

# Evaluation of the Feasibility of Freshwater Injection Wells in Mitigating Ground-Water Quality Degradation at Selected Well Fields in Duval County, Florida

*By* Nicasio Sepúlveda and Rick M. Spechler

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# CONTENTS

Abstract .....	1
Introduction .....	2
Purpose and Scope .....	5
Description of Study Area .....	5
Well-Numbering System.....	6
Acknowledgments.....	6
Hydrogeologic Framework .....	7
Surficial Aquifer System.....	9
Intermediate Confining Unit .....	9
Floridan Aquifer System.....	9
Upper Floridan Aquifer.....	9
Middle Semiconfining Unit .....	10
Lower Floridan Aquifer and Fernandina Permeable Zone .....	10
Potential for Upward Flow of Poor-Quality Water .....	11
Simulation of Ground-Water Flow.....	11
Conceptual Model.....	12
Steady-State Flow Approximation.....	13
Average Hydrologic Conditions for 2000.....	14
Calibration of Ground-Water Flow Model.....	19
Hydraulic Properties from Calibrated Model .....	23
Simulated Potentiometric Surfaces .....	30
Ground-Water Flow Budget.....	33
Sensitivity Analyses.....	36
Application of Ground-Water Flow Model.....	36
Application of Steady-State Ground-Water Flow Model.....	39
Transient Ground-Water Flow Model.....	44
Effects of Parameter Uncertainty on Simulated Upward Flow from the Fernandina Permeable Zone .....	52
Vertical Leakance of Semiconfining Unit.....	52
Transmissivity of the Fernandina Permeable Zone.....	52
Specified-Head Cells Along the Lateral Boundaries of the Fernandina Permeable Zone.....	55
Model Limitations.....	56
Summary and Conclusions .....	56
References.....	58

## FIGURES

1. Map showing location of wells tapping the Upper Floridan aquifer, the upper zone of the Lower Floridan aquifer, and the Fernandina permeable zone in and near the area with well fields of interest .....	3
2. Map showing location of hydrogeologic sections and average chloride concentrations measured during 2002 at selected Jacksonville Electric Authority well fields.....	4
3. Diagram showing stratigraphic units, general lithology, and hydrogeologic units in Duval County, Florida .....	7
4. Graphs showing generalized hydrogeologic sections A-A' and B-B' .....	8
5. Diagram showing geologic units and corresponding layering scheme in the model .....	12
6-9. Maps showing:	
6. Estimated altitude of the water table of the surficial aquifer system, average 2000 conditions .....	14
7. Average 2000 heads in the Upper Floridan aquifer, upper zone of the Lower Floridan aquifer, and Fernandina permeable zone.....	15

8.	Linearly regressed potentiometric surface of the Upper Floridan aquifer for the average 2000 conditions obtained from average 1993-94 conditions .....	17
9.	Specified heads along the lateral boundary cells of the upper zone of the Lower Floridan aquifer, average 2000 conditions .....	18
10.	Graph showing comparison of simulated to measured heads in all hydrogeologic units for the calibrated model .....	20
11-22.	Maps showing:	
11.	Average 2000 ground-water withdrawal rates from the Upper Floridan aquifer.....	21
12.	Average 2000 ground-water withdrawal rates from the upper zone of the Lower Floridan aquifer .....	22
13.	Transmissivity of the Upper Floridan aquifer from the calibrated model .....	23
14.	Transmissivity of the upper zone of the Lower Floridan aquifer from the calibrated model .....	24
15.	Leakance of the intermediate confining unit from the calibrated model .....	25
16.	Simulated vertical leakage rates to and from the Upper Floridan aquifer through the intermediate confining unit, average 2000 conditions .....	26
17.	Leakance of the middle semiconfining unit from the calibrated model .....	27
18.	Simulated vertical leakage rates from the upper zone of the Lower Floridan aquifer through the middle semiconfining unit, average 2000 conditions .....	28
19.	Simulated vertical leakage rates from the Fernandina permeable zone through the semiconfining unit, average 2000 conditions .....	29
20.	Simulated potentiometric surface of the Upper Floridan aquifer, average 2000 conditions .....	30
21.	Simulated potentiometric surface of the upper zone of the Lower Floridan aquifer, average 2000 conditions.....	31
22.	Simulated potentiometric surface of the Fernandina permeable zone, average 2000 conditions .....	32
23.	Diagram showing simulated steady-state volumetric flow budget for the model area, average 2000 conditions.....	33
24.	Map showing simulated steady-state lateral flow to and from the upper zone of the Lower Floridan aquifer across model boundaries, average 2000 conditions.....	34
25.	Map showing simulated steady-state lateral flow to and from the Fernandina permeable zone across model boundaries, average 2000 conditions.....	35
26.	Diagram showing simulated steady-state volumetric flow budget for the well field subareas of Brierwood, Deerwood 3, Main Street, and Community Hall, time-averaged 2000 conditions.....	37
27.	Graph showing model sensitivity to changes in selected model parameters.....	38
28.	Map showing steady-state head buildups in the upper zone of the Lower Floridan aquifer after 6 million gallons per day (Mgal/d) are injected into Brierwood and 12 Mgal/d are injected into Deerwood 3 wells .....	40
29-31.	Diagrams showing:	
29.	Simulated steady-state net volumetric flow budget differences between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the upper zone of the Lower Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells .....	41
30.	Simulated steady-state net volumetric flow budget differences for the well field subareas between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the upper zone of the Lower Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells .....	42
31.	Simulated steady-state net volumetric flow budget differences for the well field subareas between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the Upper Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells .....	43
32-38.	Graphs showing:	
32.	Simulated monthly upward flows from the Fernandina permeable zone for 2000, for scenarios 1 through 6, with injection rates of 6 million gallons per day (Mgal/d) in Brierwood and 12 Mgal/d in Deerwood 3 well fields .....	47
33.	Simulated monthly upward flows from the Fernandina permeable zone for 2000, for scenarios 7 through 12, with injection rates of 6 million gallons per day (Mgal/d) in Brierwood and 12 Mgal/d in Deerwood 3 well fields .....	48

34. Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000 under scenario 8 conditions, for various injection rates in Brierwood and Deerwood well fields.....	50
35. Simulated monthly upward flows from the Fernandina permeable zone for 2000, under scenario 8 conditions, for various withdrawal rates at Brierwood and Deerwood 3 well fields, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only .....	51
36. Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000, under scenario 8 conditions, for various vertical leakances of the semiconfining unit overlying the Fernandina permeable zone, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only .....	53
37. Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000, under scenario 8 conditions, for various transmissivities of the Fernandina permeable zone, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only .....	54
38. Simulated monthly upward flows from the Fernandina permeable zone for 2000, under scenario 8 conditions, for various differences in specified heads, between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer, along lateral boundaries of the model, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only .....	55

## TABLES

1. Maximum chloride concentrations measured in ground water at selected wells in Duval County, Florida, 1999 to 2002.....	2
2. Site identification numbers of wells used in this study and corresponding local well numbers .....	6
3. Geographical information system coordinates of the corners of the ground-water flow model grid.....	11
4. List of parameter values used to compute the average 2000 freshwater and environmental-water heads at Fernandina permeable zone wells.....	18
5. Water-level residual statistics for the calibrated steady-state model .....	20
6. Water-level residual statistics for the calibrated transient model .....	45
7. Monthly withdrawals during 2000 at Brierwood, Deerwood 3, and Main Street well fields .....	46
8. Simulated scenarios of injection, withdrawal, and intervening rest months at Brierwood and Deerwood 3 well fields.....	46

## CONVERSION FACTORS, DATUMS, ACRONYMS, AND ABBREVIATIONS

Multiply	By	To obtain
<b><i>Length</i></b>		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
<b><i>Area</i></b>		
acre	0.4047	hectare
square mile (mi <sup>2</sup> )	2.590	square kilometer
<b><i>Flow Rate</i></b>		
cubic foot per second (ft <sup>3</sup> /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
<b><i>Hydraulic Conductivity</i></b>		
foot per day (ft/d)	0.3048	meter per day
<b><i>*Transmissivity</i></b>		
foot squared per day (ft <sup>2</sup> /d)	0.09290	meter squared per day
<b>Leakance</b>		
foot per day per foot [(ft/d)/ft]	1.0	meter per day per meter

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

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information (latitude-longitude) is referenced to the North American Datum of 1927 (NAD27).

Acronyms and abbreviations used in report:

CY	calendar year
FPZ	Fernandina permeable zone
FAS	Floridan aquifer system
g/mL	grams per milliliter
ICU	intermediate confining unit
JEA	Jacksonville Electric Authority
LFA	Lower Floridan aquifer
MSCU	middle semiconfining unit
mg/L	milligrams per liter
MLR	multiple linear regression
MODFLOW	U.S. Geological Survey Modular Three-Dimensional Ground-Water Flow Model
NWIS	National Water Information System
RMS	root-mean-square
SCU	semiconfining unit
SLR	simple linear regression
SJRWMD	St. Johns River Water Management District
S	storage coefficient
SAS	surficial aquifer system
UFA	Upper Floridan aquifer
uzLFA	upper zone of Lower Floridan aquifer
USGS	U.S. Geological Survey

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## ABSTRACT

The Fernandina permeable zone contains brackish water in parts of Duval County, Florida. Upward flow from the Fernandina permeable zone to the upper zone of the Lower Floridan aquifer increases chloride concentrations in ground water in parts of Duval County. Numerical models of the ground-water flow system in parts of Duval, St. Johns, and Clay Counties, Florida, were used to (1) estimate the vertical flows between the low-quality water of the Fernandina permeable zone and the high-quality water of the upper zone of the Lower Floridan aquifer in the vicinity of Deerwood 3 and Brierwood well fields, based on 2000 ground-water withdrawal rates; (2) determine how such vertical flows change as several scenarios of injection, withdrawal, and intervening rest periods are simulated in the two well fields; and (3) evaluate the effects of changes in less certain hydraulic parameters on the vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer. The ground-water flow system was simulated with a four-layer model using MODFLOW-2000, which was developed by the U.S. Geological Survey. The first layer consists of specified-head cells simulating the surficial aquifer system with prescribed water levels. The second layer simulates the Upper Floridan aquifer. The third and fourth layers simulate the upper zone of the Lower Floridan aquifer and the Fernandina permeable zone, respectively. Average flow conditions in 2000 were approximated with a steady-state simulation. The changes

in upward flow from the Fernandina permeable zone due to periods of injections and withdrawals were analyzed with transient simulations. The grid used for the ground-water flow model was uniform and composed of square 250-foot cells, with 400 columns and 400 rows.

The active model area encompasses about 360 square miles in parts of Duval, St. Johns, and Clay Counties, Florida. Ground-water flow simulation was limited vertically to the bottom of the Fernandina permeable zone. The steady-state ground-water flow model was calibrated using time-averaged 2000 heads at 20 control points. Environmental-water heads in the Fernandina permeable zone were calculated for wells with variable water density. Transmissivity of the Upper Floridan aquifer, the upper zone of the Lower Floridan aquifer, and the Fernandina permeable zone, and the leakance of the intermediate confining unit, the middle semiconfining unit, and the semiconfining unit were obtained from regional ground-water flow models and adjusted until a reasonable fit between simulated and computed heads was obtained.

Root-mean-square residuals, calculated from simulated and time-averaged heads for the steady-state model, in the Upper Floridan aquifer, the upper zone of the Lower Floridan aquifer, and the Fernandina permeable zone were 1.75, 1.99, and 1.14 feet, respectively. Based on the 20 control points from all units, the overall residual for the steady-state model was 1.75 feet. Monthly measured heads at 20 sites during May and September 2000 and at 16 sites for the remaining months of

2000 were used to compute residuals for the 12 one-month-duration stress periods. These residuals were used to calibrate storage coefficient. Root-mean-square residuals for the transient model, calculated from simulated heads at the end of the 12 stress periods and time-averaged heads, in the Upper Floridan aquifer, the upper zone of the Lower Floridan aquifer, and the Fernandina permeable zone, were 1.52, 1.79, and 1.52 feet, respectively, with 1.78 feet being the overall residual.

The calibrated hydraulic properties from the steady-state ground-water flow model, and the calibrated storage coefficient from the transient model, were used to simulate hypothetical transient scenarios of injection, withdrawal, and intervening rest periods to assess changes in flow between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer. Based on the simulated flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer and the 18 million gallons per day of water available for injection, the reversal of the prevailing upward flow from the Fernandina permeable zone was not achieved. However, steady-state and transient simulations indicate that the upward flow of water from the Fernandina permeable zone could be reduced by as much as 64 percent, from 0.11 to 0.04 cubic foot per second, if only injection periods are simulated.

## INTRODUCTION

The Floridan aquifer system (FAS) is the principal source of water supply in northeast Florida. As the population of this area increases, the demand for water also increases. In some areas of Florida, declining water levels and increasing mineralization of ground water have become problems for local and state water-management officials. Water samples from the upper zone of the Lower Floridan aquifer (LFA) in the Deerwood 3 well field in Duval County, Florida (fig. 1) have chloride concentrations as high as 290 milligrams per liter (mg/L) as listed in table 1. This chloride concentration is greater than the secondary drinking water standard for chloride, which was set to 250 mg/L by the Florida Administrative Code (p. 56, table 4, 2000), and by the U.S. Environmental Protection Agency (2000). Projected increases in ground-water withdrawals from the upper zone of the LFA could cause further

upward migration of water with high chloride concentrations from the Fernandina permeable zone (FPZ) to the upper zone of the LFA, resulting in increased chloride concentrations.

In 2000, the U.S. Geological Survey (USGS), in cooperation with the Jacksonville Electric Authority (JEA) and the St. Johns River Water Management District (SJRWMD), initiated an investigation to assess the effects of freshwater injection wells in mitigating ground-water degradation in the vicinity of selected well fields in Duval County, Florida. The ground-water flow model developed for this study was used to assess the effects of a series of injection, withdrawal, and intervening rest scenarios on the upward flow from some areas in the FPZ with greater chloride concentrations to the high-quality water of the upper zone of the LFA in northeastern Florida. The steady-state ground-water flow model was calibrated by using time-averaged heads for calendar year (CY) 2000 at 20 control points from the Upper Floridan aquifer (UFA), the upper zone of the LFA, and the FPZ. The transient simulations were performed using the calibrated hydraulic properties from the steady-state model, and the calibrated storage coefficient from the transient model.

**Table 1.** Maximum chloride concentrations measured in ground water at selected wells in Duval County, Florida, 1999 to 2002

[Source: Jacksonville Electric Authority, written communication, 2003; mg/L, milligrams per liter]

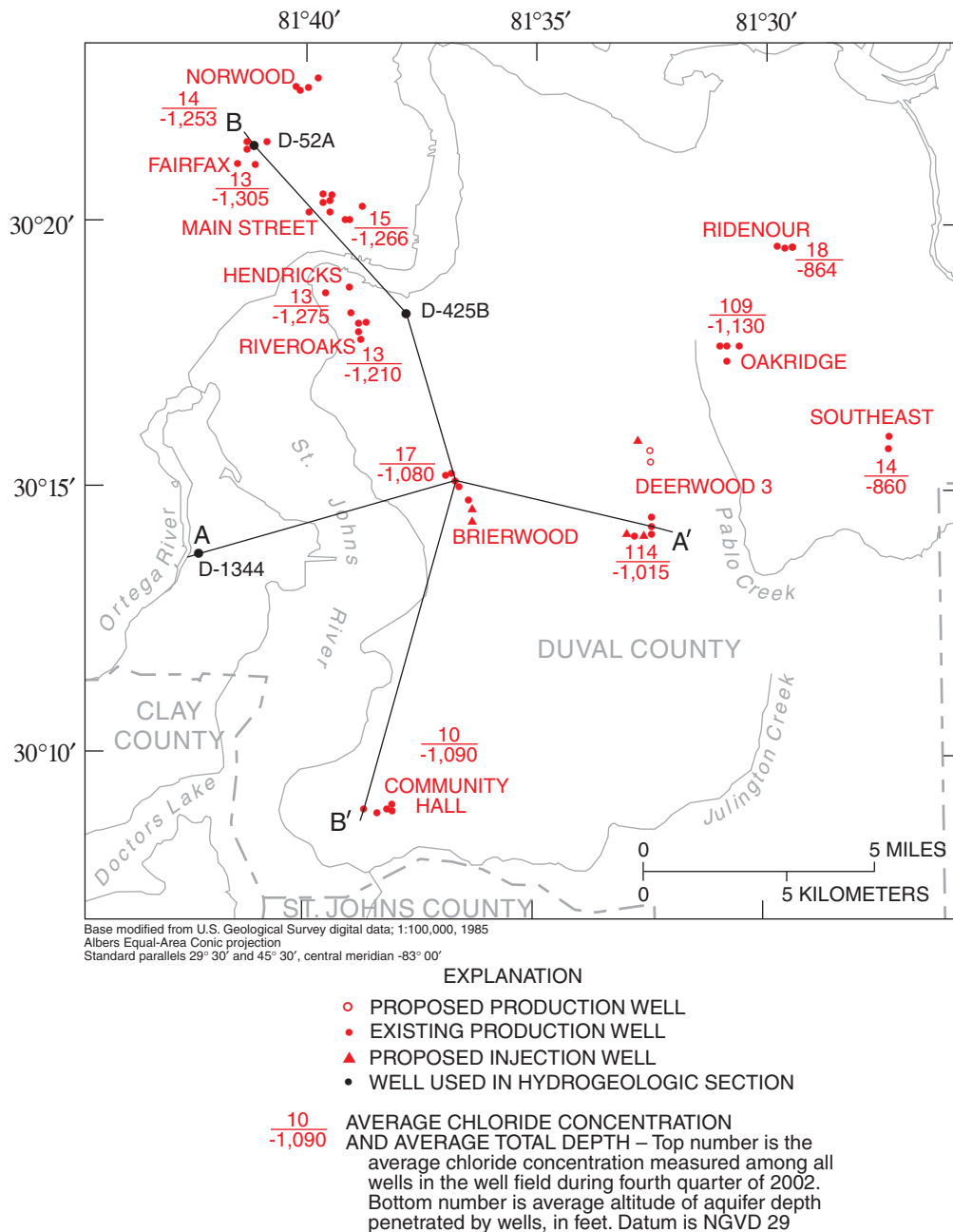
Well field	Well number	Total depth (feet)	Date of measurement	Chloride concentration (mg/L)
Brierwood	6001	1,100	10-09-02	14
Brierwood	6002	1,100	11-19-02	18
Brierwood	6003	1,100	10-09-02	14
Brierwood	6004	1,100	10-09-02	17
Brierwood	6005	1,100	10-11-02	26
Deerwood 3	5701	980	10-02-02	71
Deerwood 3	5702	1,198	10-02-02	140
Deerwood 3	5703	1,180	10-02-02	290
Deerwood 3	5704	1,000	10-02-02	71
Deerwood 3	5705	1,000	10-02-02	94
Deerwood 3	5706	970	1-25-99	20
Main Street	0103	1,282	10-19-02	15
Main Street	0104	1,302	11-01-02	17
Main Street	0108	1,248	10-19-02	16
Main Street	0119	1,284	10-19-02	14
Main Street	0120	1,282	10-19-02	13
Community Hall	M501	624	10-14-02	10
Community Hall	M502	900	11-18-02	10
Community Hall	M503	1,225	3-19-99	10
Community Hall	M504	1,225	10-09-02	9.2
Community Hall	M505	1,100	3-19-99	9.7





The injection and withdrawal scenarios simulated in this study are based on the assumption that 18 million gallons per day (Mgal/d) will be withdrawn from the Main Street well field (fig. 1), in addition to the current withdrawals from this well field. This water will be pumped into the upper zone of the LFA injection wells in the Brierwood and Deerwood 3 well

fields (fig. 2). Upward flows from the FPZ at the Brierwood and Deerwood 3 well fields are shown in this report with the purpose of assessing potential degradation of potable water in the upper zone of the Lower Floridan aquifer due to upward movement of brackish water from the FPZ in the vicinity of these two well fields. Steady-state simulations take into account



**Figure 2.** Location of hydrogeologic sections and average chloride concentrations measured during 2002 at selected Jacksonville Electric Authority well fields.

ground-water withdrawals from Brierwood and Deerwood 3 well fields, while transient simulations consider ground-water withdrawals from these two well fields only during stress periods of withdrawals. Ground-water withdrawals from all other well fields are considered in steady-state and transient simulations. Temporal variations in the upward flow from the FPZ resulting from several periods of injections followed by periods of withdrawals were simulated with the transient ground-water flow model.

## Purpose and Scope

This report presents the results of a study to evaluate the feasibility of using injection and withdrawal scenarios to mitigate ground-water quality degradation of the potable water supply resulting from the upward flow of poor-quality water from the FPZ in well fields in Duval County, Florida. The injection and withdrawal scenarios were simulated using the calibrated transient model. The model was used to (1) estimate the vertical flows from the FPZ to the upper zone of the LFA, in particular in the vicinity of Deerwood 3 and Brierwood well fields, based on 2000 ground-water withdrawal rates; (2) evaluate changes in the vertical flows under several hypothetical scenarios of injection, withdrawal, and intervening rest periods; and (3) evaluate the effects of selected parameter uncertainty on the simulated vertical flows between the FPZ and the upper zone of the LFA. A conceptual model of the flow system and applications of a finite-difference flow model based on this conceptualization are presented. The simulated scenarios are designed to represent realistic injection and withdrawal conditions considered by JEA. This report discusses the imposition of boundary conditions, regressions used to derive the specified heads along the lateral boundaries of the model, calibration strategies of steady-state simulations, sensitivity analyses, volumetric flow estimates among hydrogeologic units, and the transient simulation of injection, withdrawal, and intervening rest scenarios.

The initial distribution of hydraulic properties of the study area were obtained from Durden (1997) and Sepúlveda (2002a). The geologic structure of the study area was analyzed from geophysical logs and interpretive reports by Phelps and Spechler (1997); Spechler (1994, 1996); and Spechler and Wilson (1997).

Geographical information system data bases (Environmental Systems Research Institute, Inc., 1997)

were developed to manage spatially distributed information that covered the model area. Digital coverages were projected into a uniform coordinate system to achieve consistency of coordinate systems among data bases. All data bases were projected to the Albers equal-area conic projection with standard parallel 29°30', 45°30', and central meridian -83°00' (Snyder, 1983). The 1927 North American Datum was used for all data bases generated in this study; the unit length was feet.

## Description of Study Area

Public-water supply wells in Duval County, Florida, are classified by location relative to the St. Johns River. Well fields southeast of the St. Johns River are referred to as south grid wells, whereas well fields northwest of the St. Johns River are referred to as north grid wells. Bierwood and Deerwood 3 well fields are in the south grid; Main Street well field is in the north grid (fig. 1).

The study area encompasses most of the well fields in the south grid of Duval County (fig. 2). Those wells south or east of the St. Johns River are referred to as the south grid. Some north-grid well fields are within the study area. The extent of the study area (fig. 2) is about 19 miles (mi) north to south from central Duval County to northern St. Johns County and about 19 mi west to east in Duval County. The land-surface altitude ranges from sea level to about 60 feet (ft). Most of the study area is characterized as a ground-water discharge area except in the north-central part, where the water-table altitude is higher than the potentiometric surface of the underlying FAS. The climate is classified as subtropical and is characterized by warm, normally wet summers and mild, dry winters.

Within Duval County, Florida, the FPZ is the deepest productive unit of the FAS. The FPZ is characterized by increasing chloride concentrations in areas roughly east of longitude -81°35' (fig. 2). The freshwater-saltwater interface in the FPZ is estimated to be east of Brierwood but west of the Deerwood 3 well field, based on chloride concentrations measured at well fields tapping the upper zone of the LFA. The upward flow of ground water from the FPZ causes increased chloride concentrations in wells tapping the upper zone of the LFA. The increased chloride concentrations are not observed in well fields that tap only the UFA. The water to be injected into the Deerwood 3

and Brierwood wells is proposed to be withdrawn from a north-grid well field, Main Street, located in the northwestern part of the study area. Chloride concentrations measured in the Main Street well field are less than 20 mg/L.

Ground-water withdrawals for CY 2000 within the study area totaled about 111 Mgal/d, or nearly 172 cubic feet per second (ft<sup>3</sup>/s), distributed as 23 and 88 Mgal/d, or about 36 and 136 ft<sup>3</sup>/s, from the Upper and Lower Floridan aquifers, respectively (Thomas Lund, Jacksonville Electric Authority, written commun., 2001). This includes 90 Mgal/d for public-water supply (including estimated pumping from self-supplied domestic wells), 19 Mgal/d for commercial or industrial (including thermoelectric-power generation and recreational uses), and 2 Mgal/d for irrigation purposes. All ground-water withdrawals were compiled from consumptive user permit data bases and water-use data files from the SJRWMD and biannual operating reports by JEA based on meter readings. The locations of self-supplied domestic wells were obtained from a data base supplied by the City of Jacksonville (Jason C. Sheasley, written commun., 2002). The estimated water-use rate from self-supplied domestic wells in Duval County was assumed to be 167 gallons per person per day (Beth Wilder, St. Johns River Water Management District, written commun., 2002).

## Well-Numbering System

Two well-numbering systems are used in this report. The first is a 15-digit number based on latitude and longitude, used to identify wells in the USGS National Water Information System (NWIS). The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote degrees, minutes, and seconds of longitude; and the last two digits denote a sequential number for a site within a 1-second grid. The second numbering system is based on local well numbers. Local numbers have been assigned to wells in each county in northeastern Florida as the wells were inventoried. The prefixes D, SJ, and C denote wells in Duval, St. Johns, and Clay Counties, respectively. All local numbers were assigned by the USGS, except for well number D-1344, which was assigned by the SJRWMD (table 2).

**Table 2.** Site identification numbers of wells used in this study and corresponding local well numbers

[UFA, Upper Floridan aquifer; uzLFA, upper zone of the Lower Floridan aquifer; FPZ, Fernandina permeable zone; USGS, U.S. Geological Survey]

USGS site identification	Local well number	Aquifer
300507081272701	SJ-163	UFA
300649081485901	C-0005	UFA
300717081381001	SJ-015	UFA
300758081230501	SJ-005	UFA
300824081305401	D-0169	UFA
300834081421301	C-0007	UFA
300926081343002	D-1313	UFA
301157081465201	D-1292	UFA
301212081252401	SJ-063	UFA
301333081324101	D-2847	UFA
301408081253101	SJ-060	UFA
301551081415701	D-0129	UFA
301617081421601	D-0115	UFA
301710081323603	D-3824	UFA
301844081403801	D-0018	UFA
301846081350901	D-3544	UFA
301852081234201	D-0160	UFA
302304081383202	D-122A	UFA
302330081463001	D-0420	UFA
302550081331501	D-3840	UFA
302608081354903	D-0264	UFA
302724081244801	D-0395	UFA
302801081375101	D-0145	UFA
300656081463401	C-0094	uzLFA
301522081331303	D-4610	uzLFA
301537081441901	D-0075	uzLFA
301604081361501	D-0450	uzLFA
301639081330802	D-1155	uzLFA
302022081393501	D-0176	uzLFA
302127081411002	D-52A	uzLFA
302227081435001	D-0592	uzLFA
302608081354902	D-0263	uzLFA
301132081225801	SJ-150	FPZ
301345081421701	D-1344 <sup>1</sup>	FPZ
301817081374902	D-425B	FPZ
302052081323201	D-3060	FPZ
302159081235601	D-2386	FPZ

<sup>1</sup>Local number assigned by St. Johns River Water Management District.

## Acknowledgments

The authors would like to thank Jacksonville Electric Authority and the St. Johns River Water Management District for providing the 2000 water-use data for the study area.

## HYDROGEOLOGIC FRAMEWORK

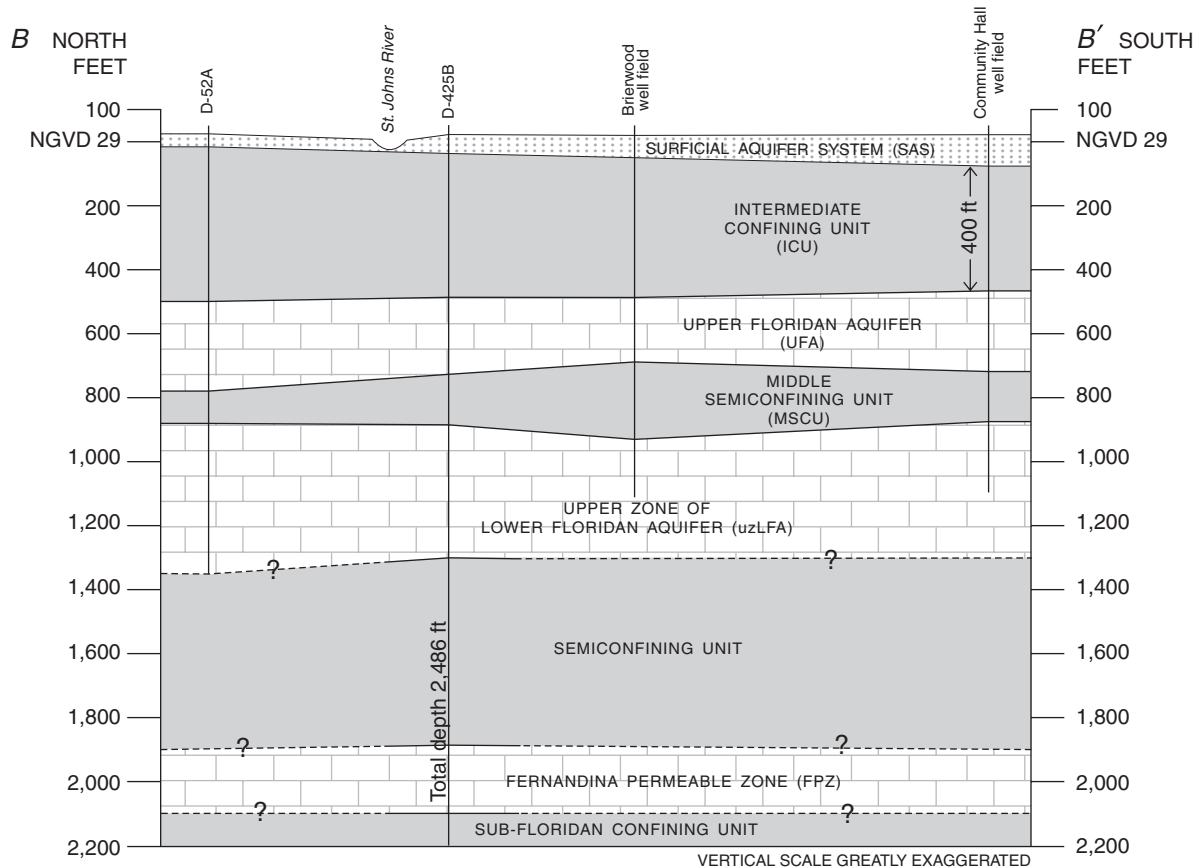
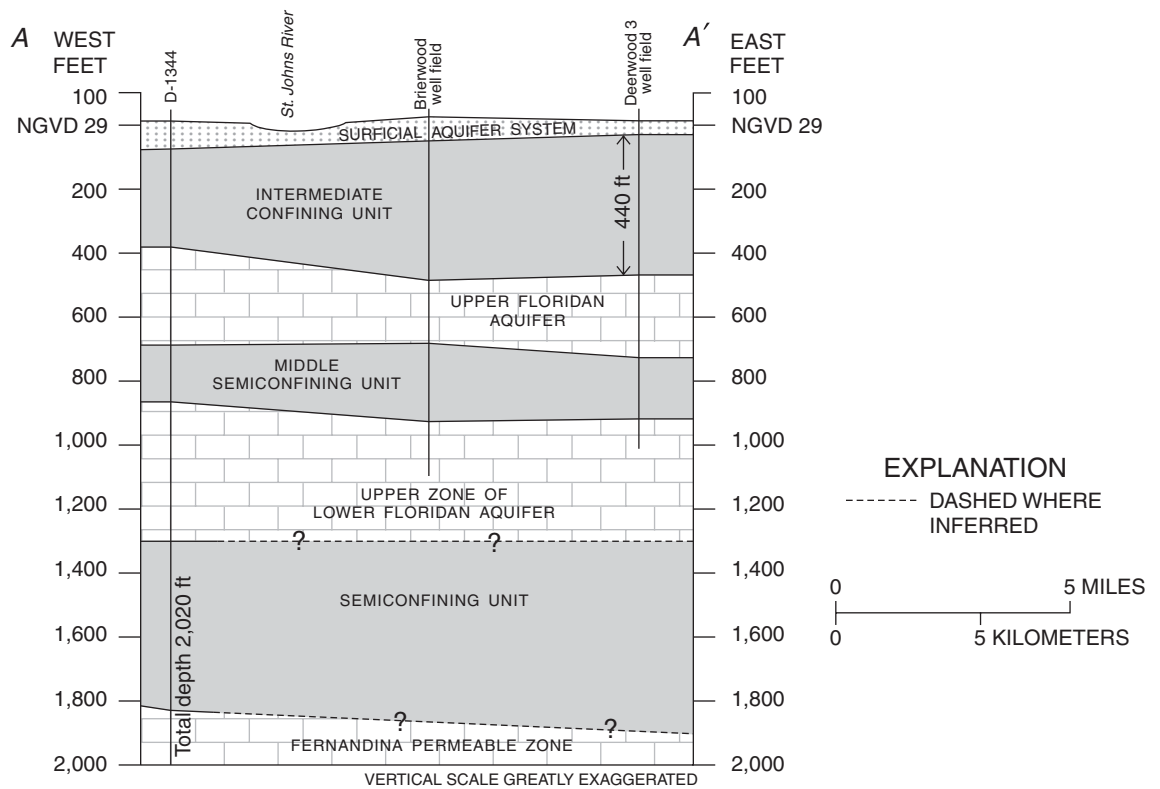
The study area is underlain by a thick sequence of sedimentary rocks that overlie deeper volcanic, metamorphic, and sedimentary rocks. The primary water-bearing sediments are composed of limestone, dolomite, shell, and sand that range in age from late Paleocene to Holocene. Stratigraphic units and corresponding hydrogeologic units penetrated by wells in the study area are described in figure 3. Stratigraphic units, in ascending order, are: the Cedar Keys Formation of late Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Hawthorn Group of Miocene age, and the undiffer-

entiated surficial deposits of late Miocene to Holocene age.

