Technical Publication No. 97-2

FINITE-DIFFERENCE SIMULATION OF THE FLORIDAN AQUIFER SYSTEM IN NORTHEAST FLORIDA AND CAMDEN COUNTY, GEORGIA

by

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March 14, 1997

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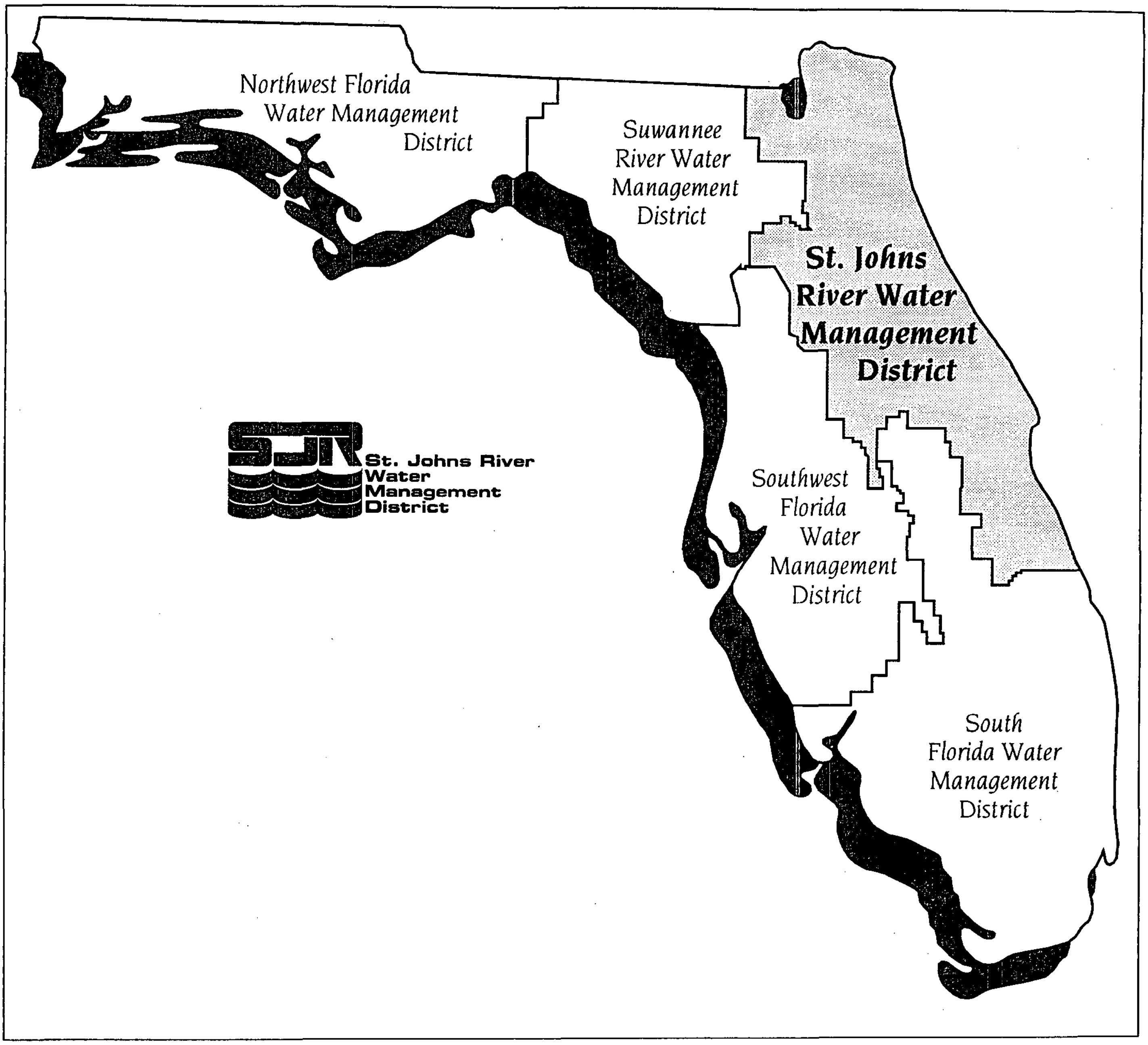
Palatka, Florida

1997



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EXECUTIVE SUMMARY

This study was performed in support of the Water Supply Needs and Sources Assessment of St. Johns River Water Management District. As such, the primary objective was to predict changes in hydraulic-head levels in the Floridan aquifer system of the study area that will occur in response to projected increases in ground water withdrawals between 1985 and 2010. The study area included parts of northeast Florida and Camden County, Georgia. Another objective was to enhance the understanding of interactions that occur between the aquifers within the Floridan aquifer system and between the Floridan aquifer system and the overlying surficial aquifer system. A further objective was to improve estimates of the hydraulic properties of the Floridan aquifer system and of the overlying upper confining unit. Ground water flow models of the predevelopment (prior to 1880) and postdevelopment (1985) Floridan aquifer system in northeast Florida and Camden County, Georgia, were developed to fulfill this objective.

The study area includes parts of Duval, Clay, St. Johns, and Nassau counties, Florida; Camden County, Georgia; and a sizable offshore area in the Atlantic Ocean. It lies between longitudes 81°7′ and 81°52′ west and latitudes 29°51′ and 31°2′ north and encompasses approximately 3,660 square miles.

In descending order, the ground water system of the study area consists of a surficial aquifer system, an intermediate aquifer system, and the Floridan aquifer system. The surficial aquifer system is separated from the Floridan aquifer system by the upper confining unit, which consists of the Hawthorn Group and overlying Pliocene deposits. The intermediate aquifer system is contained in the upper confining unit.

The Floridan aquifer system has been differentiated into three aquifers separated by two semiconfining units. These are, from top to bottom, the Upper Floridan aquifer, the middle semiconfining unit, the Lower Floridan aquifer, the lower semiconfining unit, and the Fernandina permeable zone. The Floridan aquifer system is bounded at its base by a lower confining unit that consists of low-permeability anhydrite beds.

Three models were developed as a result of the study: the predevelopment, postdevelopment, and revised predevelopment flow models. The predevelopment flow model is a model of the Floridan aquifer system within the study area prior to the onset of significant ground water withdrawals. The postdevelopment flow model is a model of the Floridan aquifer system under 1985 pumping conditions. The revised predevelopment flow model is a modified version of the original predevelopment flow model. The model code selected for use is the modular three-dimensional finite-difference ground water flow model (MODFLOW).

The calibration of the predevelopment flow model served as a precursor to the calibration of the postdevelopment flow model. The hydraulic parameters derived from the calibration of the predevelopment flow model were used as initial values in the calibration of the postdevelopment and revised predevelopment flow models.

All three models represent ground water flow conditions as being constant with respect to time (i.e., steady state). All three models consist of four aquifer layers and four semiconfining unit layers. In descending order, the layers represent the surficial aquifer system (aquifer layer 1), the upper confining unit (semiconfining unit layer 1), the Upper Floridan aquifer (aquifer layer 2), the middle semiconfining unit (semiconfining unit layer 2), the Lower Floridan aquifer (aquifer layer 3), the lower semiconfining unit (semiconfining unit layer 3), the Fernandina permeable zone (aquifer layer 4), and the lower confining unit (semiconfining unit layer 4).

The results of predictive simulations performed using the postdevelopment flow model indicate that by the year 2010, the potentiometric surface of the Upper Floridan aquifer will decline approximately 0–5 ft relative to 1985 water levels throughout most of the study area due to projected increases in withdrawals from wells. In parts of the southern half of the study area, the potentiometric surface of the Upper Floridan aquifer will decline approximately

5–20 ft relative to 1985 water levels, also due to projected increases in withdrawals from wells. In the area of Fernandina Beach, levels of hydraulic head will increase approximately 0–10 ft relative to 1985 levels due to projected decreases in withdrawals from wells. The total of the projected 2010 withdrawal rates is 330 million gallons per day, an increase of approximately 44% over the total of the estimated 1985 withdrawal rates.

Additionally, the results of the study indicate that the transmissivity of the Lower Floridan aquifer is considerably higher on average than that of the Upper Floridan aquifer and that upward leakage from the Lower Floridan aquifer accounts for a significant proportion of the total recharge to the Upper Floridan aquifer within the study area (59%). The results of the study indicate that a significantly greater quantity of ground water flows through the Lower Floridan aquifer than through the Upper Floridan aquifer or the Fernandina permeable zone (1.68 inches per year [in/yr] versus 1.25 and 0.13 in/yr, respectively).

The study results show that withdrawals from wells account for approximately 65% and 30%, respectively, of the total discharge from the Upper and Lower Floridan aquifers and have resulted in significant changes in the Floridan aquifer system since predevelopment times. Levels of hydraulic head in the Upper Floridan aquifer have declined by an average of approximately 25 ft within the study area. The quantity of ground water moving through the Upper and Lower Floridan aquifers and the Fernandina permeable zone has increased significantly (1.68 in/yr in the predevelopment system versus 3.06 in/yr in the postdevelopment system). Discharge from the Floridan aquifer system to the surficial aquifer system has decreased significantly since predevelopment times (0.52 in/yr in the predevelopment system versus 0.28 in/yr in the postdevelopment system). Likewise, recharge to the Floridan aquifer system from the surficial aquifer system has increased significantly since predevelopment times (0.09 in/yr in the predevelopment system versus 0.15 in/yr in the postdevelopment system).

