinkholes and less where there were fewer sinkholes. However, a sinkhole might have been “plugged” by filling with low permeability sediments yet still leave a land-surface depression; likewise, a “buried sinkhole” that produced a breach in the intermediate confining unit could exist where there is no longer an obvious land-surface depression. In a mantled karst environment such as exists in the study area, it would be extremely difficult to collect data at such a fine resolution as to accurately represent the true heterogeneity of leakance. Alternatively, model-calibrated leakance values reported by Murray and Halford (1996) were used, although these also produced significant discrepancies with measured water-level data in some areas. One possible solution would be to determine leakance values and leakance zonation simultaneously, an approach referred to as data-driven zonation (Eppstein and Dougherty, 1996). This approach avoids overparameterization and the need to know zonation structure prior to calibration. A simplified procedure based on the concept of data-driven zonation was used to estimate leakance of the intermediate confining unit.

Forty-five zones initially were used to represent intermediate confining unit leakance. A denser spacing of leakance zones was established where more water-level data were available. The parameter estimation routine was run for several iterations in order to obtain correlation coefficients between all parameters. Next, adjacent leakance zones with correlation coefficients greater than 0.7 or to which the model was

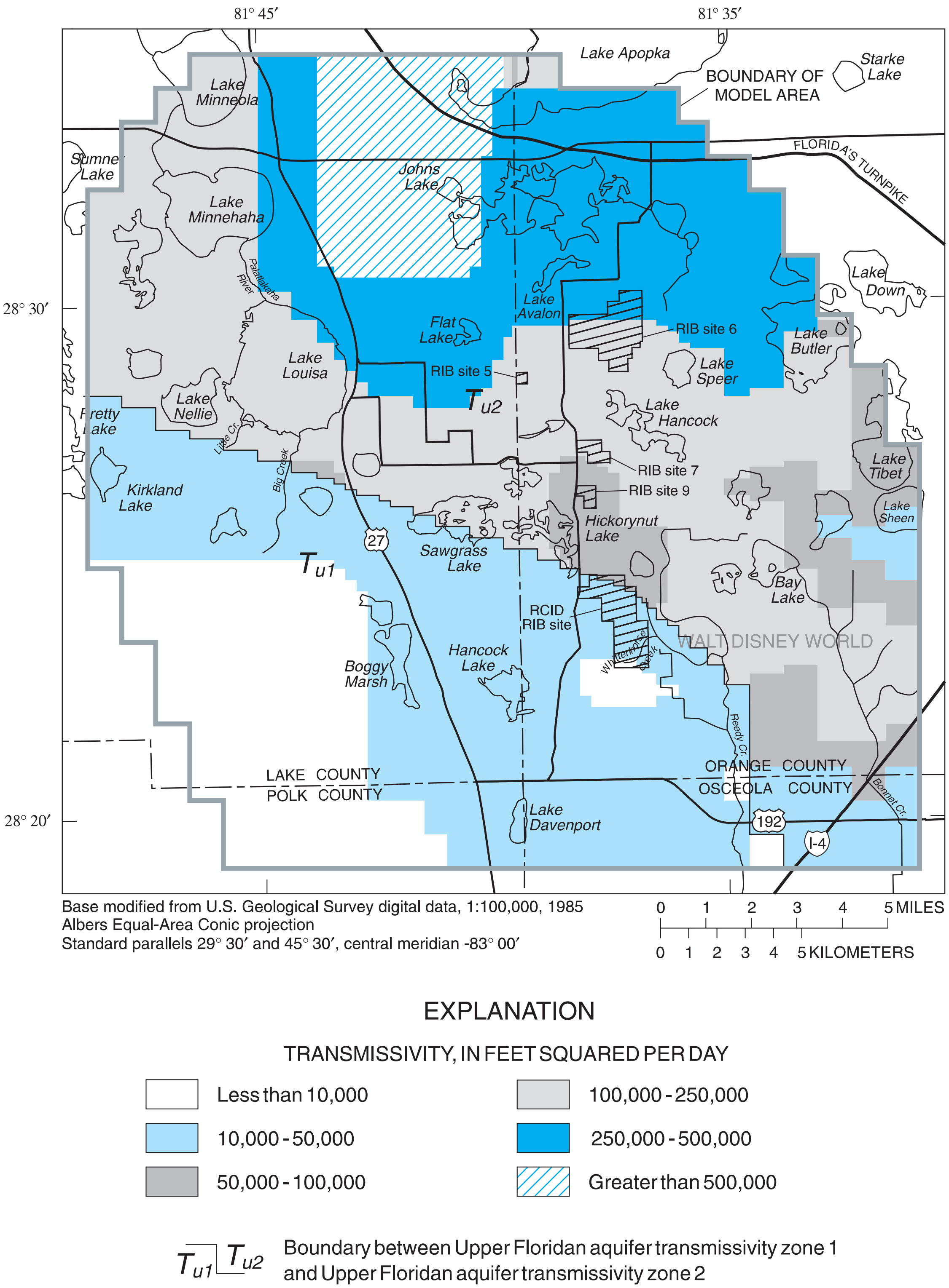


Figure 29. Calibrated transmissivity of the Upper Floridan aquifer and delineation of zones used for parameter estimation.

relatively insensitive (that is, the main diagonal value of the covariance matrix was less than 1 percent of the maximum main diagonal value) were combined into one zone. This two-step process was repeated until all adjacent leakance zones had correlation coefficients less than 0.7 and a main diagonal value greater than 1 percent of the maximum main diagonal value. The zonation structure resulting from this iterative process was further adjusted to account for other leakance information (such as areas of higher leakance as inferred from estimated water-table altitude, for example parameter V_{99}) to yield the final intermediate confining unit leakance distribution (fig. 30).

Calibrated leakance values generally are greater than those reported in previous studies (Grubb and Rutledge, 1979; Planert and Aucott, 1985; Tibbals, 1990; Murray and Halford, 1996) with the exception of those reported by Camp Dresser and McKee, Inc. (1984). The discrepancy between calibrated values in this study and those from earlier studies may be the result of several factors. The present model used a more detailed set of geologic, water-level, and evapotranspiration data for model construction and calibration. Only the present model and the model by Murray and Halford (1996) included the effects of reclaimed water applied at Water Conserv II and the RCID RIBs. Reclaimed-water application is a large stress on the local aquifer system, and the magnitude of this stress is relatively well known. This combination of known stress and aquifer response is a valuable data set for model calibration. However, Murray and Halford (1996) simulated the surficial aquifer system as a specified-head layer. Only the present model and the model constructed by Camp Dresser and McKee, Inc. (1984) actively simulated the surficial aquifer system with variable-head cells. Variable-head cells are a more realistic representation of the aquifer system, and thus might have contributed to the more accurate estimation of parameter values. The finer discretization of the present model and the model by Camp Dresser and McKee, Inc. (1984) (regularly spaced square cells 1,000 ft on a side) may also have contributed to the more accurate estimation of parameter values.

Parameters generally are not highly correlated, as indicated by small correlation coefficients (most less than 0.60, table 7); parameters that are highly correlated are not desirable because they cannot be independently estimated. The most highly correlated parameter pairs are K_{s1} and V_{15} and T_{u1} and T_{u2}, with correlation coefficients of 0.82 and -0.75, respectively. V_{15} is adjacent to several other zones with considerably greater leakances (V_{10}, V_{11}, and V_{99}, table 6 and fig. 30), which contributes to the relatively high correlation between K_{s1} and V_{15}. For example, the water table could be lowered by increasing K_{s1}, thereby causing more water to move laterally and leak to the Upper Floridan aquifer through the adjacent high leakance zones. Alternatively, an increase in V_{15} would lower the water table by increasing the vertical leakage to the Upper Floridan aquifer directly through the V_{15} zone. The fairly high correlation between T_{u1} and T_{u2} primarily is a result of the large transmissivities typical in both zones.

Effective recharge (N), leakance of the middle semiconfining unit (V_{ms}), and transmissivity of the Lower Floridan aquifer (T_{lf}) were specified in the model and were not adjusted during calibration. N was specified because more data were available on the spatial distribution and magnitude of N relative to other parameters. In addition, as will be explained in a later section, N was highly correlated to Upper Floridan aquifer transmissivity. The high correlation coefficients associated with V_{ms} and T_{lf} (table 7) also precluded independent estimation of them. The absence of Lower Floridan aquifer potentiometric-surface measurements contributed to these high correlation coefficients.

The calibrated model generally produced simulated water levels in close agreement with measured water levels (table 8 and fig. 31). Approximately 83 percent of the simulated water levels are within ±3 ft of the measured water levels. No spatial trends in the distribution of water-level residuals are apparent (figs. 32, 33, 34, 35, and 36).

The simulated water table (fig. 32) generally conforms to that based on measured data (fig. 11). The largest differences typically occur in areas of little or no water-table control; for example, the northwestern part of the model area. The simulated water table differs markedly from measured data in several areas. For example, the simulated water table is about 25 ft lower than measured water levels south of Water Conserv II RIB site 6 (near site numbers 19 and 20, fig. 3) and 15 ft lower than measured water levels south of Flat Lake near Water Conserv II AAS HA-7 (near site numbers 21 and 24, fig. 3). These discrepancies probably are the result of localized heterogeneity in hydrologic properties or long-term transient effects that are not adequately represented by a steady-state simulation, or both. Consequently, no attempt was made to match these anomalous measurements during model calibration.

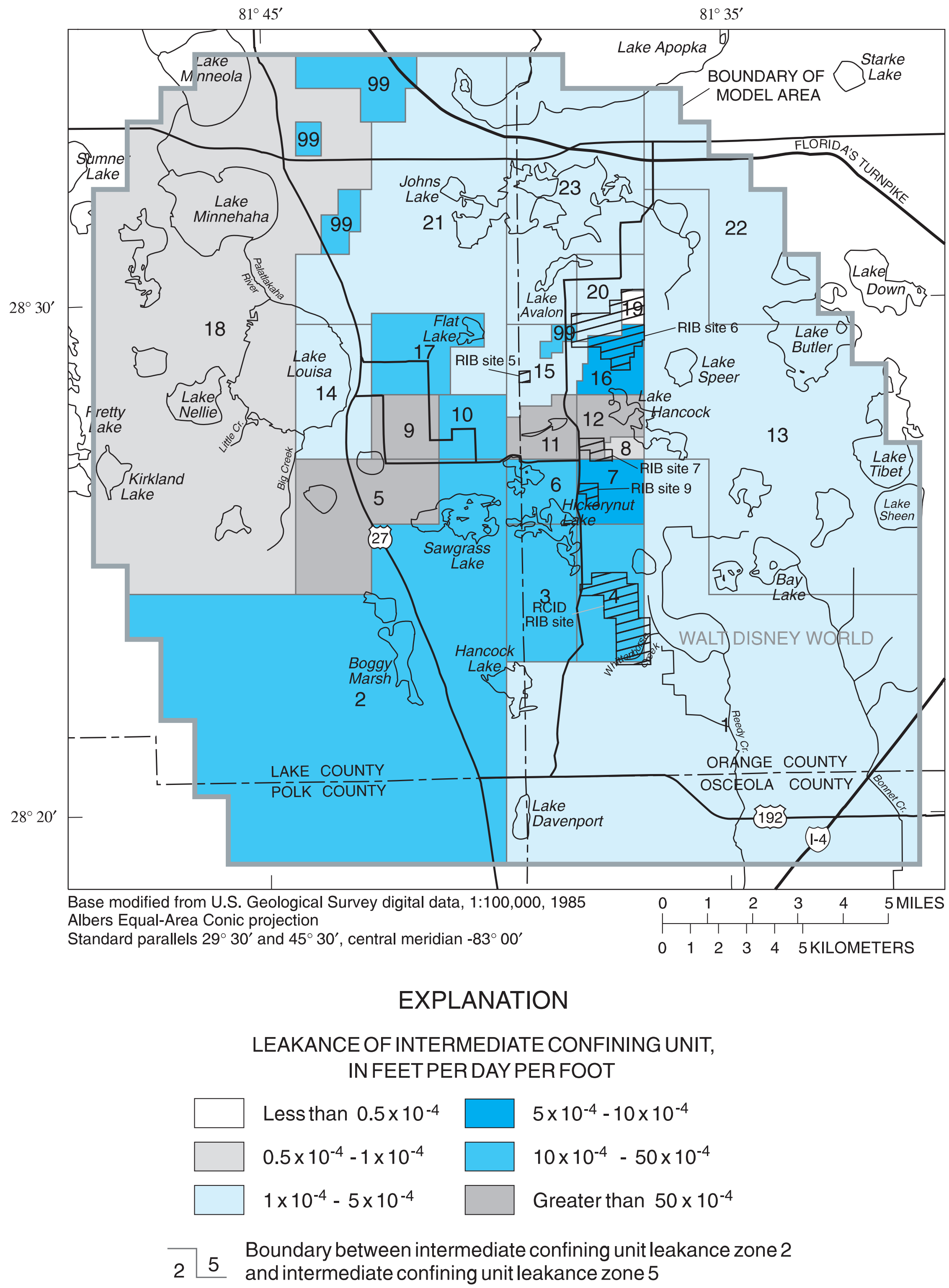


Figure 30. Calibrated leakance of the intermediate confining unit and delineation of zones used for parameter estimation.

Table 7. Selected correlation coefficients between parameters from the calibrated model

[mi^2, square mile; --, no correlation coefficient greater than 0.60]

Parameter[1]	Zone area (mi^2)	Number of water-level measure-ments[2]	Normalized main diagonal[3]	Correlated parameters and (correlation coefficents)			
				Most highly correlated	Correlation coefficents greater than 0.60		
					2nd most correlated	3rd most correlated	4th most correlated
K_{s1}	280.17	73	0.948	V_{15} (0.82)	--	--	--
K_{s2}	4.54	13	.070	V_4 (0.54)	--	--	--
V_1	54.21	7	.088	V_7 (0.22)	--	--	--
V_2	49.62	6	.037	T_{lf} (-0.67)	V_{ms} (-0.66)	--	--
V_3	4.73	3	.029	T_{u2} (-0.74)	--	--	--
V_4	4.54	15	.077	K_{s2} (0.54)	--	--	--
V_5	7.14	8	.043	T_{u2} (-0.66)	V_{18} (0.63)	--	--
V_6	2.22	3	.035	V_7 (0.24)	--	--	--
V_7	2.13	19	.332	V_8 (0.52)	--	--	--
V_8	.42	1	.012	V_{12} (0.52)	--	--	--
V_9	2.13	4	.021	V_{14} (0.37)	--	--	--
V_{10}	2.13	4	.082	V_{21} (0.53)	--	--	--
V_{11}	1.90	4	.046	T_{u2} (0.38)	--	--	--
V_{12}	1.71	7	.256	V_8 (0.52)	--	--	--
V_{13}	33.73	5	.158	V_{19} (0.28)	--	--	--
V_{14}	5.00	2	.028	V_9 (0.37)	--	--	--
V_{15}	2.54	6	.458	K_{s1} (0.82)	--	--	--
V_{16}	1.87	2	.246	V_{19} (0.49)	--	--	--
V_{17}	3.69	7	.079	V_{18} (-0.26)	--	--	--
V_{18}	53.18	4	.016	T_{u2} (-0.66)	V_5 (0.63)	T_{u1} (0.61)	--
V_{19}	.37	2	.026	V_{20} (0.61)	--	--	--
V_{20}	2.22	2	.304	V_{19} (0.61)	--	--	--
V_{21}	20.52	5	.129	V_{10} (0.53)	--	--	--
V_{22}	9.78	2	.279	V_{13} (0.11)	--	--	--
V_{23}	14.50	3	.202	V_{19} (0.19)	--	--	--
V_{99}	4.42	1	.061	V_{15} (0.55)	--	--	--
T_{u1}	100.18	7	.130	T_{u2} (-0.75)	V_{18} (0.61)	--	--
T_{u2}	184.53	29	1.000	T_{lf} (0.83)	V_{ms} (0.75)	T_{u1} (-0.75)	V_3 (-0.74)
V_{ms}	284.71	36	.044	T_{lf} (0.97)	T_{u2} (0.75)	V_2 (-0.66)	--
T_{lf}	284.71	0	.014	V_{ms} (0.97)	T_{u2} (0.83)	V_2 (-0.67)	--

[1] See table 6 for parameter symbol definitions.

[2] For hydraulic conductivity and transmissivity parameters, the number of water-level measurements is the number of measurements within a parameter's zone in the respective aquifer. For leakance parameters, the number of water-level measurements is the number of measurements within a parameter's zone in both the adjacent overlying and underlying aquifers.

[3] Normalized main diagonal of covariance matrix, that is the matrix main diagonal value divided by the maximum main diagonal value. This is a rough estimate of the relative sensitivity of the model to a parameter.

Table 8. Water-level error statistics for the calibrated model

[All residual and error values in feet]

Aquifer	Number of water-level measurements	Minimum residual	Maximum residual	Average error	Root mean square error
Surficial aquifer system	86	-9.50	5.39	-0.29	2.50
Upper Floridan aquifer	36	-3.72	4.52	.61	1.90
Entire model	122	-9.50	5.39	- .02	2.34

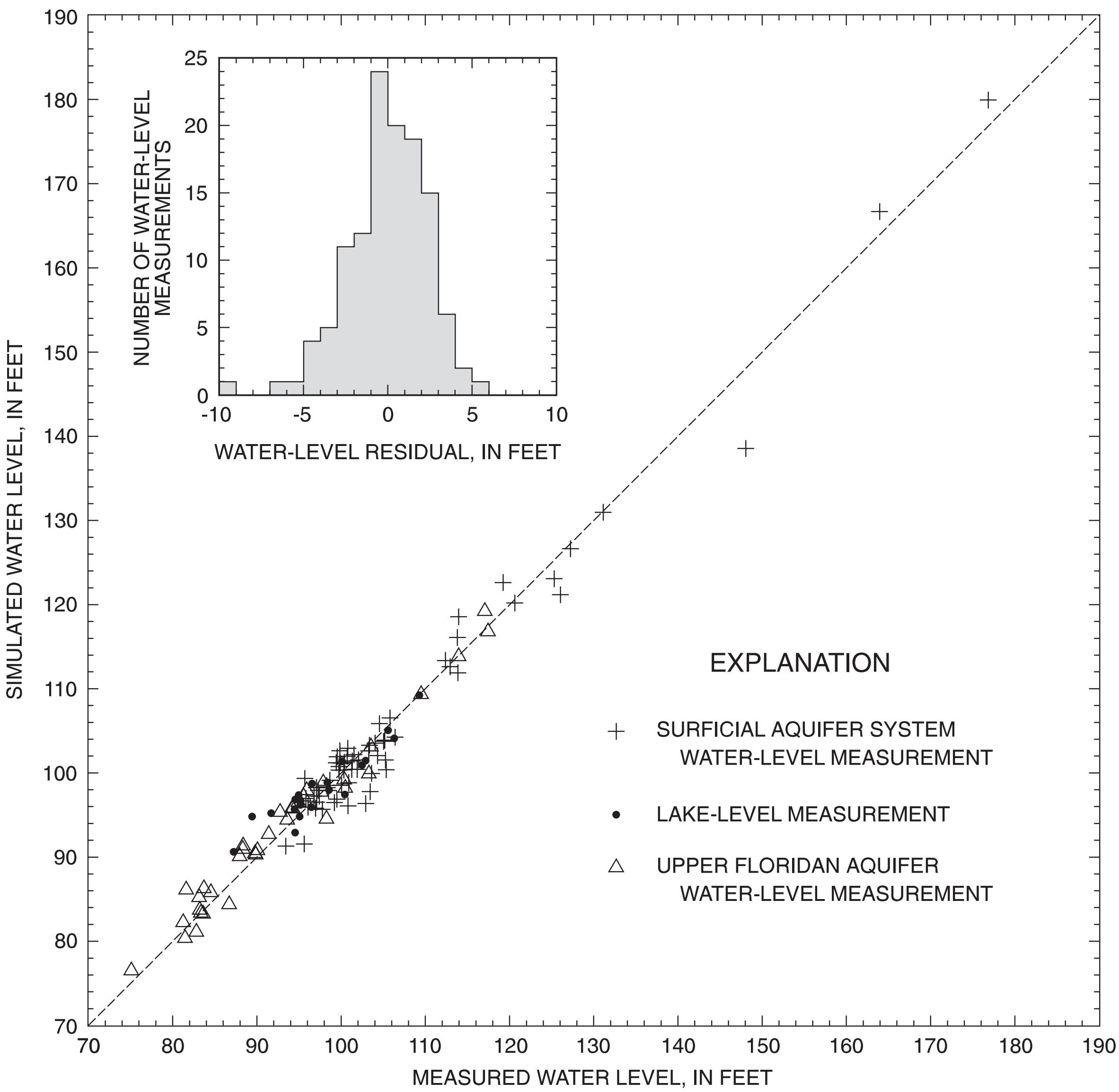


Figure 31. Comparison of simulated to measured water levels for the calibrated model.