The principal water-bearing units in the study area are the surficial aquifer system (SAS) and the FAS. The two aquifer systems are separated by the intermediate confining unit (ICU), which contains beds of lower permeability sediments that confine the water in the FAS. The three major water-bearing zones of the FAS (SAS, UFA, and LFA) are separated by less-permeable semiconfining units. Underlying the FAS are low permeability limestone and dolomite that contain considerable gypsum and anhydrites, which mark the base of the FAS. Generalized hydrogeologic sections based on geophysical and geologists' logs were generated to show the thicknesses of the hydrogeologic units (fig. 4).

Series	Stratigraphic unit	General lithology	Hydrogeologic unit	Hydrogeologic properties	
Holocene to Late Miocene	Undifferentiated surficial deposits	Discontinuous sand, clay, shell beds, and limestone	Surficial aquifer system (SAS)	Sand, shell, limestone, and coquina deposits provide local water supplies.	
Miocene	Hawthorn Group	Interbedded phosphatic sand, clay, limestone, and dolomite	Intermediate confining unit (ICU)	Sand, shell, and carbonate deposits provide limited local water supplies. Low permeability clays serve as the principle confining beds for the Floridan aquifer system below.	
Eocene	Ocala Limestone	Massive fossiliferous chalky to granular marine limestone	Floridan aquifer system (FAS)	Upper Floridan aquifer (UFA)	Public-water supply source. Water from some wells shows increasing salinity.
	Avon Park Formation	Alternating beds of massive granular and chalky limestone, and dense dolomite		Middle semiconfining unit (MSCU)	Low permeability limestone and dolomite.
	Oldsmar Formation			Lower Floridan aquifer (LFA)	Upper zone
Paleocene	Cedar Keys Formation	Uppermost appearance of evaporites; dense limestones	Sub-Floridan confining unit	Semiconfining unit	Low permeability limestone and dolomite.
				Fernandina permeable zone (FPZ)	Salinity increases with depth.

**Figure 3.** Stratigraphic units, general lithology, and hydrogeologic units in Duval County, Florida (modified from Spechler, 1994).



**Figure 4.** Generalized hydrogeologic sections A-A' and B-B' (section lines shown in figure 2).

## Surficial Aquifer System

The SAS is the uppermost water-bearing unit in the study area. The SAS sediments are of late Miocene to Holocene age, and generally consist of interbedded quartz sand, shell, and clay with some beds of dolomitic limestone. The deposits generally are discontinuous; the lithology and texture of the deposits can vary considerably over short distances both vertically and laterally. In much of the area, the SAS has two water-producing zones separated by beds of lower permeability. The aquifer generally is unconfined, but may be semiconfined where overlying beds of lower permeability are sufficiently thick and continuous. The thickness of the SAS is variable, ranging from about 20 to 120 ft in the study area.

## Intermediate Confining Unit

The ICU underlies the SAS and consists primarily of the Hawthorn Group of late-to-middle Miocene age. The unit consists of interbedded clay, silt, sand, limestone and dolomite containing abundant amounts of phosphatic sand, granules, and pebbles. Throughout the study area, the ICU serves as a confining layer that restricts the vertical movement of water between the SAS and the UFA. The thickness of the ICU varies from more than 500 ft north of Deerwood 3 well field to less than 250 ft in the extreme northern part of St. Johns County. The thickness of the ICU ranges from about 420 ft at the Community Hall and Deerwood well fields, to about 440 ft at the Brierwood well field (fig. 4).

## Floridan Aquifer System

The FAS, the principal source of ground water in northeastern Florida, underlies all of Florida, and parts of Alabama, Georgia, and South Carolina. Miller (1986, p. B45) defined the FAS as a vertically continuous sequence of carbonate rocks of generally high permeability that is hydraulically connected in varying degrees and whose permeability is, in general, one to several orders of magnitude greater than those rocks that bound the system. In the study area, the aquifer is composed of a sequence of highly permeable carbonate rocks of Eocene and Late Paleocene age that averages about 1,650 ft in thickness and includes the following stratigraphic units in descending order: the

Ocala Limestone, the Avon Park Formation, the Oldsmar Formation, and the upper part of the Cedar Keys Formation (fig. 3).

The FAS is divided into two aquifers of relatively high permeability, referred to as the Upper Floridan and the Lower Floridan aquifers. The water-bearing zones within the FAS consist of soft, porous limestone and porous highly fractured dolomite beds. These aquifers are separated by a less permeable unit called the middle semiconfining unit (MSCU), which restricts the vertical movement of water within the aquifer. The LFA can be subdivided into two principal water-bearing zones, the upper zone of the LFA and the FPZ, separated by a less permeable unit. The UFA produces freshwater, but mineralization increases with depth. Monitor well D-2386 in eastern Duval County (fig. 1), drilled to a depth of 2,026 ft, showed chloride concentrations increasing from 6.4 mg/L in the UFA to 3,300 mg/L in the FPZ (Brown and others, 1984).

## Upper Floridan Aquifer

The UFA generally corresponds to the Ocala Limestone, and in some areas also includes the uppermost part of the Avon Park Formation. The Ocala Limestone is fossiliferous and characterized by high permeability and high effective porosity. Permeability has been enhanced by dissolution of the rock along bedding planes, joints, and fractures.

The top of the UFA is about 450 to 550 ft below NGVD 29 in the study area (fig. 4). However, in specific locations such as the southwestern part of the study area near Jacksonville Naval Air Station, the top of the UFA could be as shallow as 250 ft below NGVD 29 (Spechler, 1994). The top of the UFA averages about 450 ft below NGVD 29 at the Community Hall well field and about 500 ft below NGVD 29 at the Brierwood and Deerwood 3 well fields.

The surface of the UFA is irregular and paleokarstic, and includes sinkhole-like depressions. Some of the depressions could be erosional features formed before the Hawthorn Group was deposited. However, most were formed by sinkhole collapse caused by the gradual dissolution of the underlying carbonate material. Marine seismic reflection profiles show that the continental shelf off the coast of northeastern Florida is underlain by solution-deformed limestone of Late Cretaceous to Eocene age (Meisburger and Field, 1976; Popenoe and others, 1984; Kindinger and others, 2000). Dissolution and collapse features are scattered throughout the area. Seismic reflection

investigations along the St. Johns River in northeastern Florida by Snyder and others (1989) and Spechler (1994, 1996) also revealed the presence of buried collapse and other karstic features that originated in the rocks of the FAS. Using land-based seismic reflection, such features also were observed in Duval and St. Johns County (Odum and others, 1997). At Fort George Island, located northeast of the study area in eastern Duval County (fig. 1), land-based seismic reflection surveys show a large solution feature estimated to measure about 650 ft by 1,550 ft (Odum and others, 1997).

Seismic profiles also show that the karst solution feature likely breached the MSCU within the FAS and possibly the semiconfining unit (SCU) that separates the upper zone of the LFA from the FPZ. Two collapse features that are visible in the seafloor off the coast of St. Johns County were studied by Spechler and Wilson (1997) and Swarzenski and others (2001). The largest of the two, Red Snapper Sink, is located 26 miles east of Crescent Beach, Florida, and is approximately 400 ft in diameter and 482 ft deep (Spechler and Wilson, 1997). Collapse features can create conduits of relatively high vertical hydraulic conductivity, providing a hydraulic connection between freshwater zones and deeper, more saline zones within the aquifer system.

### **Middle Semiconfining Unit**

The MSCU separates the UFA and LFA and is composed of beds of relatively less permeable limestone and dolostone of variable thickness. In the study area, the MSCU generally is present in the upper part of the Avon Park Formation, but also can include the lower part of the Ocala Limestone, where hard dolostone or limestone is present. Flow logs indicate that the MSCU is considerably less transmissive than either the UFA or LFA, and the unit restricts vertical ground-water flow in the aquifer system.

The top of the MSCU, determined primarily by using flow logs, is variable throughout the area and ranges from about 700 to 800 ft below NGVD 29. The top of the unit generally is recognized by a decrease in flow as observed on flowmeter logs. Thickness of the unit ranges from about 100 to 250 ft over the study area and ranges from about 165 ft at the Community Hall well field to about 200 ft at the Deerwood 3 and Brierwood well fields.

### **Lower Floridan Aquifer and Fernandina Permeable Zone**

The LFA underlies the MSCU and includes the lower part of the Avon Park Formation, all of the Oldsmar Formation, and the upper part of the Cedar Keys Formation. The aquifer is highly productive and is composed of alternating beds of limestone and dolomite. The LFA contains two main water-bearing zones, the upper zone of the LFA and the FPZ, separated by a less-permeable semi-confining unit. The top of the upper zone of the LFA usually can be identified on flow logs as an interval contributing a noticeable increase in flow to the well. Permeability within this zone is related mostly to secondary porosity developed along bedding planes, joints, and fractures, developed by repeated episodes of active dissolution of the rock matrix (Phelps and Spechler, 1997).

Flowmeter logs show that the upper zone of the LFA commonly contains a single flow zone, whereas in other areas, less permeable strata separate two distinct flow zones (Leve, 1966). The top of the upper zone of the LFA is variable throughout the study area and generally ranges from about 800 to 950 ft below NGVD 29. At the Community Hall well field, flowmeter traverses indicate that the altitude of the top of the upper zone of the LFA is about 875 ft below NGVD 29 (fig. 4). At the Brierwood and Deerwood 3 well fields, the top of the aquifer is estimated at about 900 and 950 ft below NGVD 29, respectively. At Brierwood, Deerwood 3, and Community Hall well fields, the total thickness of the LFA, including the SCU and the FPZ, ranges from about 1,150 to 1,250 ft.

The FPZ is a high-permeability unit that lies at the base of the FAS in parts of southeastern Georgia and northeastern Florida (Miller, 1986, p. B70). In the areas of Fernandina Beach and Jacksonville (fig. 1), the unit is present in the lower Oldsmar and upper Cedar Keys Formations (Krause and Randolph, 1989, p. D23). The upper part of the zone consists of limestone that is commonly dolomitized and locally cavernous. Little is known about the extent or thickness of the FPZ because of the sparsity of data. In the few wells that have penetrated the zone in northeastern Florida, data indicate that the zone extends over the northern half of St. Johns and all of Duval and Nassau Counties. The top of the FPZ is estimated at 1,900 ft below NGVD 29 within the study area. The thickness of the zone is estimated to range from about 100 ft in the Jacksonville area to more than 500 ft in southeastern Georgia (Krause and Randolph, 1989, p. D23).



The sub-Floridan confining unit underlies the LFA. The unit typically is characterized by low permeability and serves as the hydraulic base of the FAS. The sub-Floridan confining unit consists of dolomite and limestone deposits that may contain abundant evaporite minerals. The top of the sub-Floridan confining unit generally corresponds with the top of the Cedar Keys Formation in the study area.

### Potential for Upward Flow of Poor-Quality Water

Chloride concentrations of ground water from the FPZ southeast of the St. Johns River generally are greater than those of the upper zone of the LFA throughout Duval County. Water from wells tapping the FPZ in the eastern part of Duval County generally has greater chloride concentration than water from wells farther inland (Sepúlveda, 2002a). The vertical leakance of the SCU and the vertical hydraulic gradient between the upper zone of the LFA and the FPZ determine the resulting upward flux of water. Most public-water supply wells in the study area deeper than 900 ft penetrate the UFA and parts of the upper zone of the LFA; therefore the potential exists for upward migration of water of poor quality in areas where water in the FPZ has elevated chloride concentrations and where the vertical leakance of the SCU is large. Even in areas where the vertical leakance of the SCU might be relatively small, the presence of discrete fractures or deeply buried karst features provide pathways for upward migration of poor-quality water in areas of elevated chloride concentrations in the FPZ (Spechler, 1994). Ground-water development has resulted in increased upward flow from the FPZ through the fractures or karst features. A single fracture or solution feature was the source of brackish water in several wells in Duval County (Phelps and Spechler, 1997).

### SIMULATION OF GROUND-WATER FLOW

MODFLOW-2000 (Harbaugh and others, 2000) was used to simulate ground-water flow in the FAS in Duval County. The regional ground-water flow system was simulated as a quasi three-dimensional ground-water flow model with four layers, representing the SAS, the UFA, the upper zone of

the LFA, and the FPZ. A steady-state ground-water flow model in the FAS was constructed and calibrated to time-averaged data for CY 2000. Simulated hydraulic properties obtained from Durden (1997) and Sepúlveda (2002a) were integrated with the hydrogeologic data discussed in previous sections to generate the initial distribution of model parameters. The model parameters were further refined with calibration to time-averaged heads in 2000. Monthly measured heads were used to calibrate the storage coefficient of the transient ground-water flow model. The calibrated transient model was used to assess the rate of upward flow from the FPZ to the upper zone of the LFA by simulating scenarios of injection, withdrawal, and intervening rest months at the Deerwood 3 and Brierwood well fields (fig. 2) while maintaining withdrawal rates for CY 2000 at all other wells. The potential range of values in vertical flow between the FPZ and the upper zone of the LFA due to parameter uncertainty was assessed with the calibrated model.

A uniformly spaced grid of square 250-ft cells was used to discretize the ground-water flow system horizontally. The coordinates of the grid corners given in table 3 facilitate reproduction of the grid. The grid consisted of 400 rows and 400 columns and was oriented along a north-south axis for simplicity because boundary conditions were not aligned along any particular axis. The solution of the ground-water flow equation allows for areal variations in transmissivity to simulate regional heterogeneities. Because no estimates of anisotropy were available, an isotropic transmissivity distribution was assumed.

**Table 3.** Geographical information system coordinates of the corners of the ground-water flow model grid

[Albers X and Y coordinates refer to Albers equal-area conic projection with standard parallels 29°30' and 45°30' and central meridian -83°00'; UTM X and Y coordinates refer to Universal Transverse Mercator projection, zone 17 (Snyder, 1983)]

Grid corner	Albers X coordinate (meters)	Albers Y coordinate (meters)	UTM X coordinate (feet)	UTM Y coordinate (feet)
Upper left	120208.16	813936.00	1405000	11030000
Upper right	151255.75	813936.00	1505000	11030000
Lower right	151255.75	782792.38	1505000	10930000
Lower left	120208.16	782792.38	1405000	10930000

## Conceptual Model

The SAS, UFA, the upper zone of the LFA, and the FPZ were designated layers 1 through 4, respectively (fig. 5). The SAS (layer 1) provides a specified-head boundary that, in part, determines the movement of water to and from the UFA. The areal distribution of the water-table altitude, estimated from the algorithm presented by Sepúlveda (2002b) by using river-stage data and water-level measurements from SAS wells for CY 2000, was used to specify heads in layer 1. Confining layers (ICU, MSCU, and SCU) were simulated by using vertical leakage arrays. A quasi three-dimensional flow model was developed by simulating lateral flow within the aquifers and vertical flow within the confining units.

Average hydrologic conditions for 2000 (discussed below) were used for calibration of steady-state

simulations in the model area. Hydrologic conditions change in time due to changes in ground-water withdrawal patterns and changes in discharge or recharge patterns. Specified heads for each month of CY 2000 were derived by performing linear regressions between time-averaged heads for CY 2000 and monthly measured heads.

The vertical ground-water flow is determined by the vertical leakance of the confining units and the differences among the altitude of the water table of the SAS, and the heads in the UFA, the upper zone of the LFA, and the FPZ. The altitude of the water table of the SAS is influenced by recharge from rainfall and irrigation infiltration, and by diffuse upward leakage from the UFA in areas where the water table is below the potentiometric surface of the underlying UFA. The heads representing average hydraulic conditions for CY 2000 in the UFA, the upper zone of the LFA, and

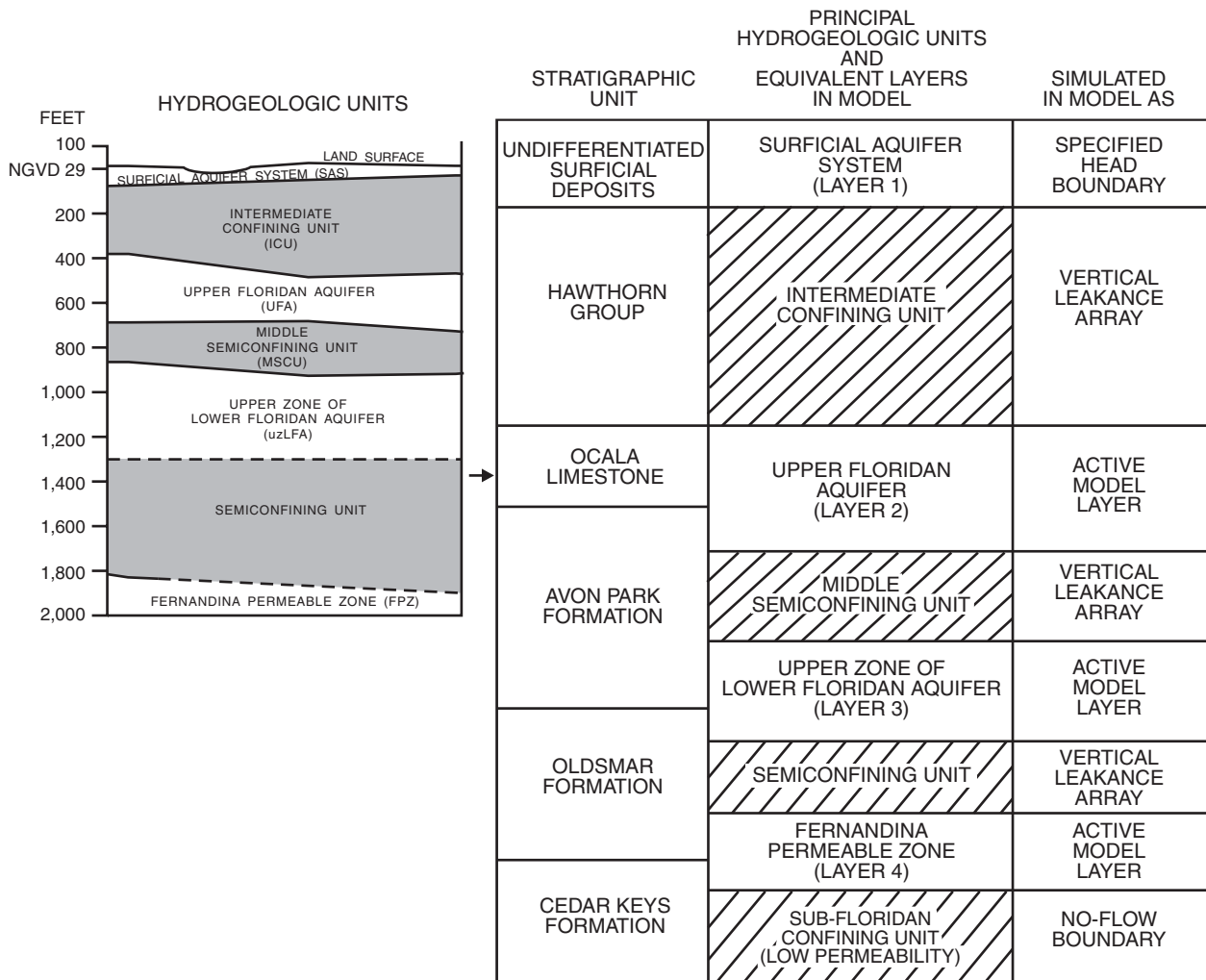


Figure 5. Geologic units and corresponding layering scheme in the model.

the FPZ were calculated at 20 control points. These time-averaged heads were used to perform linear regressions with 1993-94 measured heads for which a more detailed areal distribution of heads was known. These linear regressions made it possible to assess the hydraulic gradients between each set of two hydrogeologic units separated by a common confining unit. Details of these average heads and the linear regressions are presented later in the section Average Hydrologic Conditions for 2000.

In most of the study area, there is upward flow from the UFA to the SAS. The UFA discharges to the SAS throughout the St. Johns River. The flow from the UFA to the St. Johns River in the study area is difficult to measure; however, in 1990, Spechler (1995) estimated this upward flow, for a substantially larger reach of the St. Johns River than the reach within the study area, by using the results of a regional ground-water flow model. Ground-water discharge from the UFA to the SAS along the St. Johns River reach within the study area was estimated to be about 11 ft<sup>3</sup>/s by Spechler (1995), a rough estimate obtained from a more areally extensive river reach.

Model boundaries were assigned to approximate the ground-water flow system as accurately as possible. The simulation of the SAS as a layer of specified heads allows the UFA to discharge to or receive leakage from the SAS at rates dictated by the relative head difference between the water table and the UFA and the vertical leakance of the ICU. The altitude of the water table was used to define these specified heads. A no-flow condition was applied along the lateral boundaries of layer 2 (UFA) based on the estimated average potentiometric surface for CY 2000, which is shown later. Flow entering or leaving cells in the UFA is assumed to occur either as horizontal flow to neighboring cells or vertical flow to either the SAS (layer 1) or the upper zone of the LFA (layer 3), through the ICU or MSCU.

Heads were specified at cells comprising the lateral boundaries of the upper zone of the LFA and the FPZ. Details of the computations of these heads are presented later in the section Average Hydrologic Conditions for 2000. The lateral inland movement of water with greater chloride concentrations in the FPZ made it impractical to impose a no-flow boundary along the lateral boundaries of the model. Although the FPZ in the eastern half of the study area is saline, small horizontal hydraulic gradients could be generated. This model is restricted to simulating the movement of freshwater within the aquifers.

## Steady-State Flow Approximation

The assessment of the error introduced in the model by a steady-state flow approximation required analyzing the differences in heads at the beginning and end of the year. Head differences between the beginning and the end of the year were computed for the period 1995-2000 in the UFA and the upper zone of the LFA. Wells at which these differences were computed included two wells with continuous water-level recorders tapping the UFA (D-3824 and D-3840 in fig. 1), and wells for which monthly head measurements were available in and near the study area (UFA wells C-0007, D-0018, D-0129, D-0145, D-0160, D-0264, D-122A, D-3544, SJ-005, SJ-015, and the upper zone of the LFA and FPZ wells in fig. 1). The year that resulted in the smallest difference in heads at these wells was 2000. Head data for CY 2000 were used to evaluate the magnitude of the error introduced in the model by a steady-state approximation.

A steady-state flow approximation over a time interval,  $\Delta t$ , implies that the magnitude of the product of the storage coefficient,  $S$ , and the time rate of changes in head over the same time interval,  $\Delta h/\Delta t$ , is small compared to other aquifer stresses such as ground-water withdrawals, aquifer-river flux exchanges, or, in general, to the non-storage terms of the ground-water flow equation (Harbaugh and others, 2000). The storage coefficient,  $S$ , of a confined limestone aquifer in Duval County could vary from 0.001 to 0.02 (Domenico, 1972). For calculation purposes, the specific storage of the UFA and the upper zone of the LFA are assumed to be  $2.5 \times 10^{-5} \text{ ft}^{-1}$ . The specific storage is defined as the storage coefficient divided by the thickness of the aquifer. Assuming the average thickness of the UFA is 250 ft and that of the upper zone of the LFA is 420 ft, the storage coefficients used in this model for these two aquifers become 0.0063 and 0.0105, respectively.

The largest head difference between January 2000 and December 2000 was 3.26 ft, measured at D-1155, a well tapping the upper zone of the LFA. This value was obtained by analyzing data from continuous water-level recorders tapping the UFA and from wells for which monthly head measurements were available. This head difference implies that the largest value  $S \Delta h/\Delta t$  can assume for 2000 is 0.000094 foot per day (ft/d), or approximately 0.41 inches per year (in/yr). This suggests that the error introduced to the model is within the limits of measuring aquifer recharge to the aquifer from rainfall infiltration.

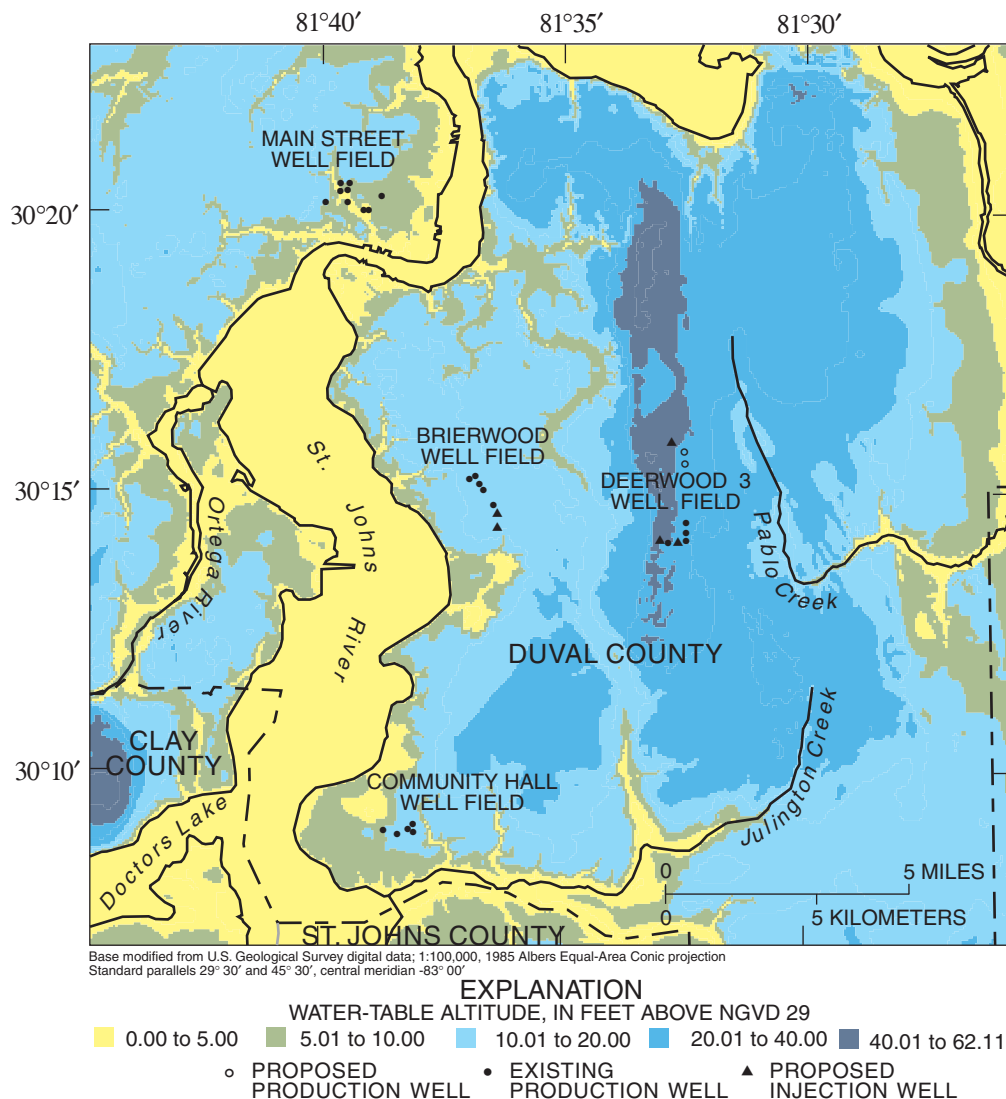
## Average Hydrologic Conditions for 2000

The development of a ground-water flow model based on the local hydrogeologic framework described above required the computation of average 2000 heads at the control points for the layers of the model. The water-table altitude was approximated by using a statistical approach that produced reliable results in Florida (Sepúlveda, 2002b).

The altitude of the water table for 2000 was approximated by using a multiple linear regression among the measured levels in SAS wells, the interpolated minimum water-table altitude, and the difference between land-surface altitude and the minimum water-table altitude (Sepúlveda, 2002b). The minimum water-table altitude is defined as the surface interpolated strictly from the measured altitude at drains in the SAS such as streams and lakes. The altitude of the

water table was strongly correlated with the minimum water-table altitude and the difference between land-surface altitude and minimum water-table altitude. Water-level measurements at SAS wells were compiled from SJRWMD and USGS data bases. A digital land-surface elevation model was generated from digitized hypsography obtained from the SJRWMD and USGS.

The minimum water-table altitude was generated from the stages interpolated for all points forming the river meanderings. The shoreline, assigned a water-table altitude of 0 ft, was used in the generation of the minimum water table in the northeastern corner of the model area (fig. 6). The minimum water table was bounded above by land-surface altitude and below by the altitude of the top of the ICU. Water-table altitudes, which were computed at the center of the grid cells, generally decrease coastward. The estimated dis-



**Figure 6.** Estimated altitude of the water table of the surficial aquifer system, average 2000 conditions.

tribution of the water table shows an extensive area where the altitude of the water table is at least 20 ft (fig. 6). The water-table altitude generally is less than 5 ft in the vicinity of the St. Johns River.