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INTRODUCTION

The Floridan aquifer system in northeast Florida and southeast Georgia is a system of carbonate aquifers and intervening semiconfining units. The inherent complexity of the Floridan aquifer system is due, in part, to variations in properties that govern rates and directions of flow, such as hydraulic conductivity and land surface elevation. These complexities are compounded by withdrawals from hundreds of wells scattered throughout the area that penetrate the Floridan aquifer system to varying depths and withdraw water from it at rates that vary temporally and spatially.

Complex, regional ground water flow systems such as the Floridan aquifer system are simulated most commonly using numerical ground water models. The main purpose of such models is to predict the responses of ground water systems to hypothetical changes in stresses, such as proposed withdrawals from wells.

In this study, a numerical, finite-difference ground water flow model is used to simulate the Floridan aquifer system in northeast Florida and Camden County, Georgia. In finite-difference ground water flow models, the partial derivatives in the equation of ground water flow are represented as finite differences. This representation results in a relatively simple algebraic approximation of the ground water flow equation that can be solved as a system of linear equations. This approach enables the development of ground water flow models that are capable of representing high levels of complexity in ground water systems.

OBJECTIVES

This study was performed in support of the Water Supply Needs and Sources Assessment (Vergara 1994) of St. Johns River Water Management District (SJRWMD). As such, the primary objective was to predict changes in hydraulic-head levels in the Floridan aquifer system of the study area that will occur in response to projected increases in ground water withdrawals between 1985 and 2010. The study area included parts of northeast Florida and Camden County, Georgia. Another objective was to enhance the understanding of interactions that occur between the aquifers within the Floridan aquifer system and between the Floridan aquifer system and the overlying surficial aquifer system. An additional objective was to improve estimates of the hydraulic properties of the Floridan aquifer system and of the overlying upper confining unit. Ultimately, the ground water flow models resulting from this study will provide a basis for the development and use of ground water quality models as well.

PREVIOUS STUDIES

The ground water system of northeast Florida and southeast Georgia has been the subject of numerous publications. Publications that provide generalized descriptions of the ground water system of northeast Florida and/or southeast Georgia include those by Bermes et al. (1963); Clark et al. (1964); Leve (1966); Fairchild (1972); Fairchild and Bentley (1977); Causey and Phelps (1978); Franks (1980); Johnston, Krause et al. (1980); Hayes (1981); Scott (1983); Spechler and Stone (1983); Brown (1984); Krause et al. (1984); Spechler and Hampson (1984); Miller (1986); Bush and Johnston (1988); Huddlestun (1988); Johnston and Bush (1988); Scott (1988); Krause and Randolph (1989); Sprinkle (1989); Clarke et al. (1990); Toth (1990); and Durden and Motz (1992).

Reports that present data from well tests performed on the Floridan aquifer system in northeast Florida include those by Leve and Goolsby (1966); Bentley (1977, 1979); Brown (1980); Johnston, Bush et al. (1980); and Brown et al. (1984, 1985, 1986).

Reports that describe ground water flow models with boundaries that encompass the present area of interest either partly or entirely include those by Bush (1982), Krause (1982), Krause and Randolph (1989), and Durden and Motz (1991).

METHODS

Ground water flow models of the predevelopment and postdevelopment Floridan aquifer system in northeast Florida and

Camden County, Georgia, were developed to fulfill the objectives of this study. The information used in the development of the models was obtained from published and unpublished hydrologic reports and data of the U.S. Geological Survey (USGS), Florida Bureau of Geology, SJRWMD, Georgia Department of Natural Resources, Georgia Geological Survey, and others. Prior to model development, the pertinent reports, data, and other information were compiled and reviewed. Model development consisted of the following three interrelated steps: (1) calibration of a steady-state predevelopment flow model, (2) calibration of a steady-state postdevelopment flow model, and (3) calibration of a revised steady-state predevelopment flow model.

A trial-and-error procedure was used to calibrate each of the models, the essential steps of which follow:

1. The transmissivity of the aquifers and the leakance of the semiconfining units of the Floridan aquifer system and overlying upper confining unit were estimated based on available information.

2. The potentiometric surface of the Upper Floridan aquifer was simulated and compared to an estimated potentiometric surface.

3. Differences in the simulated and estimated potentiometric surfaces were noted.

4. The estimates of transmissivity and leakance used in the simulation were adjusted to decrease the differences.

5. Steps 2 through 4 were repeated until the differences were minimized using physically realistic estimates of transmissivity and leakance.

The initial estimates of transmissivity and leakance used in the predevelopment flow model were derived primarily from previous modeling studies and aquifer performance tests. Simulated predevelopment potentiometric surfaces of the Upper Floridan aquifer were compared to the estimated predevelopment potentiometric surface of Johnston, Krause et al. (1980).

The initial estimates of transmissivity and leakance used in the postdevelopment flow model were the estimates resulting from the calibration of the predevelopment flow model. Simulated postdevelopment potentiometric surfaces were compared to an estimated postdevelopment potentiometric surface that was derived using the results of Johnston, Bush et al. (1980), Schiner and Hayes (1985), and Clarke (1987). In addition, simulated values of hydraulic head in the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone were compared to values of hydraulic head observed in monitoring wells located within the area corresponding to the model domain.

To construct the initial version of the revised predevelopment flow model, the estimates of transmissivity and leakance in the predevelopment flow model were replaced with estimates resulting from the on-going calibration of the postdevelopment flow model. The revised predevelopment flow model was then calibrated as part of the process of calibrating the postdevelopment flow model. In this process, trial estimates of transmissivity and leakance were tested by simulating both the predevelopment and postdevelopment potentiometric surfaces of the Upper Floridan aquifer. This process was continued until both the predevelopment (Johnston, Krause et al. 1980) and postdevelopment (derived from Johnston, Bush et al. 1980, Schiner and Hayes 1985, and Clarke 1987) potentiometric surfaces of the Upper Floridan aquifer and other available hydraulic-head data could be simulated adequately using the same, physically realistic estimates of transmissivity and leakance.

The adequacy of the model calibrations was gauged using several different approaches. In each of the calibrations, simulated values of hydraulic head were compared to values interpolated from the maps of the estimated potentiometric surfaces of the Upper Floridan aquifer. In the calibration of the postdevelopment flow model, simulated values of hydraulic head were compared to values observed in monitoring wells in the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone, as well.

Quantitative comparisons were made by calculating the mean, standard deviation, and mean of absolute values of the differences in simulated and interpolated and simulated and observed values of hydraulic head. Additionally, quantitative comparisons were made by determining the percentages of simulated values of hydraulic head within 5 and 10 feet (ft) of corresponding interpolated and observed values of hydraulic head.

Qualitative comparisons were made by comparing plots of simulated lines of equal elevation of hydraulic head of the Upper Floridan aquifer to estimated lines of equal elevation of hydraulic head shown on the maps of the estimated predevelopment (Johnston, Krause et al. 1980) or postdevelopment (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987) potentiometric surfaces of the Upper Floridan aquifer. Additionally, qualitative comparisons were made by inspection of plots of lines of equal difference in simulated and interpolated values of hydraulic head in the Upper Floridan aquifer.

The postdevelopment flow model was used to simulate the potentiometric surface of the Upper Floridan aquifer in September 2010. Based on this potentiometric surface, drawdowns in September 2010 relative to the simulated September 1985 potentiometric surface of the Upper Floridan aquifer were determined.

Description of Study Area

Location and Extent

The study area encompasses parts of Duval, St. Johns, Clay, and Nassau counties, Florida; Camden County, Georgia; and a sizable offshore area in the Atlantic Ocean (Figure 1). The study area ranges approximately from latitudes 29°51′ to 31°2′ north and from longitudes 81°7′ to 81°52′ west. The boundaries of the study area encompass approximately 3,660 square miles (mi^2).

Climate

The climate of the study area is humid subtropical (Bermes et al. 1963). About 60% of the average yearly rainfall occurs in June through October (Rao et al. 1989). Between 1941 and 1970, average annual rainfall ranged from approximately 52 inches in the northeast corner of the study area to 56 inches in the southwest corner (Krause and Randolph 1989). The average annual temperature at Jacksonville (Figure 1) during the period 1951–80 was 68°F (NOAA 1986).

Industry and Population

The largest municipality within the study area is Jacksonville, the regional industrial center. Important industries there include manufacturing of paper, chemicals, and building supplies. Outside Jacksonville, primary industries include agriculture and the production of wood pulp and paper. Military installations located within the study area include Jacksonville Naval Air Station, Mayport Naval Station near Jacksonville, and Kings Bay Naval Base near St. Marys, Georgia.