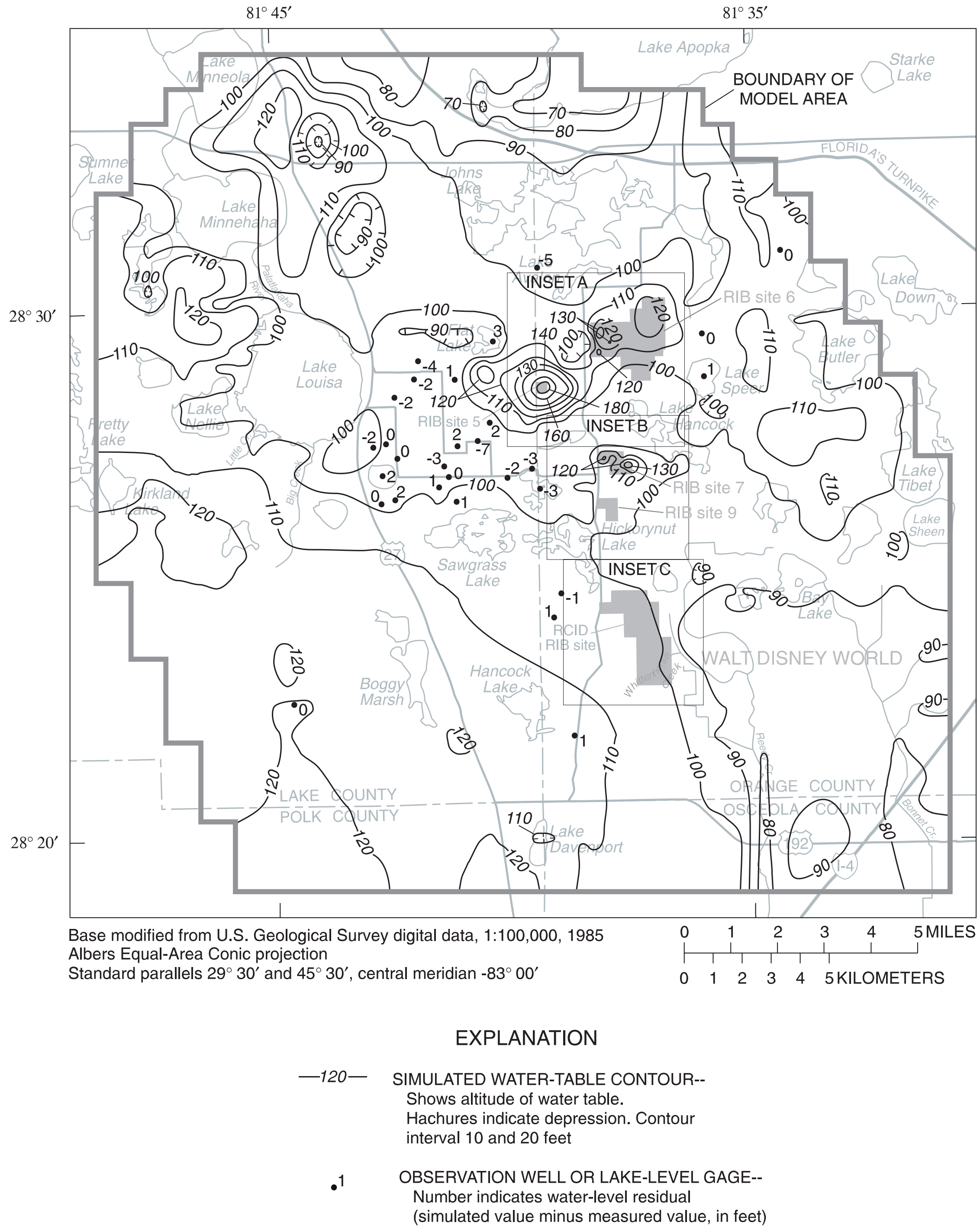
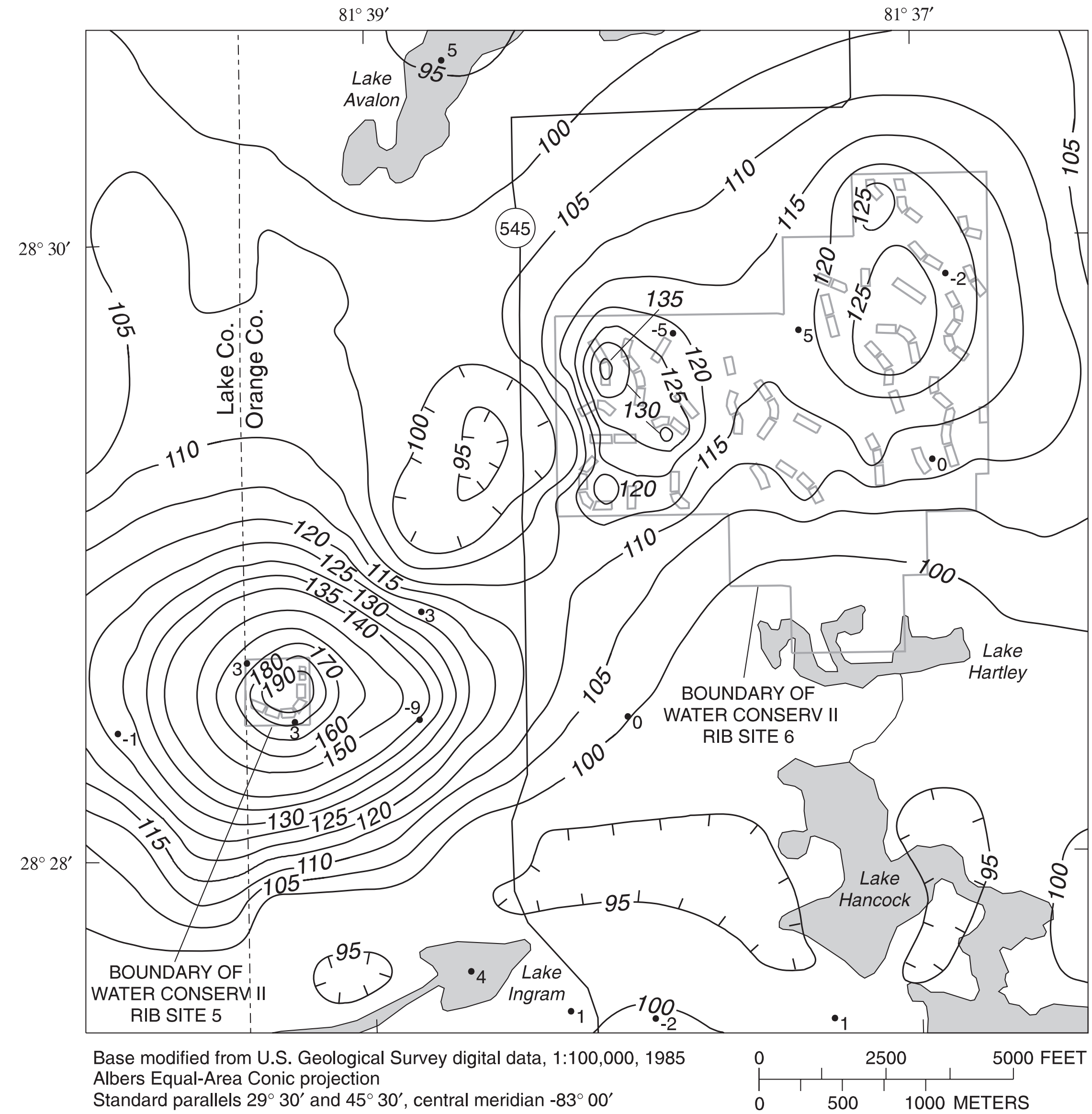


Figure 32. Simulated water table and water-level residuals for the surficial aquifer system, 1995 (insets A, B, and C shown in figs. 33, 34, and 35, respectively).



EXPLANATION

—95— SIMULATED WATER-TABLE CONTOUR-- Shows altitude of water table. Hachures indicate depression. Contour interval 5 and 10 feet

•1 OBSERVATION WELL OR LAKE-LEVEL GAGE-- Number indicates water-level residual (simulated value minus measured value, in feet)

◇ RAPID INFILTRATION BASIN

Figure 33. Simulated water table and water-level residuals for the surficial aquifer system at the Water Conserv II RIB sites 5 and 6, 1995 (inset A, fig. 32).

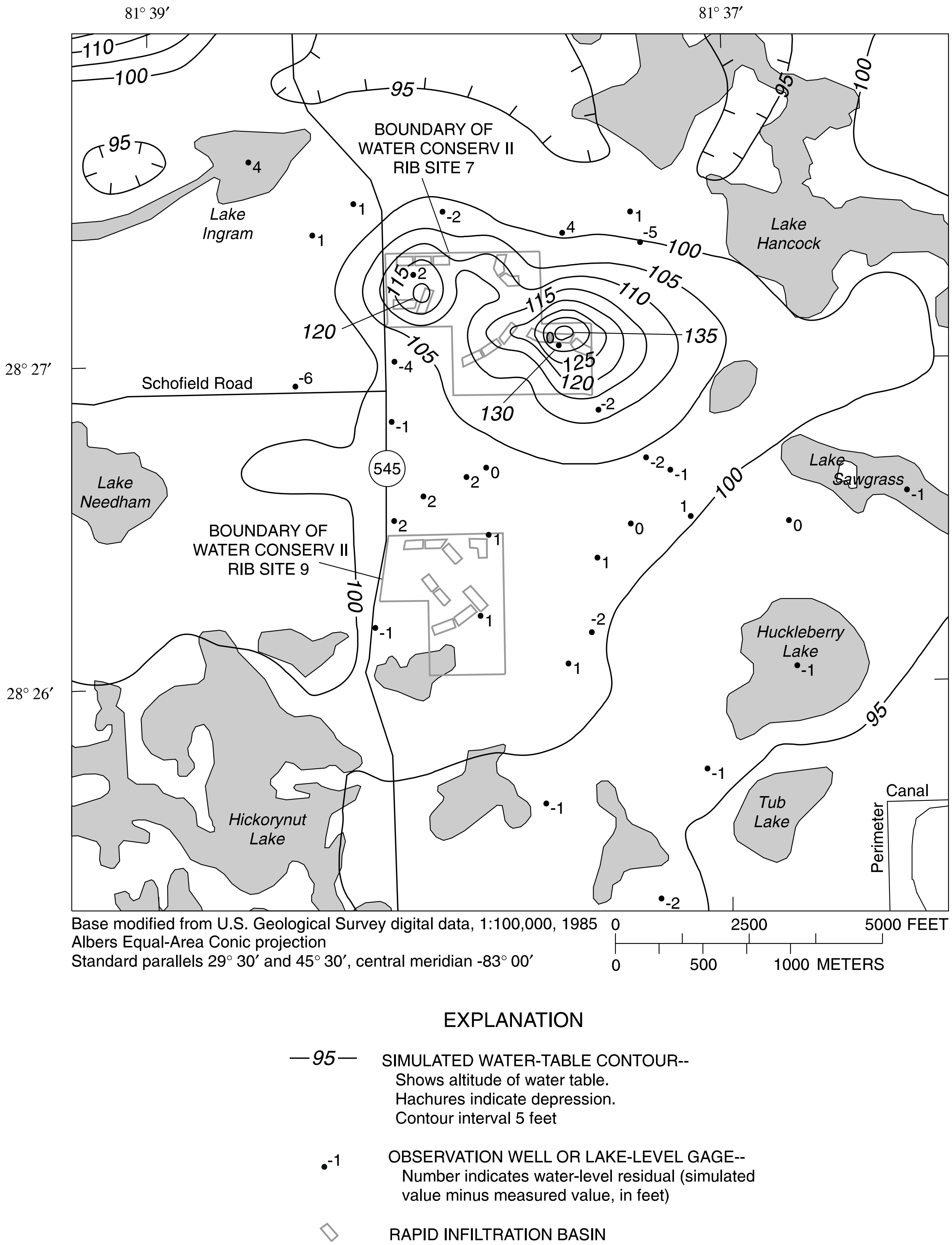
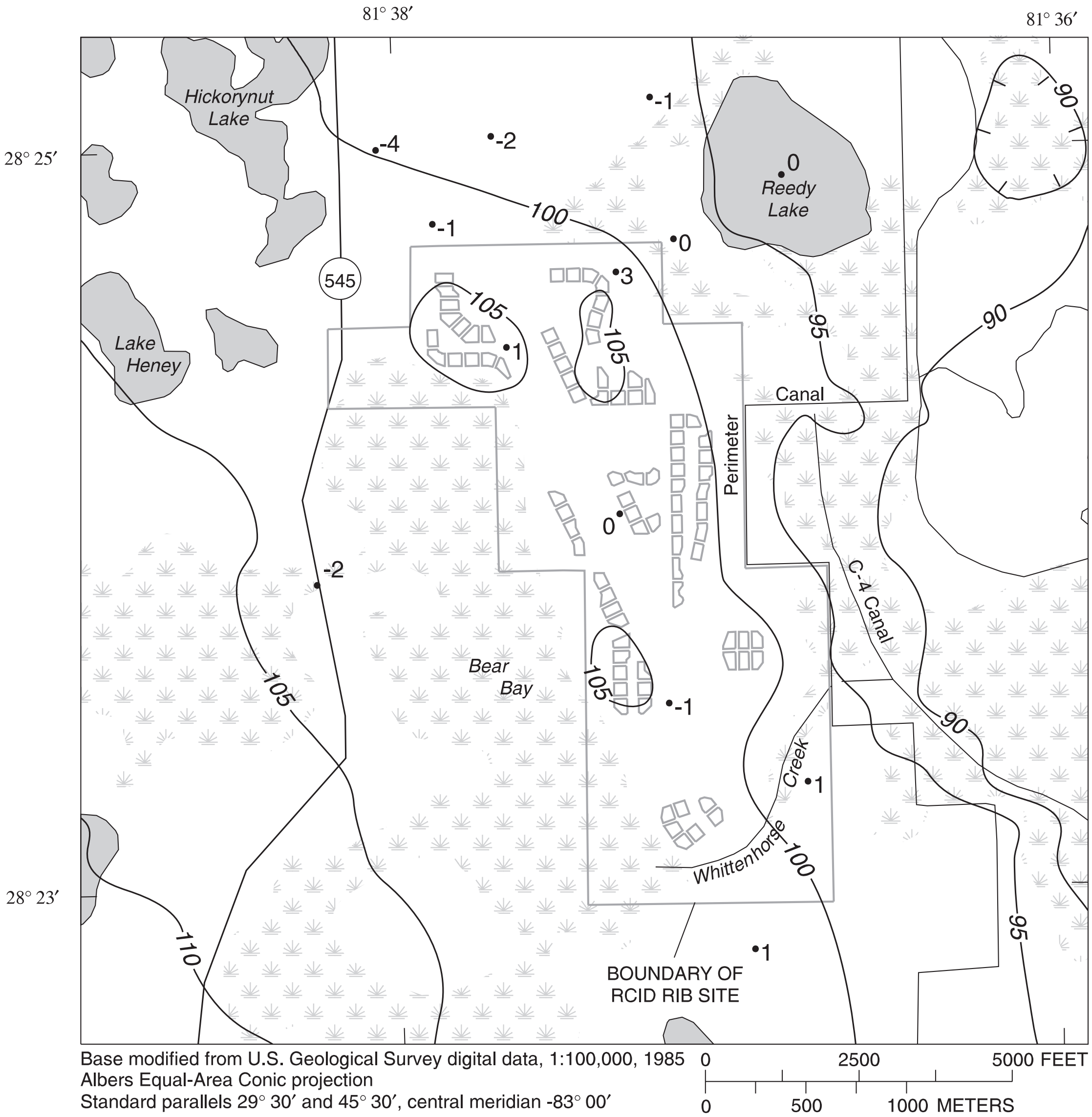


Figure 34. Simulated water table and water-level residuals for the surficial aquifer system at the Water Conserv II RIB sites 7 and 9, 1995 (inset B, fig. 32).