Time-averaged heads for CY 2000 in the UFA were calculated for 12 wells with monthly head measurements in Duval County and parts of St. Johns and Clay Counties, and regressed for another 12 wells for which only biannual head measurements were available. These head measurements were compiled from USGS data bases (U.S. Geological Survey, 2001a, 2001b, 2002a, 2002b). Annual average heads calculated for wells with monthly head measurements were regressed with the heads measured during May 2000 and September 2000 at the same wells by using the multiple linear regression (MLR):

$$h_{Ave} = \beta_M h_{May} + \beta_S h_{Sep} + \beta_I, \quad (1)$$

where

$h_{Ave}$  is the calculated 2000 average head at a UFA well, in feet;

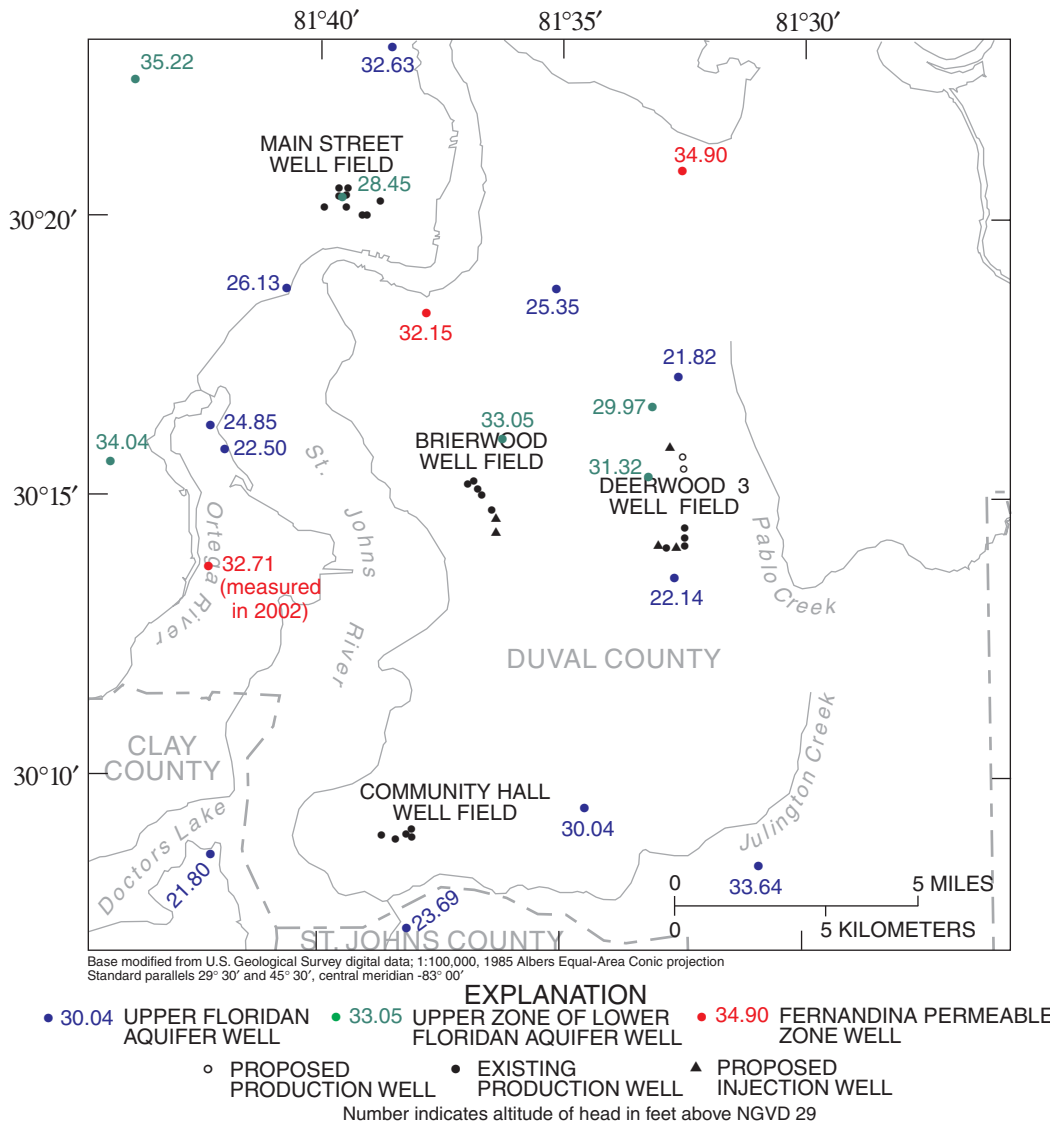
$h_{May}$  is the measured May 2000 head at the same UFA well, in feet;

$h_{Sep}$  is the measured September 2000 head at the same UFA well, in feet;

$\beta_S$  and  $\beta_M$  are the dimensionless MLR coefficients; and

$\beta_I$  is the intercept of the MLR, in feet.

Time-averaged 2000 heads in the model area were calculated at 11 sites in the UFA (fig. 7), seven of which were calculated by averaging monthly head measurements and four were computed by using equation 1.



**Figure 7.** Average 2000 heads in the Upper Floridan aquifer, upper zone of the Lower Floridan aquifer, and Fernandina permeable zone.

The time-averaged 2000 heads calculated from monthly measurements at 12 UFA sites and the average heads for the UFA regressed from equation 1 using May 2000 and September 2000 measurements at another 12 sites were used to represent the average 2000 hydrologic conditions or “average hydrologic conditions.”

Regression coefficients  $\beta_S$  and  $\beta_M$  represent the influence of the May 2000 ( $h_{\text{May}}$ ) and September 2000 ( $h_{\text{Sep}}$ ) measurements on regressed annual averages  $h_{\text{Ave}}$ . A total of 12 points was available to perform the MLR in equation 1, which had a correlation coefficient of 0.99, a root-mean-square (RMS) residual of 0.15 ft, and residuals ranging from -0.20 to 0.21 ft. The regression coefficients,  $\beta_I = 0.24$ ,  $\beta_M = 0.34$ , and  $\beta_S = 0.66$ , were used to estimate 2000 average heads at UFA wells for which only May 2000 and September 2000 measurements were available. Equation 1 was used only for UFA wells because there were no wells tapping the upper zone of the LFA or the FPZ with biannual head measurements.

The areal distribution of the time-averaged 2000 heads in the UFA was obtained by regressing the heads in the UFA within the area shown in figure 1 with the 1993-94 time-averaged heads in the UFA at the same sites and by using the regression coefficients to interpolate heads in the UFA from the estimated potentiometric-surface map for 1993-94 (Sepúlveda, 2002b, fig. 18). The simple linear regression (SLR) used to generate average 2000 heads in the UFA was:

$$h_{2000} = \alpha_1 h_{1993-94} + \beta_1, \quad (2)$$

where

$h_{2000}$  is the calculated 2000 average head at a UFA well, in feet;

$h_{1993-94}$  is the calculated 1993-94 average head at the same UFA well, in feet;

$\alpha_1$  is the dimensionless SLR coefficient; and

$\beta_1$  is the intercept of the SLR, in feet.

A total of 24 points was available to perform the SLR, which had a correlation coefficient of 0.96, an RMS residual of 2.25 ft, and residuals ranging from -6.67 to 3.21 ft. Of these 24 points, 11 were inside the model area. The regression coefficients,  $\beta_1 = -9.12$  and  $\alpha_1 = 1.14$ , were used to estimate CY 2000 average heads in the UFA at the center of the grid cells. These heads were used to obtain a computer-generated potentiometric surface for the UFA, which suggests that lateral flow entering or leaving the model area is negligible (fig. 8).

Time-averaged 2000 heads were calculated from monthly head measurements at eight wells in the upper zone of the LFA, six of which were in the model area (fig. 1). The time-averaged heads computed for the upper zone of the LFA were used to generate spec-

ified-head conditions along the lateral boundaries of the model by performing another SLR to generate the areal distribution of time-averaged 2000 heads. Heads in the UFA at these sites were interpolated from the potentiometric surface for the UFA derived from equation 2. The following SLR was used to regress calculated time-averaged 2000 heads in the upper zone of the LFA with interpolated UFA heads:

$$h_{\text{UZLFA}} = \alpha_2 h_{\text{UFA}} + \beta_2, \quad (3)$$

where

$h_{\text{UZLFA}}$  is the calculated 2000 average head at an upper zone of the LFA well, in feet;

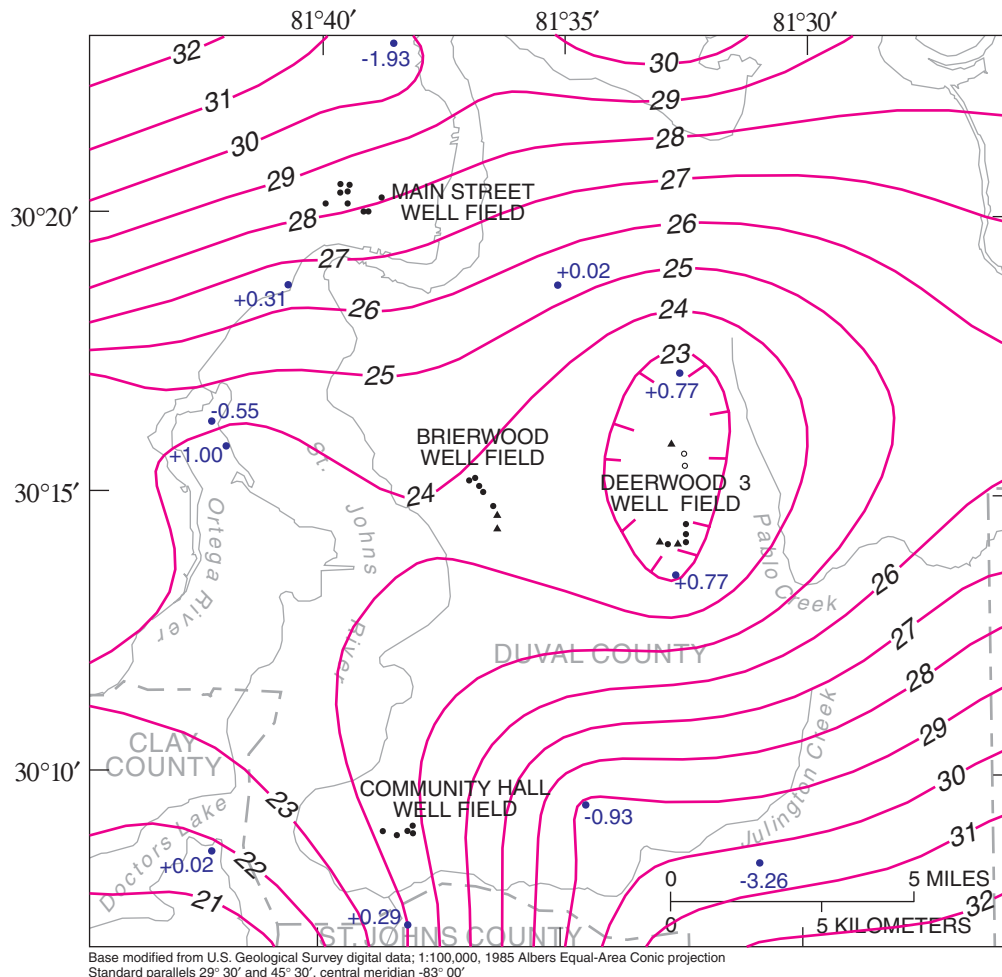
$h_{\text{UFA}}$  is the interpolated 2000 average UFA head at the same site, in feet;

$\alpha_2$  is the dimensionless SLR coefficient; and

$\beta_2$  is the intercept of the SLR, in feet.

Eight points were available to perform the SLR, which had a correlation coefficient of 0.96, an RMS residual of 0.63 ft, and residuals ranging from -1.10 to 0.83 ft. The SLR represented by equation 3 resulted in regression coefficients  $\beta_2 = -0.71$  and  $\alpha_2 = 0.91$ , which were used to regress 2000 average heads in the upper zone of the LFA at the center of the grid cells from interpolated 2000 average heads in the UFA. Results of the SLR were used to regress the specified heads at the center of the grid cells comprising the lateral boundaries of the upper zone of the LFA (fig. 9).

Time-averaged 2000 heads were calculated from monthly head measurements at five sites in the FPZ, three of which were in the model area. Environmental-water and freshwater heads were computed for wells tapping the FPZ and having variable ground-water density (Luszczynski, 1961). Environmental-water head at a given point in ground water of variable density is the freshwater head reduced by the difference of salt mass in freshwater and the salt mass in the environmental water between the given point and the top of the saturated zone (Luszczynski, 1961). Wells D-425B, D-1344, D-3060, D-2386, and SJ-150 (fig. 1) tap only the FPZ. The open interval of well D-425B extends from an altitude of -2,035 to -2,466 ft. The water from well D-425B is more characteristic of the FPZ wells than of the upper zone of the LFA wells (Phelps, 2001). Measured chloride concentrations at D-425B and D-1344 (Phelps, 2001; St. Johns River Water Management District, 2002) indicated freshwater in the FPZ, thus, the point-water, environmental-water, and freshwater heads were the same. Measured chloride concentrations at D-3060, D-2386, and SJ-150 implied the need to compute environmental-water and freshwater heads to account for variable ground-water density.



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**

- 30- REGRESSED POTENTIOMETRIC CONTOUR IN THE UPPER FLORIDAN AQUIFER --  
Derived from simple linear regression established by equation 2.  
Contour interval is 1 foot. Hachures indicate depression. Datum is NGVD 29
- +0.29 • UPPER FLORIDAN AQUIFER WELL -- Number indicates difference, in feet,  
between regressed and measured head in 2000
- PROPOSED PRODUCTION WELL      • EXISTING PRODUCTION WELL      ▲ PROPOSED INJECTION WELL

**Figure 8.** Linearly regressed potentiometric surface of the Upper Floridan aquifer for average 2000 conditions obtained from average 1993-94 conditions.

The environmental-water heads were computed from (Luszczynski, 1961):

$$\rho_f H_{ew} = \rho_i H_p - Z_i (\rho_i - \rho_a) - Z_r (\rho_a - \rho_f) \quad (4)$$

where

- $H_{ew}$  is the environmental-water head, in feet;
- $H_p$  is the point-water head, in feet;
- $Z_i$  is the altitude of the top of the open interval, referred to as point  $i$ , in feet;
- $Z_r$  is the altitude of a reference point  $r$  from which average density is computed, in feet;
- $\rho_f$  is the density of freshwater, equal to 1.000 gram per milliliter (g/mL);

$\rho_i$  is the density of water at the top of the open interval or point  $i$ , in g/mL; and

$\rho_a$  is the average density of water between points  $i$  and  $r$ , in g/mL.

The elevation  $Z_r$  could be taken to be the land-surface altitude. The freshwater head was computed from the equation (Luszczynski, 1961):

$$\rho_f H_{fw} = \rho_i H_p - Z_i (\rho_i - \rho_f) \quad (5)$$

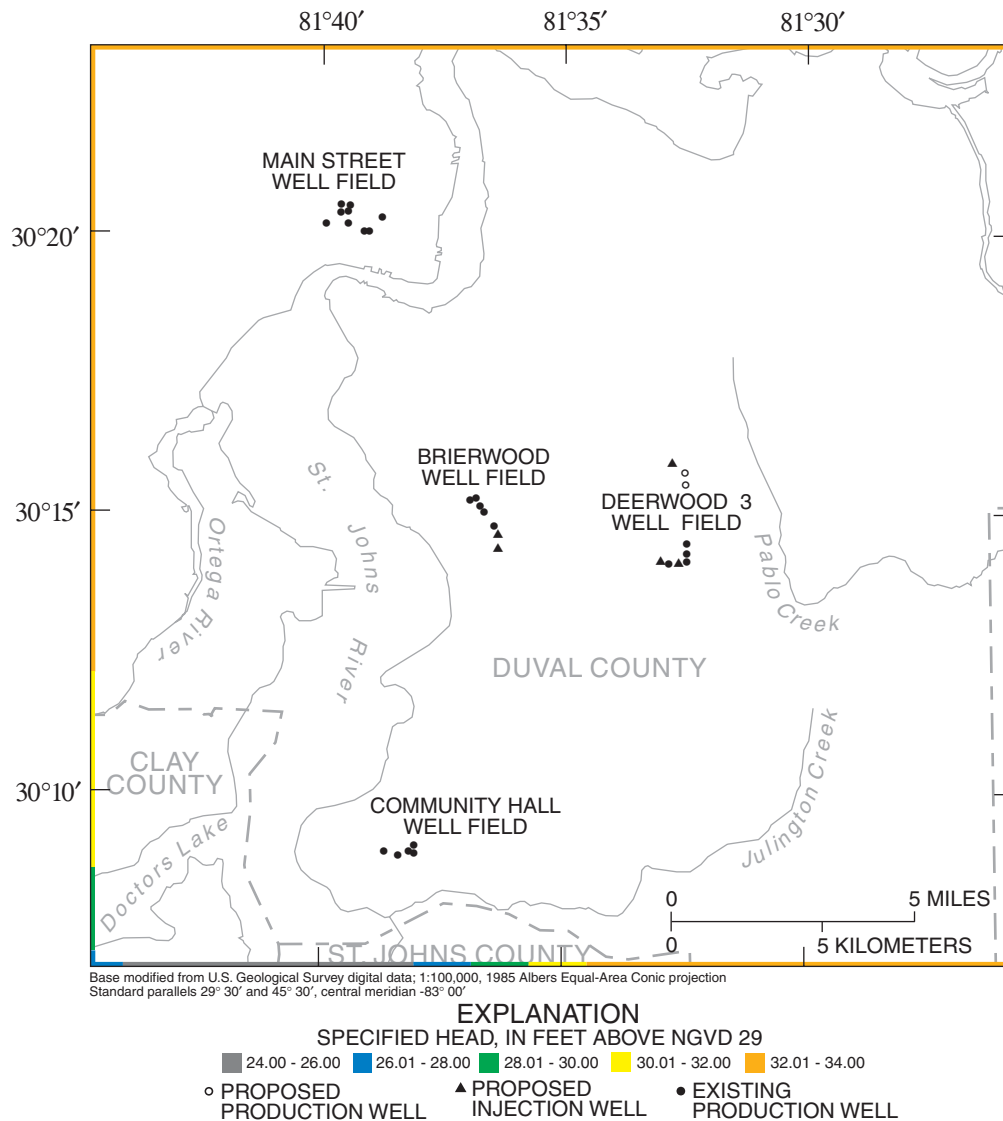
The maximum difference between freshwater and environmental-water heads among wells tapping the FPZ within the study area was about 2 ft (table 4).



**Table 4.** List of parameter values used to compute the average 2000 freshwater and environmental-water heads at Fernandina permeable zone wells

[Datum is NGVD 29; g/mL, grams per milliliter. For the calculation of freshwater and environmental-water heads, refer to equations 4 and 5. Ground-water density values were estimated from a simple linear regression between specific conductance and density values (Phelps and Spechler, 1997)]

Well name	Average point-water head, $H_p$ (feet)	Altitude of top of open interval $Z_i$ (feet)	Altitude of reference point $Z_r$ (feet)	Density $\rho_i$ of water at point $Z_i$ (g/mL)	Average ground-water density $\rho_a$ between points $Z_i$ and $Z_r$ (g/mL)	Average freshwater head, $H_{fw}$ (feet)	Average environmental-water head, $H_{ew}$ (feet)
D-1344	32.71	-1,858	7	1.000	1.000	32.71	32.71
D-425B	32.15	-2,032	18	1.000	1.000	32.15	32.15
D-3060	18.54	-2,027	23	1.009	1.001	36.95	34.90
D-2386	37.88	-1,874	17	1.002	1.001	41.73	39.81
SJ-150	-4.56	-1,975	5	1.023	1.002	40.76	36.80



**Figure 9.** Specified heads along the lateral boundary cells of the upper zone of the Lower Floridan aquifer, average 2000 conditions.



Heads specified along the lateral boundaries of the FPZ (layer 4) were 1.5 ft higher than the specified heads at the upper zone of the LFA (fig. 9). The differences between the environmental-water heads in the FPZ and the heads in the upper zone of the LFA, which ranged from 1.3 to 2.2 ft, averaged about 1.5 ft. Heads in the upper zone of the LFA at the sites of the FPZ wells (fig. 1) were interpolated using the results of equation 3. The average difference between the environmental-water heads in the FPZ and the heads in the upper zone of the LFA was used to determine the heads in the FPZ to be specified along the lateral boundaries of the model.

## Calibration of Ground-Water Flow Model

Computed time-averaged heads in the UFA, the upper zone of the LFA, and the FPZ for CY 2000 were the control points used to calibrate the steady-state ground-water flow model. The number of control points for the UFA, the upper zone of the LFA, and the FPZ, respectively, were 11, 6, and 3. Hydraulic parameters were systematically adjusted to reduce the difference between simulated and computed average heads until an acceptable model calibration was achieved.

The steady-state ground-water flow model was calibrated by adjusting input hydraulic parameters within reasonable ranges from the initial distributions of values, which were taken from Sepúlveda (2002a), for all hydrogeologic units except the FPZ, and from Durden (1997) for the FPZ. The initial distributions of aquifer properties were adjusted until simulated heads closely approximated average 2000 heads (fig. 7). Simulated heads and flows from a calibrated, deterministic ground-water flow model commonly depart from measured heads and flows, even after a diligent calibration effort. The difference between model results and what actually occurs in the aquifers, referred to as model error, is the cumulative result of simplification of the conceptual model, grid scale, measurement errors, and the difficulty in obtaining sufficient measurements to account for all spatial variations in hydraulic properties and stresses throughout the model area.

Hydraulic parameters that were adjusted during calibration of the steady-state ground-water flow model included: the transmissivity of the UFA, the upper zone of the LFA, and the FPZ; and the vertical leakance of the ICU, the MSCU, and the SCU. The calibration process was iterative and consisted of

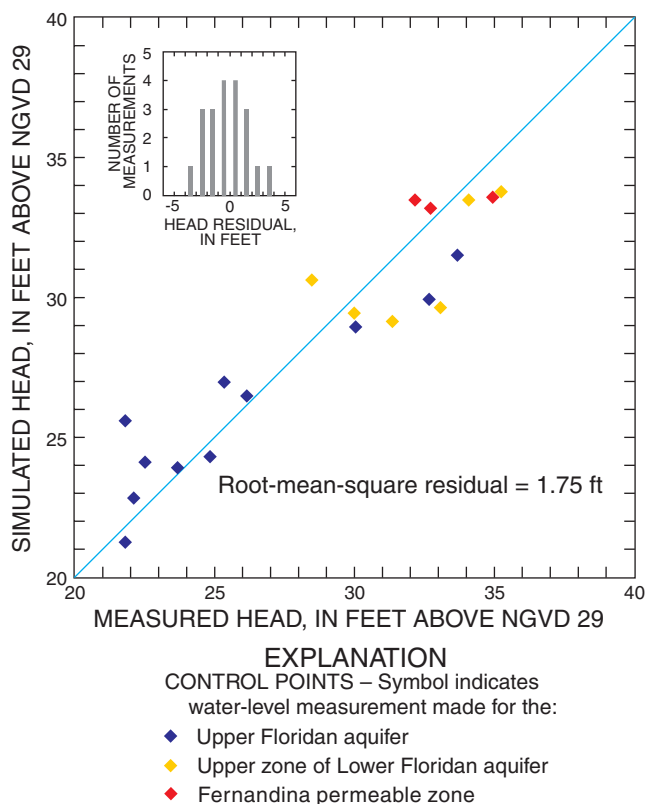
(1) assigning initial hydraulic parameters from models developed by Durden (1997) and Sepúlveda (2002a); (2) comparing simulated and average heads for the steady-state period of 2000 at the 20 control points (fig. 7); and (3) adjusting and generalizing hydraulic parameters to minimize the difference between simulated and average heads for 2000. The guiding principle of calibration was that the model parameter with the highest sensitivity for a given area or aquifer was adjusted first; other less sensitive parameters were adjusted only if reasonable residuals were not achieved. In cases where two parameters were about equally sensitive, each was adjusted separately.

The initial distributions of hydraulic parameters were used to define contiguous zones of equal values. The areal extents of the transmissivity zones for the UFA, upper zone of the LFA, and FPZ were independent from each other. The areal extents of the vertical leakance zones for the ICU, MSCU, and the SCU also were independent from each other. The areal extents of these zones were modified during calibration. Due to the limited number of control points in the FPZ, the calibration of transmissivity for the FPZ and of the vertical leakance of the SCU was limited to selecting one uniform value for the study area for each of these two parameters. The hydraulic properties of the FPZ were calibrated based on the average environmental-water head in the FPZ. This was different from the freshwater-equivalent head only at D-3060 (table 4). The environmental-water head was computed because this head defines the hydraulic gradients along the vertical component of flow. The assumption that the vertical component of flow in the FPZ exerts a more dominant effect than the lateral component of flow in the FAS resulted in computing the environmental-water head at D-3060 (eq. 4).

Simulated heads, at the center of the cells where the control points were located, were compared to the measured heads at the control points, as no spatial interpolation was deemed necessary given the small size of the uniform grid cells. Vertical interpolation was not necessary because of the discontinuity and associated refraction of potential fields across zones of different transmissivities.

Simulated and measured heads in the UFA, upper zone of the LFA, and FPZ agreed reasonably well throughout the study area (fig. 10). The RMS residuals between simulated and measured heads for the UFA, upper zone of the LFA, and FPZ were 1.75, 1.99, and 1.14 ft, respectively, with all residuals less

than 3.8 ft (table 5). The histogram of residuals for all hydrogeologic units appears to be normally distributed (fig. 10), indicating that the error in the model also is normally distributed.



**Figure 10.** Comparison of simulated to measured heads in all hydrogeologic units for the calibrated model.

**Table 5.** Water-level residual statistics for the calibrated steady-state model

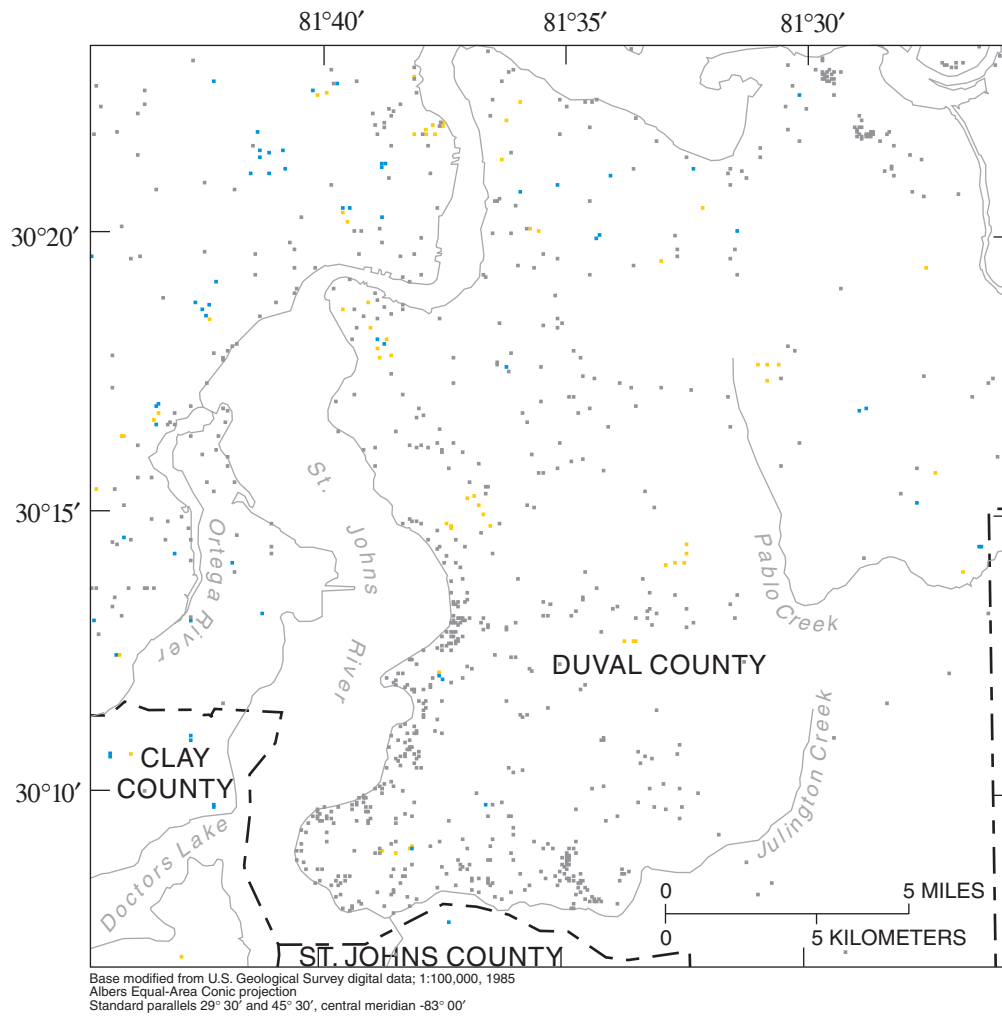
[Min., minimum; Max., maximum; RMS, root-mean-square]

Aquifer	Number of measurements	Residual (feet)			
		Min.	Max.	Mean	RMS
Upper Floridan aquifer	11	-2.71	3.75	0.14	1.75
Upper zone of the Lower Floridan aquifer	6	-3.44	2.15	-.98	1.99
Fernandina permeable zone	3	-1.29	1.39	.21	1.14
Entire model	20	-3.44	3.75	-.19	1.75

The process of modifying the initial transmissivity distribution of the UFA, the upper zone of the LFA, and the FPZ during calibration included: (1) finding values that decreased the absolute value of residuals at control points; (2) generalizing transmissivity values to two significant figures; (3) making transmissivity changes to areas where residuals were large and sensitive to changes in transmissivity; (4) making changes to areas where new ground-water withdrawals occurred; and (5) distributing previously simulated transmissivity values for the entire thickness of the LFA (Sepúlveda, 2002a) into transmissivity values for the upper zone of the LFA and for the FPZ.

The process of modifying the initial vertical leakage distribution of the ICU, the MSCU, and the SCU during calibration included: (1) finding values that decreased the absolute value of residuals at control points; (2) generalizing vertical leakances to one significant figure; (3) making vertical leakage changes to areas where residuals were large and sensitive to changes in leakage; (4) limiting recharge to the UFA to less than 1 in/yr in areas where the estimated altitude of the water table was higher than the simulated heads in the UFA; and (5) limiting the discharge from the UFA to the SAS along the St. Johns River reaches to about 11 ft<sup>3</sup>/s, as a ground-water flow model-based estimate by Spechler (1995) suggested.

Average ground-water withdrawals for 2000 in the UFA (23 Mgal/d) and in the upper zone of the LFA (88 Mgal/d) were compiled from JEA data bases and assigned to corresponding grid cells. Self-supplied water from domestic wells was estimated to be, at most, 0.01 Mgal/d from each well; these were simulated as withdrawals from the UFA (fig. 11). Assigned ground-water withdrawals to each aquifer for wells with open intervals tapping more than one aquifer were set equal to the total withdrawal rate multiplied by the ratio of the simulated transmissivity of the interval open to the aquifer and the simulated transmissivity of the entire open interval of the well. Larger withdrawals from the upper zone of the LFA than those from the UFA reflect that the upper zone of the LFA is much more transmissive than the UFA (fig. 12).