Population centers within the study area include Jacksonville, Jacksonville Beach, Mayport, St. Augustine, Fernandina Beach, Green Cove Springs, and Orange Park, Florida, and St. Marys and Kingsland, Georgia (Figure 1). In 1990, the total population of the

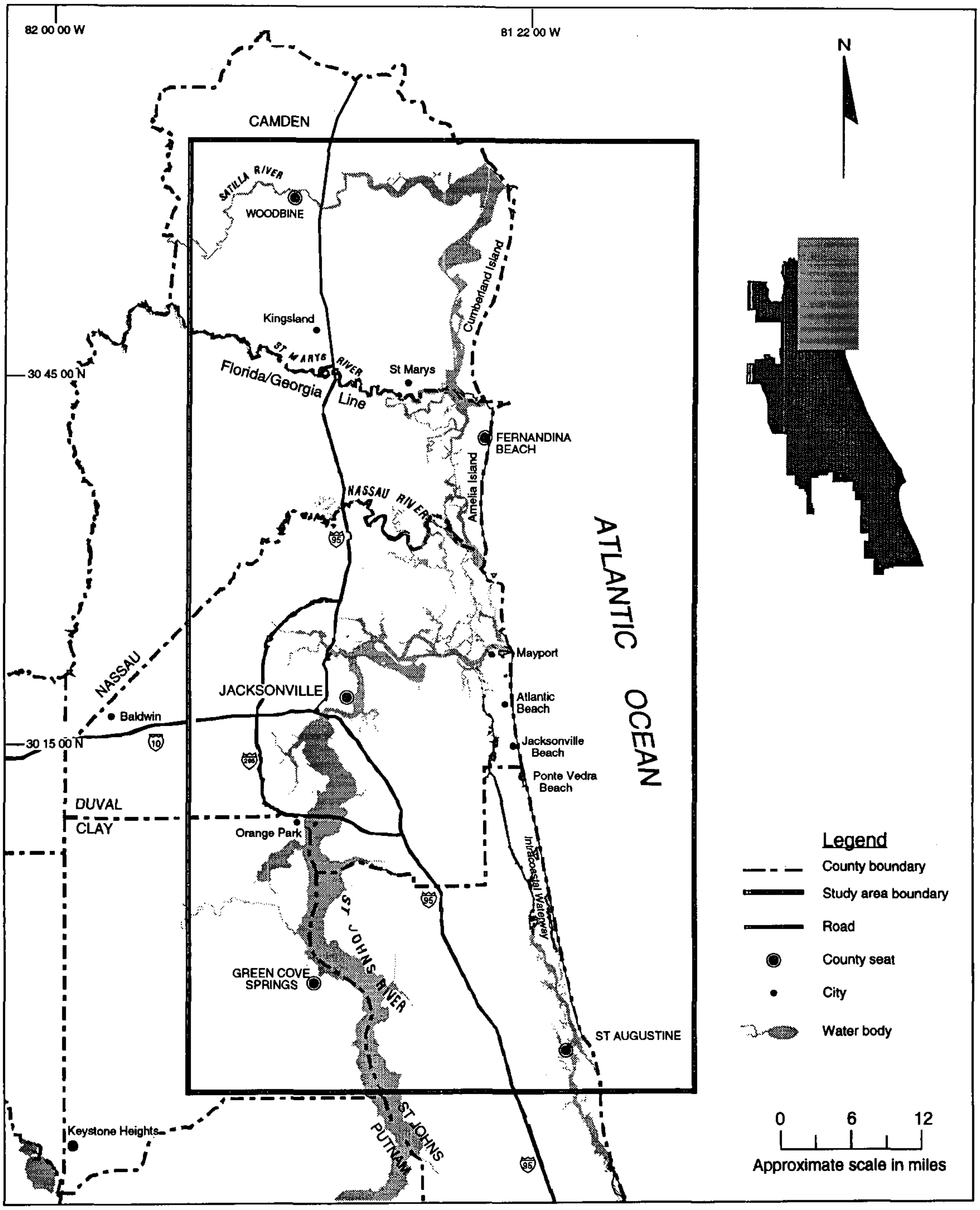


Figure 1. Location of study area

five counties of the study area was approximately 936,894 (Hoffman 1992), of which 71.8% was concentrated in Duval County (Table 1).

Table 1. Population of counties within the study area, 1990

County	Population in 1990
Duval	672,971
Clay	105,986
St. Johns	83,829
Nassau	43,941
Camden	30,167

Source: Hoffman 1992

SURFACE WATER FEATURES

Rivers, streams, and swamps are the most common surface water features within the study area. Western and central Duval County, western St. Johns County, and eastern Clay County are drained principally by the St. Johns River (Figure 1). Eastern Duval and St. Johns counties are drained principally by the Intracoastal Waterway. Northern Duval and southern Nassau counties are drained principally by the Nassau River, and Northern Nassau and southern Camden counties are drained principally by the St. Marys River. Central Camden County is drained principally by the Satilla River (Figure 1). Swamps are common throughout the study area, particularly in the coastal areas of Nassau, northeast Duval, and Camden counties.

Geologic Setting

The geologic units within the study area form the framework of the ground water system. These units include the pre-Hawthorn Tertiary carbonate units, the Hawthorn Group, and the post-Miocene deposits (Table 2; Figures 2–5) and range in age from 65 million to 11 thousand years B.P. (Table 3).

Table 2. Summary of geologic units in the study area

Geologic Epoch	Stratigraphic Unit	Approximate Thickness (feet)	Lithology
Pleistocene and Recent	Pleistocene and recent deposits	10–100	Discontinuous beds of loose sand, clayey sand, sandy clay, clay, marl, and shell
Pliocene	Pleistocene and recent deposits	10–110	Clay, clayey sand, sandy clay, sand, shell, and carbonate rock
Middle Miocene	Hawthorn Group	100–400	Interbedded clay, quartz sand, carbonate, and phosphate
Late Eocene	Ocala Limestone	200–400	Limestone
Middle Eocene	Avon Park Formation	700–1,100	Interbedded limestone and dolomite
Early Eocene	Oldsmar Formation	400–800	Interbedded limestone and dolomite
Paleocene	Cedar Keys Formation	Unknown	Interbedded dolomite and anhydrite

Source: Bermes et al. 1963; Clark et al. 1964; Leve 1966; Fairchild 1972; Scott 1983; Miller 1986; Clarke et al. 1990

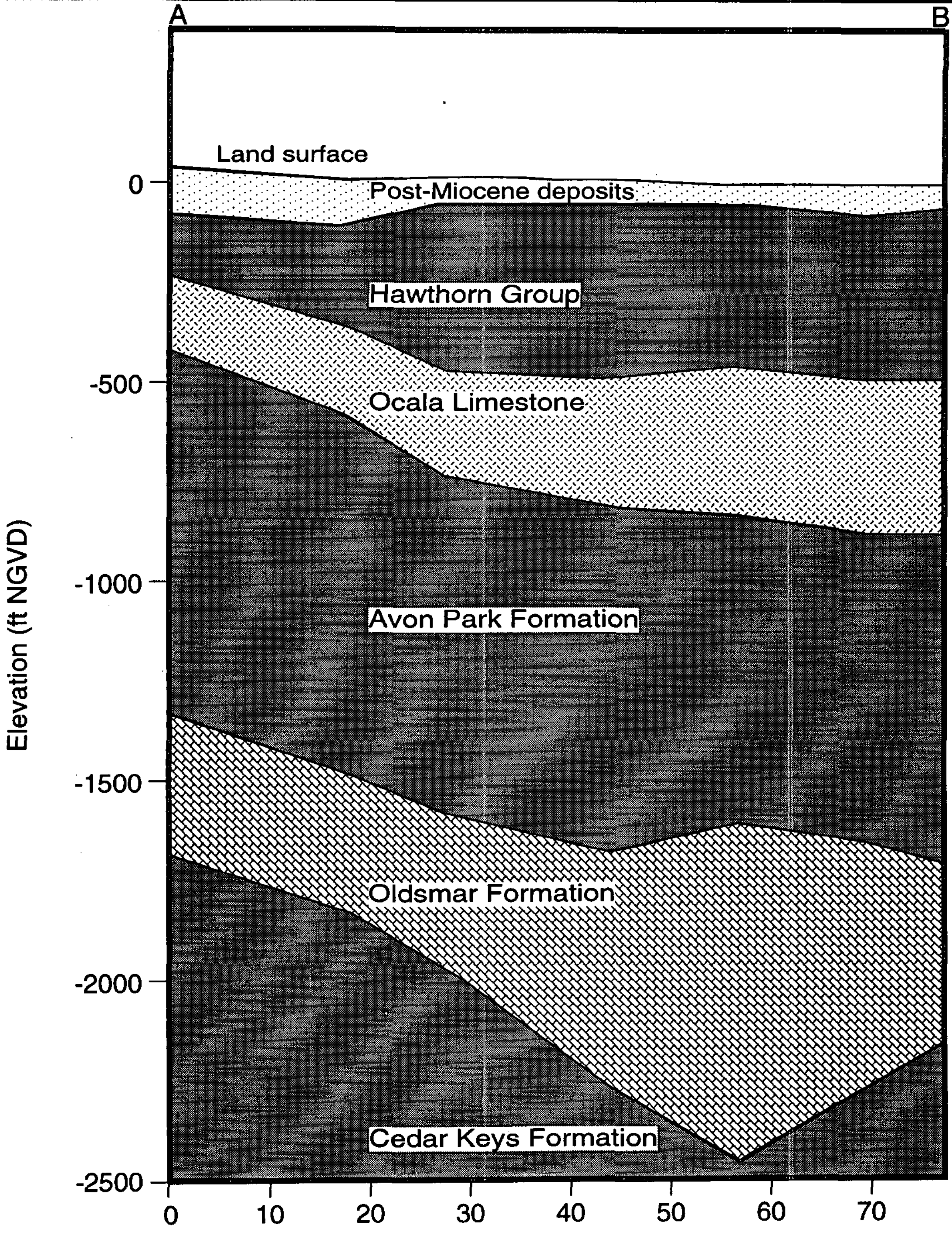


Figure 2. Generalized geologic cross-section A-B (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