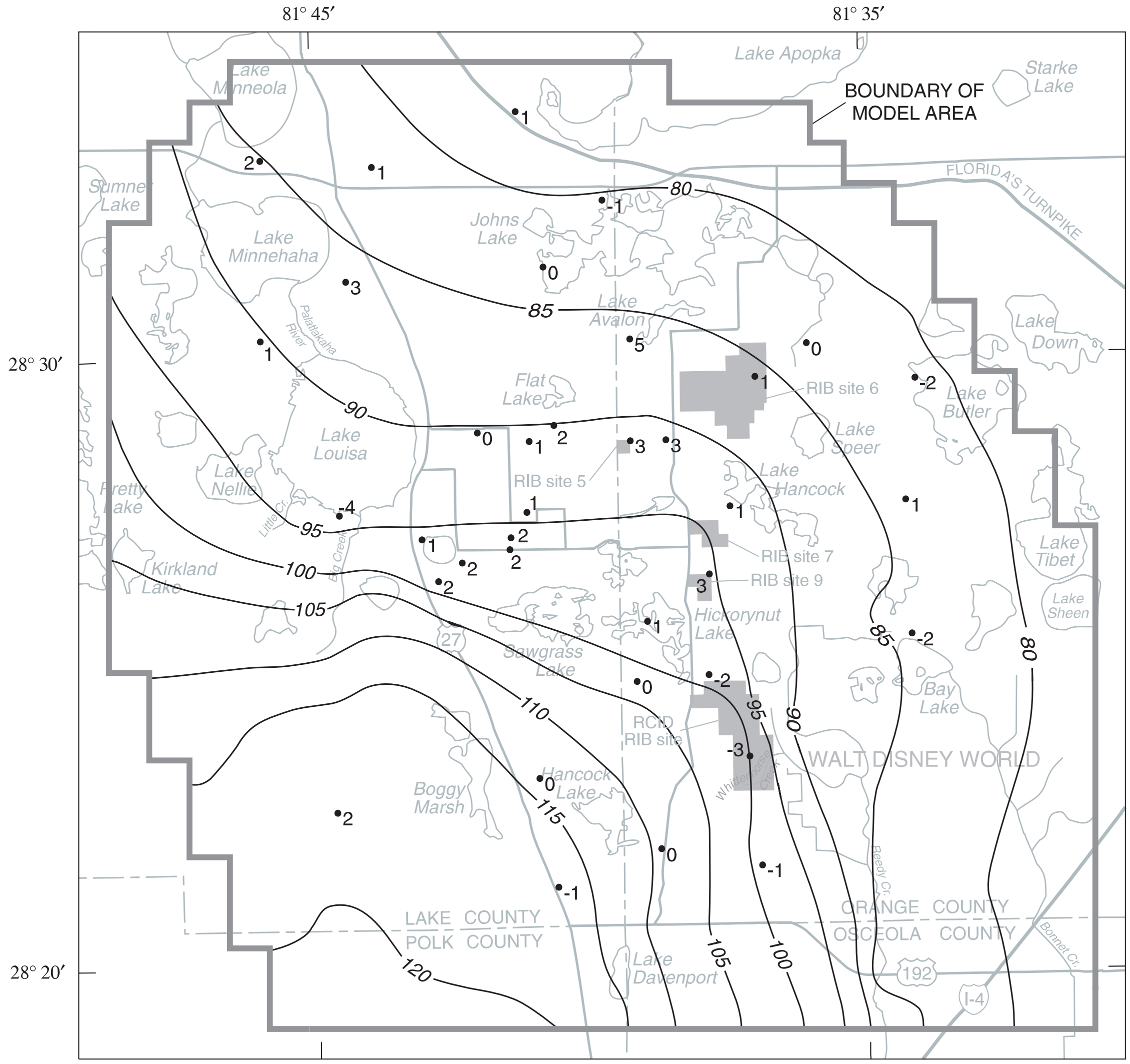
EXPLANATION

—110— SIMULATED WATER-TABLE CONTOUR-- Shows altitude of water table. Hachures indicate depression. Contour interval 5 feet

•1 OBSERVATION WELL OR LAKE-LEVEL GAGE-- Number indicates water-level residual (simulated value minus measured value, in feet)

◇ RAPID INFILTRATION BASIN

Figure 35. Simulated water table and water-level residuals for the surficial aquifer system at the RCID RIB site, 1995 (inset C, fig. 32).



Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Albers Equal-Area Conic projection
Standard parallels 29° 30′ and 45° 30′, central meridian -83° 00′

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

—120— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells. Contour interval 5 feet

•-1 OBSERVATION WELL -- Number indicates water-level residual (simulated value minus measured value, in feet)

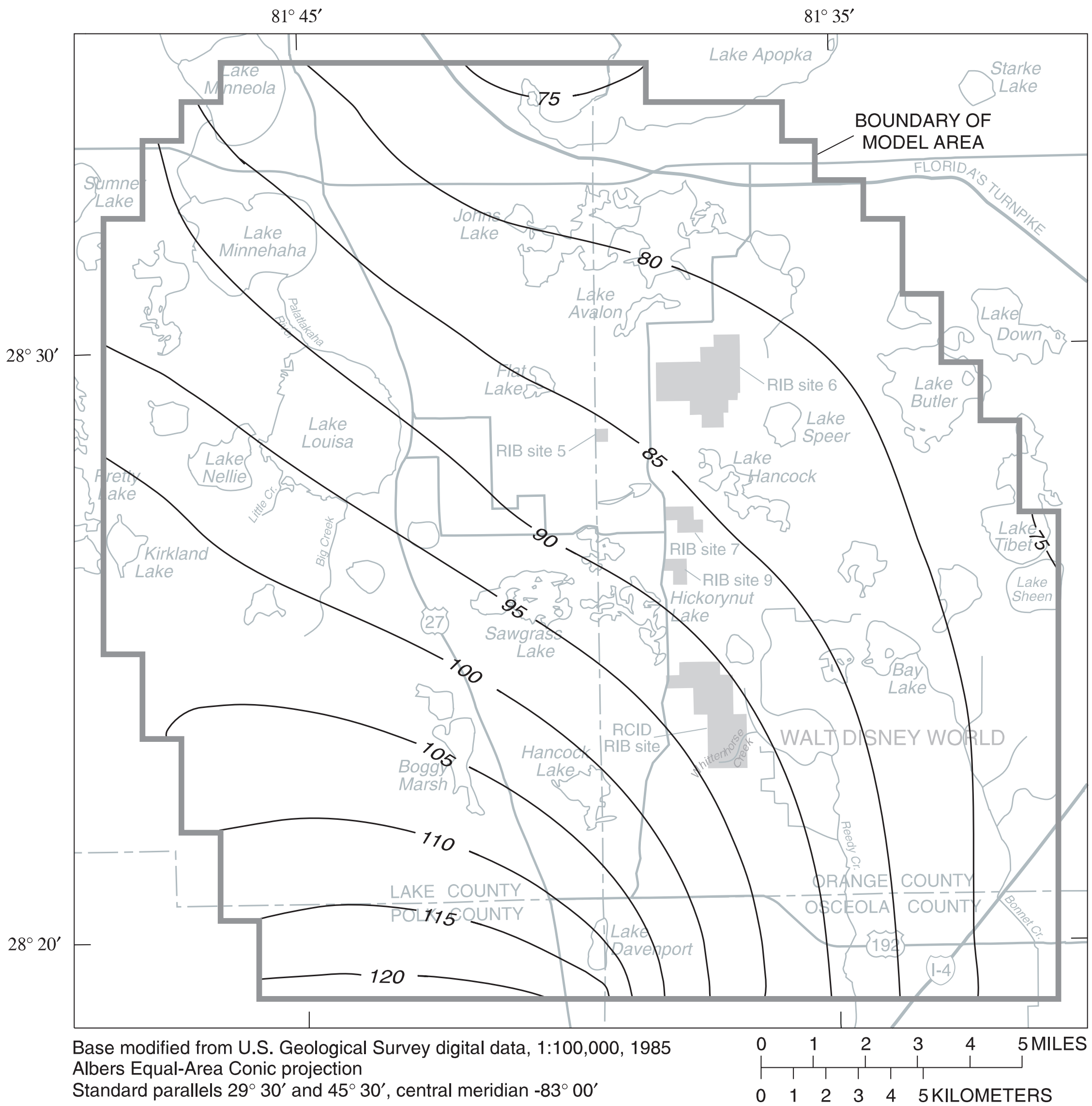
Figure 36. Simulated potentiometric surface and water-level residuals for the Upper Floridan aquifer, 1995.

Because the model is not intended to represent the effects of individual RIBs, the simulated water table at the RCID and Water Conserv II RIB sites is somewhat generalized and shows the effects of a cluster of RIBs or the RIB site as a whole (figs. 33, 34, and 35). The effects of the RIBs on the water table primarily is a function of the reclaimed-water application rate and the hydraulic properties of the surficial aquifer system and the intermediate confining unit. The calibrated surficial aquifer system hydraulic conductivity is 30 ft/d at all four Water Conserv II RIB sites; therefore, differences in water-table configuration among the four sites is the result of different reclaimed-water application rates and variations in the leakance of the intermediate confining unit. Average 1995 reclaimed-water-application rates at Water Conserv II RIB sites 5, 6, and 7 were 3.6, 4.4, and 7.3 Mgal/d, respectively; no reclaimed water was applied to the RIBs at Water Conserv II RIB site 9 during 1995. The largest water-table mound occurred at RIB site 5 (fig. 33), even though the reclaimed-water application rates were greater at RIB sites 6 and 7. A comparison of model-calibrated intermediate confining unit leakance (fig. 30) at the three RIB sites shows that leakance generally is highest at RIB site 7 and lowest at RIB site 5. That is, a higher intermediate confining unit leakance at RIB site 7 allows water in the surficial aquifer system to more easily move to the Upper Floridan aquifer, thereby reducing water-table altitude (fig. 34). The spatial distribution of RIBs also affects the height of water-table mounds. The 4.4 Mgal/d applied at RIB site 6, when considered on a flow per unit area basis, is less than 3.6 Mgal/d applied over the much smaller area of RIB site 5; consequently, even if hydrologic properties at the two sites were identical a higher water-table mound would exist at RIB site 5. The simulated water table at the RCID RIB site (fig. 35) is considerably flatter than that at Water Conserv II RIB sites 5, 6, or 7. The model-calibrated surficial aquifer system hydraulic conductivity of 150 ft/d (compared to 30 ft/d) allows water to more easily move laterally in the surficial aquifer system and subsequently discharge to local surface-water features. In addition, the intermediate confining unit leakance is relatively high and the RIBs are located over a fairly large area; both of these factors, in combination with the high surficial aquifer hydraulic conductivity, contribute to small water-table mounds at the RCID RIB site.

The simulated potentiometric surface of the Upper Floridan aquifer (fig. 36) generally agrees with that based on measured data (fig. 13). Local variations in the measured potentiometric surface (such as southeast of Lake Louisa, fig. 13) may be the result of reduced transmissivity caused by sand-filled cavities associated with sinkholes. No attempt was made to adjust hydrologic properties on a node-by-node basis to produce a closer match to these measurements. Large mounds in the simulated potentiometric surface of the Upper Floridan aquifer do not exist where they were present in the surficial aquifer system. This is the result of the high calibrated transmissivity of most of the Upper Floridan aquifer (fig. 29) which allows water to very easily move through the aquifer (compared to the surficial aquifer system) to points of discharge, such as wells and specified-head boundaries.

The simulated potentiometric surface of the Lower Floridan aquifer is shown in figure 37. The potentiometric surface of the Lower Floridan aquifer probably should more closely resemble that of the Upper Floridan aquifer; however, no data exist within the model area for confirmation.

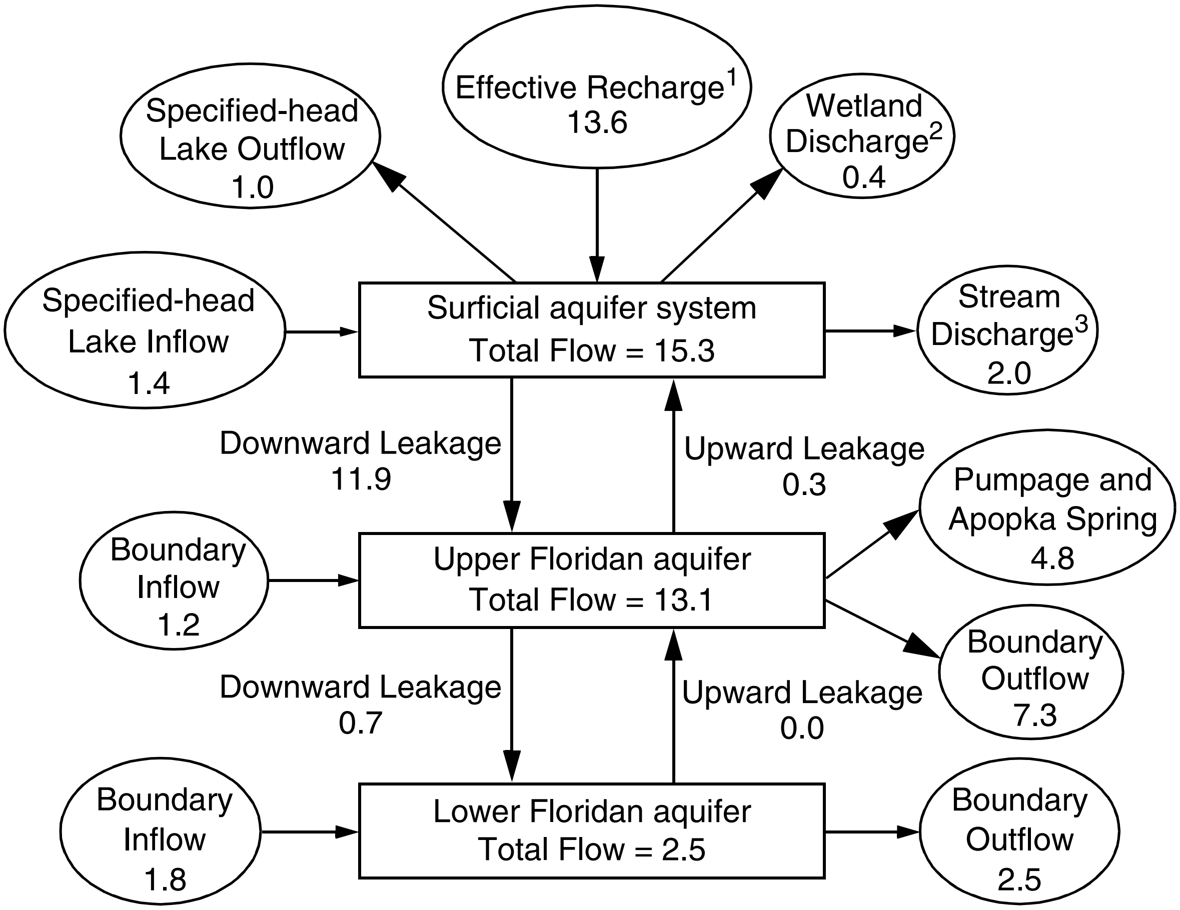
The volumetric water budget for the calibrated model is shown in figure 38. Of the 18 in/yr of flow through the surficial and Floridan aquifer systems (sum of inflows or outflows shown in “bubbles” in figure 38), about 75 percent consisted of effective recharge to the surficial aquifer system and the remaining 25 percent was inflow from specified-head boundaries. Most of the 18 in/yr circulated through the surficial aquifer system and the Upper Floridan aquifer. In addition, simulated net leakage between the surficial and Upper Floridan aquifer systems was 11.6 in/yr downward and represented 76 and 89 percent of the total flows in the surficial aquifer system and the Upper Floridan aquifer, respectively. These results are in agreement with the high leakance characteristics of the intermediate confining unit. Consequently, hydrologic conditions in the surficial aquifer system can have relatively significant effects on conditions in the Upper Floridan aquifer; likewise, hydrologic conditions in the Upper Floridan aquifer can have relatively significant effects on conditions in the surficial aquifer system. Little water from the Upper Floridan aquifer (about 5 percent of its total flow) reached the Lower Floridan aquifer. The small leakance assigned to the middle semiconfining unit (about 20 times smaller than the average leakance of the intermediate confining unit) inhibits the exchange of water between the Upper and Lower Floridan aquifers. Again, if data were available concerning the hydrologic properties of the middle semiconfining unit and the Lower Floridan aquifer, the resulting simulated flow system of the Floridan aquifer system might be different.



EXPLANATION

—120— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells. Contour interval 5 feet

Figure 37. Simulated potentiometric surface of the Lower Floridan aquifer, 1995.



[1]Reduced by 1.6 to account for increase in surficial aquifer system storage.
[2]Wetlands not draining to key gaging stations. Simulated by the MODFLOW Drain Package (fig. 22).
[3]All streams plus wetlands draining to key gaging stations. Simulated by the MODFLOW River Package (fig. 22).

Figure 38. Simulated volumetric water budget of the aquifer system in the model area, 1995. All values are in inches per year averaged over the model area.

The simulated water budget (fig. 38) compares reasonably well with the surficial aquifer system water budget discussed earlier in the report (fig. 18). Because effective recharge was specified in the model, the value of 13.6 in/yr is equal to the sum of its component values (eq. 8) shown in figure 18, with the exception of 0.7 in/yr of effective recharge that was applied to specified-head lakes and consequently was not accounted for by the model. The simulated stream discharge was less than the measured discharge in Little, Big, Whittenhorse, and Reedy Creeks (site numbers 24, 34, 57, and 62, fig. 2) because MODFLOW only simulates the ground-water discharge (base flow) component of stream discharge. The simulated net leakage to the Upper Floridan aquifer was approximately 30 percent greater than that estimated from the surficial aquifer system water budget. However, this difference probably is within the margin of error to which leakage to the Upper Floridan aquifer can be independently estimated.

Sensitivity Analyses

In order to determine how varying model parameters affected simulation results, each parameter, except *N*, was varied independently from 0.1 to 1 times its calibrated value (in increments of 0.1) and from 1 to 10 times its calibrated value (in increments of 1). Model sensitivity was described in terms of *RMSE*. The sensitivity of the model to changes in one parameter while all others were held at their calibrated values is shown in figure 39. The model is most sensitive to T_{u2} and K_{s1}; an increase of 2 times (or decrease of 0.5 times) the calibrated value of either parameter more than doubles *RMSE* to approximately

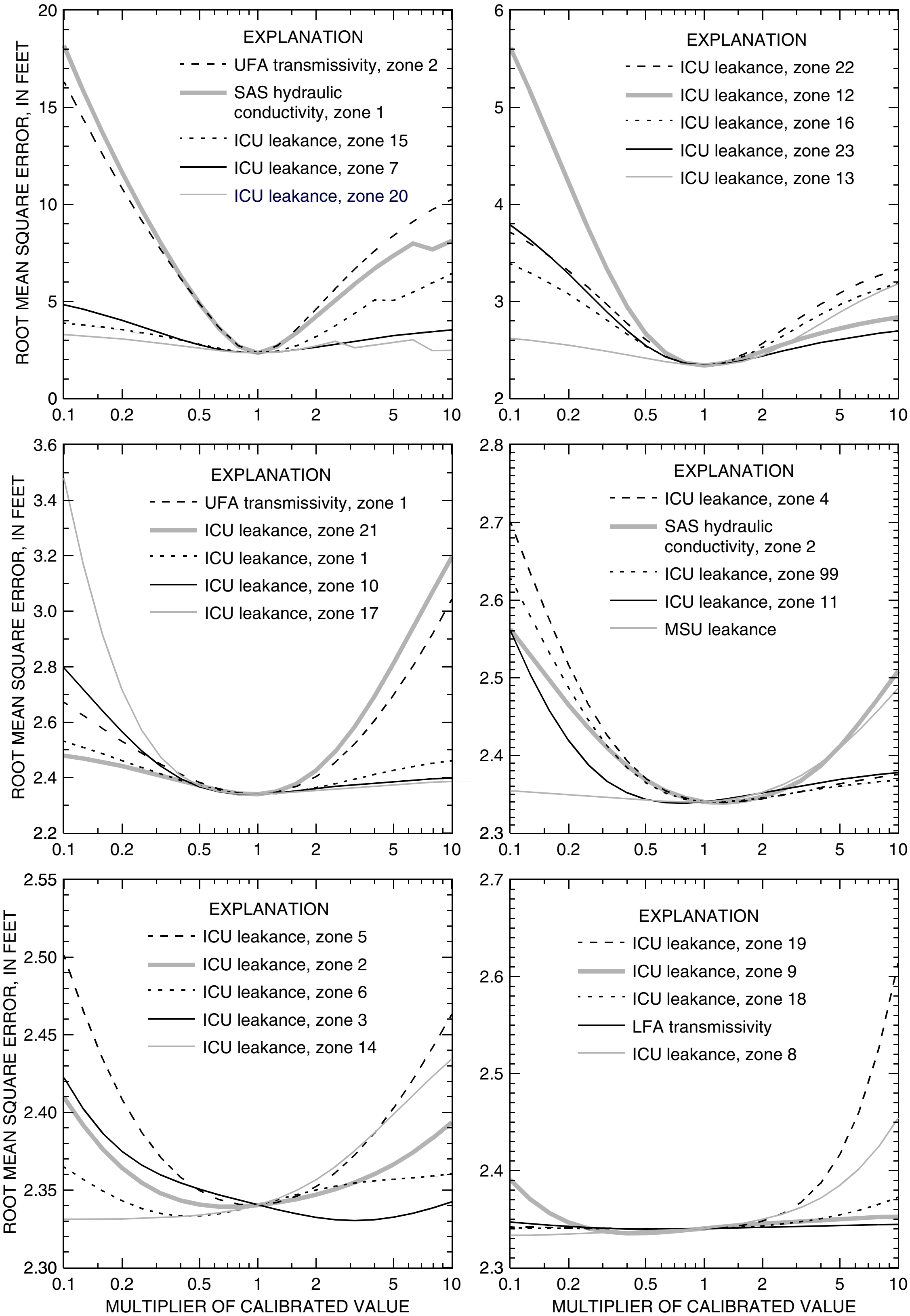


Figure 39. Model sensitivity to independent changes in selected model calibration parameters (SAS, surficial aquifer system; ICU, intermediate confining unit; UFA, Upper Floridan aquifer; MSU, middle semiconfining unit; LFA, Lower Floridan aquifer).