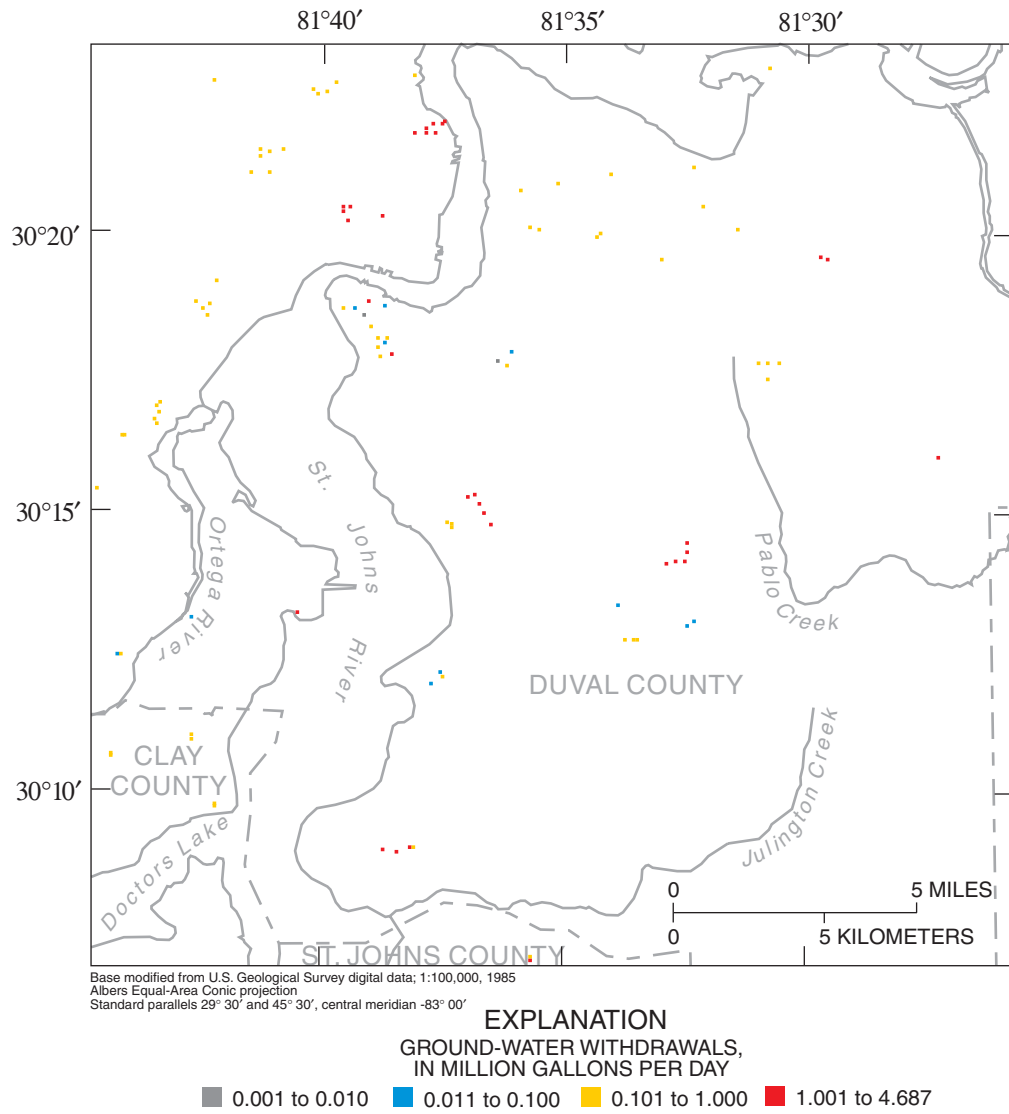


**EXPLANATION**

GROUND-WATER WITHDRAWALS,  
 IN MILLION GALLONS PER DAY

- 0.001 to 0.010    ■ 0.011 to 0.100    ■ 0.101 to 0.917

**Figure 11.** Average 2000 ground-water withdrawal rates from the Upper Floridan aquifer.

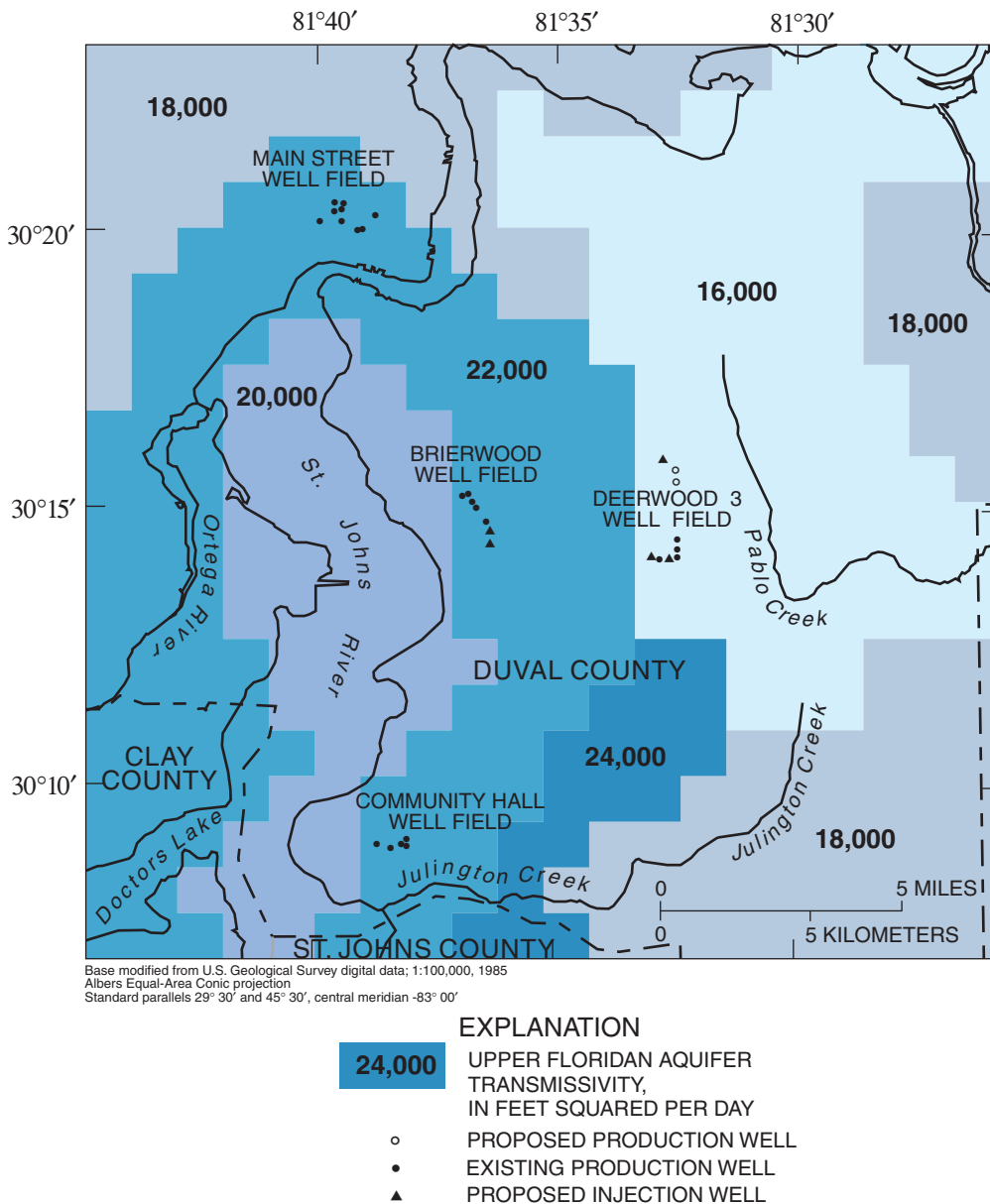


**Figure 12.** Average 2000 ground-water withdrawal rates from the upper zone of the Lower Floridan aquifer.

## Hydraulic Properties from Calibrated Model

Transmissivity in the UFA from the calibrated model ranged from 16,000 feet squared per day ( $\text{ft}^2/\text{d}$ ) in the northeastern and north-central parts of the model area to 24,000  $\text{ft}^2/\text{d}$  in south-central parts of the model area (fig. 13). The distribution of transmissivity for the UFA in the model area is similar to that simulated by Sepúlveda (2002a). The main difference between the calibrated distribution of the UFA in this

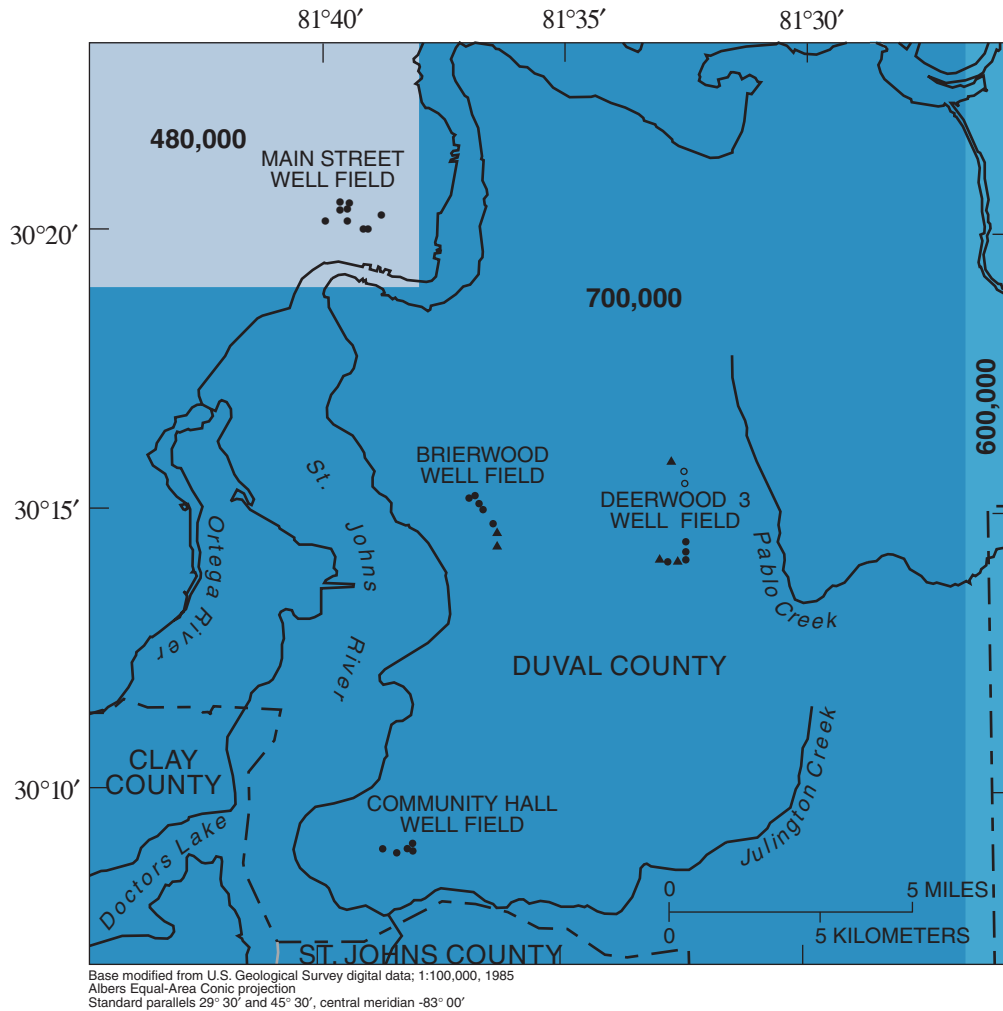
study and that simulated in regional models (Durden, 1997; Sepúlveda, 2002a) occurred in the northwestern part of the model area, where the simulated transmissivity (18,000  $\text{ft}^2/\text{d}$ , fig. 13) is one-fourth of that simulated by regional models. This difference could be explained by the fact that the locations of self-supplied domestic wells were not available in the regional models. The rearrangement of aquifer stresses necessitated the redistribution of transmissivity to account for changes in aquifer stresses. Only seven zones of transmissivity were generated as a result of calibration.



**Figure 13.** Transmissivity of the Upper Floridan aquifer from the calibrated model.

Transmissivity of the upper zone of the LFA ranged from 480,000 to 700,000 ft<sup>2</sup>/d, with only three distinct transmissivity zones in the model area (fig. 14). The only difference between the transmissivity distribution shown in figure 14 and that presented in regional models is in the northwestern corner of the model area, where the upper zone of the LFA has a

value that is 80,000 ft<sup>2</sup>/d less transmissive than the simulated value in both regional models (Durden, 1997; Sepúlveda, 2002a). The model area had only one transmissivity zone for the FPZ, with a calibration value of 60,000 ft<sup>2</sup>/d. The limited number of control points in the FPZ precluded the discretization of the model area into more transmissivity zones.



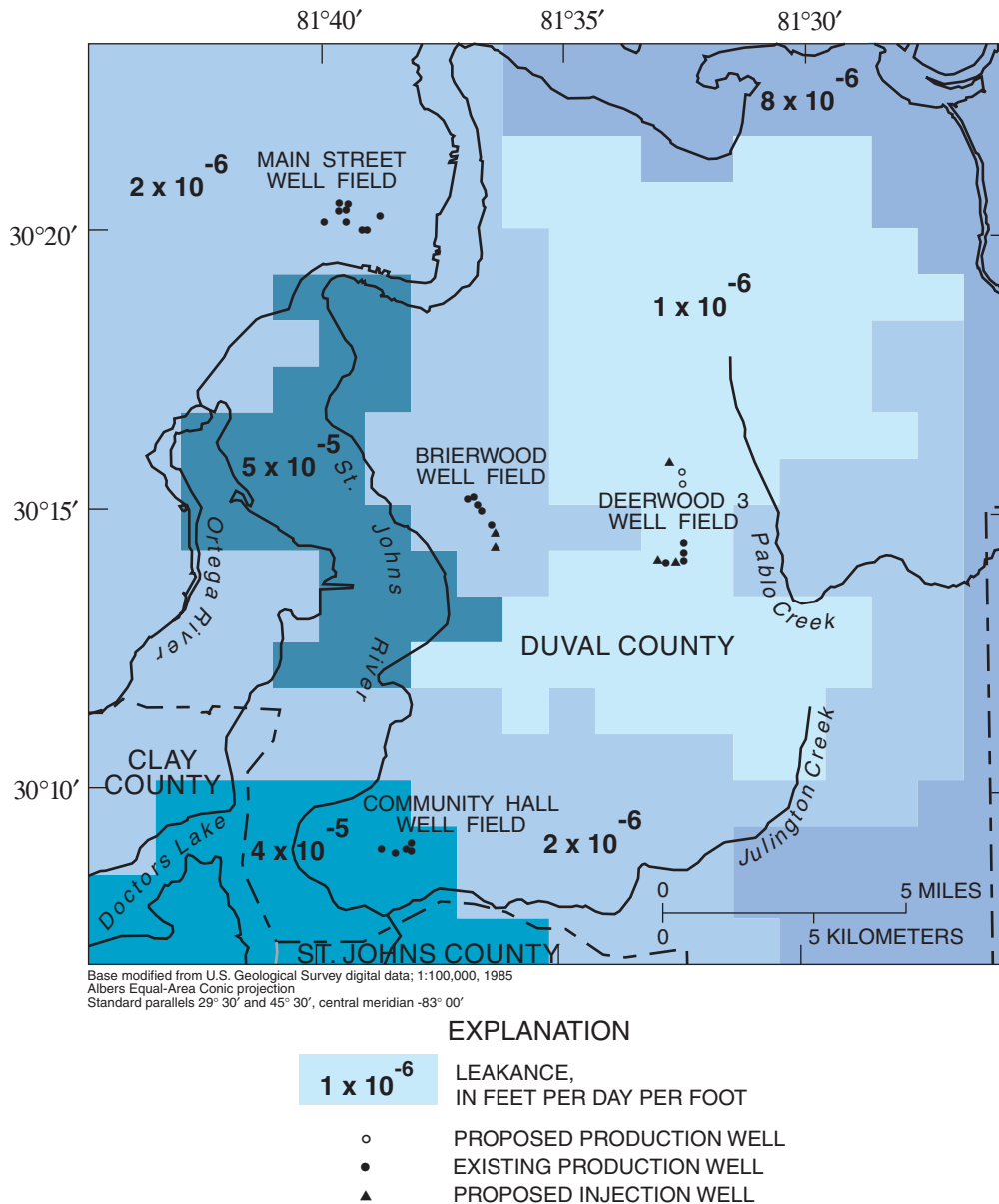
**EXPLANATION**

- 480,000** UPPER ZONE OF LOWER FLORIDAN AQUIFER TRANSMISSIVITY, IN FEET SQUARED PER DAY
- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

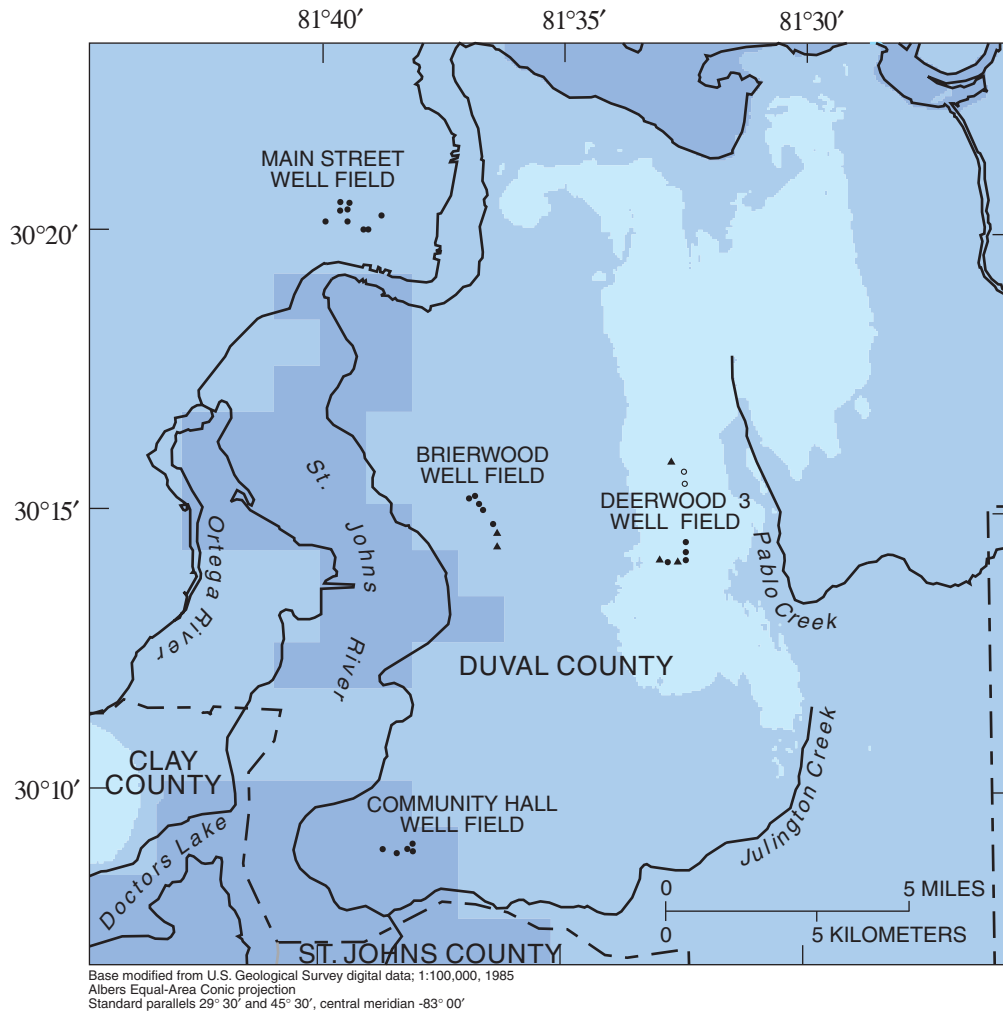
**Figure 14.** Transmissivity of the upper zone of the Lower Floridan aquifer from the calibrated model.

The distribution of the simulated vertical leakage of the ICU (fig. 15) is similar to that presented in previous regional models. The ICU is simulated to have the largest vertical leakage value in parts of the St. Johns River. The cumulative discharge from the UFA to the SAS from cells in reaches of the St. Johns River in the model area was simulated to be 10.79 ft<sup>3</sup>/s. This flow is within the discharge range that was esti-

mated from Spechler (1995). A large area of the model where the water-table altitude is higher than simulated heads of the UFA was assigned the lowest leakage value to match measured heads in the UFA within this area of low recharge (fig. 16). The simulated vertical leakage between the SAS and the UFA ranged from 5.88 in/yr of upward leakage from the UFA to 0.67 in/yr of recharge from the SAS to the UFA.



**Figure 15.** Leakage of the intermediate confining unit from the calibrated model.



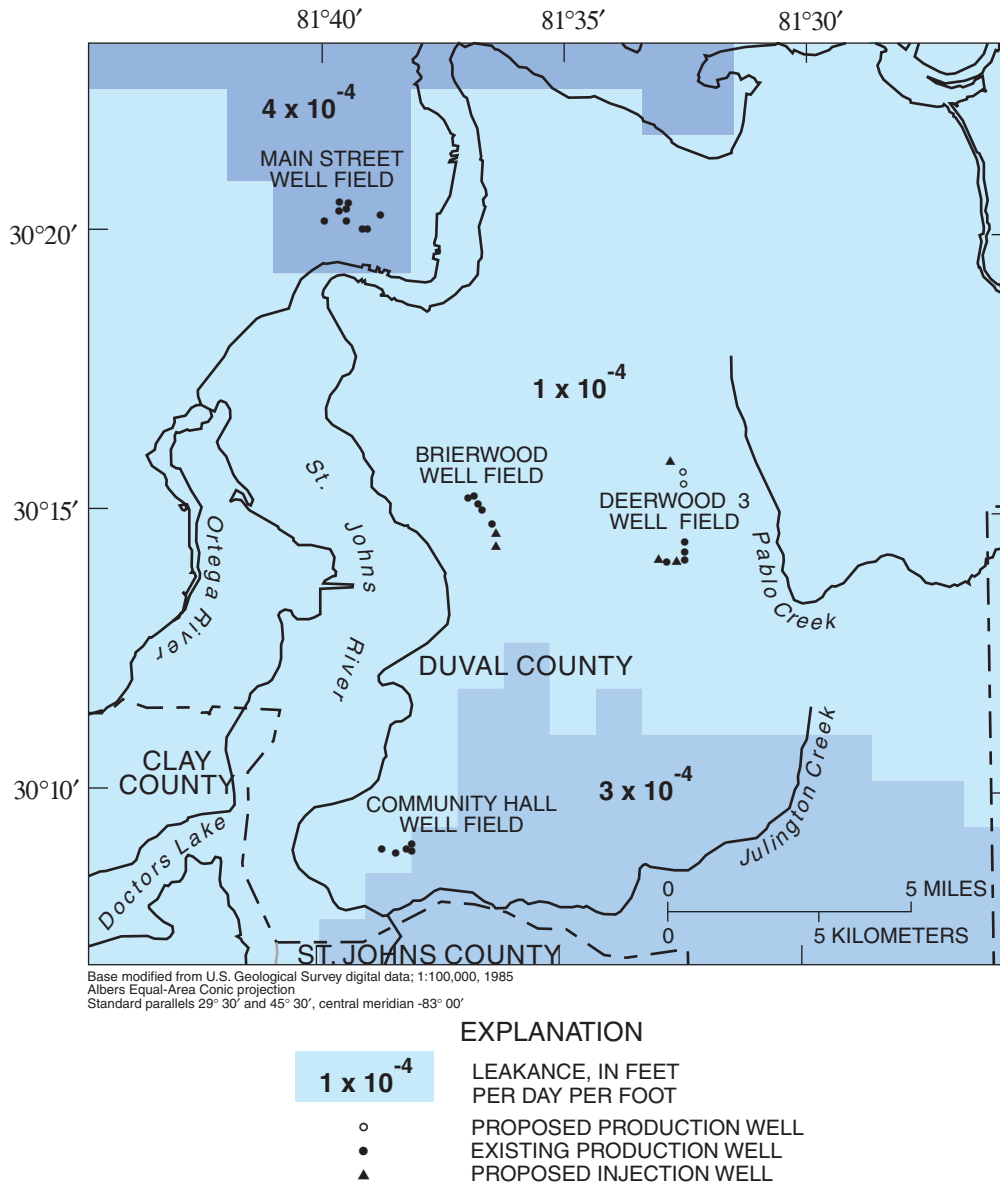
- EXPLANATION**  
 VERTICAL LEAKAGE RATE, IN INCHES PER YEAR --  
 Negative leakage rates indicate upward leakage and  
 positive leakage rates indicate downward leakage
- -5.88 to -1.00
  - -0.99 to 0.00
  - 0.01 to 0.67
- PROPOSED PRODUCTION WELL
  - EXISTING PRODUCTION WELL
  - ▲ PROPOSED INJECTION WELL

**Figure 16.** Simulated vertical leakage rates to and from the Upper Floridan aquifer through the intermediate confining unit, average 2000 conditions.

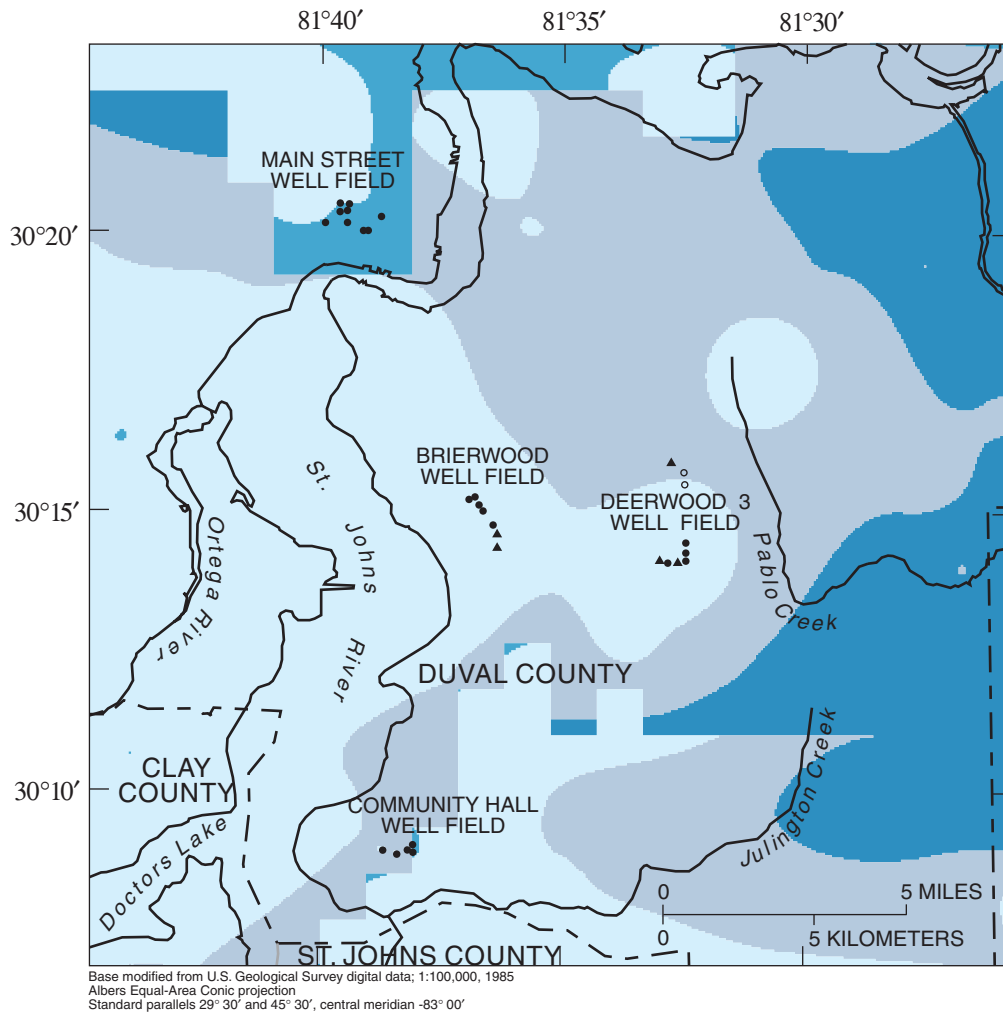


The lack of control points in the upper zone of the LFA limited the number of zones of uniform vertical leakance assigned to the MSCU (fig. 17). Except for zones of uniform vertical leakance of the MSCU in the northwestern and south-central parts of the model area, a uniform value of  $1 \times 10^{-4}$  foot per day per foot

(ft/d)/ft was assigned as vertical leakance of the MSCU. The model area was simulated to be a discharge area from the upper zone of the LFA (fig. 18). The highest leakage rate from the upper zone of the LFA to the UFA, simulated in the northwestern part of the model area, was 8.45 in/yr.



**Figure 17.** Leakance of the middle semiconfining unit from the calibrated model.



**EXPLANATION**  
 VERTICAL LEAKAGE RATE, IN INCHES PER YEAR --  
 All rates are negative, indicating upward leakage

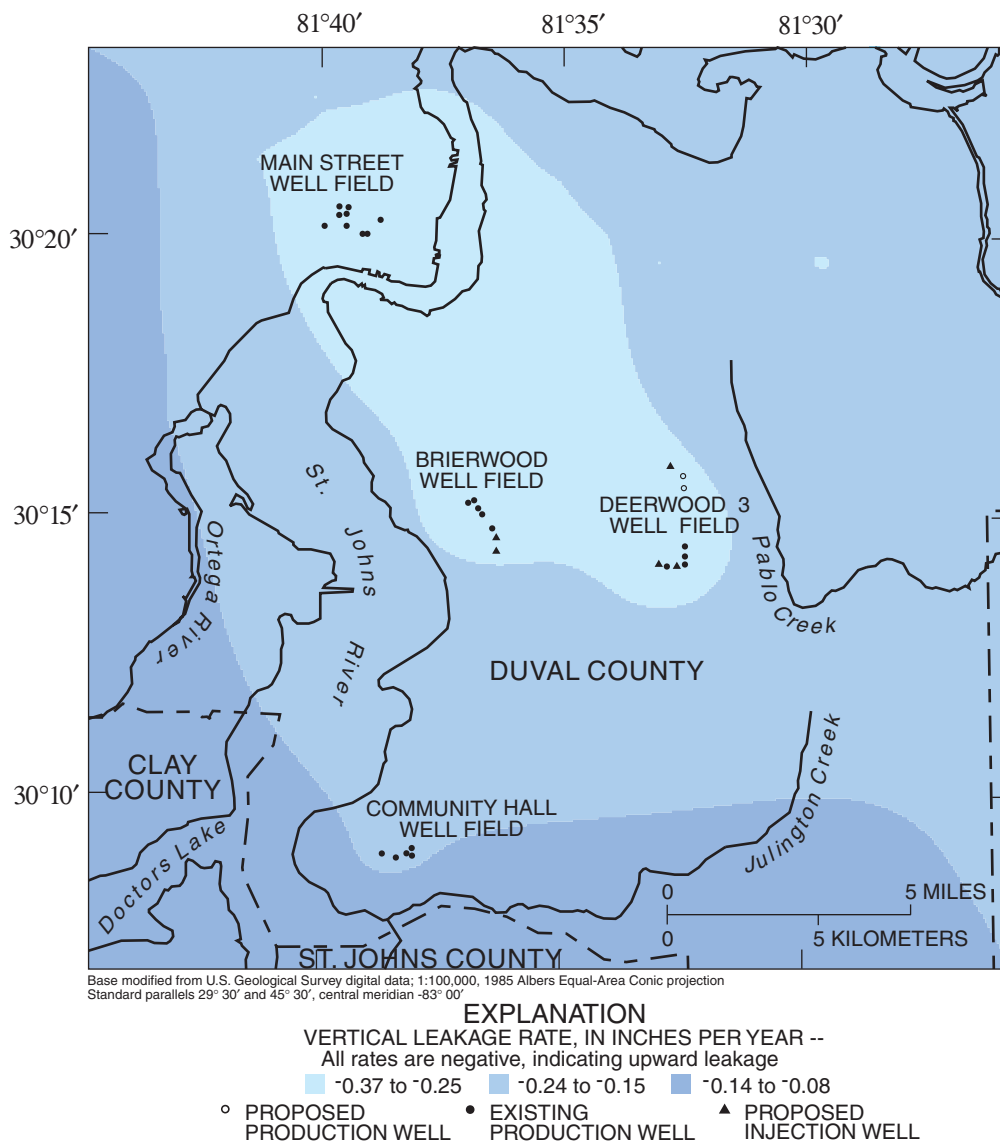
■ -8.45 to -5.00   ■ -4.99 to -2.00   ■ -1.99 to -1.00   ■ -0.99 to -0.04

- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

**Figure 18.** Simulated vertical leakage rates from the upper zone of the Lower Floridan aquifer through the middle semiconfining unit, average 2000 conditions.