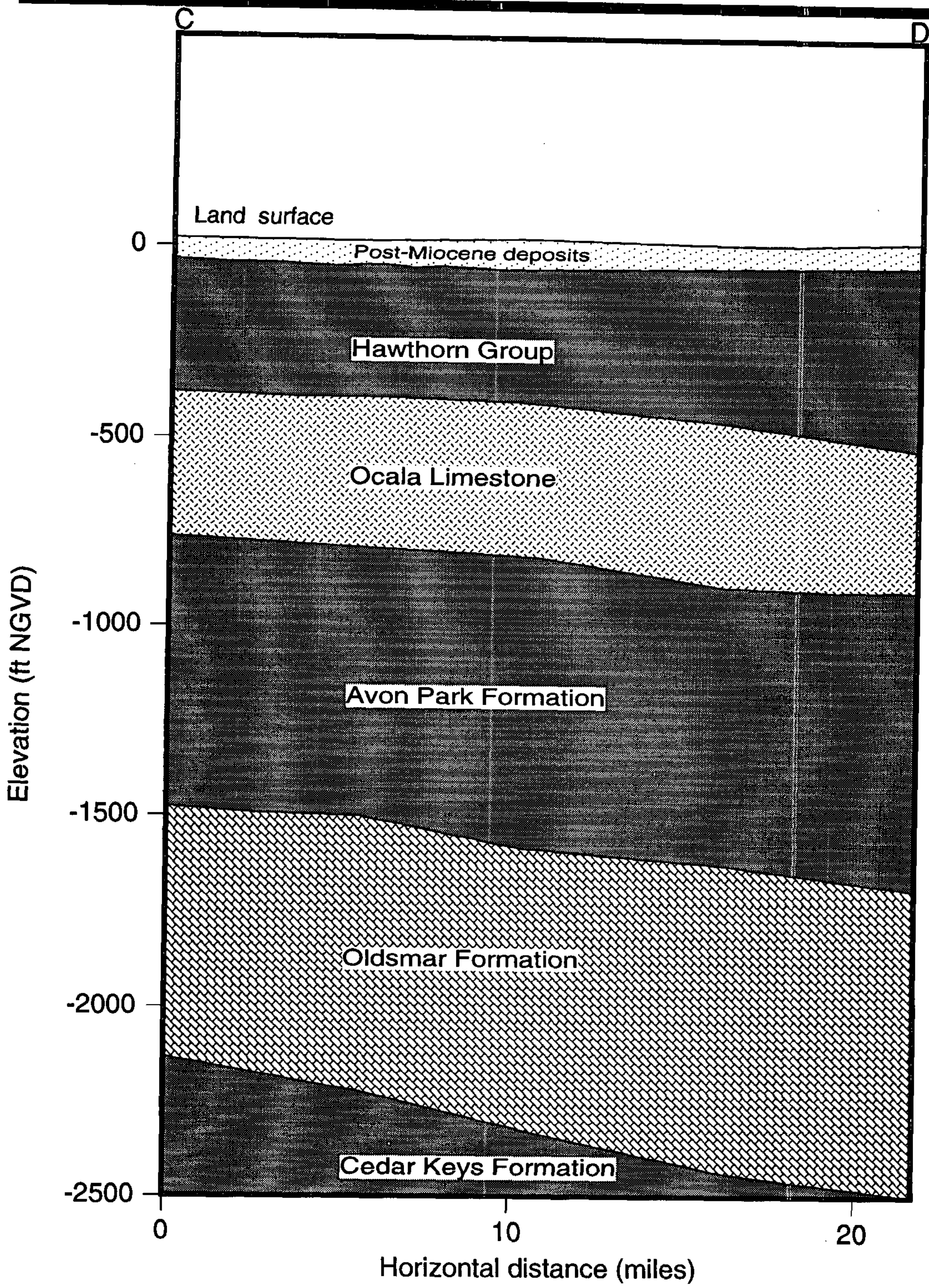


Figure 3. Generalized geologic cross-section C-D (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

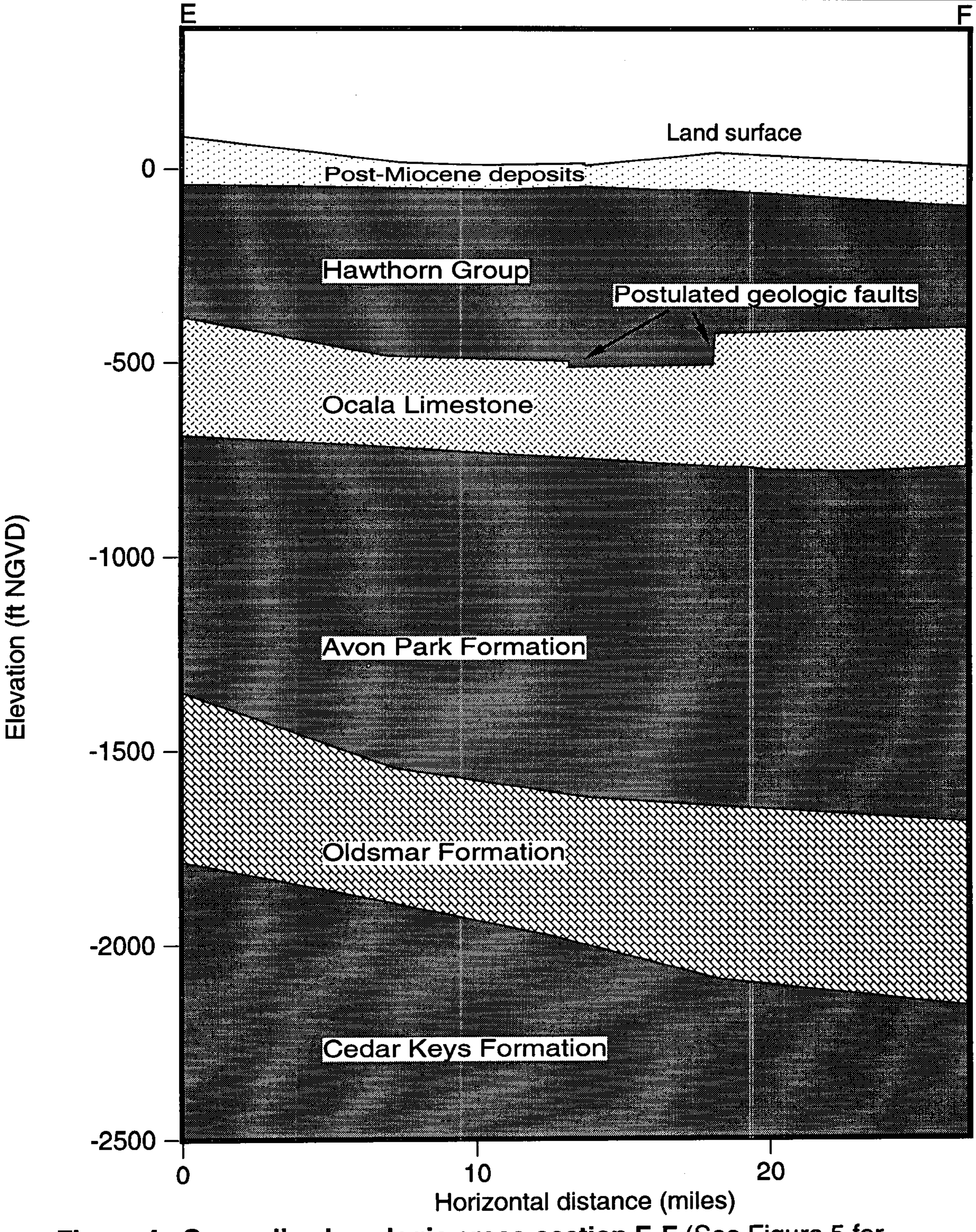


Figure 4. Generalized geologic cross-section E-F (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