5 ft. For many of the parameters to which the model is least sensitive (for example, V_{18} and T_{lf}), an increase of 10 times (or decrease of 0.1 times) the calibrated value causes less than a 5 percent increase in *RMSE*.

Several other observations can be made concerning figure 39. The “kinks” in the sensitivity plots for K_{s1}, V_{15}, and V_{20} are most likely the result of surficial aquifer system cells going dry as hydraulic conductivity or leakance increases. *RMSE* could decrease as cells, where water-level measurements are located, go dry and are assigned a residual value of zero by the parameter estimation program. Many of the sensitivity plots minima do not occur at a multiplier value of 1. This only occurs in the less sensitive parameters (for example, V_3), and means that a slightly better *RMSE* could have been achieved had the parameter estimation routine been allowed to run through more iterations. However, notice that the absolute minimum *RMSE* could only be reduced by about 0.01 ft (from 2.34 to 2.33 ft). This small reduction in *RMSE* is insignificant and is well within the range of uncertainty of even the water-level measurements.

The magnitude of the main diagonal of the covariance matrix is a rough estimate of the relative sensitivity of the model to a parameter. Table 7 lists the normalized main diagonal value (that is, the main diagonal value divided by the maximum main diagonal value) for each parameter. The larger the value of the normalized main diagonal for a particular parameter, the more sensitive the model, as a whole, is to that parameter.

In considering model sensitivity to a particular parameter it is important to note both the areal size of its zone (relative to total model area) and the number of water-level measurements most influenced by the parameter (such as the number of measurements within its zone). For example, the model as a whole is very insensitive to the value of V_8 (table 7; fig. 39)—its area is only 0.1 percent of the total model area and there is only one water-level measurement within its zone. However, the altitude of the surficial aquifer system water table in the V_8 zone and its immediate vicinity is very sensitive to V_8. Zone areas and number of water-level measurements within a zone are included in table 7 for each parameter. This information along with the magnitude of the normalized main diagonal value and the sensitivity plots in figure 39 should all be considered when assessing, in a qualitative manner, the relative sensitivity of the model (either as a whole or locally) to each parameter.

A different type of sensitivity analysis was performed for effective recharge which entailed the recalibration of the model to two different sets of effective recharge values. Effective recharge was a specified, not a calibrated, parameter. An incorrectly specified effective recharge matrix would affect the values, to some degree, of all other calibrated parameters. Therefore, based on the uncertainty associated with the estimation of the component values of *N* (eq. 8) a low *N* matrix and a high *N* matrix were compiled to serve as lower and upper bounds on a range of most likely *N* matrix values. For the low *N* matrix, *ET* was increased by 15 percent and S_y was increased to 0.45; similarly, for the high *N* matrix, *ET* was decreased by 15 percent and S_y was decreased to 0.25. The calibrated parameter values for the model using the average 1995 *N* matrix were used as initial values for recalibration to the two alternative *N* matrices. However, to prevent surficial aquifer system cells from drying during recalibration to the low *N* alternative, all initial values of intermediate confining unit leakance parameters were divided by 2.

Model results using each of the three *N* matrices indicate that most parameters did not change significantly, with the exception of T_{u1}, T_{u2}, and some leakance parameters (table 9). Even though some individual leakance parameters changed significantly, the zone-area-weighted average leakance of the intermediate confining unit changed only slightly for the two alternative *N* matrices. A 46 percent increase in Upper Floridan aquifer transmissivity (zone-area-weighted average of T_{u1} and T_{u2} for the high *N* alternative) caused by a 45 percent increase in *N* indicates a high correlation between these parameters. In fact, the model calibrated to the high *N* alternative has a slightly smaller *RMSE* than the model calibrated to the average 1995 *N* alternative. However, such a small reduction in RMSE is not enough to discount the average 1995 *N* values, which are better supported by independent data. The low *N* alternative probably is not an accurate representation because the average error could never be reduced to 0 or nearly 0; consequently, the *RMSE* was greater, though not drastically greater. The alternative models show that a relatively small *RMSE* alone does not assure a well calibrated model and either some stresses or hydraulic conductivities must be known.

Lateral flow probably occurs across model boundaries in some areas of the surficial aquifer system (fig. 11); however, the locations of lateral flow are not well known because few measured water-level

Table 9. Calibrated and alternative values of parameters using alternative effective recharge values

[in/yr, inch per year; *ET*, evapotranspiration averaged over model area; Δ*S*, change in surficial aquifer system storage averaged over model area; *N*, effective recharge averaged over model area; ICU, intermediate confining unit; RMSE, root mean square error]

Parameter[a]	Calibrated parameter value		
	Average 1995 effective recharge	Low effective recharge	High effective recharge
	ET = 38.30 in/yr ΔS = 1.63 in/yr N = 14.27 in/yr	ET = 44.01 in/yr ΔS = 2.10 in/yr N = 8.06 in/yr	ET = 32.53 in/yr ΔS = 1.17 in/yr N = 20.47 in/yr
K_{s1}	30	29	31
K_{s2}[b]	150	150	150
V_1	4.1x10^{-4}	2.7x10^{-4}	6.2x10^{-4}
V_2	13x10^{-4}	26x10^{-4}	11x10^{-4}
V_3	47x10^{-4}	41x10^{-4}	53x10^{-4}
V_4	42x10^{-4}	55x10^{-4}	41x10^{-4}
V_5	53x10^{-4}	41x10^{-4}	55x10^{-4}
V_6	21x10^{-4}	13x10^{-4}	16x10^{-4}
V_7	6.9x10^{-4}	4.8x10^{-4}	8.3x10^{-4}
V_8	0.55x10^{-4}	0.24x10^{-4}	0.51x10^{-4}
V_9	72x10^{-4}	20x10^{-4}	70x10^{-4}
V_{10}	18x10^{-4}	15x10^{-4}	19x10^{-4}
V_{11}	69x10^{-4}	58x10^{-4}	56x10^{-4}
V_{12}	54x10^{-4}	70x10^{-4}	48x10^{-4}
V_{13}	1.0x10^{-4}	0.37x10^{-4}	1.9x10^{-4}
V_{14}	1.2x10^{-4}	0.40x10^{-4}	1.3x10^{-4}
V_{15}	2.3x10^{-4}	2.4x10^{-4}	2.2x10^{-4}
V_{16}	8.3x10^{-4}	7.8x10^{-4}	8.5x10^{-4}
V_{17}	38x10^{-4}	29x10^{-4}	39x10^{-4}
V_{18}	0.66x10^{-4}	0.49x10^{-4}	0.64x10^{-4}
V_{19}	0.32x10^{-4}	0.15x10^{-4}	0.33x10^{-4}
V_{20}	2.1x10^{-4}	1.7x10^{-4}	2.4x10^{-4}
V_{21}	2.0x10^{-4}	1.6x10^{-4}	2.4x10^{-4}
V_{22}	1.0x10^{-4}	0.63x10^{-4}	1.4x10^{-4}
V_{23}	4.1x10^{-4}	2.8x10^{-4}	5.5x10^{-4}
V_{99}	40x10^{-4}	45x10^{-4}	46x10^{-4}
T_{u1}	0.30[c]	0.24[c]	0.50[c]
T_{u2}	2.0[c]	1.4[c]	2.7[c]
Average ICU leakance[d]	9.3x10^{-4}	10x10^{-4}	9.8x10^{-4}
Average error	0.02	-0.26	0.07
RMSE	2.34	2.75	2.31

[a] See table 6 for parameter symbol definitions.

[b] K_{s2} was not allowed to exceed 150 ft/day. A higher value would have yielded a smaller RMSE but probably is not realistic.

[c] This value is a multiplier for the spatially variable parameter values.

[d] Average ICU leakance weighted by zone area from table 7.

data were available near model boundaries. Therefore, in order to test model sensitivity to surficial aquifer system boundary conditions, all cells adjacent to the lateral model boundary were assigned specified-head values (interpolated from fig. 11). A comparison of model results from two model simulations, one using the specified-head surficial aquifer system boundary condition and one using the no-flow boundary condition, was made for all interior model cells (that is, excluding all cells adjacent to model boundaries in all three layers). Only interior model cells were compared because MODFLOW does not calculate flows between specified-head cells (for example, a specified-head surficial aquifer system cell overlying a specified-head Upper Floridan aquifer cell). Model results for the specified-head boundary condition compared to the no-flow boundary condition indicate the following: (1) the average simulated water table was 0.14 ft higher (less than 0.01 ft higher at reclaimed-water application sites), (2) the average rate of leakage through the intermediate confining unit decreased 0.01 in/yr, and (3) the average flux in the surficial aquifer system from interior model cells to lateral boundary cells increased 0.05 in/yr. These results are in agreement with the hypothesis that regional lateral flow in the surficial aquifer system is minimal. Consequently, the model is insensitive to changes in the surficial aquifer system boundary condition.

HYDROLOGIC EFFECTS OF RECLAIMED-WATER APPLICATION

The ground-water flow model was used in conjunction with particle-tracking analyses and analyses of existing data to form a process-oriented evaluation of the hydrologic effects of reclaimed water applied by the Water Conserv II and RCID facilities. Specifically, this evaluation includes an appraisal of the following under current (1995) and proposed future conditions: changes in surface-water and ground-water levels, directions and rates of reclaimed water movement through the surficial and Floridan aquifer systems, and locations and magnitudes of reclaimed water discharge from the surficial and Floridan aquifer systems.

MODPATH (Pollock, 1994), a USGS particle-tracking program, was used to supplement ground-water flow model results. The program tracks “particles” of water based on output from MODFLOW simulations. Particle-tracking can only simulate the advective transport of solutes and cannot be used to calculate solute concentrations in ground water because it does not consider dispersion, degradation, or retardation processes.

Aquifer and confining unit top altitudes, base altitudes, and effective porosities are the only hydrologic data required, in addition to standard MODFLOW input and output, for a steady-state particle-tracking analysis. Aquifer and confining unit top and base altitudes were based on interpolation of data collected during this study as well as data reported by Miller (1986), as previously discussed (for example, fig. 8). Inaccuracies in aquifer or confining unit top or base altitudes can affect particle-tracking results. For example, particle traveltime through a confining unit simulated by a leakance array is directly proportional to confining unit thickness. The mantled karst environment in the study area makes accurately defining aquifer and confining unit top and base altitudes very difficult. Consequently, interpolated data are necessarily generalized and can differ significantly from actual values at any particular site.

Effective porosity is the fraction of interconnected pore space in a volume of rock or unconsolidated sediment. Particle traveltimes are proportional to the effective porosity estimates; if effective porosity estimates are doubled, ground-water velocities will be halved and traveltimes will double. No data exist in the study area on effective porosity of the aquifers or confining units. Measurements of the total porosity of the surficial aquifer system range from 0.36 to 0.51 (Camp Dresser and McKee, Inc., 1984; Sumner and Bradner, 1996); an effective porosity value of 0.40 was used for the surficial aquifer system and intermediate confining unit. The choice of a representative effective porosity value for the Floridan aquifer system is complicated by the dual porosity characteristic of karst limestone. That is, total porosity can consist of primary or rock porosity, which is characteristic of an unfissured volume of rock, and secondary porosity, which is the result of fissures and solution openings. Robinson (1995) performed particle-tracking analyses to simulate ground-water traveltimes measured during tracer tests conducted in the Upper Floridan aquifer in Hillsborough County, Florida. Effective porosity values of 0.003 to 0.015 were required to reproduce the traveltime for the first peak in tracer concentration, whereas a value of 0.21 was required to reproduce the traveltime for the second peak in tracer concentration. Robinson (1995) indicated that this bimodal distribution of tracer arrival time probably was the result of conduit flow through secondary porosity producing the first peak and diffuse flow through the rock matrix (primary porosity) producing the second peak. Laboratory measurements of effective porosity reported by Knochenmus and Robinson (1996) for rock cores from wells in Hillsborough, Pasco, and Pinellas Counties, Florida, were 0.17 to 0.49 for the Ocala Limestone and 0.02 to 0.25 for the Avon Park Formation. Given these uncertainties, a uniform effective porosity value of 0.20 was used for the Upper and Lower Floridan aquifers and the middle semiconfining unit.

Particle starting locations were based on reclaimed water volumetric flow rates so that one particle represented approximately 1,000 gal/d of applied reclaimed water. For example, a model cell completely containing one RIB which receives 64,000 gal/d of reclaimed water would have 64 evenly spaced particles assigned to that cell. Particles were allowed to move through the ground-water system in a forward-tracking manner until they exited the model.

In interpreting the particle-tracking results discussed in the following sections, it is important to remember that a steady-state analysis does not allow for temporal variations in hydrologic stresses. For example, reclaimed water has not always been applied at the same rates and locations as it was in 1995. If the historical hydrologic stresses had been applied in a transient analysis, reclaimed water traveltimes and directions could have been different than those discussed below. For example, a transient simulation and particle-tracking analysis where the spatial distribution of reclaimed water remained constant over time but the application rate increased from 10 to 20 Mgal/d over a 10-year period probably would produce slower ground-water velocities and shallower reclaimed water flow paths compared to a steady-state analysis that assumes a constant 20 Mgal/d application rate. Similarly, spatial variations in application rate over time probably would cause movement of reclaimed water in different directions as well as with different traveltimes under transient conditions as compared to steady-state conditions where spatial variations remain constant over time.

Effects Under Current Conditions

Reclaimed-water application (2.5 in/yr) accounted for approximately 14 percent of the total simulated flow (18 in/yr, fig. 38) through the surficial and Floridan aquifer systems in the model area in 1995. This result is significant considering the RIBs and irrigation sites combined area comprises only about 3 percent of the total 285 mi^2 model area. Reclaimed water is not spread uniformly across the model area; in areas such as RIB sites, reclaimed-water application dominates the hydrologic system, exceeding natural net recharge rates by 10 times or more. Consequently, reclaimed-water application probably has altered the hydrologic system to some degree.

Actual pre-application conditions (for example, during 1985 before either facility started operation) could not be accurately determined because few historical data are available on aquifer stresses. Therefore, an assumed pre-application condition was simulated by removing all reclaimed-water application stresses and leaving all other stresses unchanged from their 1995 values, except ET at reclaimed-water irrigation sites which were assigned ET values for herbaceous vegetation (table 4). A new effective recharge array (eq. 8) was calculated using the revised ET values and excluding reclaimed water components, R_{RIB} and R_{ri}, of R_a. Consequently, differences between simulation results from the assumed pre-application conditions and the 1995 conditions are the result of only two factors—the absence of reclaimed-water application and the reduction in associated ET. It is important to note that water levels at specified-head boundaries (figs. 22 and 23) are not simulated and will show no change in the figures referenced in the following discussion.

Reclaimed-water application has caused the surficial aquifer system water table to increase in altitude over much of the model area (fig. 40). The increase has been slight (average about 2 ft) in the Water Conserv II irrigation areas, which probably is within the range of uncertainty associated with the assumed pre-application condition. In 1995, the average citrus grove using Water Conserv II reclaimed water was irrigated at a rate of 20 to 30 in/yr. With average precipitation and citrus ET of 52 and 45 in/yr, respectively, average net recharge would be about 32 in/yr; alternatively, with herbaceous vegetation ET of 27 in/yr, and no irrigation, average net recharge would be 25 in/yr. That is, much of the irrigation water is lost to the higher ET of the irrigated citrus, causing only a relatively small rise in the water table. This effect of ET on net recharge also explains the slight decrease in water-table altitude south of Johns Lake (fig. 40).
A relatively small amount of reclaimed water was applied during 1995 to the citrus groves south of Johns Lake. This produced an average net recharge of only