The vertical leakage of the SCU was simulated with a uniform value of  $2.0 \times 10^{-5}$  (ft/d)/ft. Upward leakage from the FPZ was simulated throughout the model area (fig. 19). Upward vertical leakage rates from the FPZ ranged from 0.08 to 0.37 in/yr. However, because chloride concentrations of ground water from the FPZ generally are greater southeast of the St. Johns River than to the northwest, it is more likely greater chloride concentrations would be observed in the upper zone of the LFA at Deerwood 3 and Brierwood wells than at the Main Street well field due to the upward migration of water with greater chlorides from the FPZ. The simulated rates of upward flow from the FPZ

are about the same at the locations of the Deerwood 3 and Brierwood wells. The fact that greater chloride concentrations were measured in samples from Deerwood 3 than from Brierwood wells in 2002 may be explained by either the additional upward flow induced at Deerwood 3 due to increased pumping during 2002 compared to 2000 or by the possibility that ground water from the FPZ in the vicinity of Deerwood 3 may be more mineralized than that in the Brierwood area. The magnitude of the upward leakage from the FPZ (fig. 19) is substantially smaller than the upward leakage from the upper zone of the LFA (fig. 18), mainly due to the fact that the MSCU is leakier than the SCU.

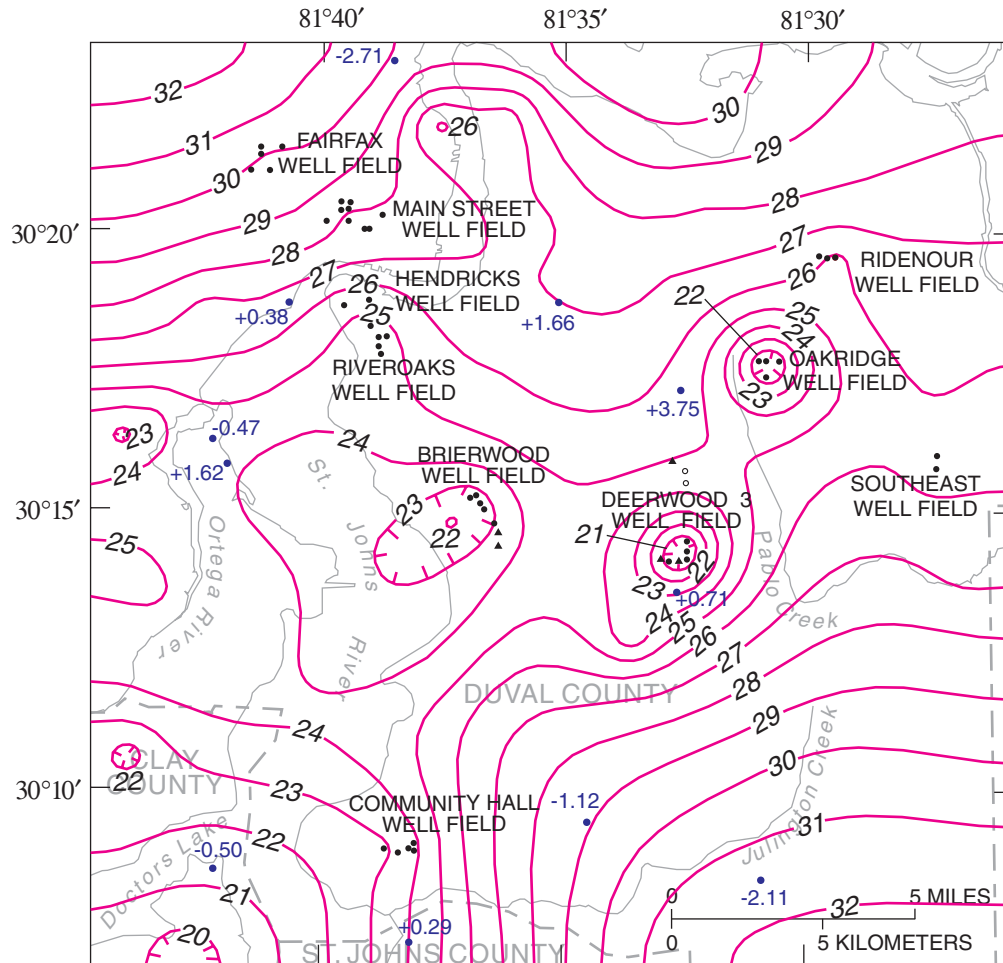


**Figure 19.** Simulated vertical leakage rates from the Fernandina permeable zone through the semiconfining unit, average 2000 conditions.

## Simulated Potentiometric Surfaces

The simulated potentiometric surface of the UFA includes cones of depression at the Deerwood 3 well field, at the Brierwood well field extending into the St. Johns River, and at the Oakridge well field (fig. 20). These cones of depression coincide with

areas of substantial pumping in the UFA (fig. 11). Simulated ground-water flow in the UFA is from the north and southeast towards the location of Brierwood, Deerwood 3, and Oakridge well fields. Simulated ground-water flow in the UFA also is from the Community Hall wells to the southwest corner of the model area along the St. Johns River.



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'

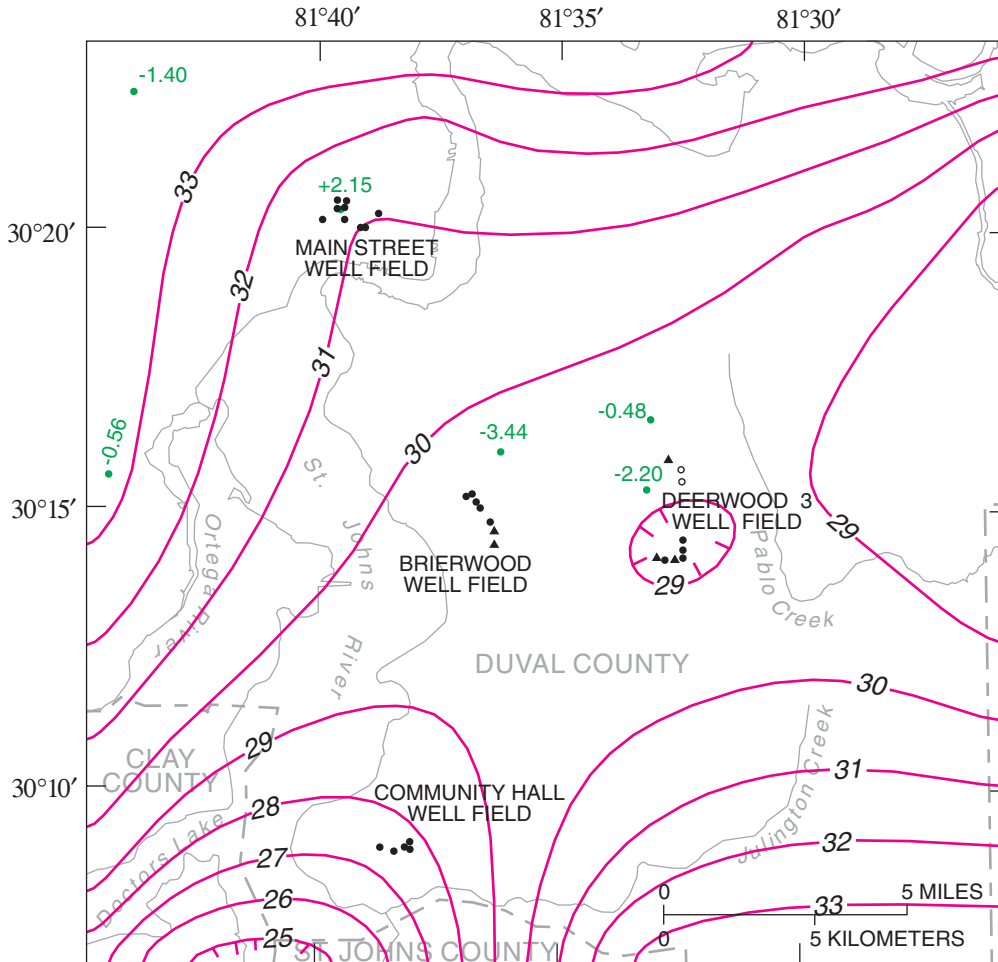
### EXPLANATION

- 30- SIMULATED POTENTIOMETRIC CONTOUR IN THE UPPER FLORIDAN AQUIFER -- Derived from model simulation. Contour interval is 1 foot. Hachures indicate depression. Datum is NGVD 29
- +0.29 ● UPPER FLORIDAN AQUIFER WELL -- Number indicates difference between simulated and measured head
- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

**Figure 20.** Simulated potentiometric surface of the Upper Floridan aquifer (model layer 2), average 2000 conditions.

The simulation of flow in the upper zone of the LFA indicates that ground water moves from the northwest and southeast areas towards the center of the model area (fig. 21). Although some of the water discharges through the eastern boundary of the model area, another flow pattern is indicated by the decreasing heads towards the southwestern boundary of the

model area. A depression in the potentiometric surface of the upper zone of the LFA surrounding the Deerwood 3 well field is indicative of the approximately 11 Mgal/d pumped from this aquifer at this well field in 2000. The simulation of flow in the FPZ indicated flow patterns similar to those that occur in the upper zone of the LFA (fig. 22).

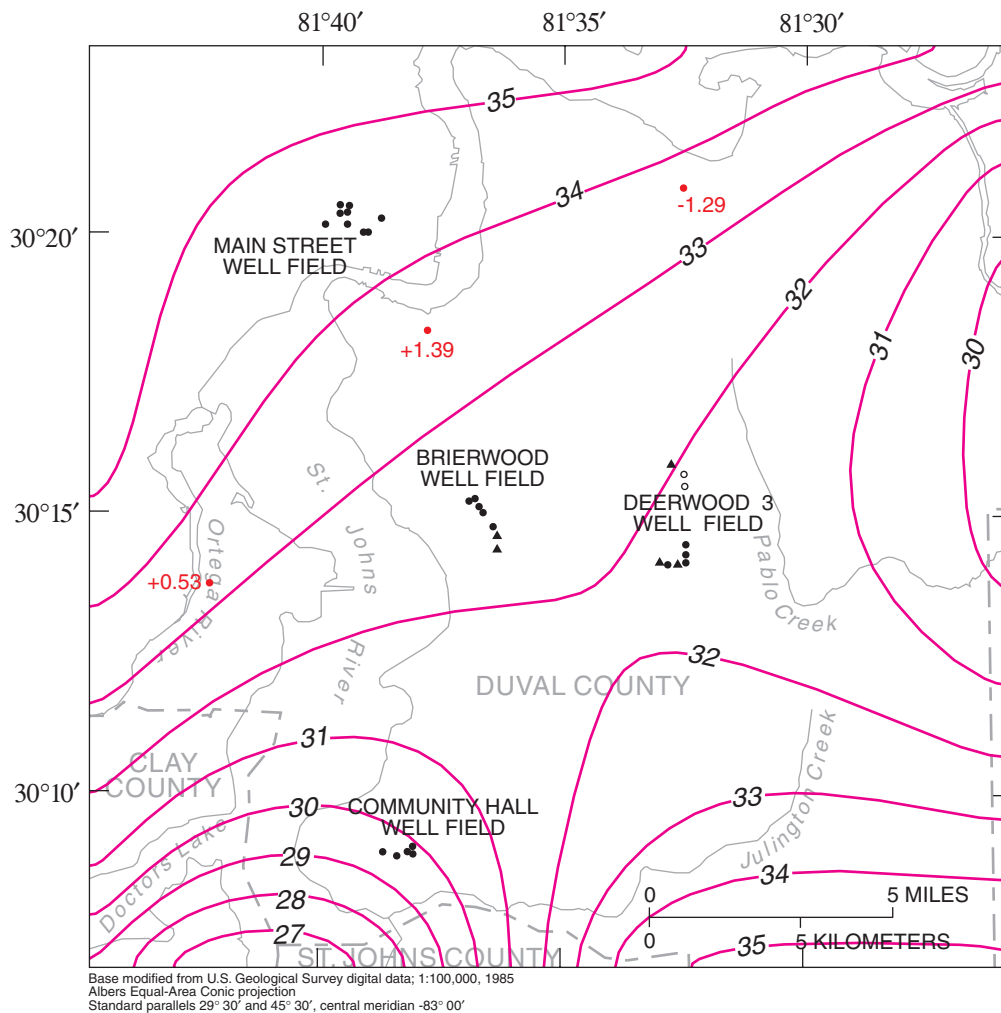


Base modified from U.S. Geological Survey digital data; 1:100,000, 1985  
 Albers Equal-Area Conic projection  
 Standard parallels 29° 30' and 45° 30', central meridian -83° 00'

**EXPLANATION**

- 30- SIMULATED POTENTIOMETRIC CONTOUR IN THE UPPER ZONE OF THE LOWER FLORIDAN AQUIFER --Derived from model simulation. Contour interval is 1 foot. Hachures indicate depression. Datum is NGVD 29
- 0.48 • UPPER ZONE OF LOWER FLORIDAN AQUIFER WELL -- Number indicates difference between simulated and measured head
- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

**Figure 21.** Simulated potentiometric surface of the upper zone of the Lower Floridan aquifer (model layer 3), average 2000 conditions.



**EXPLANATION**

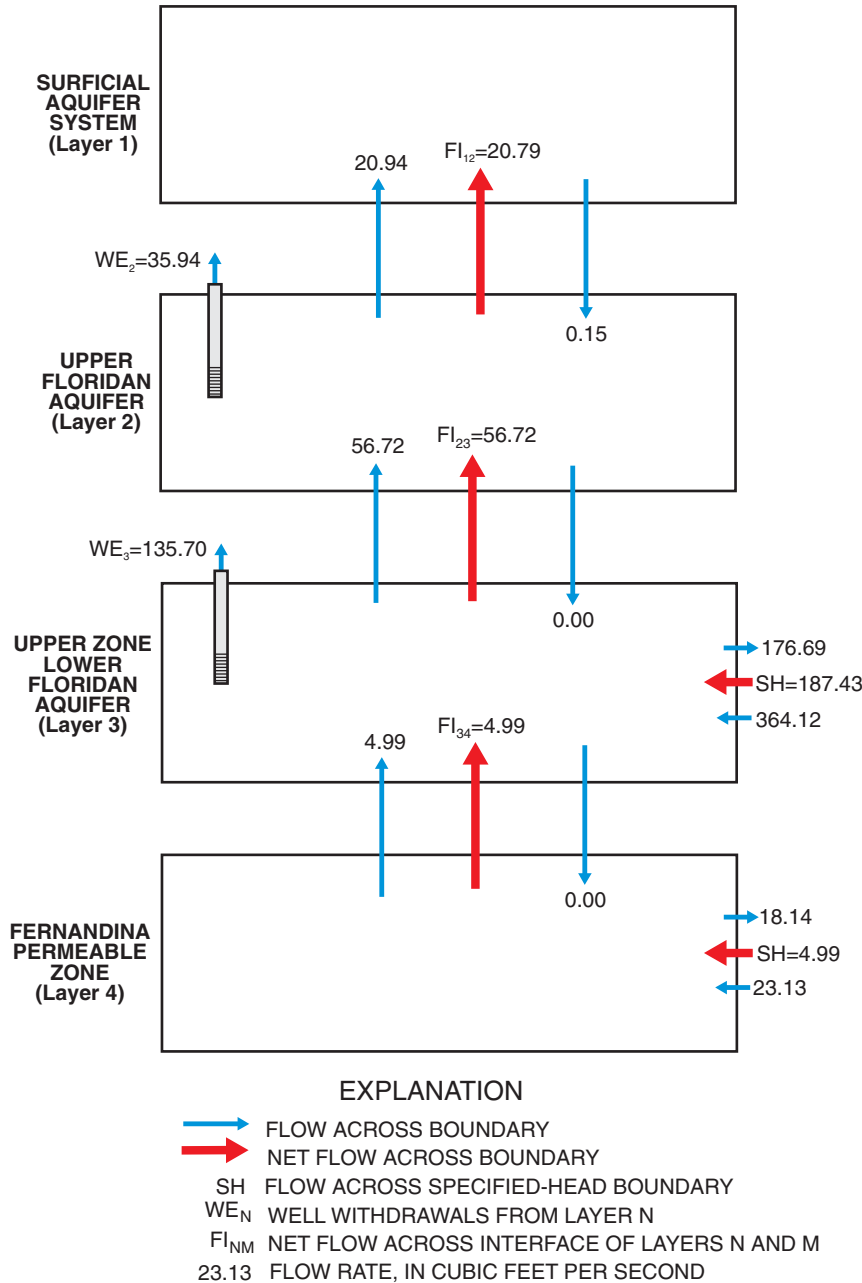
- 30 — SIMULATED POTENTIOMETRIC CONTOUR IN THE FERNANDINA PERMEABLE ZONE -- Derived from model simulation. Contour interval is 1 foot. Datum is NGVD 29
- 1.29 • FERNANDINA PERMEABLE ZONE WELL -- Number indicates difference between simulated and measured head
- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

**Figure 22.** Simulated potentiometric surface of the Fernandina permeable zone (model layer 4), average 2000 conditions.

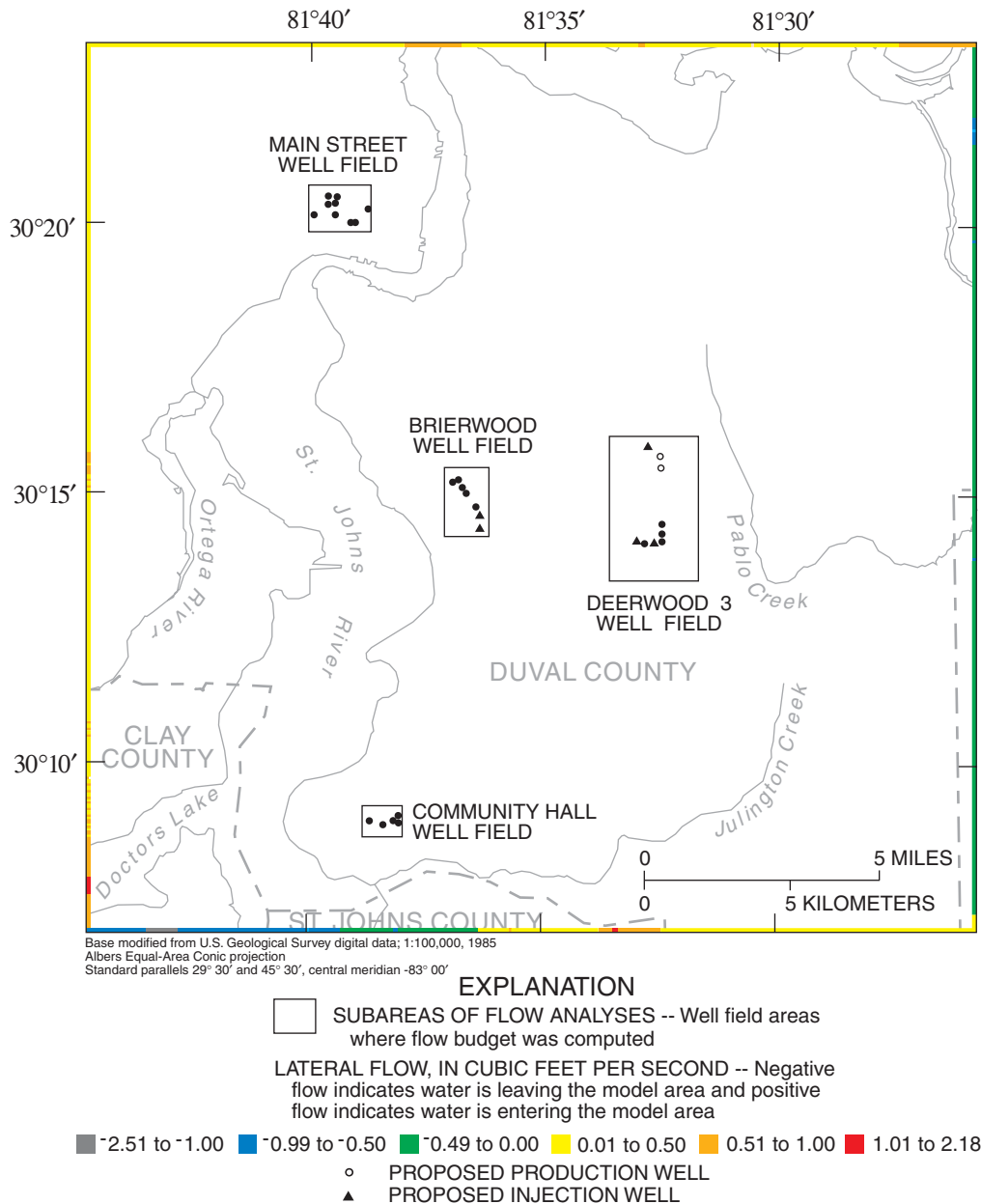
## Ground-Water Flow Budget

Volumetric flow rates simulated in the UFA, the upper zone of the LFA, and the FPZ were computed to quantify contributions of each applicable component of the ground-water flow system (fig. 23). Ground-water withdrawals and flow through the lateral boundaries of the model in the upper zone of the LFA were the largest net fluxes in the model area (135.70 and 187.43 ft<sup>3</sup>/s, respectively). Vertical leakages through

the confining units in the FAS reflect that the MSCU is more than 2 times leakier than the ICU and more than 10 times leakier than the SCU. The vertical hydraulic gradient between the SAS and the UFA is larger than that between the units within the FAS in many areas. Large vertical hydraulic gradients between the SAS and the UFA increase the vertical leakage through the ICU, whereas the presence of clay in the ICU decreases the vertical leakage.



**Figure 23.** Simulated steady-state volumetric flow budget for the model area, average 2000 conditions.

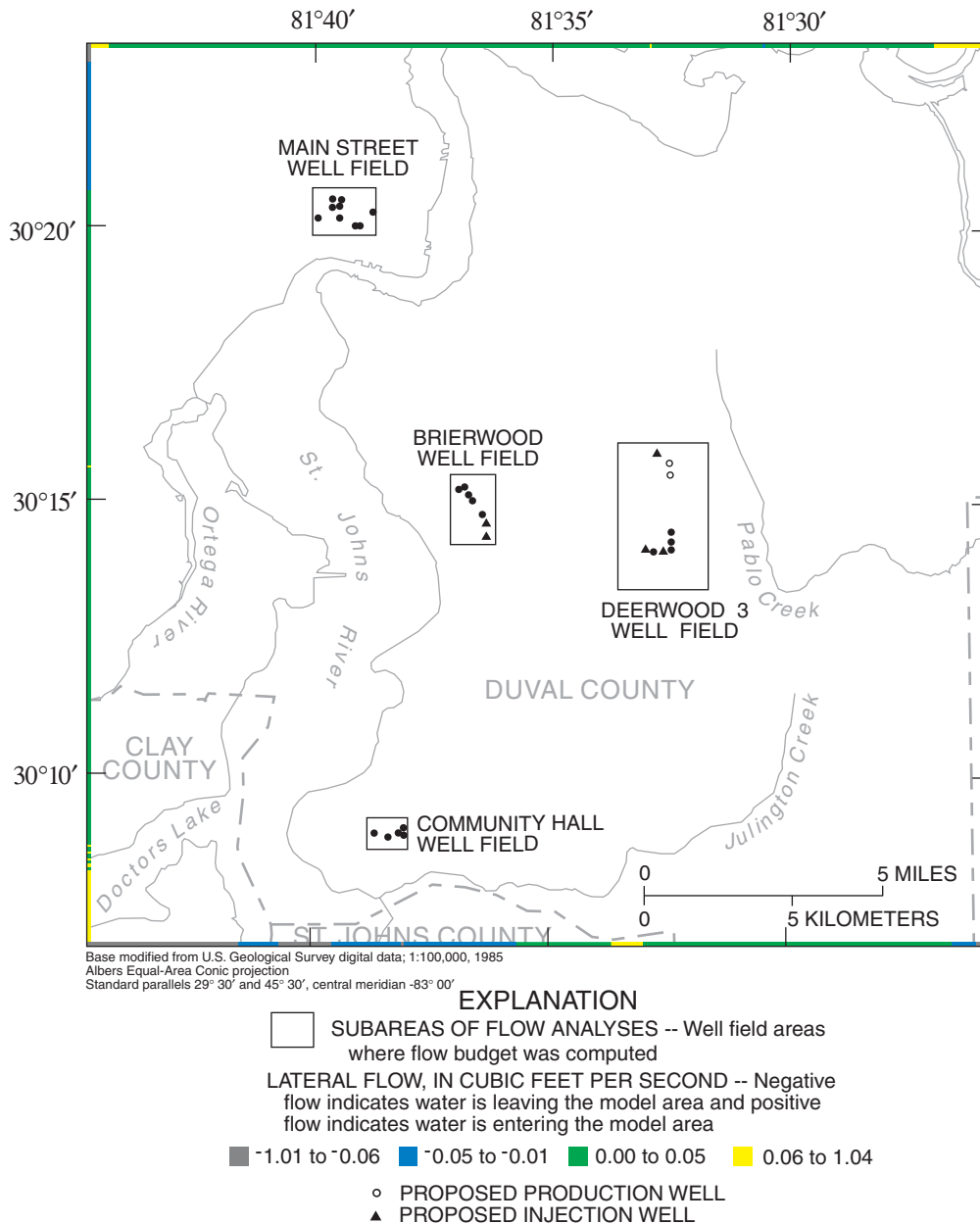


**Figure 24.** Simulated steady-state lateral flow to and from the upper zone of the Lower Floridan aquifer across model boundaries, average 2000 conditions.

Flow through cells along the lateral boundary in the upper zone of the LFA ranged from leaving the model area at a rate of 2.51 ft<sup>3</sup>/s to entering the model area at a rate of 2.18 ft<sup>3</sup>/s (fig. 24). The majority of the cells along this boundary, however, had flows less than

0.50 ft<sup>3</sup>/s. Simulations indicated that water in the upper zone of the LFA discharges through the eastern boundary of the model area and through parts of the southeastern boundary, whereas the aquifer is recharged through the western, northern, and southwestern boundaries.





**Figure 25.** Simulated steady-state lateral flow to and from the Fernandina permeable zone across model boundaries, average 2000 conditions.

Flows through the lateral boundary cells in the FPZ were mostly less than  $0.05 \text{ ft}^3/\text{s}$ , with exceptions along the southwestern boundary and scattered cells near the corners of the model area (fig. 25). These flows across the lateral boundaries of the FPZ are

substantially lower than those across the boundaries of the upper zone of the LFA because the calibrated transmissivity of the FPZ ( $60,000 \text{ ft}^2/\text{d}$ ) is at least eight times lower than that for the upper zone of the LFA (equal or greater than  $480,000 \text{ ft}^2/\text{d}$ ).

A more detailed analysis of the ground-water flow in the Brierwood, Deerwood 3, Main Street, and Community Hall wells is facilitated by computing all flows within smaller areas surrounding the well fields (fig. 25). Simulations indicate that the lateral flow in the FPZ in the Community Hall subarea is greater than for any other well field subarea. The magnitude of the upward flow from the FPZ can be used to assess the risk of increased chloride concentrations in overlying aquifers due to the greater chloride concentrations in the FPZ. Ground water pumped from wells tapping the upper zone of the LFA generally have chloride concentrations that are the result of a mixing of the respective chloride concentrations. The consistently low chloride concentrations measured in ground water in the Community Hall and Main Street well fields (less than 18 mg/L, table 1), combined with the simulated upward flow from the FPZ, indicates the FPZ contains freshwater in these two well fields. The simulated upward flow from the FPZ in the Deerwood 3 well field subarea ( $0.11 \text{ ft}^3/\text{s}$ , fig. 26) and the elevated chloride concentrations at Deerwood 3 wells (table 1) indicate the FPZ contains greater chloride concentrations than those found in Community Hall or Main Street well fields. The analysis of volumetric flows in the upper zone of the LFA indicates that as ground-water withdrawals increase from this aquifer, the lateral flows entering the subareas increase while lateral flows leaving the subareas decrease (fig. 26). The induced upward flow from the FPZ also tends to increase as ground-water withdrawals from the upper zone of the LFA at Deerwood 3 wells increase.

## Sensitivity Analyses

Sensitivity analyses were conducted to assess the relative response of simulated heads to uniform changes in the simulated value of selected model parameters and to address model uncertainty. Model parameters considered for sensitivity analysis included the transmissivities of the UFA, the upper zone of the LFA, and the FPZ; the leakances of the ICU, the MSCU, and the SCU; and the specified heads along the lateral boundaries of the upper zone of the LFA and the FPZ. The RMS residuals of the differences between simulated and computed heads were the criteria used to assess the effects of changes made to parameter values used in the model.