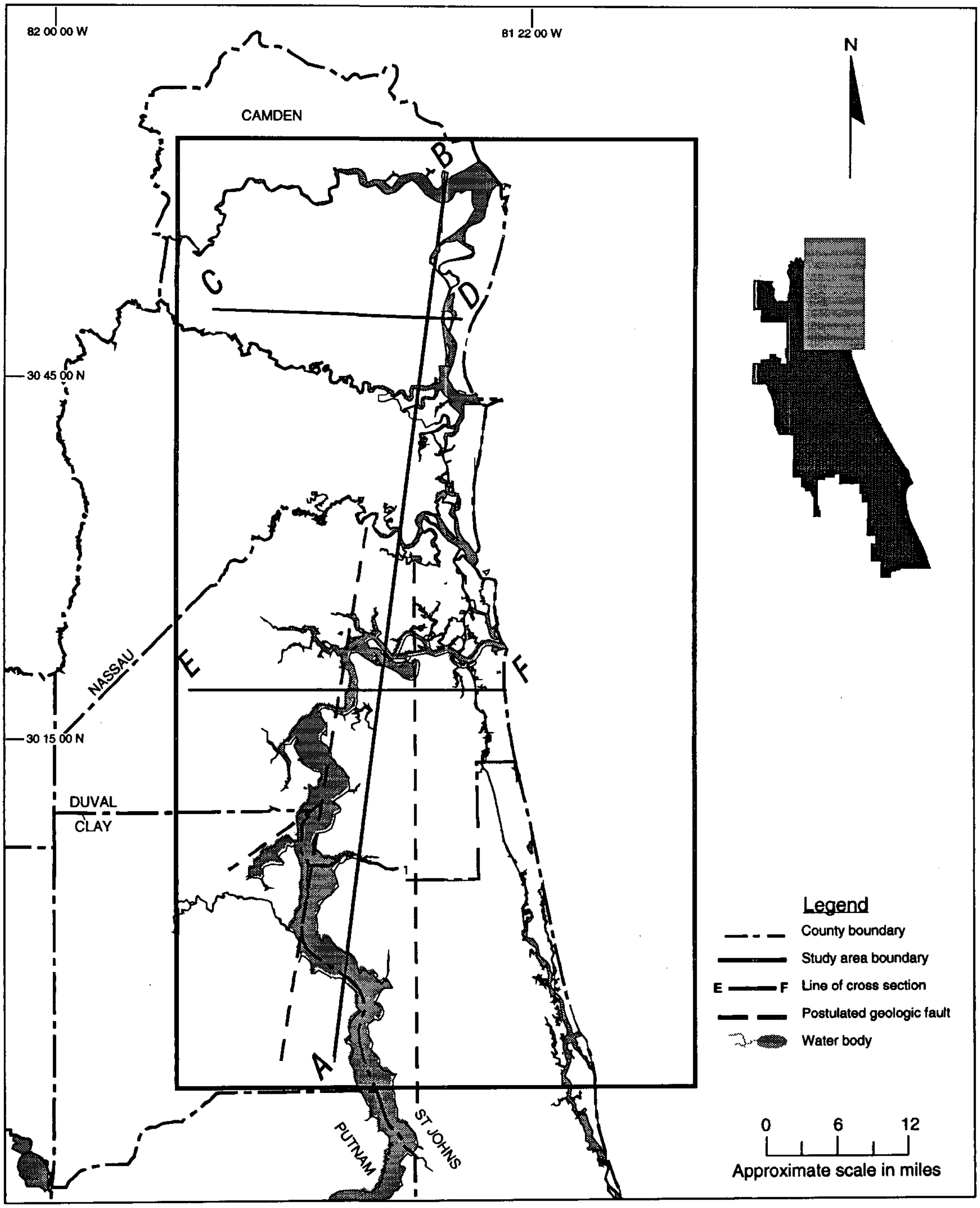


Figure 5. Locations of geologic cross sections and postulated faults in the Ocala limestone

Table 3. Time of various geologic ages before present

Geologic Epoch	Time Before Present (years x 10^6)
Pleistocene and Recent	0.011 to 1.5
Pliocene	1.5 to 12
Miocene	12 to 20
Oligocene	20 to 35
Eocene	35 to 55
Paleocene	55 to 65

Source: Batten 1987

PRE-HAWTHORN TERTIARY CARBONATE UNITS

The pre-Hawthorn Tertiary carbonate units within the study area are composed primarily of interbedded limestone and dolomite and have been differentiated stratigraphically by age (Miller 1986). These units include the Cedar Keys Formation of Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, and the Ocala Limestone of late Eocene age (Miller 1986).

Paleocene Series

The rocks of Paleocene age within the study area are referred to as the Cedar Keys Formation. The Cedar Keys Formation consists predominantly of interbedded dolomite and anhydrite. Extensive, relatively impermeable anhydrite beds occur at the base of the upper third of this formation and are recognized as the base of the Floridan aquifer system (Miller 1986).

The elevation of the surface of the Cedar Keys Formation ranges from approximately 1,600 to 2,500 feet below National Geodetic Vertical Datum (ft bNGVD) within the study area (Miller 1986). Little information is available concerning the total thickness of the Cedar Keys Formation.

Eocene Series

Early Eocene Rocks. The rocks of early Eocene age are referred to as the Oldsmar Formation. The Oldsmar Formation is composed primarily of interbedded limestone and dolomite (Miller 1986). The beds vary considerably in thickness and commonly contain cavities. The lower part of the Oldsmar Formation contains gypsum and thin beds of anhydrite, and it is usually more extensively dolomitized than the upper part. The Oldsmar Formation is designated a formation rather than a limestone due to the presence of significant amounts of dolomite, anhydrite, and other rock types, in addition to limestone (Miller 1986).

The elevation of the surface of the Oldsmar Formation ranges from approximately 1,200 to 1,800 ft bNGVD within the study area. The thickness of the Oldsmar Formation ranges from approximately 400 to more than 800 ft (Miller 1986).

Middle Eocene Rocks. The rocks of middle Eocene age are referred to as the Avon Park Formation (Miller 1986). The Avon Park Formation is composed of limestone of highly variable hardness interbedded with dolomite. The dolomite occasionally contains cavities and fractures (Miller 1986). Because the Avon Park Formation is composed almost entirely of dolomite in many places, it, too, is designated a formation rather than a limestone (Miller 1986).

The elevation of the surface of the Avon Park Formation ranges from approximately 400 to 1,000 ft bNGVD within the study area. The thickness of the Avon Park Formation ranges from approximately 700 to 1,100 ft (Miller 1986.)

Late Eocene Rocks. The rocks of late Eocene age are referred to as the Ocala Limestone. The Ocala Limestone consists of two parts, an upper and a lower member (Miller 1986). The upper member is a soft, porous coquina composed of shells and other marine fossils loosely bound within a limestone matrix. The lower member consists of fine-grained limestone of variable hardness that contains an abundance of marine fossils. In places, the lower member contains variable amounts of dolomite (Miller 1986).

The surface of the Ocala Limestone is often marked locally with irregularities that were formed as a result of limestone dissolution (Miller 1986). The dissolution of the limestone has enhanced its primary porosity (Miller 1986). The existence within the study area of two relatively large faults and one relatively small fault in the Ocala Limestone has been postulated (Miller 1986) (Figure 5).

The westernmost of the two relatively large faults runs from north-central Duval County to southeast Clay County. The relatively short fault branches from this larger fault in a northeast-southwest direction. The easternmost fault runs from the area of north-central Duval County to southwest St. Johns County. The surface of the Ocala Limestone is displaced vertically at these faults by 50 to 100 ft (Miller 1986). The existence of these faults has not been confirmed; other interpretations of the geologic data have been made.

The elevation of the surface of the Ocala Limestone ranges from approximately 200 to 500 ft bNGVD within the study area. The thickness of the Ocala Limestone ranges from approximately 200 to 400 ft (Miller 1986).

HAWTHORN GROUP

The Hawthorn Group (of middle Miocene age) overlies the rocks of Eocene age (Scott 1983). In Clay, St. Johns, Duval, and Nassau counties, Florida, the Hawthorn Group has been differentiated into the Penney Farms, Marks Head, and Coosawhatchie formations, in ascending order (Scott 1988). In Camden County, Georgia, the Hawthorn Group has been differentiated into the Parachucla, Marks

Head, and Coosawhatchie formations, also in ascending order (Huddlestun 1988).

In general, the Hawthorn Group consists of widely varying mixtures of clay, quartz sand, carbonate, and phosphate (Scott 1983). Phosphate is present within the Hawthorn Group virtually throughout its areal extent (Scott 1983). Dolomite, the most common form of the carbonate component, is distributed within the Hawthorn Group in significant amounts throughout most of the study area, as are clay and sand (Scott 1983). The relatively low permeability of the Hawthorn Group is attributed to its heterogeneity and the fine texture of its constituents, both clastic and carbonate (Miller 1986).

The elevation of the surface of the Hawthorn Group ranges from approximately 0 to more than 100 ft bNGVD within the study area. The thickness of the Hawthorn Group ranges from approximately 100 to 400 ft (Miller 1986).