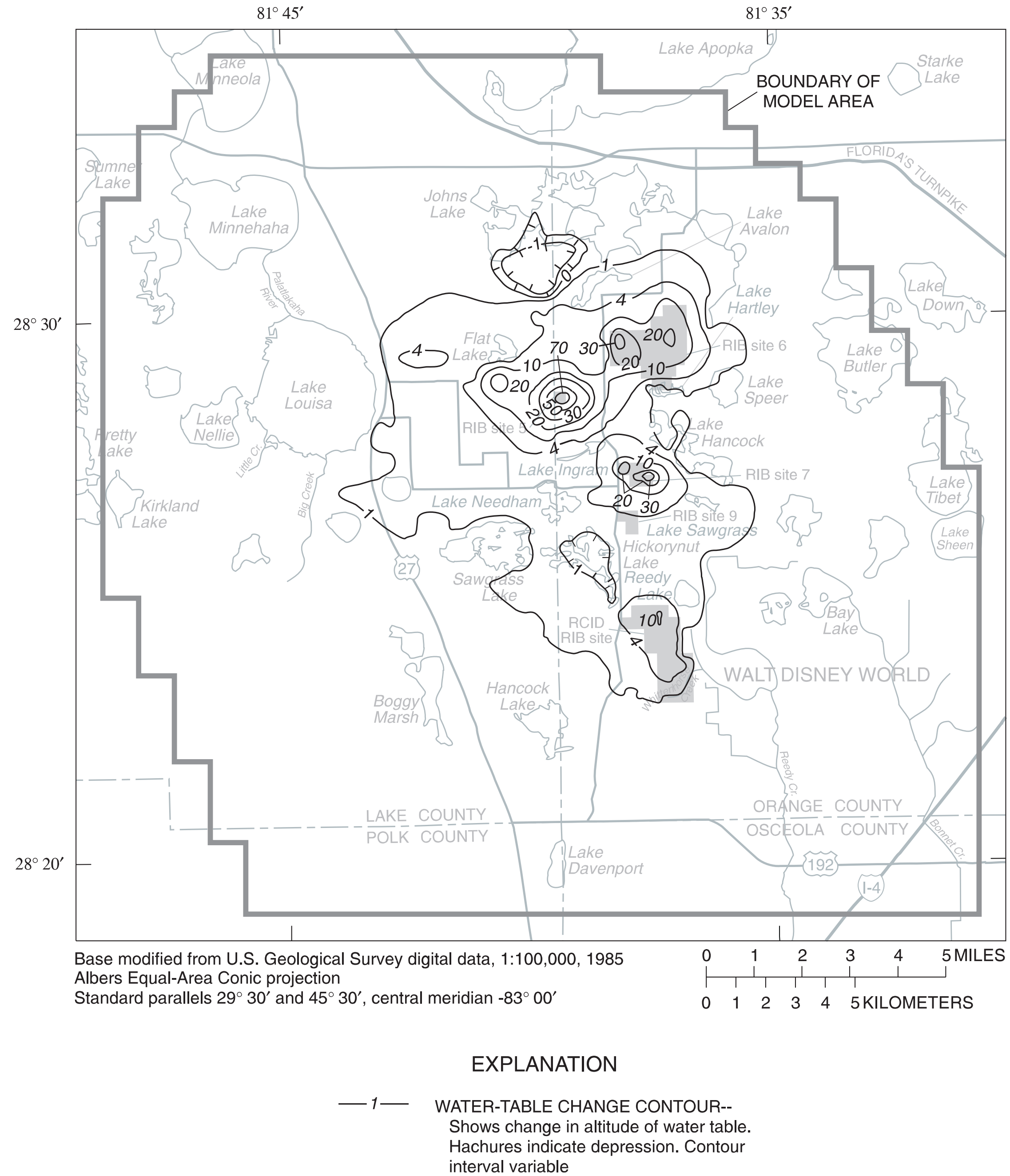


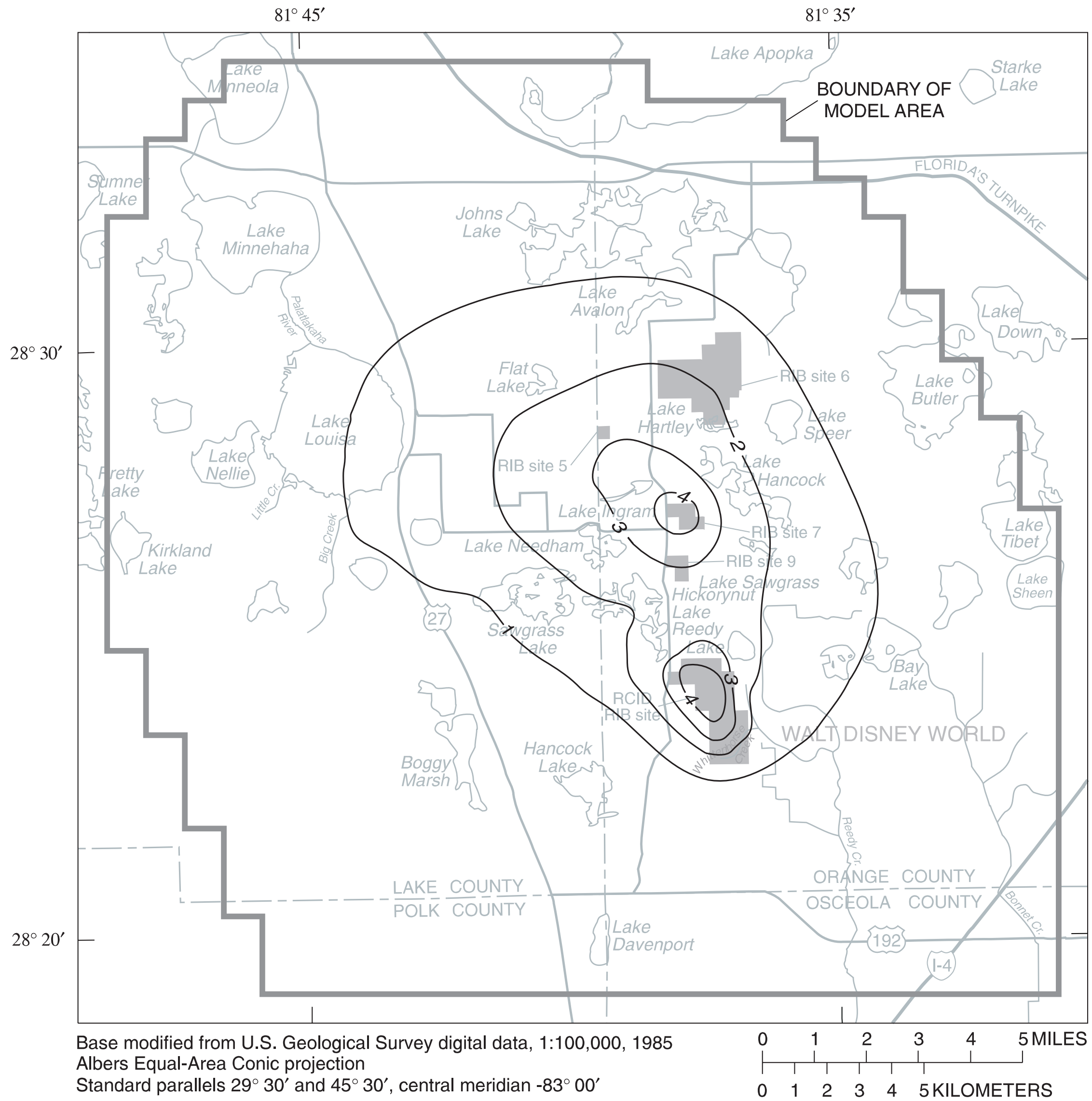
Figure 40. Simulated change in the surficial aquifer system water table from assumed pre-application conditions as a result of steady-state 1995 reclaimed-water application rates.

about 10 in/yr in 1995, compared to 25 in/yr under assumed pre-application conditions. Significant water-table mounds exist under all RIB sites (except Water Conserv II RIB site 9, which is rarely used). Based on pre-application water-level data reported by Camp Dresser and McKee, Inc. (1984) the average increase in water-table altitude from pre-application to 1995 has been approximately 40, 15, and 25 ft at Water Conserv II RIB sites 5, 6, and 7, respectively. CH2M Hill (1989) reported an average pre-application water-table altitude of 99 ft at the RCID RIB site; 1995 measured data indicate about a 5-ft increase in the water-table altitude as a result of RIB operation. These data probably have a margin of error of about 5 ft, because they do not represent average annual values and were collected in years that may have been hydrologically different from 1995 (for example, greater rainfall or less citrus irrigation). Nevertheless, these measured rises in water-table altitude generally agree with figure 40, with the exception of Water Conserv II RIB site 5. Model simulation indicates approximately a 70-ft increase at this RIB site. This discrepancy could be caused by the pre-application condition assumptions. The relatively small simulated increase in water-table altitude at the RCID RIB site is the result of high intermediate confining unit leakance, high surficial aquifer system hydraulic conductivity, and the presence of nearby surface-water features that receive ground-water discharging from the surficial aquifer system.

The accuracy of simulated increases in lake levels is difficult to ascertain and can be affected by a number of factors. The response of a lake to hydrologic stresses can be significantly affected by very local-scale hydrologic and lithologic conditions. Lee and Swancar (1997) reported that leakage through a lakebed to the Upper Floridan aquifer decreased dramatically as the surficial aquifer system vertical anisotropy (the ratio of horizontal to vertical hydraulic conductivity) increased, based on ground-water flow modeling of Lake Lucerne in Polk County. The model presented in this report represents an isotropic ground-water flow system on a more regional scale and generally does not account for variations at the scale of an individual lake; such variations are likely to exist but their magnitude and spatial distribution are unknown. Nevertheless, a qualitative interpretation of water-level changes in landlocked lakes can be estimated from figure 40. As previously explained, specified-head lakes will show no change in figure 40 (for example, Lake Hancock). In areas of high intermediate confining unit leakance, qualitative water-level changes in specified-head lakes might be inferred from simulated changes in the Upper Floridan aquifer potentiometric surface (fig. 41). Lakes Ingram, Flat, Reedy, Needham, Sawgrass (south of Hancock), Avalon, Hancock, and Hartley (fig. 40) are most likely to have had a rise in lake level induced by reclaimed-water application. Stream outflow might have mitigated lake-level rises in Lakes Hancock and Hartley. That is, an increase in lake level would be minimal if the increase in ground-water discharge to the lake caused by reclaimed-water application were balanced by a corresponding increase in stream outflow.

Increases in the Upper Floridan aquifer potentiometric surface caused by 1995 reclaimed-water application rates were less than 5 ft and were greatest under Water Conserv II RIB site 7 and the RCID RIB site (fig. 41). Water-level data collected since 1979 at an Upper Floridan aquifer well (site number 85, fig. 3) support the simulated increase in the potentiometric surface at the RCID RIB site. Measured water levels rose in this well from May 1990 to September 1991 (RCID RIB operation started September 1990) and have remained about 4 ft higher than pre-1990 water levels since 1991. The relatively small increase in the potentiometric surface under most of the reclaimed-water application sites, which is less than the typical seasonal variations due to rainfall, should not be interpreted to mean that little reclaimed water reaches the Upper Floridan aquifer. The high transmissivity of the Upper Floridan aquifer precludes the formation of large potentiometric-surface highs under average 1995 stresses, even though most of the reclaimed water is simulated to reach the aquifer.

Simulated leakage rate through the intermediate confining unit provides a better indication of the quantity and spatial distribution of surficial aquifer system water (which includes reclaimed water) that recharges the Floridan aquifer system (fig. 42). The highest rates of recharge to the Floridan aquifer system typically occur under reclaimed-water application sites, especially RIB sites. The simulated net leakage to the Floridan aquifer system under the assumed pre-application condition was 10.4 in/yr (averaged over the model area); therefore, the 11.6 in/yr simulated under 1995 conditions represents about a 10 percent increase in recharge to the Floridan aquifer system. The distribution of leakage rates generally were similar to effective recharge rates



Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Albers Equal-Area Conic projection
Standard parallels 29° 30′ and 45° 30′, central meridian -83° 00′

EXPLANATION

— 1 — POTENTIOMETRIC CHANGE CONTOUR -- Shows change in altitude of water level which would have occurred in tightly cased wells. Contour interval 1 foot

Figure 41. Simulated change in the Upper Floridan aquifer potentiometric surface from assumed pre-application conditions as a result of steady-state 1995 reclaimed-water application rates.

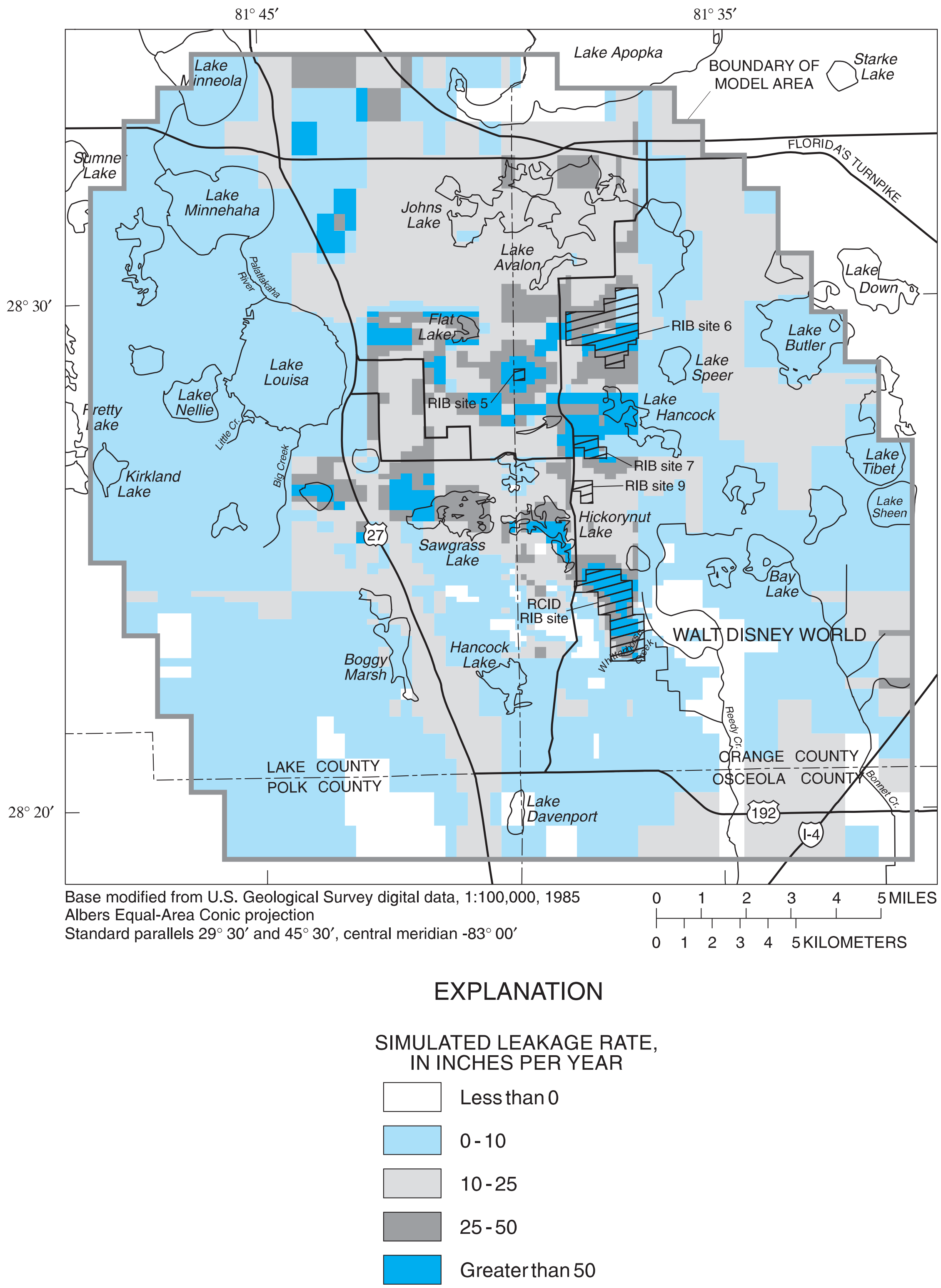


Figure 42. Simulated rate of leakage through the intermediate confining unit based on steady-state 1995 conditions.

(compare figs. 26 and 42), because the surficial aquifer system is dominated by diffuse downward leakage to the Floridan aquifer system in the study area. The largest differences were in areas where leakance of the intermediate confining unit is low or the potentiometric surface of the Upper Floridan aquifer was above the surficial aquifer system water table. Low leakance of the intermediate confining unit induces water in the surficial aquifer system to flow laterally until it discharges to surface-water features, is extracted by ET, or enters an area of higher leakance where it may more easily reach the Upper Floridan aquifer. Upward leakage from the Upper Floridan aquifer to the surficial aquifer system occurs where the potentiometric surface is above the water table (for example, along Reedy Creek and around Lake Apopka, fig. 42). Effective recharge to the surficial aquifer system in these areas is lost to ET or stream discharge and does not reach the Floridan aquifer system.

Reclaimed-water application has caused increases in ground-water levels and Floridan aquifer system recharge rates over much of the model area. However, reclaimed water is not necessarily present in the aquifer system everywhere it has induced a change in ground-water levels. For example, a local water-table mound produced by reclaimed-water application can cause an increase in the regional water-table altitude upgradient from the mound (even though no reclaimed water is present upgradient) by acting like a hydraulic dam to regional ground-water flow and decreasing the regional water-table gradient. Particle-tracking analyses were performed to help determine where reclaimed water could be present in the surficial and Upper Floridan aquifer systems, how long it takes reclaimed water to travel through the ground-water system, and in what quantities and areas reclaimed water discharges from the ground-water system.

Figure 43 depicts the maximum lateral extent of reclaimed water in the surficial aquifer system based on particle tracking analyses of simulated steady-state 1995 conditions. Reclaimed water in the surficial aquifer system generally does not travel far beyond application site boundaries because there is very little lateral flow in the surficial aquifer system. The large area of reclaimed water along Reedy Creek east of the RCID RIB site is not caused by lateral flow in the surficial aquifer system (fig. 43). Rather, some reclaimed water at the RCID RIB site moves through the intermediate confining unit, travels east through the Upper Floridan aquifer, moves upward back through the intermediate confining unit, and finally discharges from the surficial aquifer system to Reedy Creek and adjacent wetlands. Very little interaction occurs between Water Conserv II and RCID reclaimed water in the surficial aquifer system, except in a small area northwest of the RCID RIB site at some citrus groves which use Water Conserv II reclaimed water.

The traveltime of reclaimed water from the water table to the top of the Upper Floridan aquifer varies greatly (fig. 44), depending largely upon the reclaimed-water application rate. That is, traveltime is shorter in a vigorous flow system (for example, Water Conserv II RIB site 5 or the RCID RIB site) and longer in a more sluggish flow system (for example, citrus groves south of Johns Lake). Based on simulated steady-state 1995 conditions, the minimum and average traveltimes to the top of the Upper Floridan aquifer are approximately 1 and 10 years, respectively, for Water Conserv II reclaimed water and approximately 2 and 7 years, respectively, for RCID RIB reclaimed water. Water Conserv II RIB sites generally have shorter traveltimes than the RCID RIB site because the application flux rate generally is higher; the 10 year average traveltime for Water Conserv II reclaimed water is skewed somewhat by the longer traveltimes for the irrigation reclaimed water.

Not all reclaimed water exits the surficial aquifer system by leakage to the Floridan aquifer system—some of the water discharges to lakes, streams, and wetlands. The only area of significant discharge of reclaimed water to surface-water features is in the vicinity of the RCID RIB site. Based on simulated steady-state 1995 conditions, RCID reclaimed water is discharging to Bear Bay and other wetlands, Whittenhorse Creek, Perimeter and C-4 Canals, and Reedy Creek (fig. 45). This conclusion is supported by the increase in chloride concentration measured in Whittenhorse Creek (fig. 17) and the Perimeter Canal, as previously described.