The effect each parameter had on simulation results was assessed by varying independently from 0.2 to 2.0 times the values of transmissivity; from -3.0 to 3.0 ft the departure from specified heads along lat-

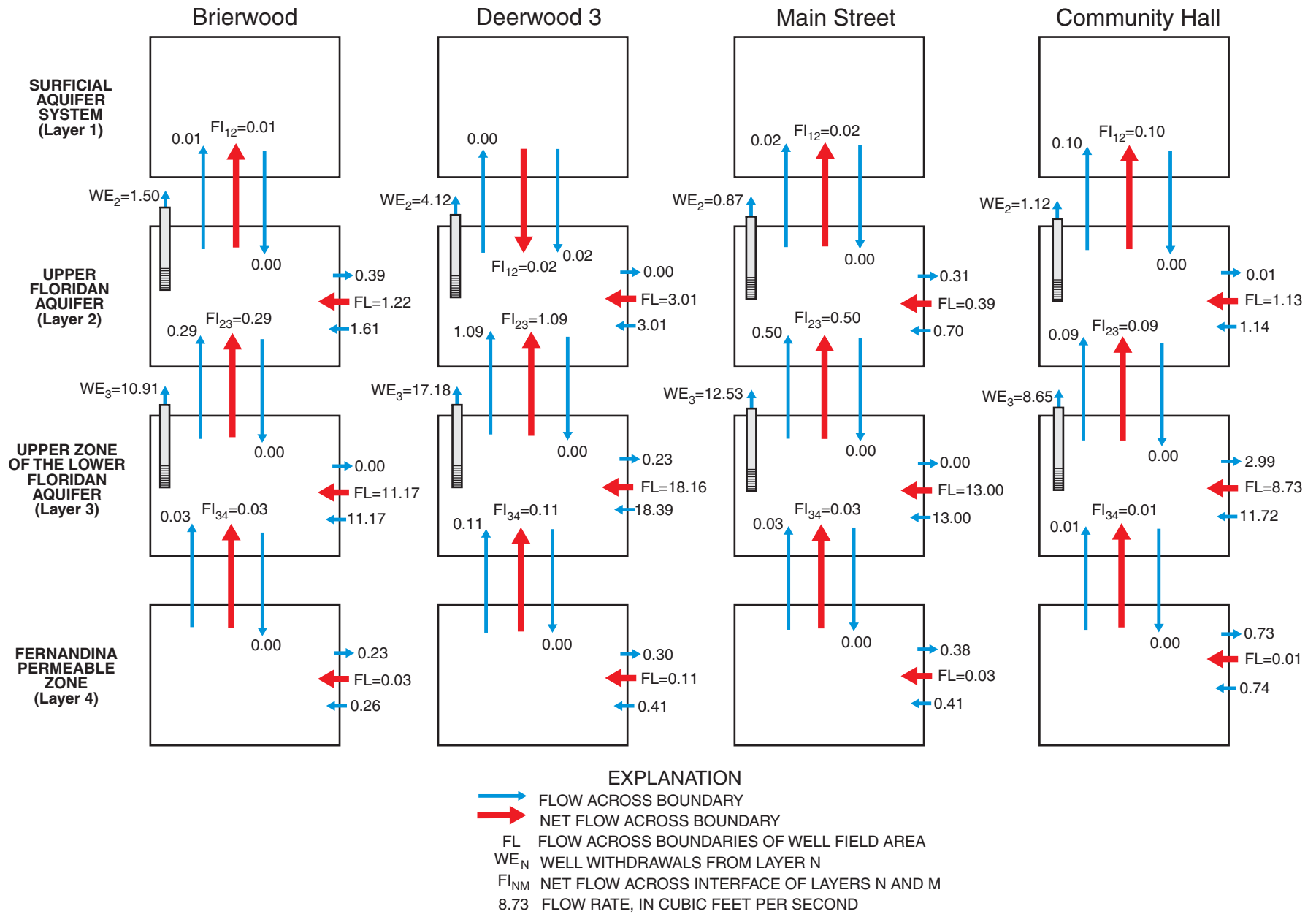
eral boundaries of the upper zone of the LFA and FPZ; and from 0.1 to 10.0 times the leakance values (fig. 27). These ranges of values may not include all the uncertainties associated with some of the parameters, but provided a perspective on parameter sensitivity.

The sensitivity analyses indicated that simulated heads were more sensitive to changes in vertical leakances of the ICU and MSCU than to changes in vertical leakance of the SCU (fig. 27). Simulated heads were more sensitive to changes in transmissivity of the UFA and upper zone of the LFA than to changes in transmissivity of the FPZ; however, this may be the result of having only three control points in the FPZ. Changes in the calibrated vertical leakance of the SCU and in the transmissivity of the FPZ and the effect these have on the simulated upward leakage from the FPZ are presented later in the report.

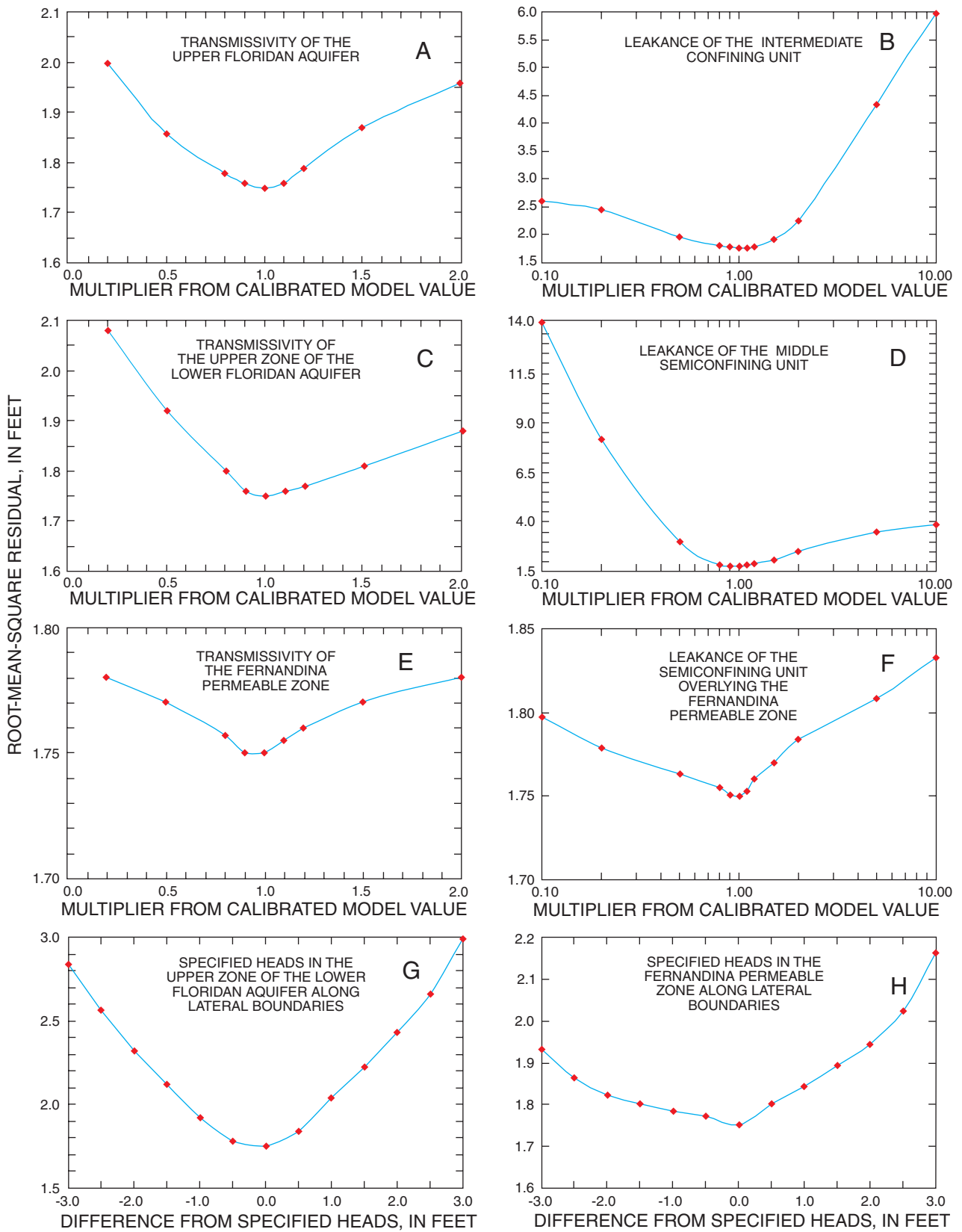
The no-flow boundary condition imposed along the lateral boundaries of the UFA was replaced with a specified-head boundary condition, with heads obtained from equation 1, to analyze the sensitivity of model results to changes in this boundary condition. The largest change in net vertical flow between the UFA and the upper zone of the LFA was  $0.02 \text{ ft}^3/\text{s}$ . This change was simulated in the Main Street well field subarea, where the upward flow from the upper zone of the LFA was 0.48, instead of  $0.50 \text{ ft}^3/\text{s}$  (fig. 26). There were no changes in the simulated upward flow from the FPZ when this change in boundary condition was performed in the UFA.

## APPLICATION OF GROUND-WATER FLOW MODEL

The calibrated steady-state ground-water flow model described in the previous sections was used to predict the effects of hypothetical changes in withdrawals and injections on the FAS. Steady-state simulations were used to determine head buildups in the potentiometric surface of the upper zone of the LFA. Transient simulations, presented later in this section, were used to analyze the effects ground-water injection and withdrawal stress periods have on the upward flow from the FPZ at the Brierwood and Deerwood 3 well fields. Reduced upward flows from the FPZ were used as the criterion to identify potential success of transient scenarios of injections and withdrawals. Storage coefficient values and the sensitivity of the simulated heads to changes in storage coefficient are presented in the transient simulations section.



**Figure 26.** Simulated steady-state volumetric flow budget for the well field subareas of Brierwood, Deerwood 3, Main Street, and Community Hall, time-averaged 2000 conditions.



**Figure 27.** Model sensitivity to changes in selected model parameters.

The simulation of injecting the water into the FPZ at Deerwood 3 and Brierwood well fields would require a density-dependent ground-water flow model to study how chloride concentrations change as injection and withdrawal stresses are implemented. The ground-water flow model presented herein cannot simulate such changes in water density. Traditional aquifer storage and recovery operations inject freshwater into poor-quality water, not as a barrier, but for storage and later recovery. The buoyancy effect would retain the freshwater near the top of the FPZ and would not be lost by downward movement. In addition, the sluggish movement of water in the FPZ would prevent much lateral loss of the freshwater bubble to be created with the injection, although annual replenishment would probably be necessary to counter bubble reduction during pumping from the south grid.

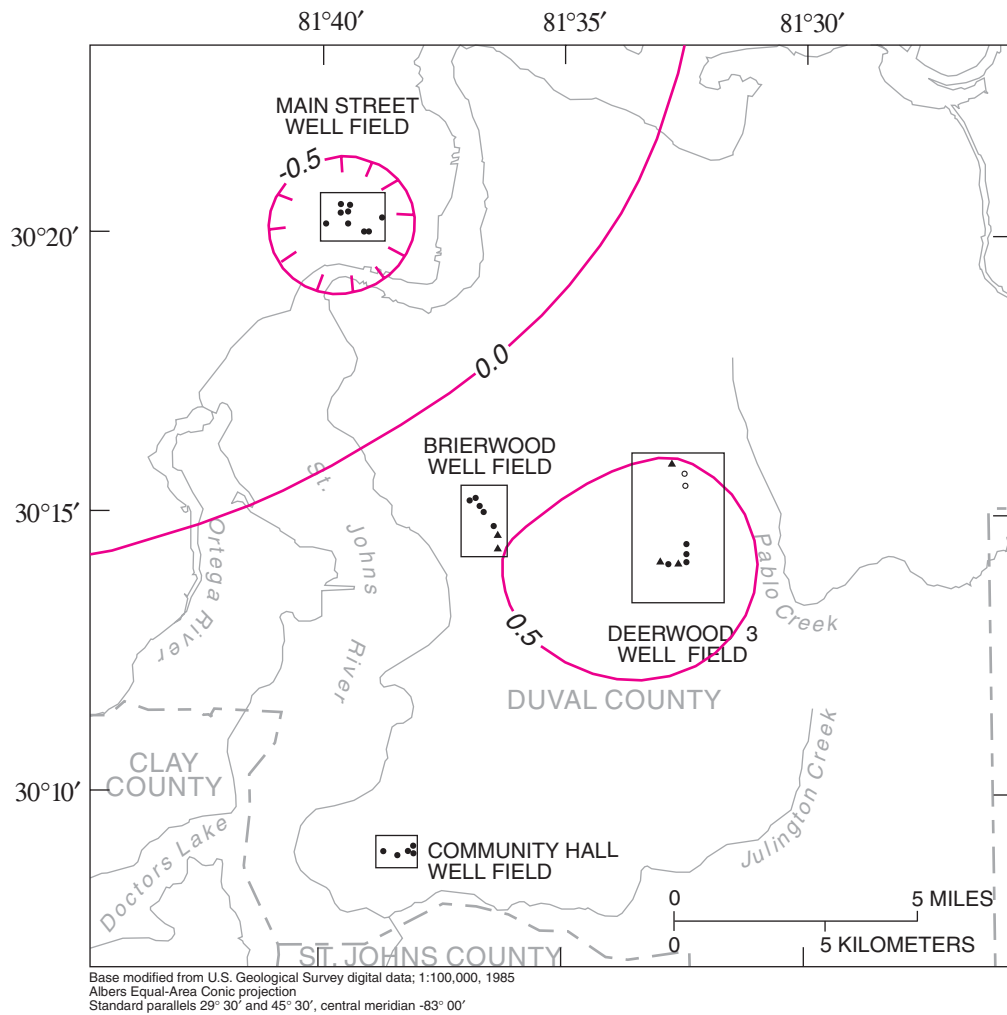
### **Application of Steady-State Ground-Water Flow Model**

The 18 Mgal/d of ground water withdrawn from the Main Street well field was simulated to be injected into the upper zone of the LFA to reduce upward flow from the FPZ through the SCU. A steady-state run simulated the injection of 6 Mgal/d through two Brierwood injection wells and 12 Mgal/d through three Deerwood 3 injection wells, into the upper zone of the LFA, to assess the head buildups that such injections could have on the potentiometric surface of the upper zone of the LFA. These injections resulted in a head buildup of less than 1 ft in the upper zone of the LFA near the Deerwood 3 well field and a drawdown of 0.5 ft in the Main Street well field, where the 18 Mgal/d are withdrawn (fig. 28). No withdrawals were considered from Brierwood or Deerwood 3 well fields when injections were simulated. The ground-water flow budget analysis for the model area indicates that the elimination of ground-water withdrawals at Brierwood and Deerwood 3 and the injection of 18 Mgal/d distributed between Brierwood and Deerwood 3 wells results in a net outflow of almost equal amount across the specified-head boundary in the upper zone of the LFA (fig. 29). The ground-water flow budget analysis for the well field subareas shows that most of the injected water in Deerwood 3 moves laterally away from the well field with less than 1 percent moving downward towards the FPZ. The upward flow from the FPZ was simulated to decrease from 0.11 ft<sup>3</sup>/s when pumping occurred at Deerwood 3 well field to 0.04 ft<sup>3</sup>/s, a net change of 0.07 ft<sup>3</sup>/s or a reduction of 64 percent, when injection occurred (figs. 26, 30). The upward

flow from the FPZ was not reversed at any cell in the model area during the injections into the upper zone of the LFA at Brierwood and Deerwood 3.

The 18 Mgal/d withdrawn from Main Street wells also were simulated to be injected into the UFA at Brierwood and Deerwood 3, rather than into the upper zone of the LFA, to assess the contrast such injection would have on the upward flow from the FPZ. A comparison of the volumetric flows shown in figure 31 with those shown in figure 30 was facilitated by making the injection rates into Brierwood and Deerwood 3 wells the same for both simulations. The only difference between the simulations shown in figures 30 and 31 was the layer into which the water was injected in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d).

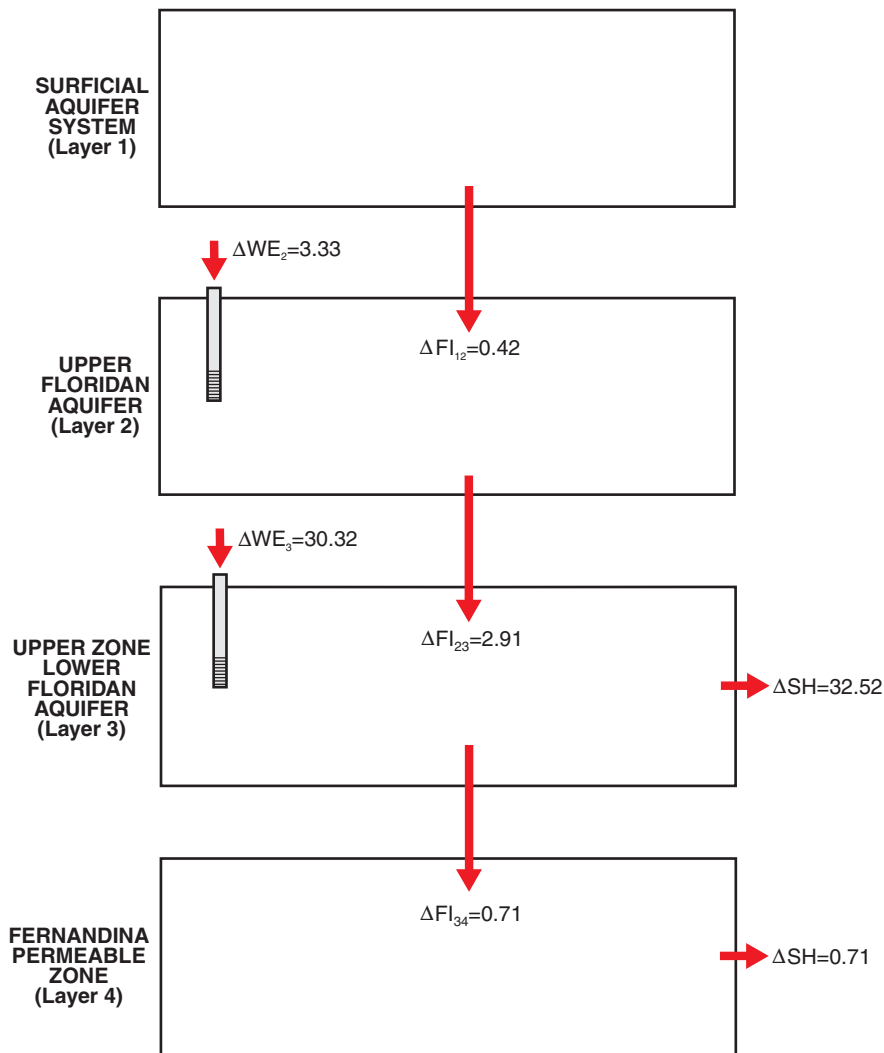
If the ground water withdrawn from the Main Street well field was simulated to be injected into the UFA, then about 17 percent of the injected water at Deerwood 3 would move downward to the upper zone of the LFA and almost all of the remaining 83 percent would move laterally in the UFA within the Deerwood 3 well field subarea (fig. 31). In the case of the Brierwood well field, the injected water moving downward is only 6 percent. The injection into the UFA reduced the upward flow from the FPZ by about 45 percent compared to the upward flow when only withdrawals and no injections occurred at the Deerwood 3 well field (from 0.11 to 0.06 ft<sup>3</sup>/s, figs. 26, 30). At no cell in the model area was the upward flow from the FPZ reversed as a result of simulated injections into the UFA at Brierwood and Deerwood 3 well fields. This type of injection was less effective in reducing the upward flow from the FPZ, a reduction in upward flow of 0.05 ft<sup>3</sup>/s, compared to a reduction of 0.07 ft<sup>3</sup>/s if water was injected into the upper zone of the LFA. Thus, injecting water into the UFA would be less effective in reducing chloride concentrations in the upper zone of the LFA. Simulation results indicate, however, that whether the injection takes place in the UFA or in the upper zone of the LFA, most of the injected water moves laterally to areas outside the well field subareas (figs. 30, 31). The net changes in flow simulated at the Community Hall well field (figs. 30, 31) due to the injections at Brierwood and Deerwood 3 well fields, and the additional withdrawals at Main Street well field, indicated these stresses have a negligible effect on the heads in the vicinity of Community Hall well field. Therefore, the analysis of vertical flows between the upper zone of the LFA and the FPZ will focus on the Main Street, Brierwood, and Deerwood 3 well fields, wells where additional withdrawals or injections are simulated.



**EXPLANATION**

- SUBAREAS OF FLOW ANALYSES --  
Areas where flow budget was computed
- 0.5— HEAD BUILDUP (OR DRAWDOWN) CONTOUR  
IN THE UPPER ZONE OF THE LOWER FLORIDAN  
AQUIFER DUE TO INJECTED (OR WITHDRAWN)  
WATER -- Derived from model simulation.  
Changes in head are relative to simulated heads  
shown in figure 20. Negative values indicate  
drawdown caused by withdrawal of 18 Mgal/d.  
Contour interval is 0.5 foot
- PROPOSED PRODUCTION WELL
- ▲ PROPOSED INJECTION WELL

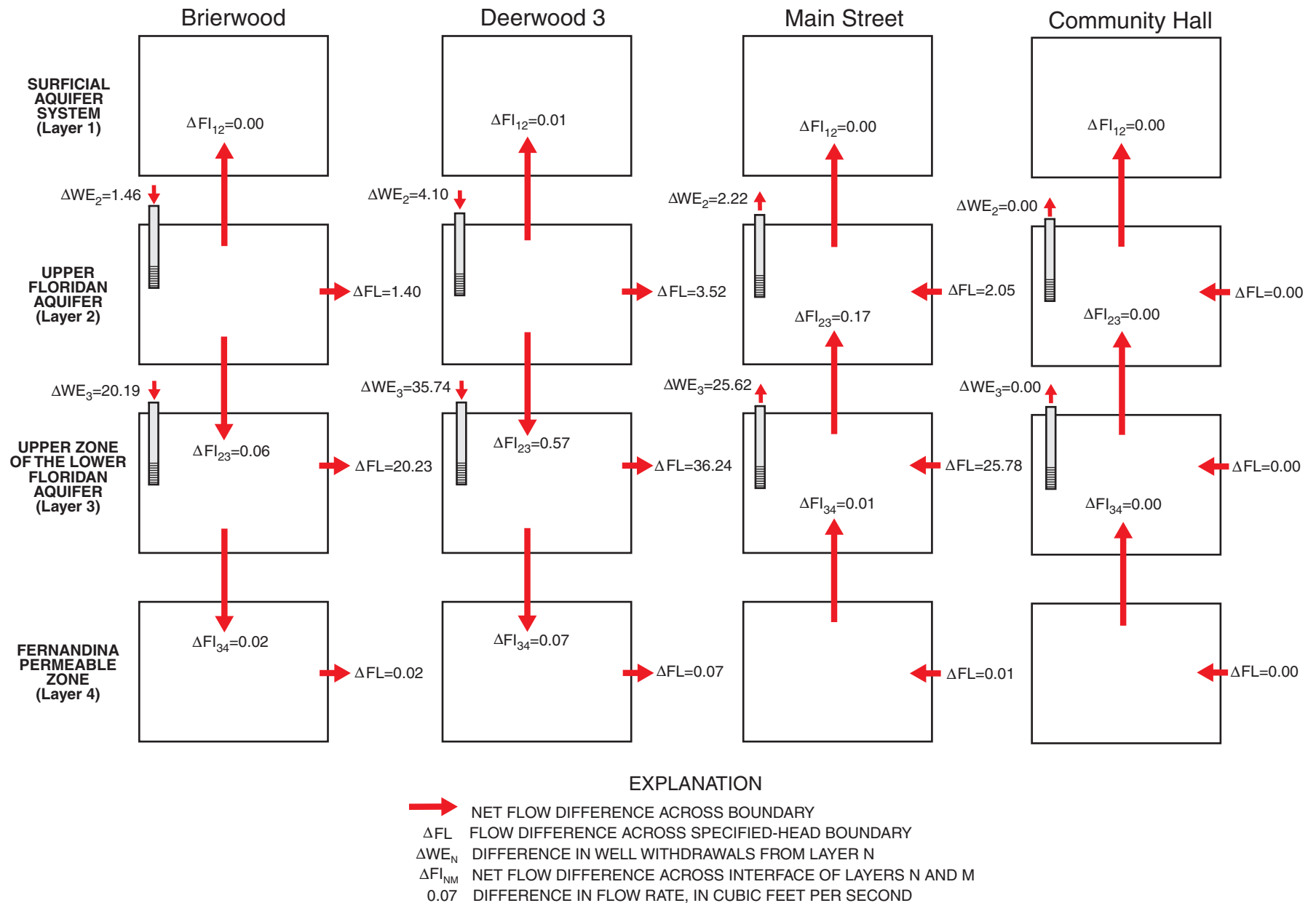
**Figure 28.** Steady-state head buildups in the upper zone of the Lower Floridan aquifer after 6 million gallons per day (Mgal/d) are injected into Brierwood and 12 Mgal/d are injected into Deerwood 3 wells (no withdrawals were simulated from Brierwood or Deerwood 3).



**EXPLANATION**

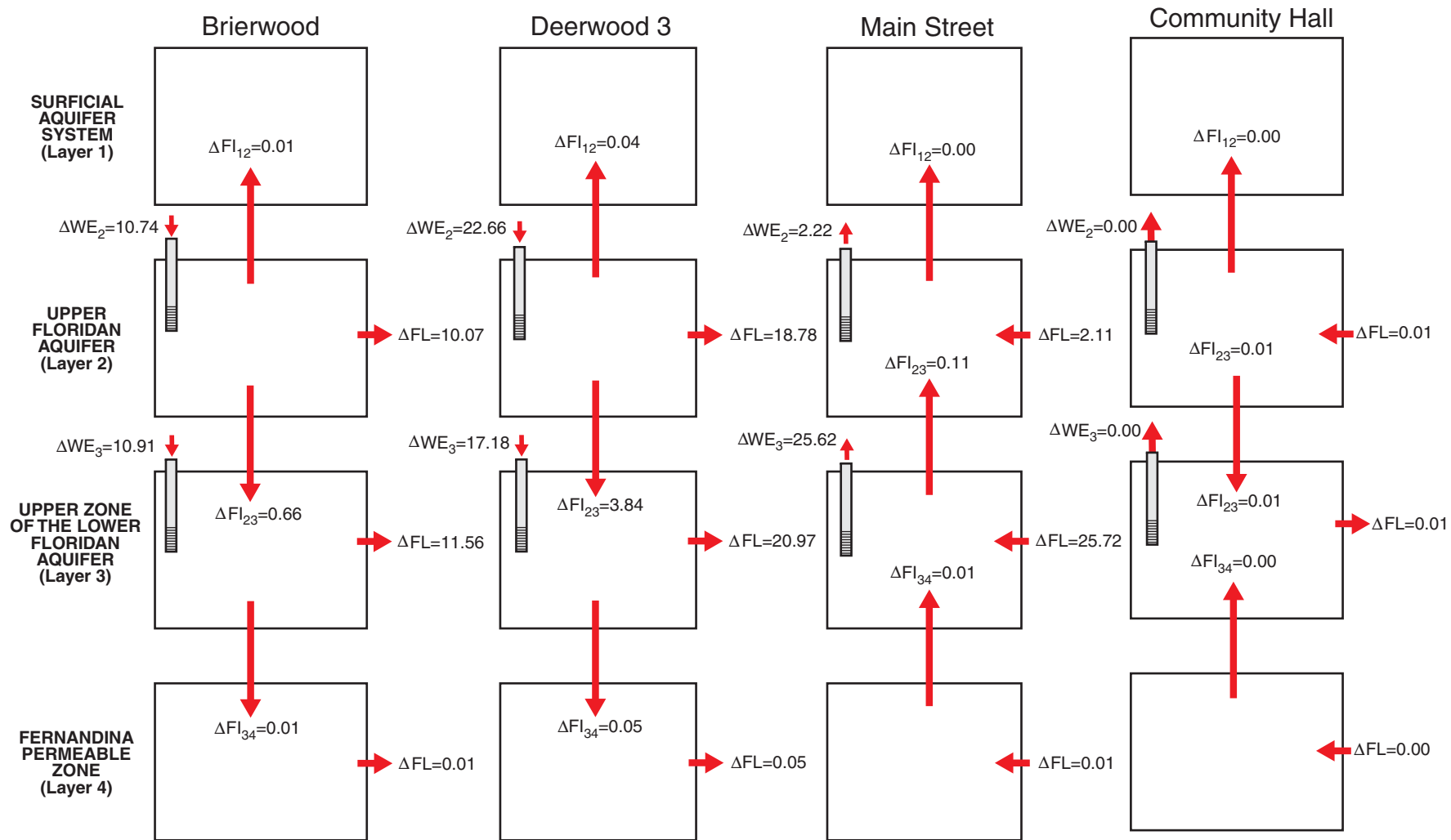
- NET FLOW DIFFERENCE ACROSS BOUNDARY
- $\Delta SH$  FLOW DIFFERENCE ACROSS SPECIFIED-HEAD BOUNDARY
- $\Delta WE_N$  DIFFERENCE IN WELL WITHDRAWALS FROM LAYER N
- $\Delta FI_{NM}$  NET FLOW DIFFERENCE ACROSS INTERFACE OF LAYERS N AND M
- 0.71 DIFFERENCE IN FLOW RATE, IN CUBIC FEET PER SECOND

**Figure 29.** Simulated steady-state net volumetric flow budget differences between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the upper zone of the Lower Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells (no withdrawals were simulated from Brierwood or Deerwood 3, see figure 23 for net flows before the injections).



**Figure 30.** Simulated steady-state net volumetric flow budget differences for the well field subareas between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the upper zone of the Lower Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells (no withdrawals were simulated from Brierwood or Deerwood 3).





**EXPLANATION**

- NET FLOW DIFFERENCE ACROSS BOUNDARY
- ΔFL FLOW DIFFERENCE ACROSS SPECIFIED-HEAD BOUNDARY
- ΔWE<sub>N</sub> DIFFERENCE IN WELL WITHDRAWALS FROM LAYER N
- ΔFI<sub>NM</sub> NET FLOW DIFFERENCE ACROSS INTERFACE OF LAYERS N AND M
- 0.07 DIFFERENCE IN FLOW RATE, IN CUBIC FEET PER SECOND

**Figure 31.** Simulated steady-state net volumetric flow budget differences for the well field subareas between flows before and after withdrawing 18 million gallons per day (Mgal/d) from the Main Street well field and injecting the water into the Upper Floridan aquifer in Brierwood (6 Mgal/d) and Deerwood 3 (12 Mgal/d) wells (no withdrawals were simulated from Brierwood or Deerwood 3).

## Transient Ground-Water Flow Model

The transmissivity and vertical leakance values derived from the calibrated steady-state ground-water flow model were not modified for the simulation of transient stresses. The storage coefficient was calibrated for the transient ground-water flow model, a parameter needed to simulate transient stresses.

The CY 2000 was divided into 12 stress periods of 1-month duration each and heads measured for each month were compared to simulated heads at the end of each period. The storage coefficients for the UFA, upper zone of the LFA, and FPZ were calibrated based on the residuals or differences between simulated and measured heads at control points for each stress period. The minimum, maximum, mean, and RMS residuals were used as criteria to calibrate the storage coefficient. The SAS was assigned a storage coefficient of 0.14. Storage coefficient values were assigned to the UFA, the upper zone of the LFA, and the FPZ by calibrating a uniform specific storage (storage coefficient divided by the thickness of the hydrogeologic unit), and using corresponding average thicknesses of 250, 420, and 170 ft. Simulated heads did not change significantly for specific storage values between  $1.5 \times 10^{-5}$  and  $3.5 \times 10^{-5} \text{ ft}^{-1}$ . Storage coefficient values outside this range resulted in overall increases to residuals. Residuals for each stress period in the transient ground-water flow model were similar to those obtained for the calibrated steady-state model (table 6). The calibrated specific storage for the transient ground-water flow model was  $2.5 \times 10^{-5} \text{ ft}^{-1}$ , which resulted in storage coefficients of 0.0063, 0.0105, 0.0042 for the UFA, upper zone of the LFA, and FPZ, respectively. Changes in transmissivity and vertical leakance values to the calibrated steady-state model decreased residuals for some stress periods but increased them in others, indicating the calibrated transmissivity and vertical leakance values from the steady-state model were the optimal values to use for the transient model.