POST-MIOCENE DEPOSITS

The post-Miocene deposits within the study area include the Pliocene, Pleistocene, and Recent deposits. The surface of the post-Miocene deposits is the land surface, the elevation of which ranges from 0 to 120 ft above NGVD within the study area. The total thickness of the post-Miocene deposits ranges from 50 to more than 100 ft (Miller 1986).

Pliocene Deposits

Typically, the Pliocene deposits within the study area contain clay, clayey sand, sand, shells, and/or carbonate rocks (Bermes et al. 1963; Leve 1966; Miller 1986; Clarke et al. 1990). In northeast Florida, these deposits are often differentiated from the Hawthorn Group by the absence or near-absence of phosphate (Leve 1966). A typical well log of Pliocene deposits in Duval County consists of three general sections: (1) an upper section of clayey sand and sandy clay, (2) a middle section of sandy clay and shell, and (3) a lower section of interbedded sandy clay, clay, and soft, porous limestone (Fairchild 1972).

Often, the contact between the Pliocene deposits and underlying Hawthorn Group is marked by an unconformity consisting of coarse sands and phosphates. A definite marker for the upper limit of the Pliocene deposits often does not exist. In such cases, the Pliocene deposits grade into the overlying Pleistocene and Recent deposits (Leve 1966).

Pleistocene and Recent Deposits

Pleistocene and Recent deposits blanket the study area. These deposits generally contain fine- to coarse-grained loose sand, clayey sand, sandy clay, marl, shell, and clay. Beds within the Pleistocene and Recent deposits are usually not extensive and may vary much in lithology and texture over short distances, both horizontally and vertically (Bermes et al. 1963; Fairchild 1972).

GROUND WATER HYDROLOGY

The ground water system within the study area consists of a surficial aquifer system, an intermediate aquifer system, and the Floridan aquifer system (Table 4; Figures 6-8). The surficial aquifer system is the uppermost aquifer system within the study area and is generally under nonartesian conditions. The intermediate aquifer system is a system of discontinuous, relatively thin, confined aquifers found within the Hawthorn Group and in Pliocene deposits above the Hawthorn Group. The Floridan aquifer system is a system of alternating aquifers and semiconfining units that consist primarily of limestone and dolomite.

The Floridan aquifer system is separated internally into three permeable zones by middle and lower semiconfining units (Brown 1984; Krause and Randolph 1989; Toth 1990). The Floridan aquifer system is separated from the overlying surficial aquifer system by the upper confining unit. The upper confining unit consists of the Hawthorn Group and, in much of the study area, the Pliocene deposits above the Hawthorn Group (Miller 1986). The Floridan aquifer system is bounded at its base by the lower confining unit, which consists of extensive beds of low-permeability anhydrite (Miller 1986).

HYDROGEOLOGIC FRAMEWORK

Surficial Aquifer System

The surficial aquifer system consists primarily of sand, clayey sand, shell, and thin limestone beds of the post-Miocene deposits (Clark et al. 1964; Bermes et al. 1983; Clarke et al. 1990). In much of the study area, the surficial aquifer system is divided by a semiconfining unit into upper and lower permeable zones. The upper permeable zone is called the water table zone; it exists generally under nonartesian conditions. The lower permeable zone is called the shallow-rock zone (Causey and Phelps 1978; Franks 1980; Hayes 1981; Spechler and Stone 1983; Brown 1984; Spechler and Hampson 1984; and Clarke et al. 1990). At many locations in the study area,

Table 4. Summary of ground water systems within the study area

<table>
<tr><th>Geologic Epoch</th><th>Geologic Unit</th><th colspan="2">Hydrologic Unit</th><th>Description</th></tr>
<tr><td>Pleistocene and Recent</td><td>Pleistocene and Recent deposits</td><td colspan="2" rowspan="2">Surficial aquifer system</td><td rowspan="2">Consists of sand, clayey sand, shell, and thin limestone beds, and is divided into an upper, water table zone and a lower, shallow-rock zone, which are separated by a semiconfining unit. Thickness of the surficial aquifer system ranges approximately from 20 to 150 feet (ft).</td></tr>
<tr><td rowspan="2">Pliocene</td><td rowspan="2">Pliocene deposits</td></tr>
<tr><td colspan="2" rowspan="2">Upper confining unit, including the intermediate aquifer system</td><td rowspan="2">Upper confining unit consists of clay, marl, and discontinuous beds of sand, shell, dolomite, and limestone (aquifers of intermediate aquifer system). Confines intermediate aquifer system and underlying Floridan aquifer system. Thickness ranges approximately from 150 to 450 ft. Aquifers of intermediate aquifer system are up to 40 ft thick.</td></tr>
<tr><td>Middle Miocene</td><td>Hawthorn Group</td></tr>
<tr><td>Late Eocene</td><td>Ocala Limestone</td><td rowspan="2">Upper Floridan aquifer</td><td rowspan="8">FLORIDAN AQUIFER SYSTEM</td><td rowspan="2">Consists primarily of limestone. Thickness ranges approximately from 300 to 700 ft.</td></tr>
<tr><td rowspan="3">Middle Eocene</td><td rowspan="3">Avon Park Formation</td></tr>
<tr><td>Middle semi-confining unit</td><td>Consists primarily of limestone and dolomite. Thickness ranges approximately from 50 to 300 ft.</td></tr>
<tr><td rowspan="2">Lower Floridan aquifer</td><td rowspan="2">Consists primarily of limestone and dolomite. Thickness ranges approximately from 400 to 1,000 ft.</td></tr>
<tr><td rowspan="3">Early Eocene</td><td rowspan="3">Oldsmar Formation</td></tr>
<tr><td>Lower semi-confining unit</td><td>Consists primarily of limestone and dolomite. Thickness ranges approximately from 100 to 200 ft.</td></tr>
<tr><td rowspan="2">Fernandina permeable zone</td><td rowspan="2">Consists primarily of limestone and dolomite. Thickness ranges approximately from 170 to 1,000 ft.</td></tr>
<tr><td rowspan="2">Paleocene</td><td rowspan="2">Cedar Keys Formation</td></tr>
<tr><td colspan="2">Lower confining unit</td><td>Consists of low-permeability anhydrite beds. Thickness is unknown.</td></tr>
</table>

Source: Bermes et al. 1963; Clark et al. 1964; Leve 1966; Fairchild 1972; Scott 1983; Miller 1986; Clarke et al. 1990

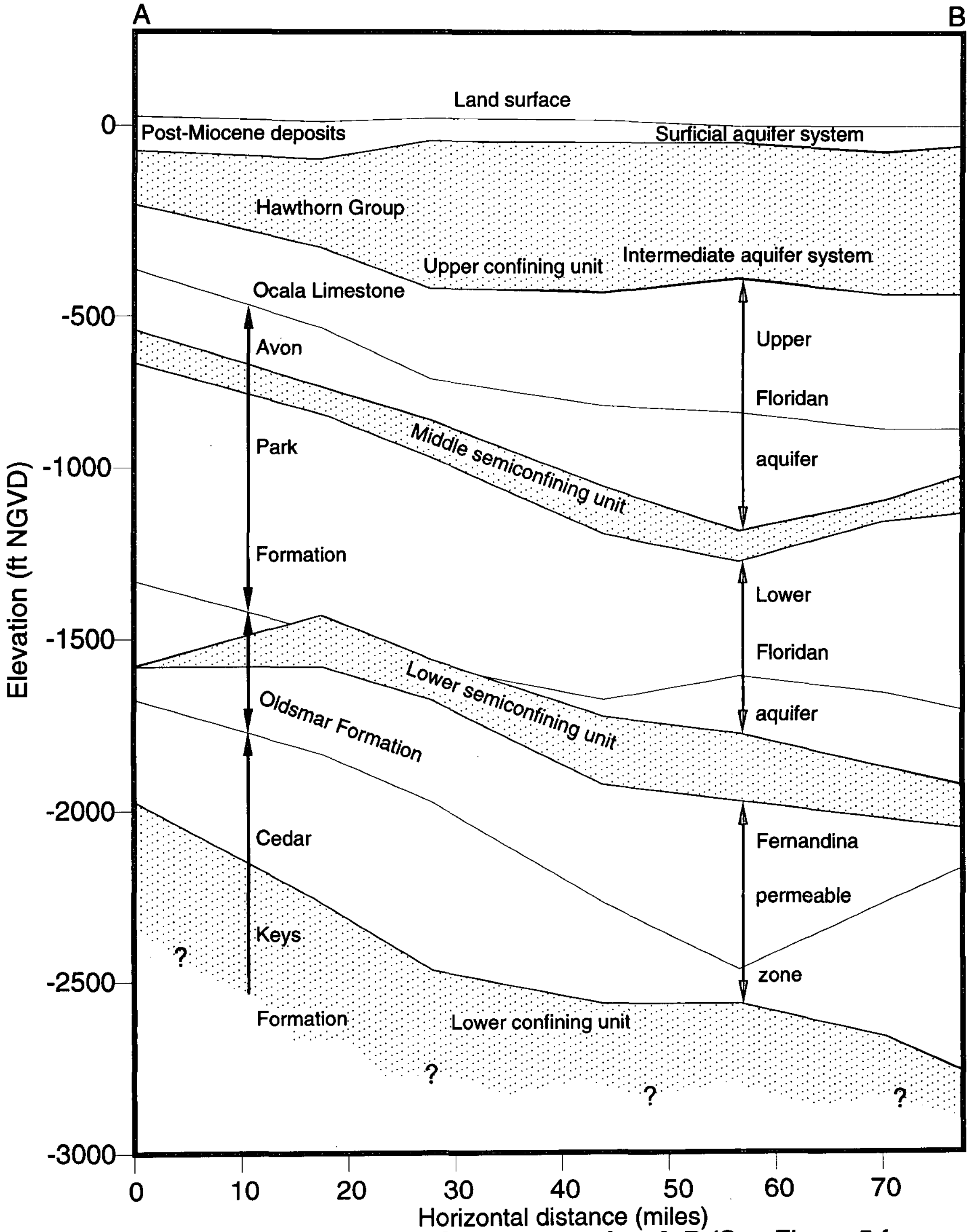


Figure 6. Generalized hydrogeologic cross-section A-B (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