Reclaimed water that has traveled through the intermediate confining unit next enters the Upper Floridan aquifer and flows primarily laterally in a direction perpendicular to potentiometric-surface contour lines. Consequently, reclaimed water could potentially be present within the Upper Floridan aquifer over a much larger area than in the surficial aquifer system (fig. 46). As depicted by the traveltime markers on selected pathlines shown in figure 46, it would take over 100 years for the reclaimed water to reach its maximum lateral extent in the model area. Traveltime of reclaimed water in the Upper Floridan aquifer is quite variable, and like the surficial aquifer

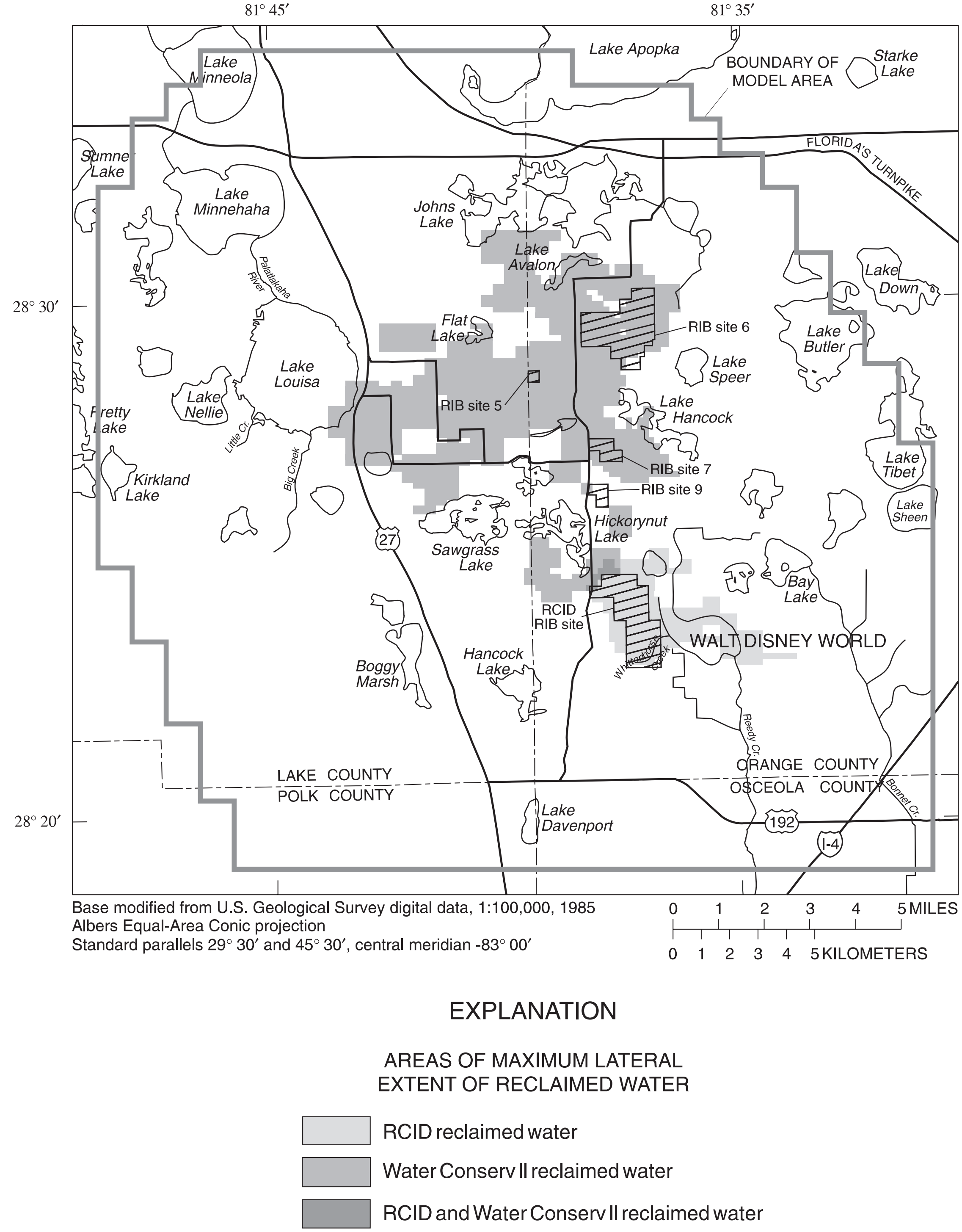


Figure 43. Areas where reclaimed water is expected to be present in the surficial aquifer system based on particle-tracking analyses of simulated steady-state 1995 conditions.

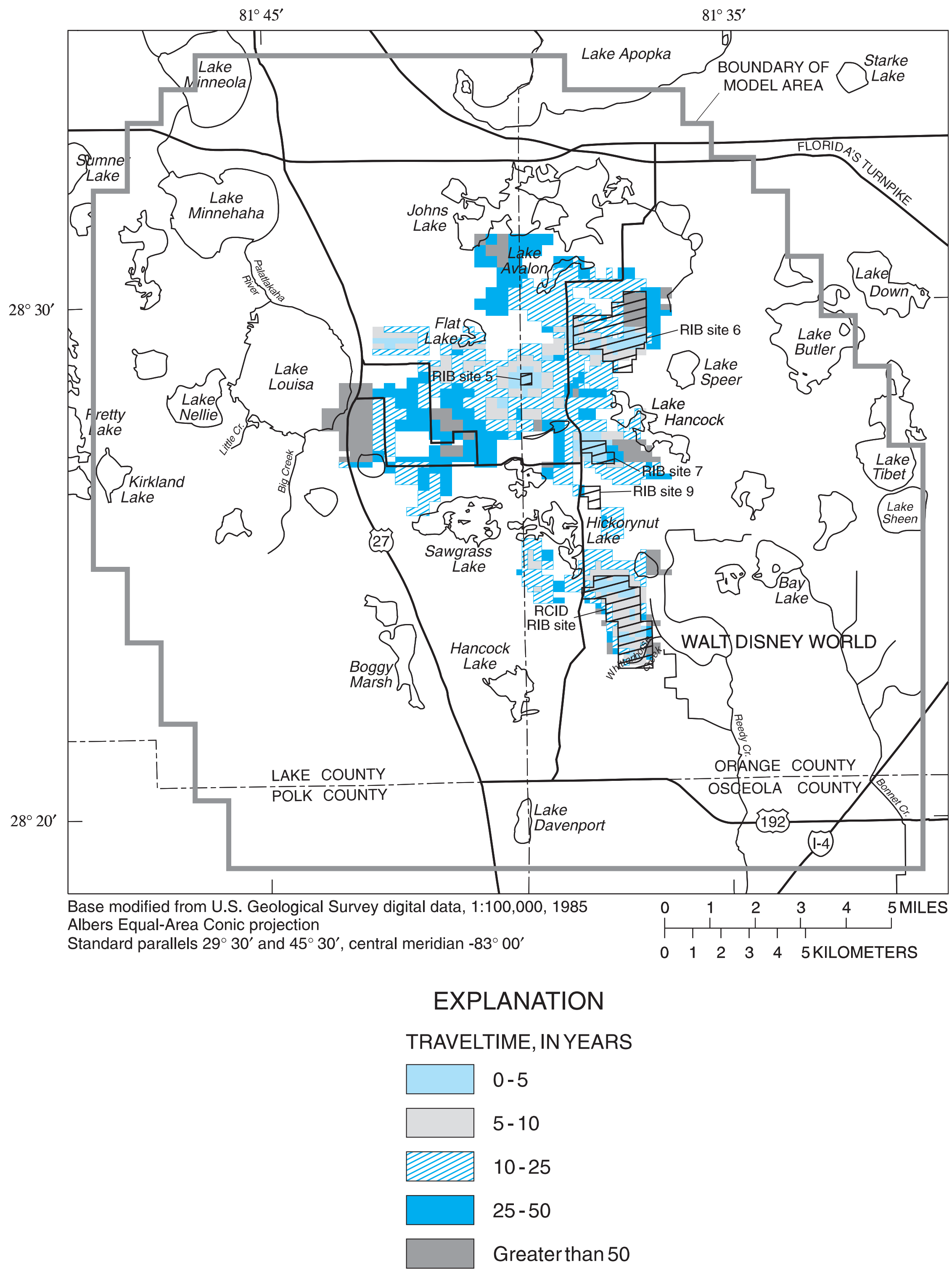


Figure 44. Traveltime of reclaimed water from the surficial aquifer system water table to the top of the Upper Floridan aquifer based on particle-tracking analyses of simulated steady-state 1995 conditions.

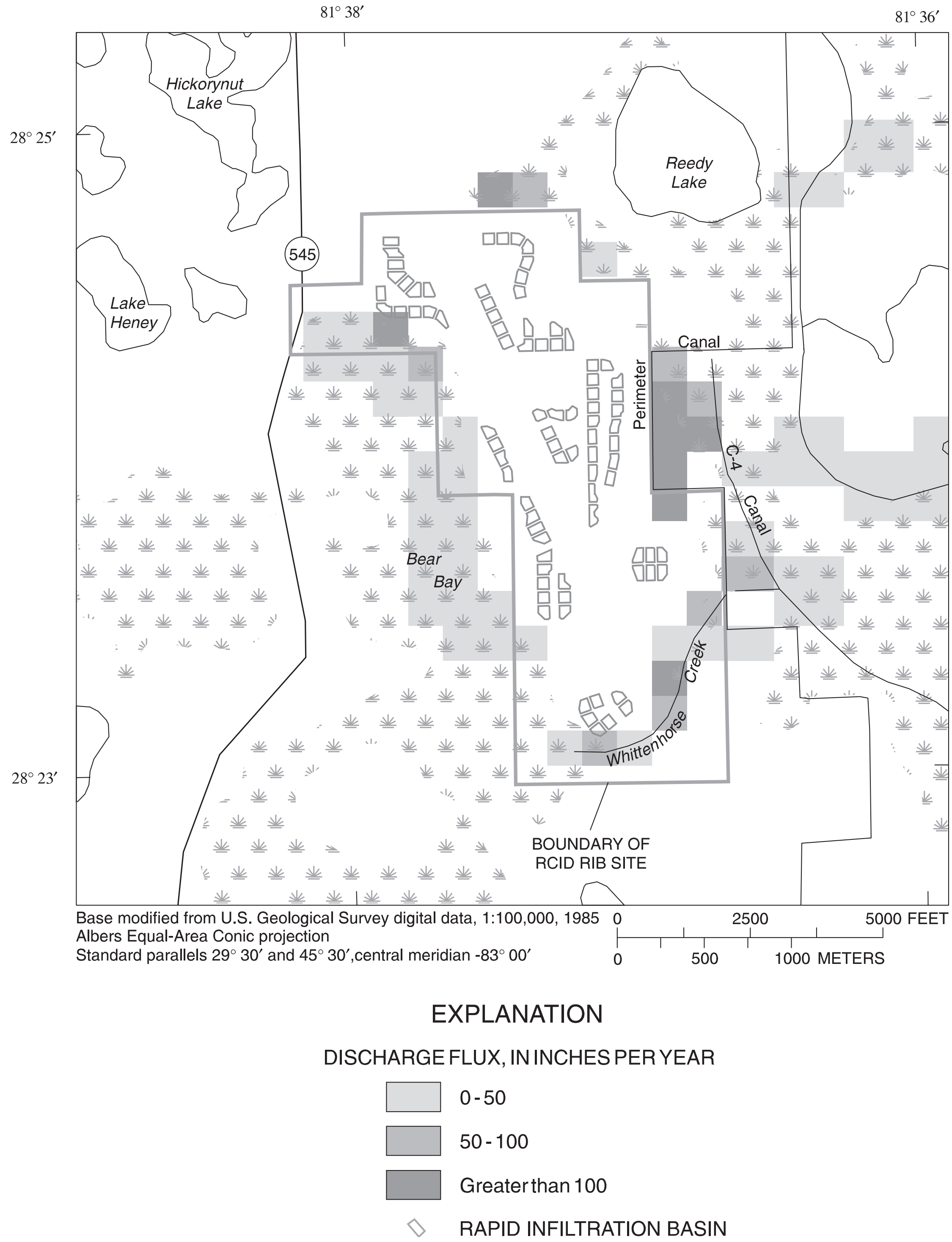


Figure 45. Areas of discharge of reclaimed water from the surficial aquifer system to surface-water features at the RCID RIB site and vicinity based on particle-tracking analyses of simulated steady-state 1995 conditions.

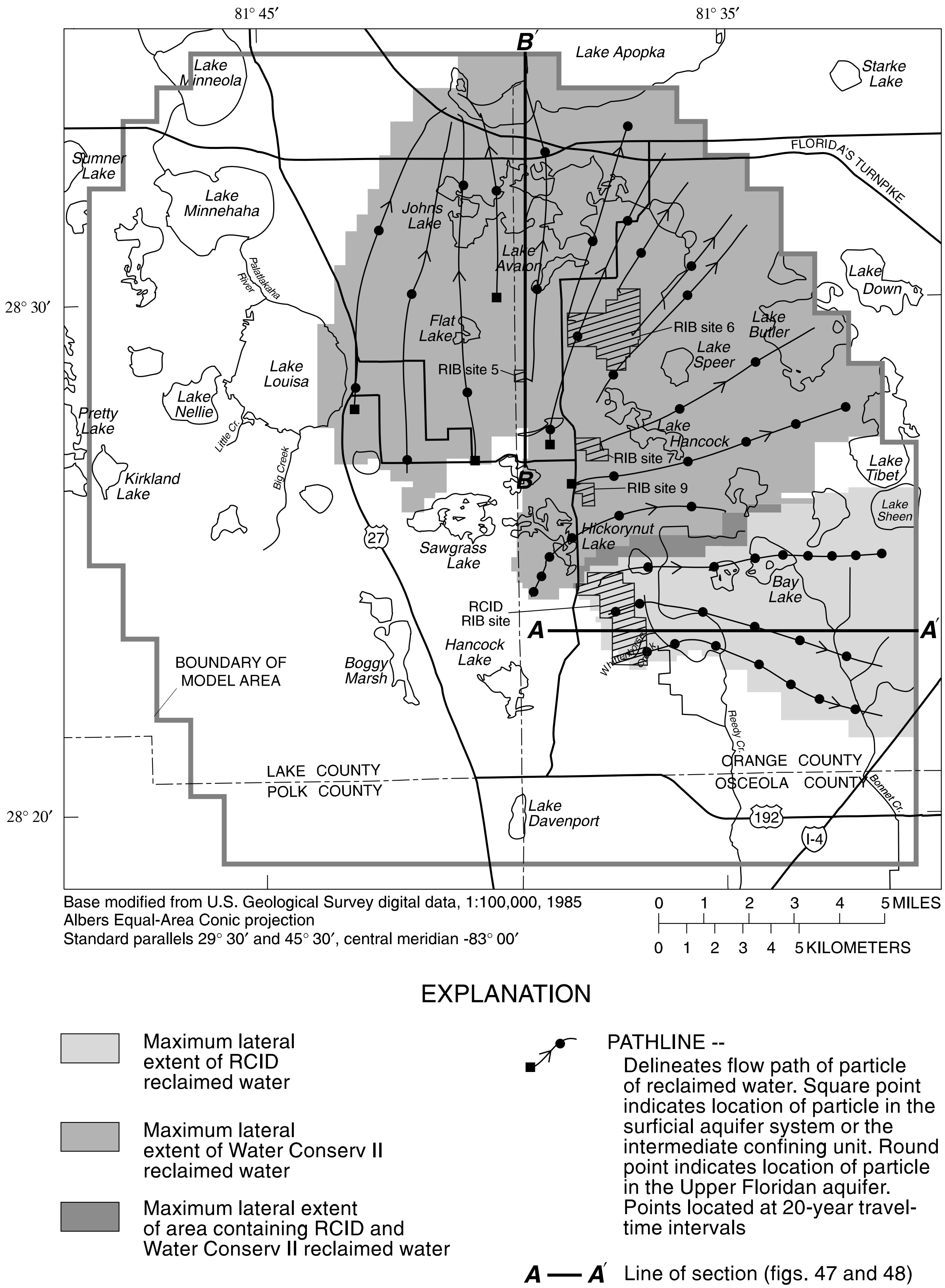


Figure 46. Areas where reclaimed water is expected to be present in the Upper Floridan aquifer and pathlines depicting directions and rates of movement of reclaimed water based on simulated steady-state 1995 conditions.

system it is largely dependent upon the local flow system. For example, reclaimed water that is within the capture area of Apopka Spring moves relatively rapidly compared to reclaimed water moving under Reedy and Bonnet Creeks. Similar to the surficial aquifer system, there is only a small area of possible mixing of Water Conserv II and RCID RIB reclaimed water in the Upper Floridan aquifer (fig. 46).

Reclaimed water is not necessarily uniformly distributed over the vertical extent of the surficial and Upper Floridan aquifers. Figures 47 and 48 show cross-sectional views of the directions and rates of movement of reclaimed water from two RIB sites. Because these figures depict three-dimensional pathlines that have been projected into two dimensions, the pathlines do not always lie within the vertical plane of the section line, which can produce apparent crossing of pathlines within a single model layer (see Upper Floridan aquifer, fig. 48). These figures demonstrate some of the major differences between the hydrologic characteristics of the RCID and Water Conserv II facilities. Several typical flow paths of RCID RIB reclaimed water that discharge to surface-water features are depicted in figure 47 by pathlines which terminate in Bear Bay, Perimeter and C-4 Canals, Reedy Creek, and other wetlands. At Water Conserv II, the lack of a well developed surface-water drainage network in close proximity to application sites allows very little discharge of reclaimed water to surface-water features. In addition, the RCID RIB site generally is surrounded by areas of low recharge to or discharge from the Upper Floridan aquifer (fig. 42). As a result, reclaimed water can more easily penetrate the entire depth of the aquifer. In contrast, Water Conserv II RIB site 5 is surrounded by areas of high recharge which constrain the reclaimed water to a smaller flow path within the Upper Floridan aquifer (fig. 48). Higher recharge also contributes to the typically shorter traveltimes of the Water Conserv II reclaimed water (evidenced by comparison of traveltime markers on pathlines in figs. 47 and 48).

Vertical anisotropy could change particle pathlines and traveltimes by increasing the resistance to vertical flow through the aquifer system. Therefore, the effects of aquifer vertical anisotropy on particle-tracking results were investigated by running the model under anisotropic conditions. In the following discussion, the magnitude of vertical anisotropy is represented by the result of dividing horizontal by vertical hydraulic conductivity. Vertical anisotropy is common in many rocks and unconsolidated sediments, and it is not unusual to find vertical anisotropy of 5 or 10 (Bouwer, 1978). Camp Dresser and McKee, Inc. (1984) reported horizontal and vertical hydraulic conductivities with vertical anisotropy values of 1 to 3 for the surficial aquifer system at Water Conserv II RIB site 6. Sumner and Bradner (1996) reported a vertical anisotropy of 3.3 for the surficial aquifer system at the RCID RIB site based on model-calibrated hydraulic conductivities. Available data based on analyses of rock cores from the Upper Floridan aquifer indicate highly variable vertical anisotropy values of 0.002 to 267 for the Ocala Limestone and 0.9 to 8 for the Avon Park Formation (Robinson, 1995).

In order to incorporate vertical anisotropy into the present model, the surficial and Upper Floridan aquifers were subdivided into 3 and 5 layers, respectively. The uppermost layer of the surficial aquifer system extended 10 ft below the water table and model layers 2 and 3 were evenly divided between the bottom of layer 1 and the top of the intermediate confining unit. All surficial aquifer system boundary conditions (fig. 22) and stresses from the calibrated model were applied to layer 1. Layers 2 and 3 had only no-flow lateral boundary conditions and no internal boundary conditions or stresses. Layer 1 hydraulic conductivities were assigned values identical to the calibrated model (fig. 28). Transmissivities for layers 2 and 3 were calculated based on hydraulic conductivities from the calibrated model and respective layer thickness. Leakance values between surficial aquifer system layers (vertical hydraulic conductivity divided by vertical distancebetween model cell nodes) were calculated so that the vertical anisotropy was 10. Model layers 4, 5, 6, 7, and 8 represented the Upper Floridan aquifer with thicknesses representing the following fractions of total aquifer thickness: $1/8$, $1/8$, $1/8$, $1/8$, and $1/2$, respectively. Transmissivity values were calculated as the product of respective fractional layer thickness and calibrated Upper Floridan aquifer transmissivity (fig. 29). Ground-water withdrawal rates at wells and Apopka Spring were calculated for each layer as the product of respective fractional layer thickness and total withdrawal rate. Boundary conditions and specified-head values for layers 4 through 8 were identical to those for layer 2 of the calibrated model (fig. 23). Leakance values between layers were calculated so that the vertical anisotropy was 100. The intermediate confining unit, middle semiconfining unit, and Lower Floridan aquifer were modeled identically to the calibrated model. No attempt was made to recalibrate the nine-layer (anisotropic) model.