Heads specified along the lateral boundaries of the upper zone of the Lower Floridan aquifer and Fernandina permeable zone were derived for each stress period by linearly regressing the monthly measured heads during CY 2000 with the time-averaged heads for CY 2000. The specified heads along the lateral boundaries of the upper zone of the LFA for each stress period were computed by first performing the SLR:

$$h_{\text{Mon}} = \alpha_3 h_{\text{Ave}} + \beta_3, \quad (6)$$

where

$h_{\text{Mon}}$  is the measured head at a control point for a given month, in feet;

$h_{\text{Ave}}$  is the time-averaged head for CY 2000 at the same site, in feet;

$\alpha_3$  is the dimensionless SLR coefficient; and

$\beta_3$  is the intercept of the SLR, in feet.

With the exceptions of May and September, 16 points were available to perform the SLR. The number of control points for May and September 2000 was 20. Correlation coefficients were either 0.98 or 0.99 for the 12 SLR performed. RMS residuals ranged from 0.34 ft for January to 0.96 ft for April, with overall residuals ranging from -2.17 to 3.04 ft. Slope and intercept values derived for each stress period are shown in table 6. These regression coefficients were used to calculate the heads to be specified along the lateral boundaries of the upper zone of the LFA for each stress period by using the specified heads for the steady-state simulations as  $h_{\text{Ave}}$  (eq. 6). The specified heads along the lateral boundaries of the FPZ were set to be 1.5 ft higher than the specified heads for the upper zone of the LFA. Residuals were computed for each stress period (table 6). In addition, residuals were calculated between the time-averaged heads for CY 2000 and the simulated heads at the end of the transient simulations. The small differences between the residuals for the steady-state model (table 5) and those computed from the transient model when using time-averaged heads for 2000 indicate the final distribution of heads in the steady-state and transient simulations were similar.

Ground-water withdrawals for CY 2000 varied from one month to another at most well fields. In particular, temporal variations in ground-water withdrawals occurred at Brierwood, Deerwood 3, and Main Street well fields (table 7), where the stress periods of injections, withdrawals, and intervening rest periods were simulated. The simulated transient scenarios were based on a withdrawal of 18 Mgal/d, or  $27.85 \text{ ft}^3/\text{s}$ , from the Main Street well field during stress periods of injections and intervening rest, in addition to withdrawals shown in table 7, and the injection, withdrawal, or intervening rest periods at Brierwood and Deerwood 3 well fields. All other withdrawals from other well fields in the model area remained unchanged. A stress period of injection is when 18 Mgal/d of water are withdrawn from the Main Street well field and injected in Brierwood and Deerwood 3 injection wells.

**Table 6.** Water-level residual statistics for the calibrated transient model

[All residuals are in feet unless otherwise indicated; 11 control points were used for the UFA in May 2000 and September 2000, 7 in all other months for the UFA, 6 for the uzLFA (Jan.-Dec.), and 3 for the FPZ (Jan.-Dec.). Residual is the difference between simulated and measured head. Min, minimum residual; Max, maximum residual; Mean, mean residual; RMS, root-mean-square residual. UFA, Upper Floridan aquifer; uzLFA, upper zone of the Lower Floridan aquifer; FPZ, Fernandina permeable zone. Intercept and dimensionless slope refer to regression coefficients used to generate specified heads from equation 6; na, not applicable]

Month	UFA				uzLFA				FPZ				Overall mean	Overall RMS	Intercept	Dimensionless slope
	Min	Max	Mean	RMS	Min	Max	Mean	RMS	Min	Max	Mean	RMS				
January	-3.44	0.57	-1.74	2.20	-3.99	1.71	-1.36	2.31	-2.06	-0.62	-1.16	1.33	-1.49	2.11	6.29	0.91
February	-2.30	1.68	-.49	1.44	-3.68	.71	-1.57	2.09	-1.46	.58	-.60	1.05	-.91	1.66	5.37	.92
March	-2.94	4.32	.18	2.17	-3.52	1.22	-1.60	2.20	-2.61	1.23	-.72	1.73	-.66	2.10	2.63	.98
April	-3.62	4.74	1.23	2.74	-4.88	-.87	-2.99	3.27	-1.77	.80	-.84	1.44	-.74	2.77	-2.18	1.09
May	-4.12	4.88	2.27	3.68	-3.90	3.03	-1.17	2.81	-1.43	1.41	-.05	1.16	.89	3.17	-9.17	1.22
June	-2.84	4.75	2.49	3.66	-3.98	2.15	-1.05	2.14	-.61	2.26	.92	1.49	.87	2.83	-8.26	1.17
July	-2.54	4.29	1.94	3.06	-2.84	3.36	-.20	2.33	-1.36	2.32	.89	1.84	.94	2.60	-6.09	1.10
August	-2.17	3.87	1.55	2.54	-2.13	1.09	-.11	1.18	-.83	2.68	1.33	2.04	.89	2.03	-4.44	1.08
September	-3.37	1.19	-2.08	2.42	-4.03	3.31	-1.21	2.61	-2.18	2.27	.38	1.92	-1.45	2.41	5.02	.85
October	-3.01	2.20	-.20	1.68	-4.70	3.49	-1.04	2.70	-1.95	2.27	.48	1.85	-.39	2.14	1.75	.95
November	-3.05	3.03	-.83	2.15	-3.34	3.31	-.62	2.21	-1.76	2.03	.11	1.55	-.57	2.07	5.13	.85
December	-2.15	1.78	-.46	1.38	-2.47	.17	-.88	1.33	-1.39	2.39	.02	1.69	-.52	1.42	4.24	.89
Year 2000	-4.12	4.88	.30	2.59	-4.88	3.49	-1.15	2.33	-2.61	2.68	.06	1.61	-.26	2.34	na	na
Residuals computed from time-averaged heads for 2000 and heads at the end of transient simulation																
	-2.11	3.41	.51	1.52	-2.62	3.13	.04	1.79	-.32	2.07	1.11	1.52	.46	1.61	na	na

A stress period of withdrawal is when pumping from Brierwood and Deerwood 3 occurs at the corresponding rate for that period during 2000 (table 7) and no additional ground-water withdrawal occurs at Main Street. A stress period of rest is when water is withdrawn from the Main Street well field and is put directly into the service line and no injection or withdrawal occurs at the Brierwood and Deerwood 3 well fields.

The first nine transient scenarios simulated in this study included a minimum of 6 months of injections, with alternating withdrawal and rest months (table 8). The scenarios simulated were based on injecting 12 Mgal/d in three Deerwood 3 injection wells and 6 Mgal/d in two Brierwood injection wells. Scenarios 10 through 12 (table 8) were used as stan-

dards for comparison of upward flow from the FPZ. A ground-water flow analysis of the Deerwood 3 well field subarea indicates that the minimum annual average upward flow from the FPZ was 0.04 ft<sup>3</sup>/s (figs. 32, 33). Additional simulations showed that increasing the duration of the injection stresses in Deerwood 3 does not necessarily reduce upward flow. If no injection or withdrawal months are simulated in Deerwood 3 (scenario 12 in table 8), then the simulated average annual upward flow from the FPZ becomes 0.08 ft<sup>3</sup>/s (fig. 33). Pumping at Deerwood 3 wells continuously for all 12 months (scenario 11 in table 8) results in an upward flow from the FPZ of 0.11 ft<sup>3</sup>/s, the highest simulated upward flow among all scenarios.

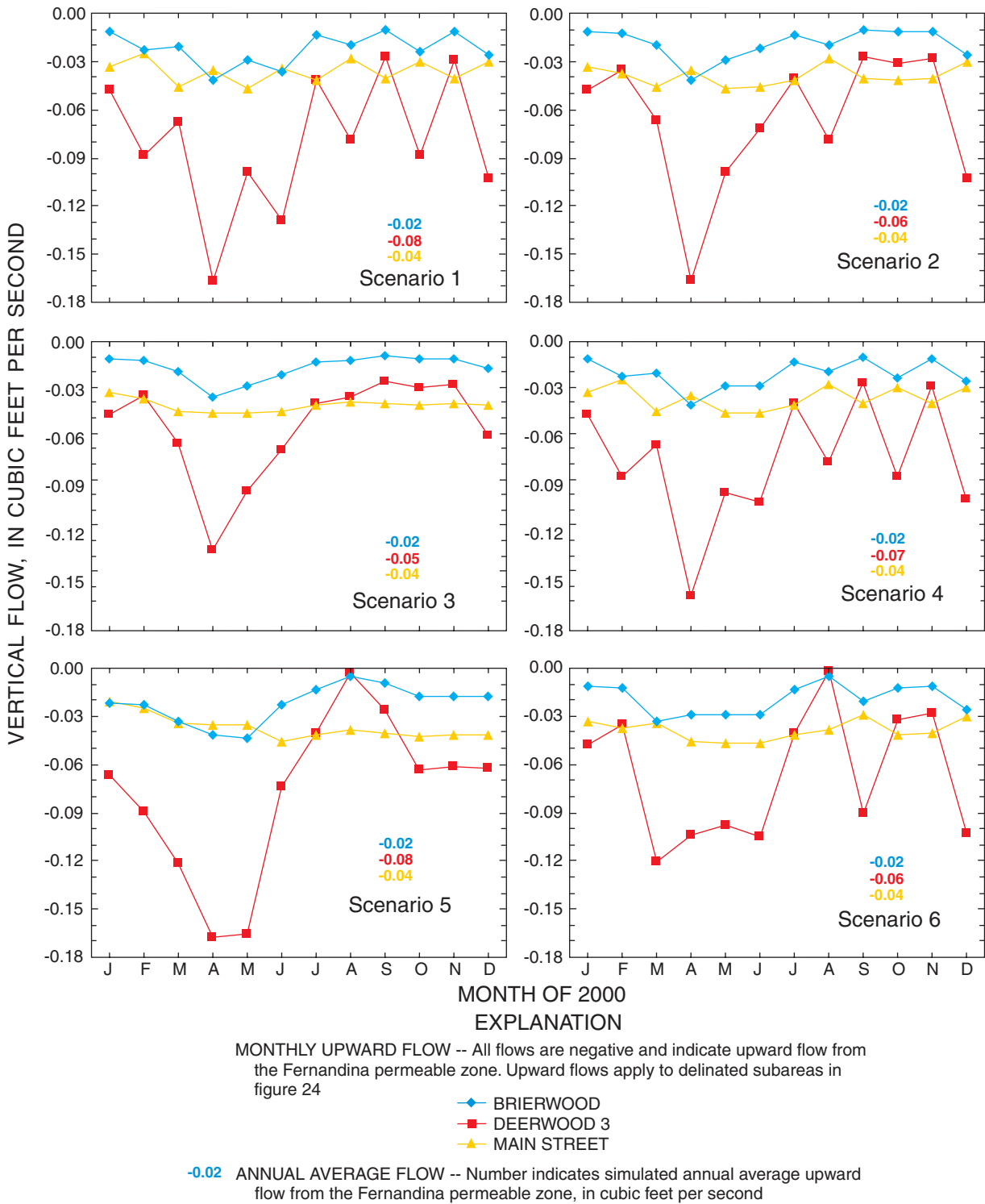
**Table 7.** Monthly withdrawals during 2000 at Brierwood, Deerwood 3, and Main Street well fields

[Source: Jacksonville Electric Authority, written communication, 2003; all measurements in cubic feet per second]

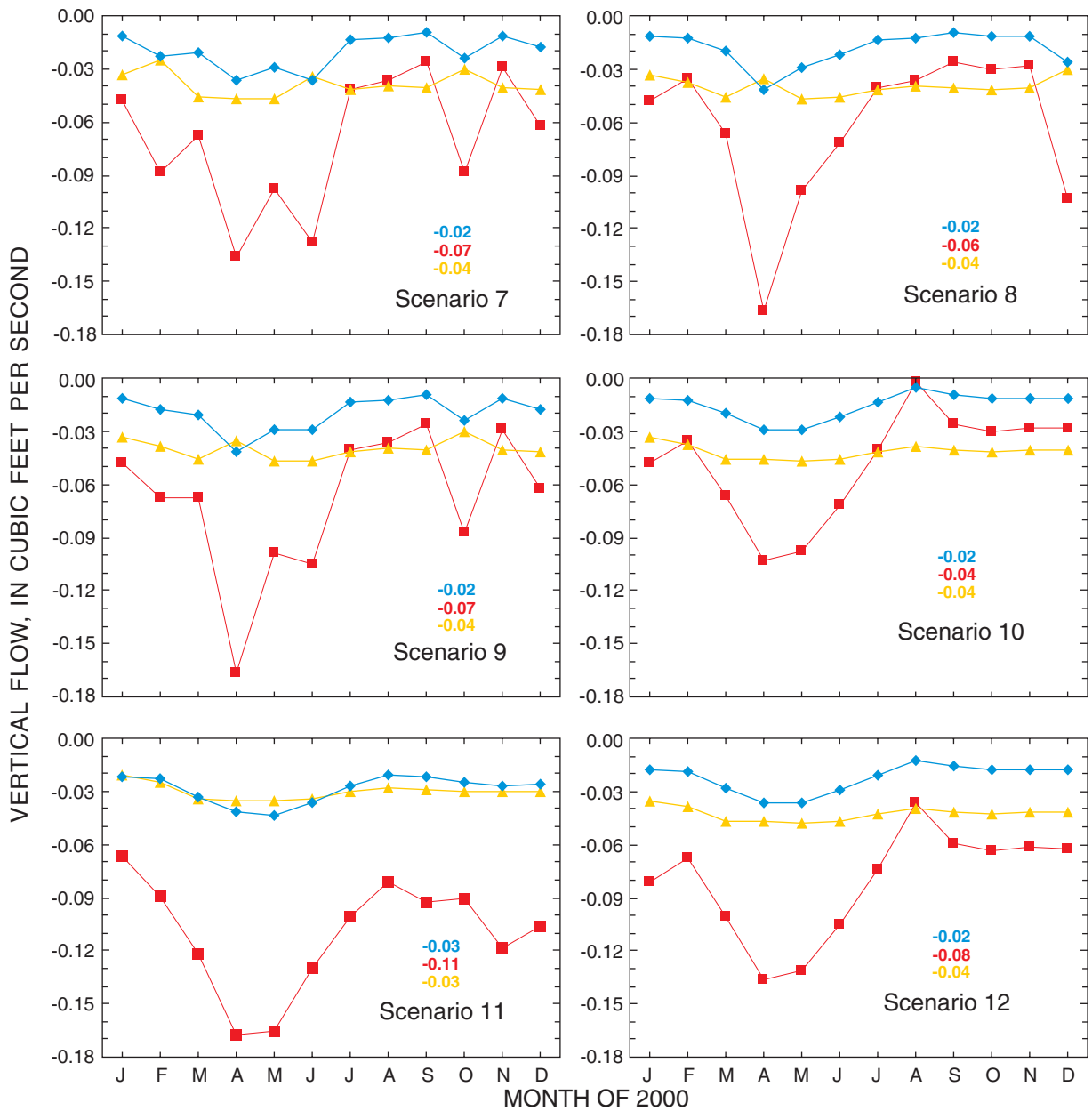
Well field	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average for 2000
Brierwood	9.16	9.80	12.85	12.28	16.16	14.37	10.72	13.94	8.43	12.61	14.57	13.57	12.37
Deerwood 3	13.54	14.47	13.62	20.85	21.94	15.80	17.96	29.74	23.88	16.44	38.70	28.43	21.28
Main Street	9.97	10.66	13.69	8.37	9.61	14.70	15.61	16.44	14.25	15.64	16.46	15.21	13.38

**Table 8.** Simulated scenarios of injection, withdrawal, and intervening rest months at Brierwood and Deerwood 3 well fields

Scenario number	Injection months	Withdrawal months	Rest months
1	Jan., Mar., May, July, Sept., Nov.	Feb., Apr., June, Aug., Oct., Dec.	
2	Jan. - Mar., May - July, Sept. - Nov.	Apr., Aug., Dec.	
3	Jan. - Mar., May - July, Sept. - Nov.		Apr., Aug., Dec.
4	Jan., Mar., May, July, Sept., Nov.	Feb., Apr., Aug., Oct., Dec.	June
5	June-Sept.	Jan. - May	Oct. - Dec.
6	Jan. - Feb., Apr. - May, July - Aug., Oct. - Nov.	Mar., Sept., Dec.	June
7	Jan., Mar., Apr., July, Sept., Nov.	Feb., June, Oct.	Apr., Aug., Dec.
8	Jan. - Mar., May - July, Sept. - Nov.	Apr., Dec.	Aug.
9	Jan., Mar., May, July, Sept., Nov.	Apr., Oct.	Feb., June, Aug., Dec.
10	Jan. - Dec.		
11		Jan. - Dec.	
12			Jan. - Dec.



**Figure 32.** Simulated monthly upward flows from the Fernandina permeable zone for 2000, for scenarios 1 through 6, with injection rates of 6 million gallons per day (Mgal/d) in Brierwood and 12 Mgal/d in Deerwood 3 well fields (see table 8 for description of scenarios).



**EXPLANATION**

MONTHLY UPWARD FLOW -- All flows are negative and indicate upward flow from the Fernandina permeable zone. Upward flows apply to delineated subareas in figure 24

- ◆ BRIERWOOD
- DEERWOOD 3
- ▲ MAIN STREET

-0.03 ANNUAL AVERAGE FLOW -- Number indicates simulated annual average upward flow from the Fernandina permeable zone, in cubic feet per second

**Figure 33.** Simulated monthly upward flows from the Fernandina permeable zone for 2000, for scenarios 7 through 12, with injection rates of 6 million gallons per day (Mgal/d) in Brierwood and 12 Mgal/d in Deerwood 3 well fields (see table 8 for description of scenarios).

Simulated upward flows from the FPZ in scenarios 8 and 9 showed that as the time between withdrawals is increased and the intervening periods of rest are replaced by periods of injection, the annual average upward flow from the FPZ decreases. The upward flow from the FPZ to the upper zone of the LFA was never reversed in any cell in the model area when 6 Mgal/d were injected at Brierwood and 12 Mgal/d in Deerwood 3. Upward flow from the FPZ was observed at all model cells and for all simulated stress periods and scenarios.

Among the first nine transient scenarios (table 8), scenario 8 had the most periods of injections, at most two periods of withdrawals, and the longest time interval between periods of withdrawals. This scenario uses all three types of stress periods and provides the optimal combination of stress periods that could minimize the upward flow from the FPZ. Scenario 8 was used to simulate how changes in the magnitude of the injection and withdrawal rates in the Deerwood 3 and Brierwood well fields would affect vertical fluxes between the FPZ and the upper zone of the LFA.

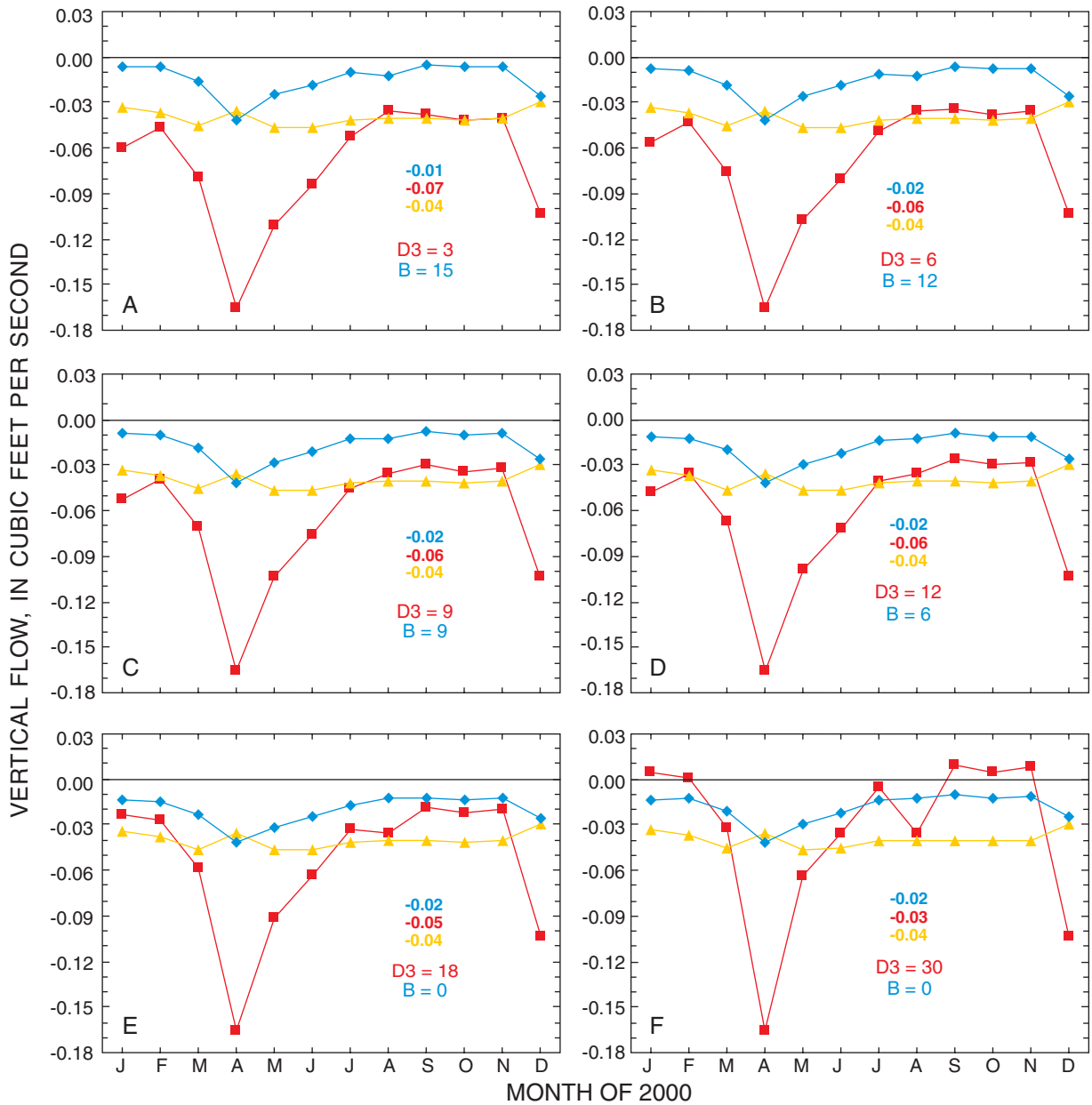
The sensitivity of transient ground-water flow to changes in storage coefficient values was analyzed by simulating two sets of values. Specific storage values of  $1.5 \times 10^{-5}$  and  $3.5 \times 10^{-5} \text{ ft}^{-1}$  were used to determine how the corresponding storage coefficient values would change the results shown in figures 32 and 33. A specific storage value of  $1.5 \times 10^{-5} \text{ ft}^{-1}$  results in storage coefficient values of 0.0038, 0.0063, and 0.0026 assuming average thicknesses of 250, 420, and 170 ft for the UFA, upper zone of the LFA, and FPZ, respectively. A second set of simulated storage coefficient values was 0.0088, 0.0147, and 0.0060 for the UFA, upper zone of the LFA, and FPZ, respectively. This second set of storage coefficient values corresponds to a specific storage value of  $3.5 \times 10^{-5} \text{ ft}^{-1}$ . No significant changes in upward flow from the FPZ from those shown in figure 33, scenario 8, were simulated when either set of storage coefficient values was used.

The magnitude of upward flow from the FPZ decreased as the injection rate increased, but did not change during both months of withdrawals (fig. 34). Of the 18 Mgal/d withdrawn from Main Street wells and available for injection to Deerwood 3 and Brierwood wells, no possible combination of injection rates resulted in the reversal of the upward hydraulic gradient from the FPZ. The upward hydraulic gradient from the FPZ could not be reversed with a combined injection rate of 18 Mgal/d between Deerwood 3 and Brierwood well fields. The higher injection rate into the Deerwood 3 wells (18 Mgal/d) resulted in the lowest

upward flow from the FPZ within the area delineated around the well field. Greater injection rates were simulated to determine the necessary injection rate (as an integer value in million gallons per day units) to Deerwood 3 for which a reversal of the upward flow from the FPZ would be achieved. An injection rate greater than 30 Mgal/d would be required to reverse the upward flow from the FPZ (fig. 34F). However, a period of withdrawal or rest at Deerwood 3 well field following a period of injection of this rate (30 Mgal/d) causes the return of upward flow from the FPZ.

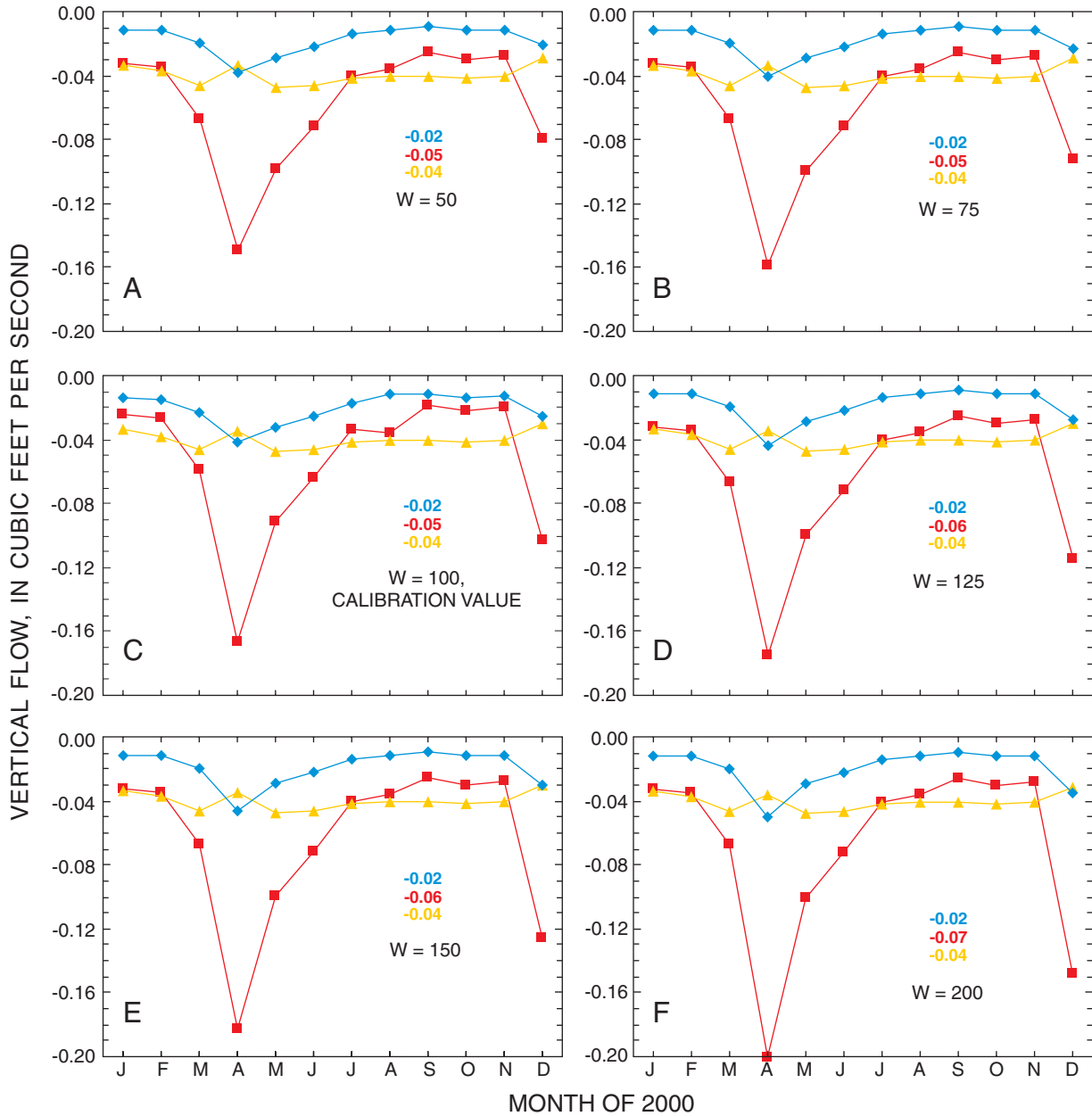
Based on the upward flows from the FPZ (fig. 34), the injection of the 18 Mgal/d into Deerwood 3 wells and no injection into Brierwood wells resulted in the lowest annual average upward flow from the FPZ at Deerwood 3 well field. Because greater chloride concentrations in ground water were measured in Deerwood 3 wells than at Brierwood wells (table 1), all simulations that followed considered the injection of 18 Mgal/d into Deerwood 3 wells to explore the conditions under which a reversal of the upward flow from the FPZ at these wells could occur. The withdrawal rates from Deerwood 3 and Brierwood wells for 2000 were varied to determine the effect these changes would have on the upward flow from the FPZ during April and December (withdrawal months). Simulation results showed that the upward flow from the FPZ increased as the withdrawals from the Deerwood 3 and Brierwood well fields increased (fig. 35). Upward flow from the FPZ increases when withdrawal rates at Deerwood 3 and Brierwood increase above 2000 rates.

The impact of head drawdowns or buildups, resulting from the withdrawal of 18 Mgal/d from the Main Street well field or the injections into Brierwood and Deerwood 3 wells, on the specified heads along the lateral boundaries of the model was analyzed. A regional steady-state ground-water flow model (Sepúlveda, 2002a) was used to compute simulated head changes along the lateral boundaries of the model area (fig. 1) due to the withdrawal of 18 Mgal/d from Main Street and its injection into the Brierwood and Deerwood 3 wells. The initial distribution of heads for the regional model was the steady-state solution from the same regional model using average 1993-94 conditions. The head changes along the boundaries of the model (fig. 1) ranged from an increase of 0.05 ft to a decrease of 0.06 ft. This indicates the effect of the specified heads along the boundaries of the model during the withdrawal of water from the Main Street wells and its injection into the Brierwood and Deerwood 3 wells was minimal.



**Figure 34.** Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000 under scenario 8 conditions, for various injection rates in Brierwood and Deerwood well fields (see table 8 for description of scenario 8).





**EXPLANATION**  
 MONTHLY UPWARD FLOW -- All flows are negative and indicate upward flow from the Fernandina permeable zone. Upward flows apply to delineated subareas in figure 24

- ◆ BRIERWOOD
- DEERWOOD 3
- ▲ MAIN STREET

-0.02 ANNUAL AVERAGE FLOW -- Number indicates simulated annual average upward flow from the Fernandina permeable zone, in cubic feet per second

W = 200 WITHDRAWAL RATES -- Simulated percentage of 2000 ground-water withdrawals applied to Brierwood and Deerwood 3 production wells during months of withdrawals

**Figure 35.** Simulated monthly upward flows from the Fernandina permeable zone for 2000, under scenario 8 conditions, for various withdrawal rates at Brierwood and Deerwood 3 well fields, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only (see table 8 for description of scenario 8).