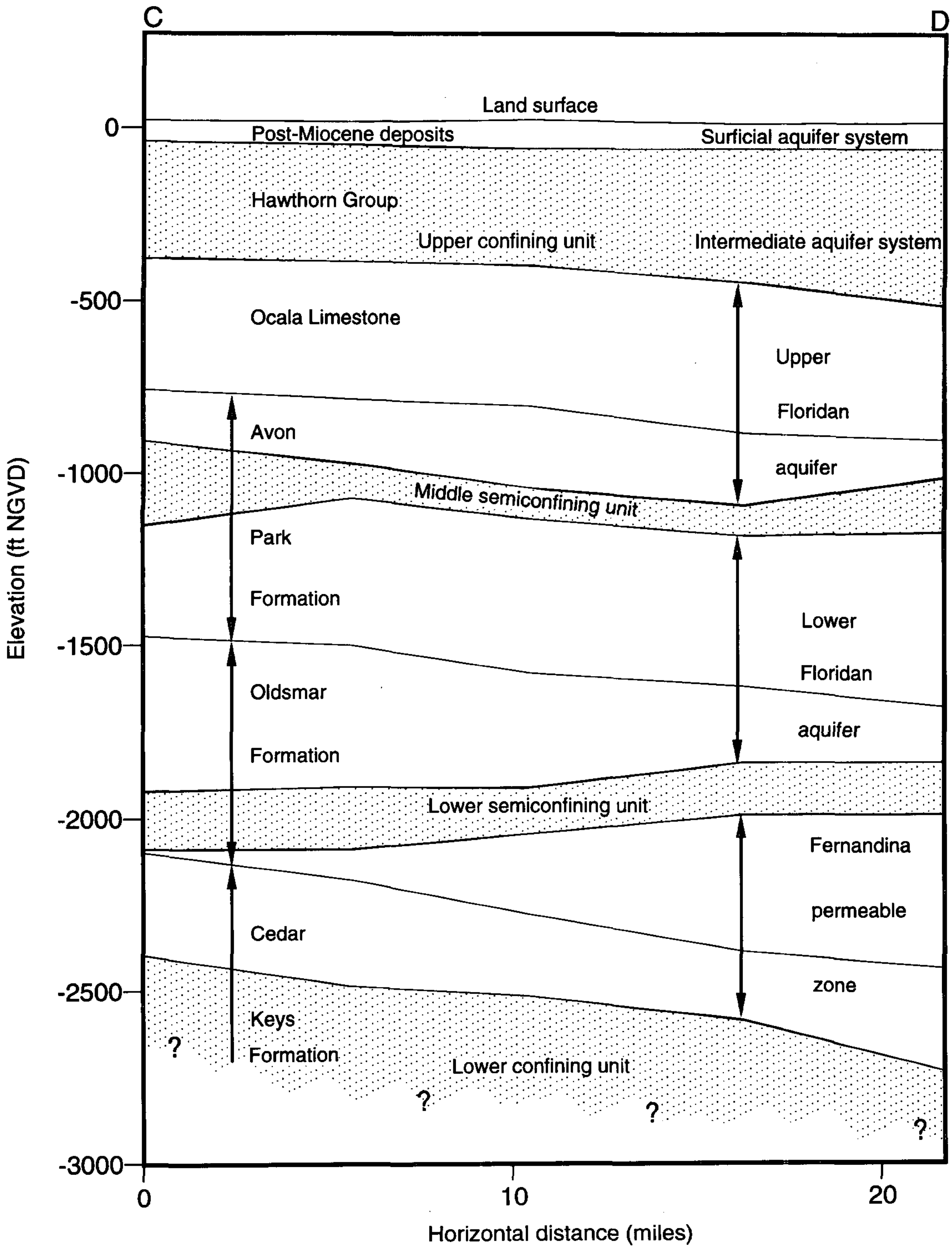


Figure 7. Generalized hydrogeologic cross-section C-D (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

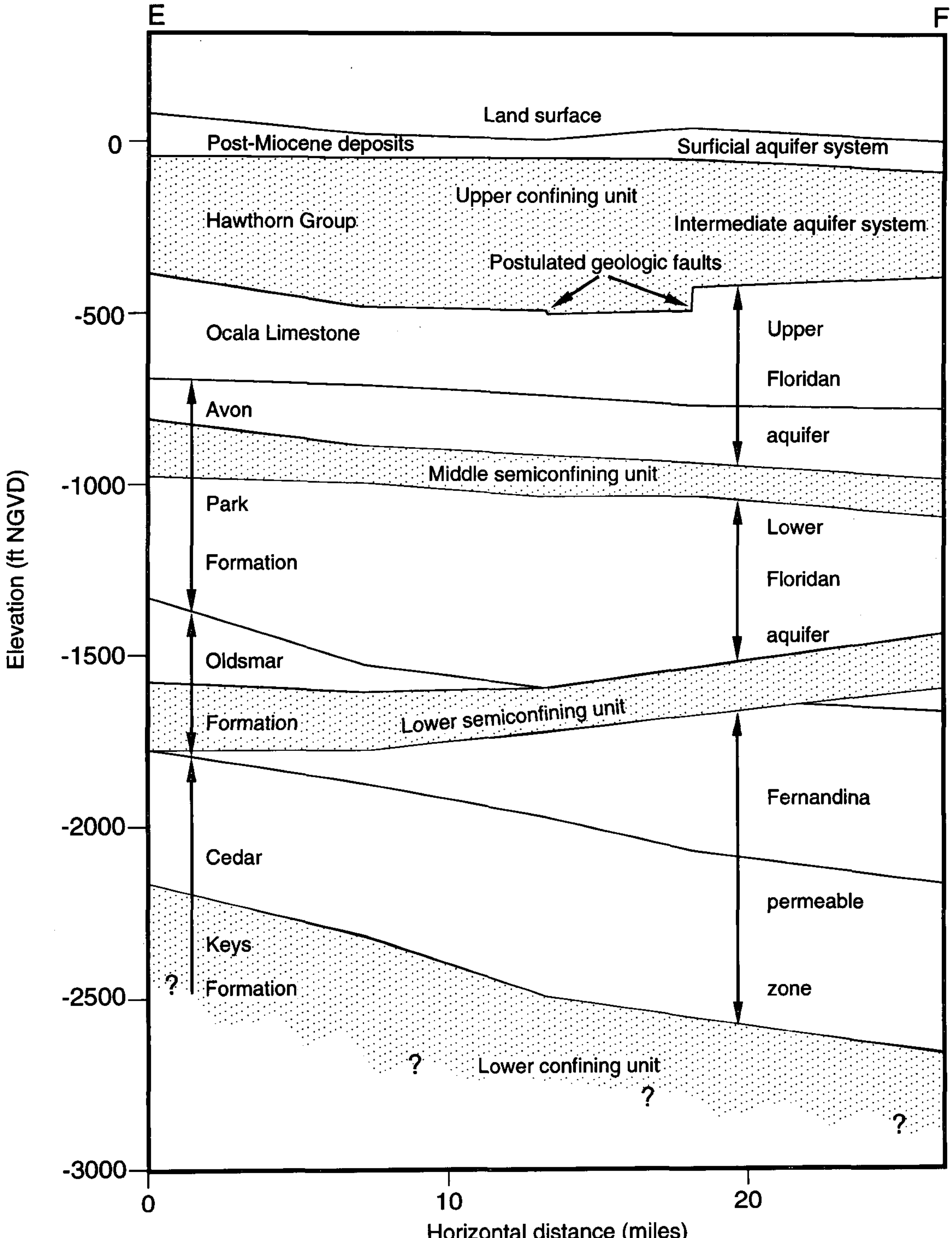


Figure 8. Generalized hydrogeologic cross-section E-F (See Figure 5 for location of cross section) (modified from Miller 1986 and pers. com. 1991)

such as Mayport (Figure 1), the surficial aquifer system functions as a single permeable unit (Franks 1980).