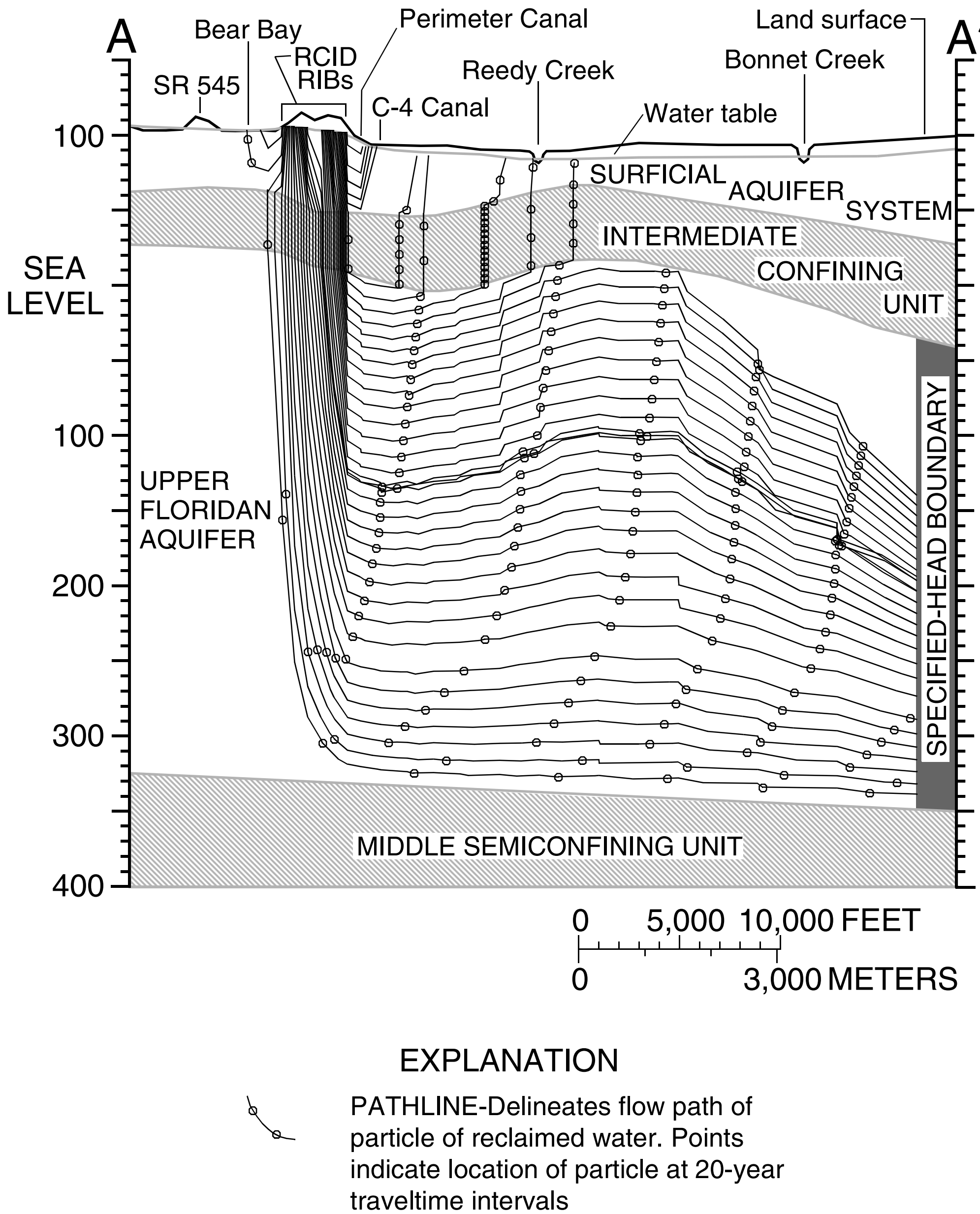
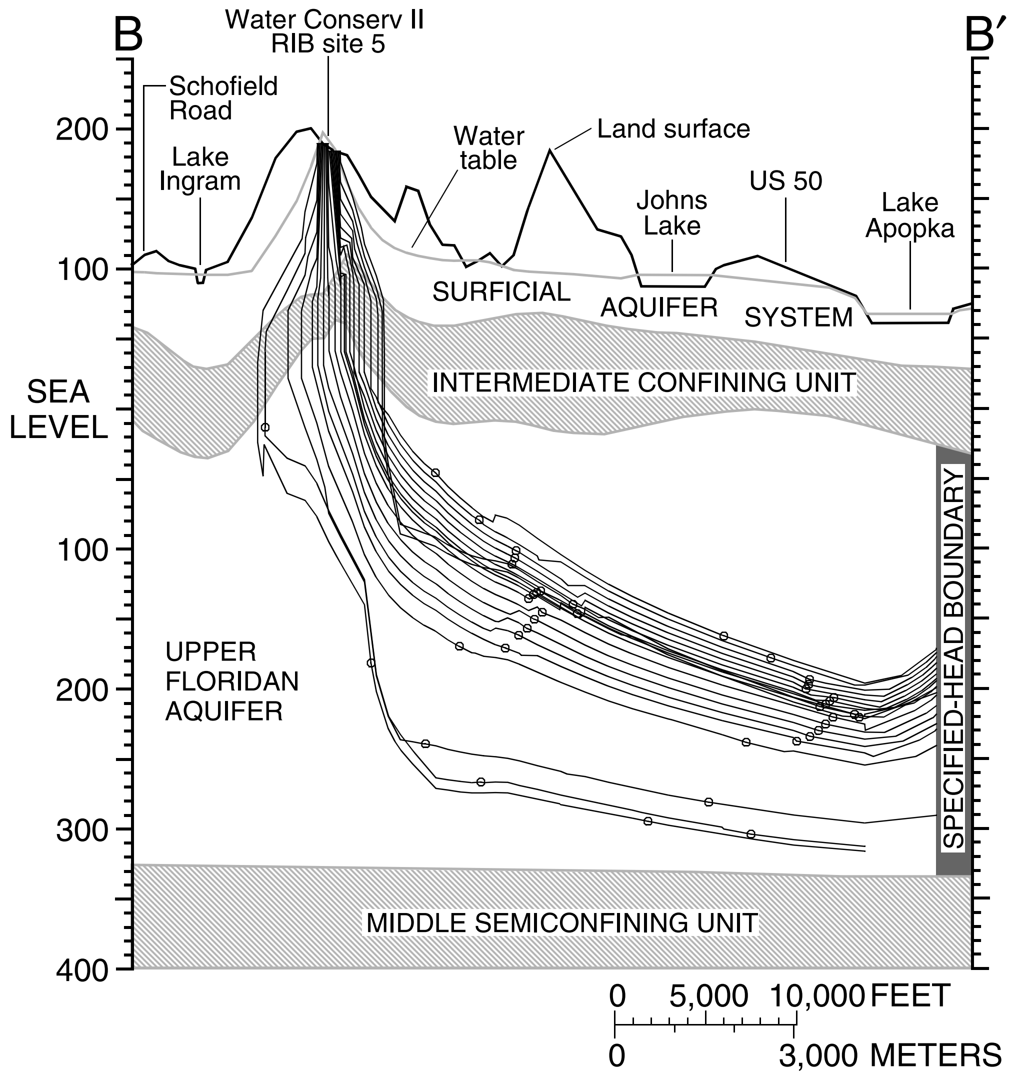
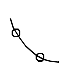


Figure 47. Projected cross-sectional view of simulated pathlines depicting directions and rates of movement of reclaimed water from several RIBs at the RCID RIB site based on simulated steady-state 1995 conditions (location of section shown in fig. 46).



EXPLANATION



PATHLINE-Delineates flow path of particle of reclaimed water. Points indicate location of particle at 20-year traveltime intervals

Figure 48. Projected cross-sectional view of simulated pathlines depicting directions and rates of movement of reclaimed water from several RIBs at Water Conserv II RIB site 5 based on simulated steady-state 1995 conditions (location of section shown in fig. 46).

A comparison of particle-tracking results from the isotropic and anisotropic models indicates that vertical anisotropy generally has little effect on reclaimed water discharge locations and magnitudes, even though the vertical anisotropy values used were relatively large (table 10). The greatest effect is an increase of 8 percent in reclaimed water discharge from the surficial aquifer system at the RCID RIB site. Because the surficial and Upper Floridan aquifers probably are anisotropic to some degree, the average percentages listed in table 10 probably are closer to their true values. No generalization can be made on changes in reclaimed water traveltimes induced by increasing vertical anisotropy, because traveltime is dependent not only on ground-water velocity but also on the distance over which movement is measured. Increasing the resistance to vertical flow by decreasing vertical hydraulic conductivity (therefore, increasing vertical anisotropy) would cause flow velocities to decrease; however, flow paths would also change, possibly becoming shorter. Depending on the relative magnitude of the changes in velocity and flow path, the result could be either a shorter or longer traveltime.

Based on the averaged results from the isotropic and anisotropic models under simulated 1995 conditions, approximately 67 percent of the reclaimed water applied at the RCID RIB site recharges the Floridan aquifer system, whereas 33 percent discharges from the surficial aquifer system to surface-water features; 99 percent of the reclaimed water applied at Water Conserv II recharges the Floridan aquifer system, whereas only 1 percent discharges to surface-water features (table 10). Discharge percentages of reclaimed water within the Floridan aquifer system (table 10) are more uncertain (compared to the partitioning of water between the surficial and Floridan aquifer systems) because of the (1) unknown accuracy of the representation of the middle semiconfining unit and Lower Floridan aquifer in the model, (2) assumption that wells penetrate the entire thickness of the Upper Floridan aquifer, and (3) assumed absence of preferential flow zones within the Upper and Lower Floridan aquifers. Nevertheless, most of the reclaimed water probably ultimately discharges from the Floridan aquifer system outside the model boundaries, because slightly over half of the reclaimed water is simulated to discharge at specified-head boundaries (table 10).

Effects Under Proposed Future Conditions

As both measured data and modeling simulations have indicated, current (1995) reclaimed-water application rates have produced noticeable changes in the ground-water and, to a lesser degree, surface-water systems in west Orange and southeast Lake Counties. However, reclaimed-water application rates at Water Conserv II and the RCID RIBs probably will increase in the future, and hydrologic effects under proposed future conditions are unknown. Consequently, model simulations are used to predict possible future hydrologic effects of reclaimed-water application.

Table 10. Discharge of reclaimed water from model based on particle-tracking analyses of simulated steady-state 1995 conditions

[Mgal/d, million gallons per day; RCID, Reedy Creek Improvement District. Average 1995 flow rate for the RCID RIB site was 6.67 Mgal/d; average 1995 flow rate for Water Conserv II was 28.1 Mgal/d]

Location of reclaimed water discharge from model	Percent of average 1995 flow rate					
	Isotropic[1]		Anisotropic[2]		Average	
	RCID	Water Conserv II	RCID	Water Conserv II	RCID	Water Conserv II
Lakes, streams, and/or wetlands	29	1	37	1	33	1
Upper Floridan aquifer wells	15	25	13	25	14	25
Apopka Spring	0	20	0	21	0	20
Upper Floridan aquifer boundaries	54	51	50	51	52	51
Lower Floridan aquifer boundaries	2	3	0	2	1	3

[1] Ratio of horizontal to vertical hydraulic conductivity was 1:1 for the entire model.

[2] Ratio of horizontal to vertical hydraulic conductivity was 10:1 for the surficial aquifer system, 100:1 for the Upper Floridan aquifer, and 1:1 for the Lower Floridan aquifer.

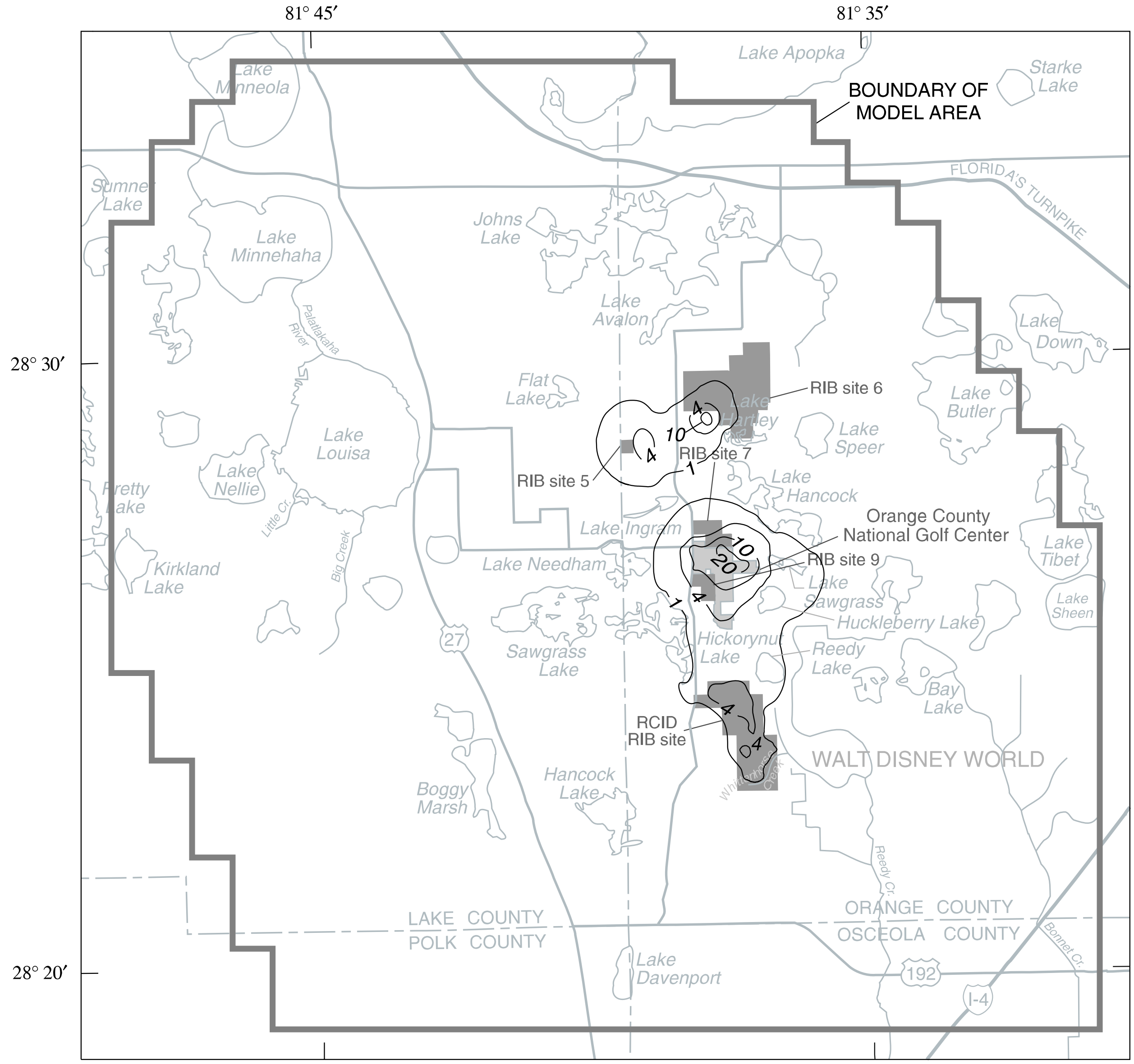
The calibrated (isotropic) ground-water flow model was used with proposed future reclaimed-water application rates for a steady-state simulation of proposed future conditions. All other stresses (for example, ground-water withdrawal rates) were left at their 1995 values. Future irrigation rates at Water Conserv II were assumed equal to 1995 rates. Average annual daily flow at the Water Conserv II RIBs was near the permitted capacity of about 16 Mgal/d in 1995; therefore, future application rates at the existing Water Conserv RIBs were left at their 1995 values. Several additional RIBs have been constructed adjacent to Water Conserv II RIB sites 5 and 6 since 1995. Combined average flow at these additional RIBs is expected to be approximately 0.9 Mgal/d (D.F. MacIntyre, PB Water, oral commun., 1996). The Orange County National Golf Center, a large golf course complex consisting of two full-length 18-hole courses and a short 9-hole course, will be constructed between Water Conserv II RIB sites 7 and 9. In addition, 15 new RIBs will be interspersed in and adjacent to the golf course. An estimated 2 Mgal/d of Water Conserv II reclaimed water will be applied for golf course irrigation and 3 Mgal/d will be applied at the golf course RIBs (D.F. MacIntyre, PB Water, oral commun., 1996). The estimated future 5.9 Mgal/d of reclaimed water makes the total Water Conserv II reclaimed-water application rate 34.0 Mgal/d. New effective recharge rates were calculated for the model using a potential ET rate (equal to E_{fws}) at the golf course. Additional RIBs may be constructed in the future at Water Conserv II, but definite locations have not been established (D.F. MacIntyre, PB Water, oral commun., 1996); consequently, no attempt was made to include these in the model. Additional RIBs probably will not be constructed by the RCID in the near future (T.W. McKim, Reedy Creek Energy Services, Inc., oral commun., 1997). The permitted capacity of the RCID RIB site is 12.5 Mgal/d; therefore, considerable capacity still exists at this site. For proposed future conditions, all 1995 RCID RIB flows were multiplied by 1.87 to yield a total reclaimed-water application rate of 12.5 Mgal/d for the RCID RIB site.

The greatest simulated increase (about 20 ft) in 1995 water-table altitude as a result of proposed future conditions was at the Orange County National Golf Center (fig. 49). Increases of up to 4 and 10 ft were simulated at the new RIBs near Water Conserv II RIB sites 5 and 6, respectively. The high surficial aquifer system hydraulic conductivity and nearby surface-water features are largely responsible for the relatively small 4-ft increase in water-table altitude at the RCID RIB site. Subject to the same limitations previously discussed concerning interpretation of lake-level changes under 1995 conditions, the following lakes are most likely to experience a rise in water level as a result of proposed future reclaimed-water application rates: Ingram, Sawgrass (south of Hancock), Needham, Huckleberry, Reedy, Hancock, and Hickorynut (fig. 49). Stream outflow might mitigate lake-level rises in Lakes Hancock and Hickorynut.

The greatest simulated increase in the 1995 Upper Floridan aquifer potentiometric surface as a result of proposed future conditions was approximately 2 ft in the northern two-thirds of the RCID RIB site (fig. 50). This is the result of a greater increase in application rate and a lower transmissivity than at Water Conserv II application sites. Average net leakage from the surficial aquifer system to the Floridan aquifer system was 11.9 in/yr, 0.3 in/yr greater than under 1995 conditions.