## EFFECTS OF PARAMETER UNCERTAINTY ON SIMULATED UPWARD FLOW FROM THE FERNANDINA PERMEABLE ZONE

This section presents a discussion of the effects of parameter changes on the simulated flow between the upper zone of the LFA and the FPZ. Vertical leakage of the SCU, transmissivity of the FPZ, and specified heads in the FPZ along the lateral boundaries of the model are the hydraulic parameters that can have the most substantial effects on the flow exchange between these two hydrogeologic units. The uncertainty of these parameters implies the true vertical fluxes between the upper zone of the LFA and the FPZ may be quantified by simulating changes to parameter values within feasible limits. The effects of the uncertainty of some model parameters on the vertical fluxes between the upper zone of the LFA and the FPZ under the conditions of scenario 8 (table 8) were analyzed simulating the injection of all available 18 Mgal/d into the Deerwood 3 injection wells. Parameter values that resulted in substantial increases of the RMS residual of 1.75 ft derived from the steady-state calibration were not tested in these parameter uncertainty simulations. The rationale for the sensitivity analysis on the upward flow from the FPZ was to study uncertainty in model prediction that results from the inability to completely describe the physical system.

### Vertical Leakage of Semiconfining Unit

Vertical leakage of the SCU was tested for values that ranged from slightly leakier than the ICU to as leaky as the MSCU. These values ranged from half the calibrated value, or  $1.0 \times 10^{-5}$  (ft/d)/ft, to about 25 times the calibrated value, or  $5 \times 10^{-4}$  (ft/d)/ft. Increases in the simulated vertical leakage of the SCU resulted in increased upward flow from the FPZ during the simulated months of withdrawals, April and December. During the simulated month of rest, August, the Brierwood and Deerwood 3 well field subareas had increases in upward flow from the FPZ relative to the remaining 9 months of the year, months of injections. In contrast, upward flow from the FPZ decreased in the Main Street well field during April and December because the withdrawals at Brierwood and Deerwood 3 during these 2 months did not require the additional withdrawal of 18 Mgal/d at the Main Street well field (fig. 36).

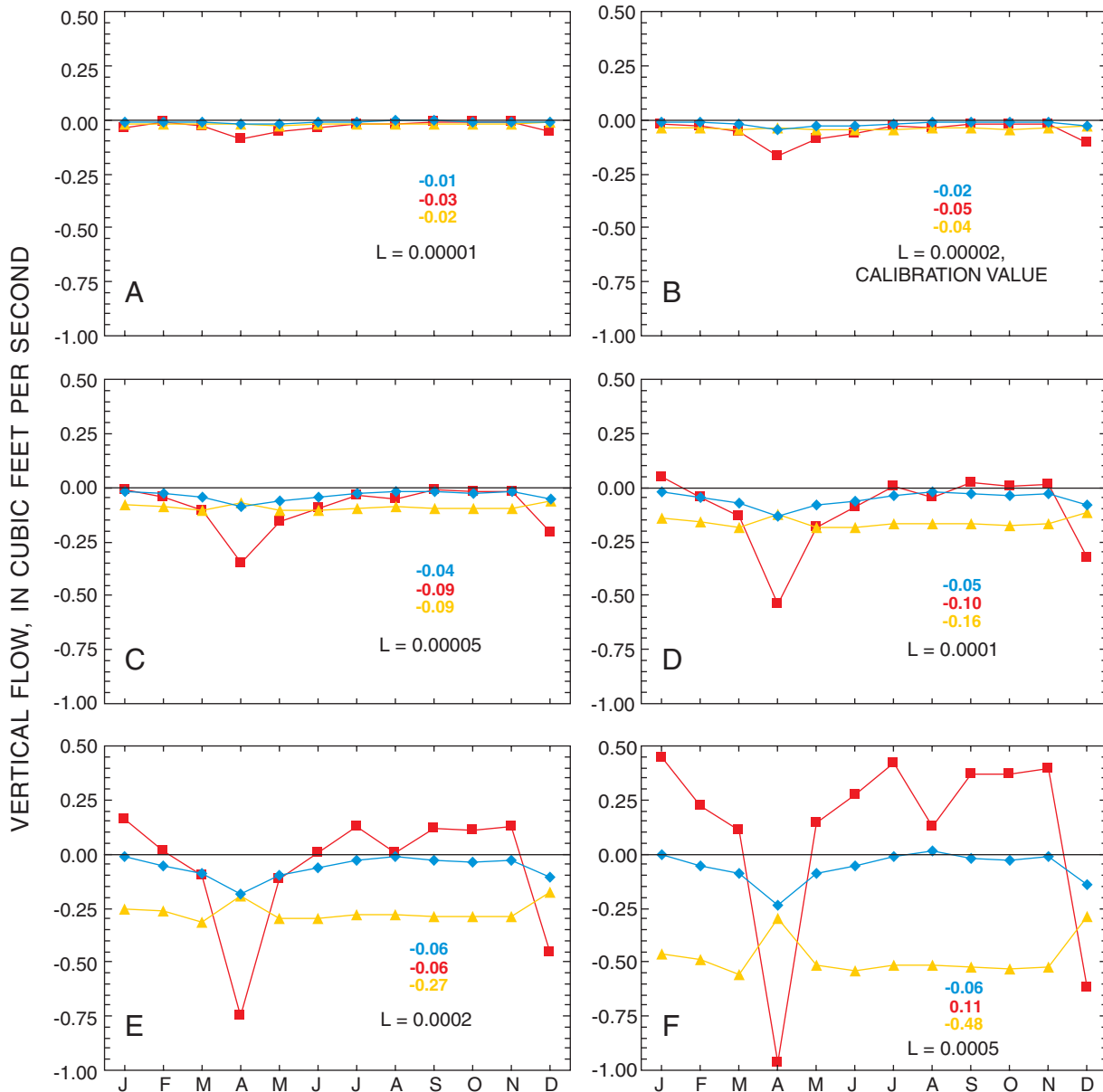
During stress periods of rest or withdrawal, the upward flow from the FPZ in the Deerwood 3 well field subarea increased as the simulated vertical

leakance of the SCU increased and decreased during stress periods of injection. The injection of water into the upper zone of the LFA in Deerwood 3 wells reverses the hydraulic gradient between the FPZ and the upper zone of the LFA when the vertical leakage of the SCU is simulated to be at least 5 times greater than the calibration value of 0.00002 (ft/d)/ft. For example, if the simulated vertical leakage of the SCU is 0.00050 (ft/d)/ft, then the flows from the FPZ in the Deerwood 3 well field subarea during the months of April and December were upward at the rate of about 0.6 and 1.0 ft<sup>3</sup>/s; flow during August, a month of rest, was downward at about 0.12 ft<sup>3</sup>/s; and flows during the 9 months of injection were downward at an average of about 0.3 ft<sup>3</sup>/s (fig. 36).

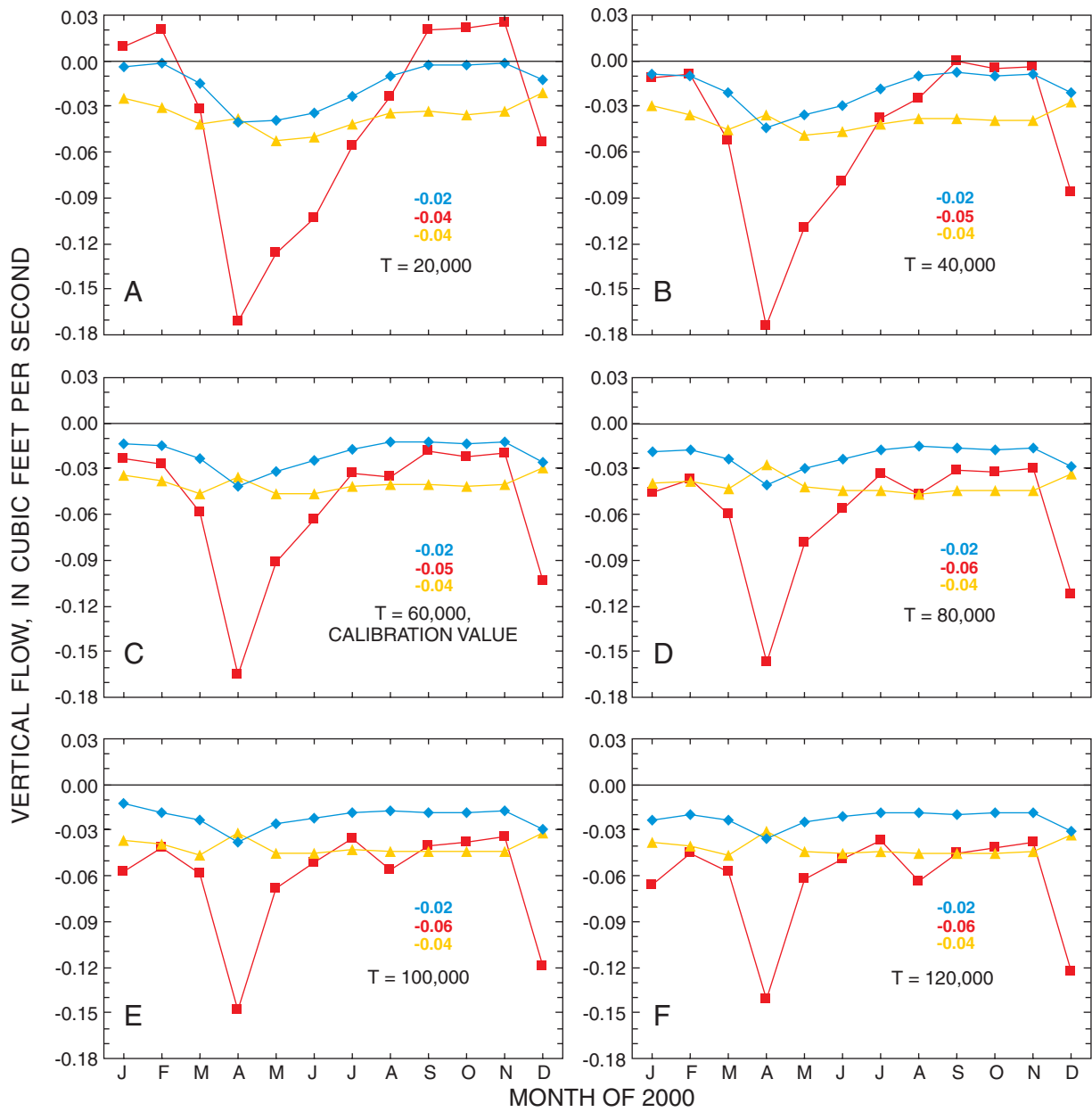
### Transmissivity of the Fernandina Permeable Zone

Transmissivity of the FPZ was tested for values that ranged from about the average simulated transmissivity of the UFA to a fourth of the transmissivity of the upper zone of the LFA. These values ranged from 20,000 to 120,000 ft<sup>2</sup>/d. Decreasing the simulated transmissivity of the FPZ decreases the upward flow from the FPZ to the upper zone of the LFA (fig. 37). This was observed for stress periods of injection, withdrawal, and intervening rest months. The results for the simulated transmissivities for the FPZ were obtained using the calibrated values for all other model parameters, and assuming that 18 Mgal/d were injected in the Deerwood 3 well field. A simulated transmissivity of 20,000 ft<sup>2</sup>/d in the FPZ resulted in the reversal of the upward hydraulic gradient from the FPZ (fig. 37).

Vertical flow rates between the FPZ and the upper zone of the LFA (fig. 37) indicate that if the transmissivity of the FPZ was 20,000 or 40,000 ft<sup>2</sup>/d (less than the calibration value), then the injection of water into Deerwood 3 wells would result in the reduction of the upward flow from the FPZ in the subarea of this well field. The injection of water into Deerwood 3 wells also would reduce the upward flow from the FPZ during the months of withdrawals if the transmissivity of the FPZ was less than the calibrated value. Transmissivity values of the FPZ greater than the calibration value of 60,000 ft<sup>2</sup>/d increased the upward flow from the FPZ. The scales used for the vertical axis in figures 36 and 37 indicate the simulated changes to the vertical leakage of the SCU had a greater effect on the simulated upward flow from the FPZ than the simulated changes to the transmissivity of the FPZ.



**Figure 36.** Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000, under scenario 8 conditions, for various vertical leakances of the semiconfining unit overlying the Fernandina permeable zone, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only (see table 8 for description of scenario 8).



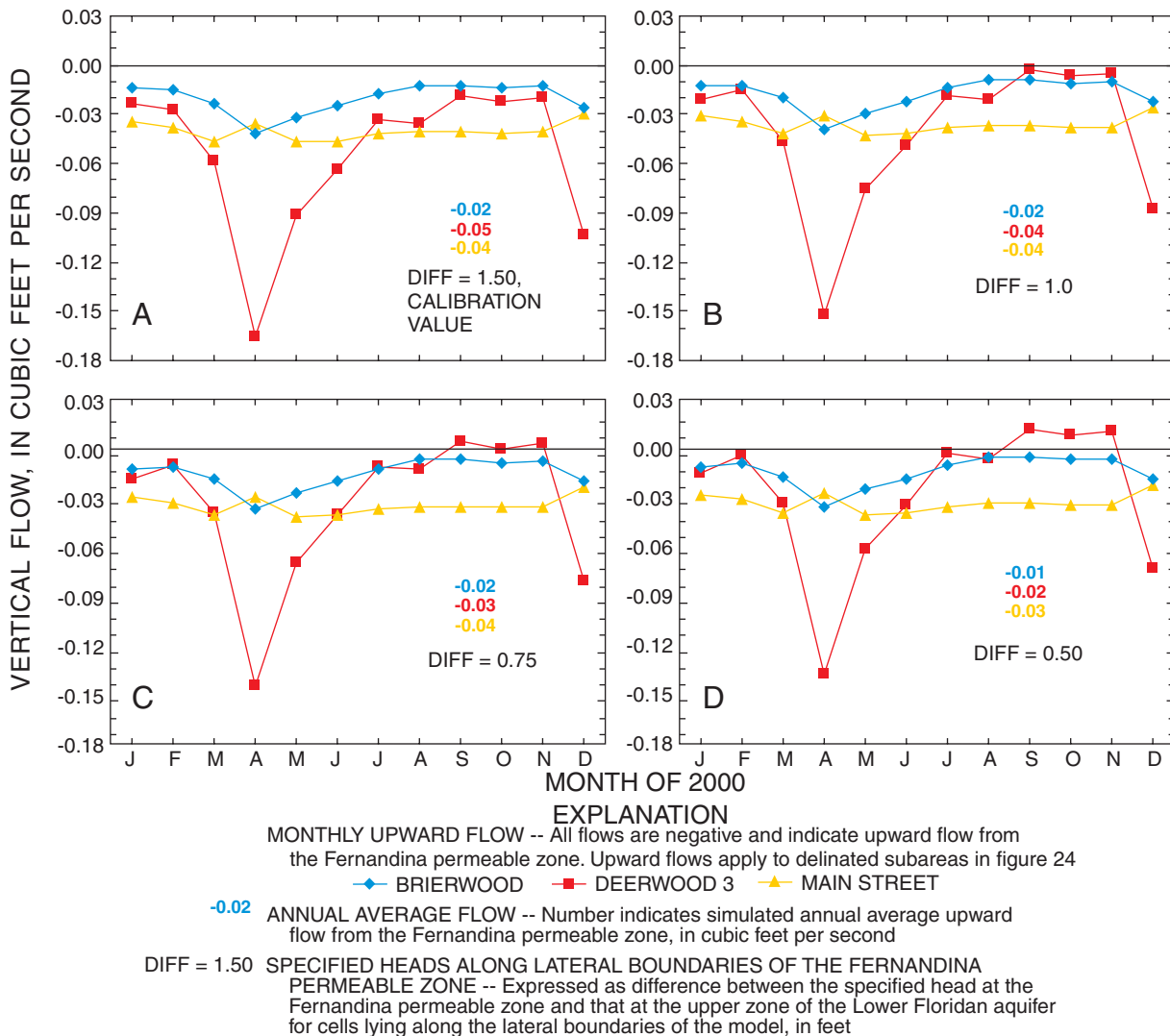
**Figure 37.** Simulated monthly vertical flows between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer for 2000, under scenario 8 conditions, for various transmissivities of the Fernandina permeable zone, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only (see table 8 for description of scenario 8).

## Specified-Head Cells Along the Lateral Boundaries of the Fernandina Permeable Zone

Several variations to the differences in heads along the lateral boundaries of the model were simulated for the purpose of assessing how these changes affect the upward flow from the FPZ. If the difference between the specified heads along the lateral boundaries of the model in the FPZ and the upper zone of the LFA is varied, then the rates of water exchanged

between these two units change. Hydrologists believe that flow from the FPZ is always upward or lateral, but not downward within the model area.

The simulated upward flow from the FPZ decreases as the difference in specified heads, along the lateral boundaries of the model, between the FPZ and the upper zone of the LFA decreases (fig. 38). This was expected based on Darcy's law because the vertical leakage was maintained constant, but the vertical hydraulic gradient decreased, thus reducing the exchange of water.



**Figure 38.** Simulated monthly upward flows from the Fernandina permeable zone for 2000, under scenario 8 conditions, for various differences in specified heads, between the Fernandina permeable zone and the upper zone of the Lower Floridan aquifer, along lateral boundaries of the model, and where water is injected, at the rate of 18 million gallons per day, in Deerwood 3 well field only (see table 8 for description of scenario 8).

## MODEL LIMITATIONS

Ground-water flow simulations generally are based on conceptual models that are simplified representations of complex heterogeneous ground-water flow systems. Assumptions such as isotropy, vertical homogeneity within each layer, and the absence of preferential flow zones are examples of simplified representations that can be sources of error in a ground-water flow model. The lack of sufficient measurements to account for the spatial variation of hydraulic properties throughout the model area necessitated these simplifications. Simplifying the model does not invalidate model results, although model results should be interpreted at scales larger than the representative grid cell.

The most important limitations of the ground-water flow models presented in this report are: simplifications in the conceptual model, inherent model assumptions, and lack of head and flow measurements in areas where spatial variability of hydraulic and hydrologic properties is poorly known. Model simulations were performed using calibrated hydraulic properties, specified heads in the upper zone of the LFA and in the FPZ along lateral boundaries of the model, time-averaged Floridan aquifer heads, and steady-state conditions in the UFA, upper zone of the LFA, and FPZ for CY 2000. An error in any of these can limit the accuracy of model simulations.

The ground-water flow equation solved by the ground-water flow model is the continuity equation for flow, derived from the principle of conservation of mass and the assumption that water is incompressible and of constant viscosity, incorporated with Darcy's law (Todd, 1980). This equation is valid for ground-water flow conditions where the velocity of ground water is low and flow is laminar. In karstic aquifers, it is possible to have turbulent flow through caverns and solution channels. Thus, the ground-water flow equation may not be valid for the entire FAS. The assumptions of laminar flow and uniform effective transmissivity throughout each grid cell to conserve mass were made.

Inaccuracies inherent in the algorithm used to estimate the heads in the UFA, the upper zone of the LFA, and the FPZ (such as lack of data and residual errors) could produce errors in simulated recharge or discharge. These inaccuracies can lead to errors in simulated vertical leakance of the confining units and leakage rates to or from the UFA, the upper zone of the LFA, and the FPZ. The assumption of uniform heads throughout the vertical thickness of each grid cell is

another possible source of error in the simulated heads.

The simulated transmissivities in the UFA, the upper zone of the LFA, the FPZ, and the vertical leakances of the ICU, MSCU, and SCU in this study had minor changes to those reported in previous ground-water flow models. The modifications to transmissivity and vertical leakance values from previous ground-water flow models were made to reduce differences between simulated and measured heads. Areas in the UFA or the upper zone of the LFA where ground-water withdrawals were minimal for 2000 may require changes to simulated transmissivity and vertical leakance because additional ground-water withdrawals may reflect unexpected responses in aquifer areas previously not stressed.

Lack of data for the upper zone of the LFA, the FPZ, the MSCU, and the SCU precludes a reliable estimation of transmissivity and vertical leakances; at most, only 20 control points were available for this study, and at times only 16. In addition, flow between the upper zone of the LFA and the FPZ can be better understood as the potentiometric surfaces of these units are refined with additional head measurements. Some heads were computed based on environmental-water heads because the assumption of uniform density in the FPZ is not valid in areas where water is of greater density.

In spite of the limitations of the ground-water flow models, these models can indicate the general movement of ground water in the study area. The calibrated steady-state flow model can be used to assess long-term head buildups (or drawdowns) due to the injections or withdrawals of water. The transient model can be used to assess the effects of various injection and withdrawal scenarios on the magnitude of upward flow from the FPZ. The sensitivity analysis of the upward flow from the FPZ was performed by simulating changes in the calibrated hydraulic properties of the SCU and FPZ, which allowed the identification of parameter values under which the upward flow from the FPZ would be reversed.

## SUMMARY AND CONCLUSIONS

The water-bearing zones within the Floridan aquifer system (FAS), the Upper Floridan aquifer (UFA) and the Lower Floridan aquifer (LFA), consist of soft, porous limestone and porous highly fractured dolomite beds. The LFA is subdivided into two

principal water-bearing zones, the upper zone of the LFA and the Fernandina permeable zone (FPZ), separated by a less permeable unit, the semiconfining unit (SCU). The UFA and LFA are separated by the middle semiconfining unit (MSCU), a unit that restricts vertical movement of water from one aquifer to another based on vertical leakance.

A four-layer finite-difference steady-state ground-water flow model of the FAS in parts of Duval, St. Johns, and Clay Counties, Florida, was developed and calibrated. The initial distribution of hydraulic properties, extracted from larger-scale, regional ground-water flow models, was calibrated to average 2000 hydrologic conditions based on 20 control points, representing wells tapping the UFA, the upper zone of the LFA, and the FPZ. A transient ground-water flow model was developed by using the calibrated hydraulic properties of the steady-state flow model and by calibrating the storage coefficient based on residuals between simulated heads and monthly measured data at the control points.

Two well fields within the study area, Deerwood 3 and Brierwood, have had elevated chloride concentrations in ground-water samples. The FPZ, which contains ground water with substantially greater chloride levels in the eastern part of the study area, is the likely source of these elevated chlorides. Throughout the model area, ground water flows upward from the FPZ to the upper zone of the LFA, and from the upper zone of the LFA to the UFA. Twelve scenarios of injection, withdrawal, and intervening rest periods were simulated to explore conditions under which the upward flow from the FPZ could be decreased or reversed, thus minimizing the mixing of poorer quality water from the FPZ with freshwater from the upper zone of the LFA.

Ground-water withdrawal rates from 2000 were used in both steady-state and transient models. As withdrawal rates increased from one month of pumping to another, upward flow from the FPZ increased, even when pumping periods were preceded by several injection periods. Injection periods were characterized by an injection rate of 18 million gallons per day (Mgal/d) distributed among Deerwood 3 and Brierwood wells. The injections into the upper zone of the LFA were more efficient in reducing the upward flow from the FPZ than injections into the UFA. During intervening rest periods, the water withdrawn from the Main Street well field would be connected directly

into the service line, thus there would be no pumping from or injection into Deerwood 3 or Brierwood wells.

An annual average upward flow from the FPZ of 0.11 cubic feet per second ( $\text{ft}^3/\text{s}$ ) was simulated before the injection of water into the Deerwood 3 wells. As water was simulated as being injected into the Deerwood 3 and Brierwood wells, upward flow from the FPZ decreased; however, the direction of the vertical flow was not reversed until simulated injection rates in Deerwood 3 were at least 30 Mgal/d. This rate exceeded the proposed rate of 18 Mgal/d to be withdrawn from the Main Street wells. The injection rate of 18 Mgal/d into the upper zone of the LFA in Deerwood 3 wells reduced the upward flow from the FPZ in the vicinity of this well field to an annual average of 0.04  $\text{ft}^3/\text{s}$ , less than the 0.11  $\text{ft}^3/\text{s}$  before any injection of water. However, a large percentage of the injected water into the upper zone of the LFA moves laterally within the same aquifer. As ground-water withdrawals at Deerwood 3 and Brierwood increase in the future, so will the induced upward flow from the FPZ.

If 18 Mgal/d of water withdrawn from the Main Street well field is injected into the UFA, instead of into the upper zone of the LFA, most of the water leaves the Deerwood 3 and Brierwood areas through lateral flow in the UFA and as a result, less water moves downward to the upper zone of the LFA. Such injection into the UFA would reduce the water moving downward into the FPZ, and thus, would not reduce the upward flow from the FPZ to the upper zone of the LFA.

Sensitivity analyses of parameters from the calibrated steady-state model showed that the model was least sensitive to the vertical leakance of the SCU, the transmissivity of the FPZ, and the specified hydraulic gradient between the upper zone of the LFA and the FPZ. As the simulated vertical leakance of the SCU was increased from 0.00002 (calibration value) to 0.0001 (ft/d)/ft or higher, injection into the upper zone of the LFA at the Deerwood 3 well field reversed the hydraulic gradient, although the upward leakage from the FPZ increased for higher vertical leakances during stress periods of withdrawals at Deerwood 3. As the simulated transmissivity of the FPZ was decreased from 60,000 feet squared per day (calibration value), upward flow from the FPZ decreased during periods of withdrawals. As the simulated difference in specified heads between the upper zone of the LFA and the FPZ decreased, so did upward flow from the FPZ.

The SCU was simulated to be leakier than the intermediate confining unit (ICU), but tighter than the MSCU. The thickness of the SCU was estimated to be about 500 feet, more than the thicknesses of the ICU or MSCU. The lack of any field measurements for the vertical leakance of the SCU resulted in relying on the calibration value of 0.00002 (ft/d)/ft. Simulation results from a wide range of injection, withdrawal, and intervening rest scenarios indicated that the upward flow from the FPZ can only be reversed if simulations are conducted using other than the calibrated values for the transmissivity of the FPZ, the vertical leakance of the SCU, and the difference in heads between the upper zone of the LFA and the FPZ.

## REFERENCES

- Brown, D.P., Johnson, R.A. and Baker, J.S., 1984, Hydrogeologic data from a test well at Kathryn Abbey Hanna Park, city of Jacksonville, Florida: U.S. Geological Survey Open-File Report 84-143, 41 p.
- Domenico, P.A., 1972, Concepts and models in groundwater hydrology: New York, McGraw-Hill, 405 p.
- Durden, D.W., 1997, Finite-difference simulation of the Floridan aquifer system in northeast Florida and Camden County, Georgia: St. Johns River Water Management District Technical Publication 97-2, 253 p.
- Environmental Systems Research Institute, Inc., 1997, ARC/INFO, version 8.0.2: Redlands, Calif.
- Florida Administrative Code, 2000, Florida drinking water standards, Chapter 62-550, Department of Environmental Protection, 60 p.
- Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.
- Kindinger, J.L., Davis, J.B., and Flock, J.G., 2000, Subsurface characterization of selected water bodies in the St. Johns River Water Management District, northeast Florida: U.S. Geological Survey Open-File Report 00-180, 46 p.
- Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403-D, 65 p., 18 pl.
- Leve, G.W., 1966, Ground-water in Duval and Nassau Counties, Florida: Florida Geological Survey Report of Investigations no. 43, 91 p.
- Luszczynski, N.J., 1961, Head and flow of ground water of variable density: Journal of Geophysical Research, v. 66, no. 12, p. 4,247-4,256.
- Meisburger, E.P., and Field, M.E., 1976, Neogene sediments of Atlantic inner continental shelf off northern Florida: American Association of Petroleum Geologists, v. 60, no. 11, p. 2,019-2,037.
- Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.
- Odum, J.K., Stephenson, W.J., Williams, R.A., Worley, D.M., Toth, D.J., Spechler, R.M., and Pratt, T.L., 1997, Land based high-resolution seismic reflection surveys of seven sites in Duval and St. Johns Counties, northeastern Florida: U.S. Geological Survey Open-File Report 97-718, 61 p.
- Phelps, G.G., 2001, Geochemistry and origins of mineralized waters in the Floridan aquifer system, northeastern Florida: U.S. Geological Survey Water-Resources Investigations Report 01-4112, 64 p.
- Phelps, G.G., and Spechler, R.M., 1997, The relation between hydrogeology and water quality of the Lower Floridan aquifer in Duval County, Florida and implications for monitoring movement of saline water: U.S. Geological Survey Water-Resources Investigations Report 96-4242, 58 p.
- Popenoe, Peter, Kohout, F.A., and Manheim, F.T., 1984, Seismic-reflection studies of sinkholes and limestone dissolution features on the northeastern Florida shelf: Proceedings of First Multidisciplinary Conference on Sinkholes, Orlando, Fla., October 15-17, 1984, p. 43-57.
- Sepúlveda, Nicasio, 2002a, Simulation of ground-water flow in the intermediate and Floridan aquifer systems in peninsular Florida: U.S. Geological Survey Water-Resources Investigation Report 02-4009, 130 p.
- 2002b, A statistical estimator of the spatial distribution of the water-table altitude: Ground Water Journal, v. 41, no. 1, p. 66-71.
- Snyder, J.P., 1983, Map projections used by the U.S. Geological Survey: U.S. Geological Survey Bulletin B-1532, 313 p.
- Snyder, S.W., Evans, M.E., Hine, A.C., and Compton, J.S., 1989, Seismic expression of solution collapse features from the Florida platform, in Proceedings of Third Multidisciplinary Conference on Sinkholes, St. Petersburg Beach, Florida, p. 281-297.
- Spechler, R.M., 1994, Saltwater intrusion and quality of water in the Floridan aquifer system, northeastern Florida: U.S. Geological Survey Water-Resources Investigations Report 92-4174, 76 p.



- 1995, Estimated discharge and chemical-constituent loading from the Upper Floridan aquifer to the lower St. Johns River, northeastern Florida, 1990-91: U.S. Geological Survey Water-Resources Investigations Report 94-4132, 32 p.
- 1996, Detection and quality of previously undetermined Floridan aquifer system discharge to the St. Johns River, Jacksonville to Green Cove Springs, northeastern Florida: U.S. Geological Survey Water-Resources Investigation Report 95-4257, 29 p.
- Spechler, R.M., and Wilson, W.L., 1997, Stratigraphy and hydrogeology of a submarine collapse sinkhole on the continental shelf, northeastern Florida, *in* Proceedings of Sixth Multidisciplinary Conference on Sinkholes, Springfield, Missouri, April 6-9, 1997, p. 61-66.
- St. Johns River Water Management District, 2002, Aquifer system monitor wells: Intermediate D-1393, Floridan D-1344, Floridan D-1394, Draft report, Division of Ground Water Programs, SJRWMD Program No. 31-58200, 28 p.
- Swarzenski, P.W, Reich, C.D., Spechler, R.M., Kindinger, J.L., and Moore, W.S., 2001, Using multiple geochemical tracers to characterize the hydrogeology of the submarine spring off Crescent Beach, Florida: *Chemical Geology*, v. 179, p.187-202.
- Todd, D.K., 1980, *Groundwater hydrology* (2d ed.): New York, John Wiley & Sons, 405 p.
- U.S. Environmental Protection Agency, 2000, *Drinking water standards and health advisories*, Washington, D.C., EPA 822-B-00-001, 12 p.
- U.S. Geological Survey, 2001a, Water resources data for Florida, water year 2000, v. 1A, northeast Florida, surface water: U.S. Geological Survey Water-Data Report, FL-00-1A, 388 p.
- 2001b, Water resources data for Florida, water year 2000, v. 1B, northeast Florida, ground water: U.S. Geological Survey Water-Data Report, FL-00-1B, 274 p.
- 2002a, Water resources data for Florida, water year 2001, v. 1A, northeast Florida, surface water: U.S. Geological Survey Water-Data Report, FL-01-1A, 398 p.
- 2002b, Water resources data for Florida, water year 2001, v. 1B, northeast Florida, ground water: U.S. Geological Survey Water-Data Report, FL-01-1B, 274 p.