Under proposed future conditions, the maximum lateral extent of reclaimed water in the surficial and Upper Floridan aquifer systems within the model area probably would be similar to that under 1995 conditions (figs. 43 and 46). The areas of increased water levels under proposed future conditions (figs. 49 and 50) are well within those areas simulated under 1995 conditions (figs. 40 and 41). The greatest difference would be in the surficial aquifer system in the vicinity of the Orange County National Golf Center where reclaimed water was not applied in 1995. Future traveltimes through the surficial aquifer system generally would decrease in areas where reclaimed-water application rates were increased. However, future traveltimes could increase if the greater reclaimed-water application rates caused longer flow paths. Future traveltimes through the Floridan aquifer system are more difficult to generalize, because greater reclaimed-water application rates would cause higher ground-water velocities but also might cause reclaimed water to move deeper through the aquifer along longer flow paths.

Particle-tracking analyses were performed for proposed future conditions using the three-layer isotropic model and the nine-layer anisotropic model (table 11). As under 1995 conditions, vertical anisotropy had the greatest effect at the RCID RIB site in the partitioning of reclaimed water between surficial aquifer system discharge and Floridan aquifer system recharge. At the RCID RIB site, vertical anisotropy caused an increase in surficial aquifer system discharge under 1995 and proposed future conditions of 8 and 6



Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Albers Equal-Area Conic projection
Standard parallels 29° 30′ and 45° 30′, central meridian -83° 00′

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

—1— WATER-TABLE CHANGE CONTOUR--
Shows change in altitude of water table. Contour interval variable

Figure 49. Simulated change in the surficial aquifer system water table from 1995 conditions as a result of steady-state proposed future reclaimed-water application rates.

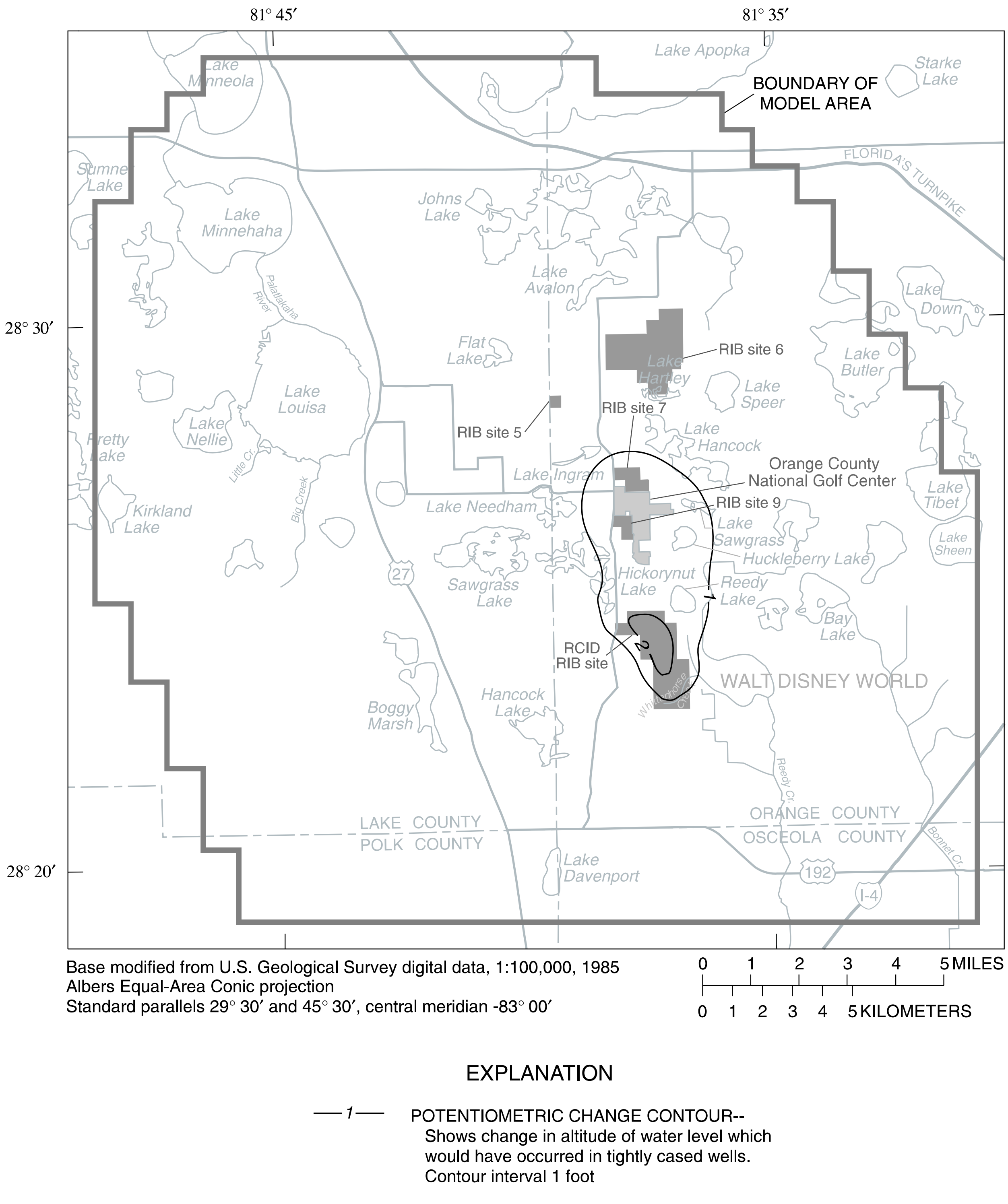


Figure 50. Simulated change in the Upper Floridan aquifer potentiometric surface from 1995 conditions as a result of steady-state proposed future reclaimed-water application rates.

Table 11. Discharge of reclaimed water from model based on particle-tracking analyses of simulated steady-state proposed future conditions

[Mgal/d, million gallons per day; RCID, Reedy Creek Improvement District. Proposed future flow rate for the RCID RIB site was 12.5 Mgal/d; proposed future flow rate for Water Conserv II was 34.0 Mgal/d]

Location of reclaimed water discharge from model	Percent of proposed future flow rate					
	Isotropic[1]		Anisotropic[2]		Average	
	RCID	Water Conserv II	RCID	Water Conserv II	RCID	Water Conserv II
Lakes, streams, and/or wetlands	47	1	53	1	50	1
Upper Floridan aquifer wells	12	27	11	26	12	26
Apopka Spring	0	17	0	18	0	18
Upper Floridan aquifer boundaries	37	52	35	52	36	52
Lower Floridan aquifer boundaries	4	3	1	3	2	3

[1] Ratio of horizontal to vertical hydraulic conductivity was 1:1 for the entire model.

[2] Ratio of horizontal to vertical hydraulic conductivity was 10:1 for the surficial aquifer system, 100:1 for the Upper Floridan aquifer, and 1:1 for the Lower Floridan aquifer.

percent, respectively. Therefore, as the reclaimed-water application rate increases, the effects of aquifer vertical anisotropy become less significant.

Based on an average of isotropic and anisotropic model results under proposed future conditions, 99 percent of the reclaimed water applied at Water Conserv II recharged the Floridan aquifer system, whereas only 1 percent discharged from the surficial aquifer system to surface-water features (table 11). At the RCID RIB site, however, the greater reclaimed-water application rate of 12.5 Mgal/d caused approximately half of the reclaimed water to discharge to surface-water features and half to recharge the Floridan aquifer system (table 11). The increase in reclaimed-water application contributed to a simulated increase in ground-water discharge to Whittenhorse and Reedy Creeks. Under the proposed future conditions (compared to 1995 conditions), surficial aquifer system discharge to Bear Bay and Whittenhorse Creek (upstream from the gaging station, site number 57, fig. 2) increased 140 percent and discharge to Reedy Creek (upstream from the gaging station, site number 62, fig. 2) increased 30 percent. The partitioning of reclaimed water discharge within the Floridan aquifer system under proposed future conditions is subject to the same limitations as previously discussed for 1995 conditions. However, the majority of reclaimed water that recharges the Floridan aquifer system probably ultimately discharges from the ground-water system outside the model boundaries.

MODEL LIMITATIONS

Results derived in this study are based primarily on ground-water flow model simulations. Consequently, these results are subject to the assumptions and limitations inherent in the model. Model results are limited by simplifications in the conceptual model, grid scale, the difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydrologic properties and stresses throughout the model area, and the distribution and quality of data used for calibration.

The conceptual model used to construct the ground-water flow model is a highly simplified representation of the true ground-water system. The simplifications in the conceptual model, necessitated by the limited ability to model extremely complex natural systems, represent the most likely source of error in the ground-water flow model. The aquifer systems are neither isotropic nor vertically homogeneous. Varying lithology produces preferential flow zones, and in the Floridan aquifer system these probably are magnified by dissolution features. The lack of data on the middle semiconfining unit and Lower Floridan aquifer might have caused an incorrect representation of these units; therefore, the leakance and transmissivity reported for these units should not be considered as calibrated values. Lateral boundaries were located well outside of reclaimed-water application sites because inaccuracies in assigned boundary conditions can adversely effect model results, especially near model boundaries. As a result, the model should not be used for analysis near any of the lateral boundaries. If sufficient data were available, transient calibration and model simulations would have more accurately portrayed the ground-water system; however, steady-state analyses are sufficient for simulating the average long-term effects of reclaimed-water application.

The horizontal and vertical discretization required by a finite-difference approximation assumes that hydrologic properties and stresses do not vary within a model cell. Because this is rarely the case in natural hydrologic systems, any variations at the scale of a model cell must be represented by an appropriate average value. The adequacy of the discretization is a function of how well an average value of the property or stress represents the effects of the actual, spatially variable values. Significant variations in hydrologic properties at a scale smaller than the smallest model cell (656 by 656 ft) are common in the mantled karst environment in the study area. These small-scale variations might significantly affect larger scale average values. In addition, the location of stresses (for example, well pumpage or RIB application rate) is distorted somewhat by discretization effects. The vertical discretization of one model layer for each aquifer does not allow for simulation of vertical flow within each aquifer. However, the majority of vertical flow probably occurs through the intermediate confining unit and middle semiconfining unit, and not within the surficial aquifer system, Upper Floridan aquifer, or Lower Floridan aquifer. Measured data indicate that the vertical head gradients across the intermediate confining unit generally are much greater than those in the surficial aquifer system. For example, the vertical head gradient in the surficial aquifer system near Island Lake was 0.001 on January 4, 1995 (see wells HA2-4 and HA2-5, fig. 16), whereas the vertical head gradient across the intermediate confining unit was 0.04 (surficial aquifer system well HA2-4 and Upper Floridan aquifer well HA2-F, site number 51, fig. 3). For comparison, Sumner and Bradner (1996) indicated that a surficial aquifer system vertical head gradient of about 0.06 existed directly under a heavily loaded RIB. However, model simulation demonstrated that flow was predominately radial (that is, a very small vertical head gradient) 30 ft beyond the edge of the flooded area within the RIB (Sumner and Bradner, 1996). Consequently, the discretization used in the present model is adequate for fulfilling the objective of modeling ground-water flow on a more regional scale, such as in the vicinity of a RIB site or a cluster of RIBs rather than an individual RIB.

Calibrated parameter values and distributions (figs. 28, 29, and 30) are dependent not only on the accuracy of measured data but also on the spatial distribution of these data, which include water levels to which the model was calibrated as well as stresses, such as reclaimed-water application rate or well pumpage. Model results are more likely to be accurate in areas where there are large known stresses and corresponding water-level measurements indicating aquifer response to those stresses. Model results in areas where there was no stress on the aquifer system or no water-level measurements should be interpreted cautiously. For example, it would be incorrect to conclude that the only area of high surficial aquifer system hydraulic conductivity in the model area is in the vicinity of the RCID RIB site (fig. 28). If a stress of similar magnitude with corresponding water-level measurements had existed elsewhere in the model area, another area of different aquifer properties might have become apparent. In other words, if additional data were available, perhaps collected under different hydrologic conditions, a recalibration of the model might yield significantly different results. However, in the areas of interest, many water-level measurements exist and the major stress (reclaimed-water application) is relatively well known.

Sensitivity analyses indicated that several model parameters, especially Upper Floridan aquifer transmissivity, were highly dependent on effective recharge. In addition, the model was relatively insensitive to many parameters. Consequently, different combinations of values for the specified effective recharge array and model parameters could yield the same head distribution. Nevertheless, after an extensive calibration effort, the hydrologic properties and simulation results derived from the ground-water flow model were within realistic and previously referenced limits.

SUMMARY

Wastewater reclamation and reuse has become increasingly popular as water agencies search for alternative water-supply and wastewater-disposal options. Several governmental agencies (Orange County, City of Orlando, and the Reedy Creek Improvement District (RCID)) in central Florida currently use the land-based application of reclaimed water (wastewater that has been treated beyond secondary treatment) as a management alternative to surface-water disposal of wastewater. Water Conserv II, a water reuse project developed jointly by Orange County and the City of Orlando, began operation in

December 1986. In 1995, the Water Conserv II facility distributed approximately 28 Mgal/d of reclaimed water for discharge to rapid-infiltration basins (RIBs) and for use as agricultural irrigation. The RCID began operation of RIBs in September 1990 and in 1995 these RIBs received approximately 6.7 Mgal/d of reclaimed water. In the future, as much as 65 Mgal/d might be directed to the Water Conserv II and RCID facilities. Analyses of existing data and data collected during the course of this study were combined with ground-water flow modeling and particle-tracking analyses to develop a process-oriented evaluation of the regional effects of reclaimed water applied by Water Conserv II and the RCID RIBs on the hydrology of west Orange and southeast Lake Counties.

The ground-water flow system beneath the study area is a multi-aquifer system that consists of a thick sequence of carbonate rocks overlain by unconsolidated sediments. The hydrogeologic units are the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system. The surficial aquifer system is unconfined and consists mainly of undifferentiated deposits of marine sand, silt, clay, and crushed shell of late Pliocene to Recent age. The intermediate confining unit separates the surficial and Floridan aquifer systems throughout the study area, except where breached by sinkholes, and retards the vertical exchange of water between these systems. The unit consists of (in varying proportions) bedded clay, silt, sand, crushed shell, and phosphatic limestone of Miocene age (Hawthorn Group) and, locally, low permeability beds of early Pliocene age. Extreme variations exist in the lithology and thickness of the intermediate confining unit as a result of the mantled karst environment in the study area; consequently, only very general trends in intermediate confining unit properties can be indicated on a regional scale. The Floridan aquifer system is composed of a sequence of highly permeable Tertiary carbonate rocks of Eocene age. The system has been subdivided into two major permeable zones, the Upper and Lower Floridan aquifers, separated by the less permeable middle semiconfining unit. The marine dolomite, gypsum, and anhydrite of the sub-Floridan confining unit form the bottom of the freshwater flow system in the study area.

Flow in the surficial aquifer system is dominated regionally by diffuse downward leakage to the Floridan aquifer system and is affected locally by lateral flow systems produced by streams, lakes, and spatial variations in recharge. Ground water generally flows laterally through the Upper Floridan aquifer to the north and east. Little data exist on the hydrologic characteristics of the middle semiconfining unit or Lower Floridan aquifer. Therefore, results presented in this report concerning the middle semiconfining unit or Lower Floridan aquifer should be interpreted with caution.

Approximately one-third of the surface area of the model is covered by lakes or wetlands. Many of the lakes are landlocked because the mantled karst environment precludes a well developed network of surface-water drainage. Response of a lake to a hydrologic stress is highly dependent on the local lithology of the surficial aquifer system and intermediate confining unit and the local variations in recharge reaching the water table.

A water budget compiled for the surficial aquifer system based on 1995 conditions indicated that rainfall and ET were the largest inflow and outflow, respectively. Rainfall was approximately 52 in/yr, whereas ET averaged 38 in/yr. ET ranged from about 27 in/yr in areas containing natural herbaceous vegetation and a deep water table to about 47 in/yr where the water table was near land surface. Variations in ET primarily are the result of spatial differences in vegetation type and water availability combined with seasonal changes in plant growth characteristics and climatological variables.

The USGS three-dimensional ground-water flow model MODFLOW was used to simulate ground-water flow in the surficial and Floridan aquifer systems. A steady-state calibration to average 1995 conditions was performed by using a parameter estimation program to vary values of surficial aquifer system hydraulic conductivity, intermediate confining unit leakance, and Upper Floridan aquifer transmissivity. The calibrated model generally produced simulated water levels in close agreement with measured water levels and was used to simulate the hydrologic effects of reclaimed-water application under current (1995) and proposed future conditions.

Based on simulated and measured data, increases of up to about 40 ft in the water table and less than 5 ft in the Upper Floridan aquifer potentiometric surface have occurred as a result of 1995 reclaimed-water application rates. The largest increases were under RIB sites. Changes in lake levels were more difficult to determine because lake levels are influenced by local flow systems and surficial aquifer system anisotropy which were not simulated by the model. The lakes most likely to have experienced increases in water levels are those nearest RIB sites. Reclaimed water that reached the water table generally moved vertically through the surficial aquifer system and intermediate confining unit and into the Floridan aquifer system. An average traveltime of 10 years at Water Conserv II and 7 years at the RCID RIBs was required for reclaimed water to move from the water table to the top of the Upper Floridan aquifer. Elevated chloride concentrations measured in Whittenhorse Creek and Perimeter Canal indicate that reclaimed water from the RCID RIB site probably is discharging to adjacent surface-water features. Approximately 67 percent of the reclaimed water applied at the RCID RIB site recharged the Floridan aquifer system, whereas 33 percent discharged from the surficial aquifer system to surface-water features; 99 percent of the reclaimed water applied at Water Conserv II recharged the Floridan aquifer system, whereas only 1 percent discharged from the surficial aquifer system to surface-water features. The majority of reclaimed water applied at both facilities probably will ultimately discharge from the Floridan aquifer system outside the model boundaries.

Proposed future conditions were assumed to consist of an additional 5.9 Mgal/d of reclaimed water distributed by Water Conserv II to discharge to new RIBs and to irrigate the new Orange County National Golf Center and an additional 5.8 Mgal/d of reclaimed water discharged to RCID RIBs. Compared to 1995 conditions, increases of up to about 20 ft in the water table and 2 ft in the potentiometric surface of the Upper Floridan aquifer were simulated. The lakes nearest the Orange County National Golf Center and the RCID RIB site were most likely to experience an increase in water level. The directions of reclaimed water movement through the ground-water system were similar to those under 1995 conditions. Future traveltimes through the surficial aquifer system generally decreased in areas where reclaimed-water application rates were increased. At Water Conserv II, 99 percent of the reclaimed water recharged the Floridan aquifer system, whereas 1 percent discharged from the surficial aquifer system to surface-water features. The greater reclaimed-water application rate at the RCID RIBs caused approximately half of the reclaimed water to discharge to surface-water features and half to recharge the Floridan aquifer system. The increase in reclaimed-water application contributed to increases of 140 and 30 percent in the simulated ground-water discharge to Whittenhorse Creek and Reedy Creek, respectively, compared to simulated 1995 values. The majority of reclaimed water that recharges the Floridan aquifer system probably will ultimately discharge from the ground-water system outside the model boundaries.

Results derived in this study were based primarily on ground-water flow model simulations. Consequently, these results are subject to the assumptions and limitations inherent in the model. Oversimplification of the conceptual model used to construct the ground-water flow model, necessitated by the extreme complexity of the natural system and transient phenomena, probably is the most likely source of error. However, the hydrologic properties and simulation results derived from the ground-water flow model and particle-tracking analyses were within realistic and previously referenced limits.

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