The depth below land surface to the water table ranges from approximately 0 to 20 ft at most locations within the study area. The depth to the water table increases generally with increasing land surface elevation (Clark et al. 1964; Causey 1975; Hayes 1981). As a result, the water table is generally a "subdued replica of the configuration of the land surface" (Miller 1986, B41). The saturated thickness of the surficial aquifer system is not known precisely at most locations within the study area, but it is often as much as 100 ft or more (Brown 1984; Hayes 1981; Spechler and Stone 1983).

Intermediate Aquifer System

The intermediate aquifer system consists principally of discontinuous carbonate, shell, and sand beds in the Hawthorn Group and the Pliocene deposits above the Hawthorn Group (Bermes et al. 1963) that are sufficiently transmissive to be considered aquifers. The degree of hydraulic connection between the intermediate aquifer system and the surficial aquifer system varies, often depending on the depth of the aquifers of the intermediate aquifer system (Bermes et al. 1963). The fluctuations of the potentiometric surfaces of the deeper aquifers of the intermediate aquifer system tend to correlate more closely with the potentiometric surface of the underlying Floridan aquifer system than with the water table of the surficial aquifer system. The fluctuations of the potentiometric surfaces of the more shallow aquifers of the intermediate aquifer system tend to correlate more closely with the water table than with the potentiometric surface of the underlying Floridan aquifer system (Clark et al. 1964).

The elevations of the top surfaces of the aquifers of the intermediate aquifer system range from approximately 10 to 300 ft bNGVD. The thicknesses of the aquifers of the intermediate aquifer system range generally from less than 1 ft to 40 ft or more (Bermes et al. 1963; Leve 1966; Clarke et al. 1990).

Upper Confining Unit

The upper confining unit of the Floridan aquifer system consists of deposits of clay, sand, sandy clay, clayey sand, marl, limestone, and carbonate of the Hawthorn Group and Pliocene deposits above the Hawthorn Group (Leve 1966). The effectiveness of the upper confining unit depends largely on its thickness; its local lithology, which often varies considerably over short distances; and the presence or absence of breaches due to karst features in the underlying limestone units of the Floridan aquifer system. Where the upper confining unit is thick and/or contains much clay, leakage is much less than where it is thin and/or sandy (Miller 1986).

Generally, the thickness of the upper confining unit increases from south to north within the study area and ranges from approximately 150 ft in southern Clay and central St. Johns counties to a maximum of more than 450 ft throughout large areas of Duval and northern Camden counties (Miller 1986). The clay content of the Hawthorn Group, which is the primary component of the upper confining unit, generally decreases from south to north in the study area. In the southern part of the study area, clays account for 10 to more than 40% of the constituents of the Hawthorn Group (Scott 1983). In the northern part, clays generally account for 10% or less of the constituents of the Hawthorn Group (Scott 1983).

Floridan Aquifer System

The Floridan aquifer system of the study area consists of the Ocala Limestone of late Eocene age, the Avon Park Formation of middle Eocene age, the Oldsmar Formation of early Eocene age, and the Cedar Keys Formation of Paleocene age (Miller 1986). Vertically alternating, areally extensive zones of high and low permeability have been delineated from the interbedded layers of limestone, dolomite, and other rock types that make up these units. The zones of high permeability function as aquifers, while the zones of low permeability function as semiconfining units. The semiconfining units restrict the vertical movement of water between the high-permeability zones (Leve 1966).

Within the study area, the Floridan aquifer system has been differentiated into three aquifers separated by two semiconfining units (Brown 1984; Krause and Randolph 1989; Toth 1990). These units are, from top to bottom, the Upper Floridan aquifer, the middle semiconfining unit (MSCU), the Lower Floridan aquifer, the lower semiconfining unit (LSCU), and the Fernandina permeable zone (Krause and Randolph 1989) (Table 4; Figures 6–8). In the local lexicon, the three aquifers are referred to often as the upper, middle, and lower permeable zones, respectively. The upper and lower boundaries of these units do not coincide necessarily with the boundaries of time-stratigraphic units or rock types, because the differentiation of the units is based on vertical variations in permeability (Miller 1986).

Upper Floridan Aquifer. The zone of high permeability that extends from the top of the Ocala Limestone through the upper third or so of the Avon Park Formation is called the Upper Floridan aquifer. The relatively high permeability of the Upper Floridan aquifer is attributed to the combination of high primary and secondary porosity in the limestone of which it is composed (Miller 1986). The relatively high degree of secondary porosity is attributed to the formation of dissolution cavities (Miller 1986).

The top surface elevation of the Upper Floridan aquifer ranges from approximately 200 ft bNGVD in southern Clay County to 500 ft bNGVD in central Duval and northeastern Camden counties. Generally, the thickness of the Upper Floridan aquifer increases from west to east within the study area and ranges from approximately 300 to 700 ft (Miller 1986).

Middle Semiconfining Unit. MSCU is composed mainly of beds of relatively low-permeability limestone and dolomite. MSCU is located generally in the upper half of the Avon Park Formation. Faults and fractures are thought to exist in MSCU in the coastal areas of northeastern Florida and southeastern Georgia. The vertical conductivity of MSCU is enhanced greatly where such features are present (Krause and Randolph 1989).

Generally, the elevation of the surface of MSCU decreases from west to east within the study area and ranges from approximately 500 to more than 1,200 ft bNGVD. The thickness of MSCU ranges from approximately 50 to 300 ft (Miller 1986).

Lower Floridan Aquifer. The Lower Floridan aquifer extends from the lower half of the Avon Park Formation into the Oldsmar Formation throughout most of the study area. In the coastal areas of Nassau and Duval counties, the Lower Floridan aquifer is found mainly within the Avon Park Formation (Miller 1986 and pers. com. 1991).

Generally, the elevation of the top surface of the Lower Floridan aquifer decreases from west to east within the study area, ranging from approximately 650 to more than 1,300 ft bNGVD (Miller 1986). In most of the study area, the thickness of the Lower Floridan aquifer ranges from approximately 400 to 1,000 ft. In coastal Nassau and Duval counties, the Lower Floridan aquifer thins, ranging from approximately 350 to 450 ft thick (Miller 1986 and pers. com. 1991). In western Duval County, the thickness of the Lower Floridan aquifer ranges from approximately 550 to 650 ft (Miller 1986 and pers. com. 1991).

Lower Semiconfining Unit. Like MSCU, LSCU is composed mainly of beds of relatively low-permeability limestone and dolomite. At many locations within the study area, LSCU is found entirely within the Oldsmar Formation. In some areas, the top of LSCU is in the Oldsmar Formation, while its bottom is in the Cedar Keys Formation (Miller 1986 and pers. com. 1991). In parts of coastal Duval County, the top of LSCU is within the Avon Park Formation, and the bottom is in the Oldsmar Formation (Miller 1986 and pers. com. 1991).

The elevation of the top surface of LSCU is quite variable. In Clay and Duval counties, the surface elevation ranges from approximately 1,500 to 1,750 ft bNGVD (J.A. Miller, pers. com. 1991). In Nassau and Camden counties, the surface elevation ranges from approximately 1,750 to 2,000 ft bNGVD. The thickness of LSCU is known at only a few locations within the study area. Generally, the thickness of LSCU ranges from 100 to 200 ft (Miller 1986 and pers. com. 1991).

Fernandina Permeable Zone. The top of the Fernandina permeable zone is generally in the Oldsmar Formation but is sometimes found in the Cedar Keys Formation. The bottom of the Fernandina permeable zone is within the Cedar Keys Formation (Miller 1986 and pers. com. 1991). The Fernandina permeable zone is locally cavernous (Miller 1986).

The elevation of the top surface of the Fernandina permeable zone ranges from approximately 1,600 to 2,200 ft bNGVD within the study area. Its thickness generally increases from west to east, ranging from approximately 170 ft in central Clay County to 1,000 ft along parts of the Atlantic coast (Miller 1986 and pers. com. 1991).

Lower Confining Unit

The lower confining unit of the Floridan aquifer system consists of thick anhydrite beds located at the base of the upper third of the Cedar Keys Formation. The elevation of the top surface of the lower confining unit of the Floridan aquifer system generally decreases from west to east within the study area and ranges from approximately 1,800 to 2,800 ft bNGVD. The thickness of the lower confining unit is unknown.

TOPOGRAPHY

Land surface topography is a primary factor in determining the configuration and position of the water table of the surficial aquifer system within the study area (Miller 1986; Durden and Motz 1991). The position of the water table relative to the potentiometric surface of the Upper Floridan aquifer is, in turn, a primary factor in determining rates of recharge to or discharge from the Floridan aquifer system. Thus, land surface topography significantly influences the flow within the Floridan aquifer system.

To facilitate a generalized discussion of the land surface topography within the study area, six topographic subregions were defined (Figure 9). Although the delineation of the boundaries of these subregions was somewhat subjective, the resulting areas are

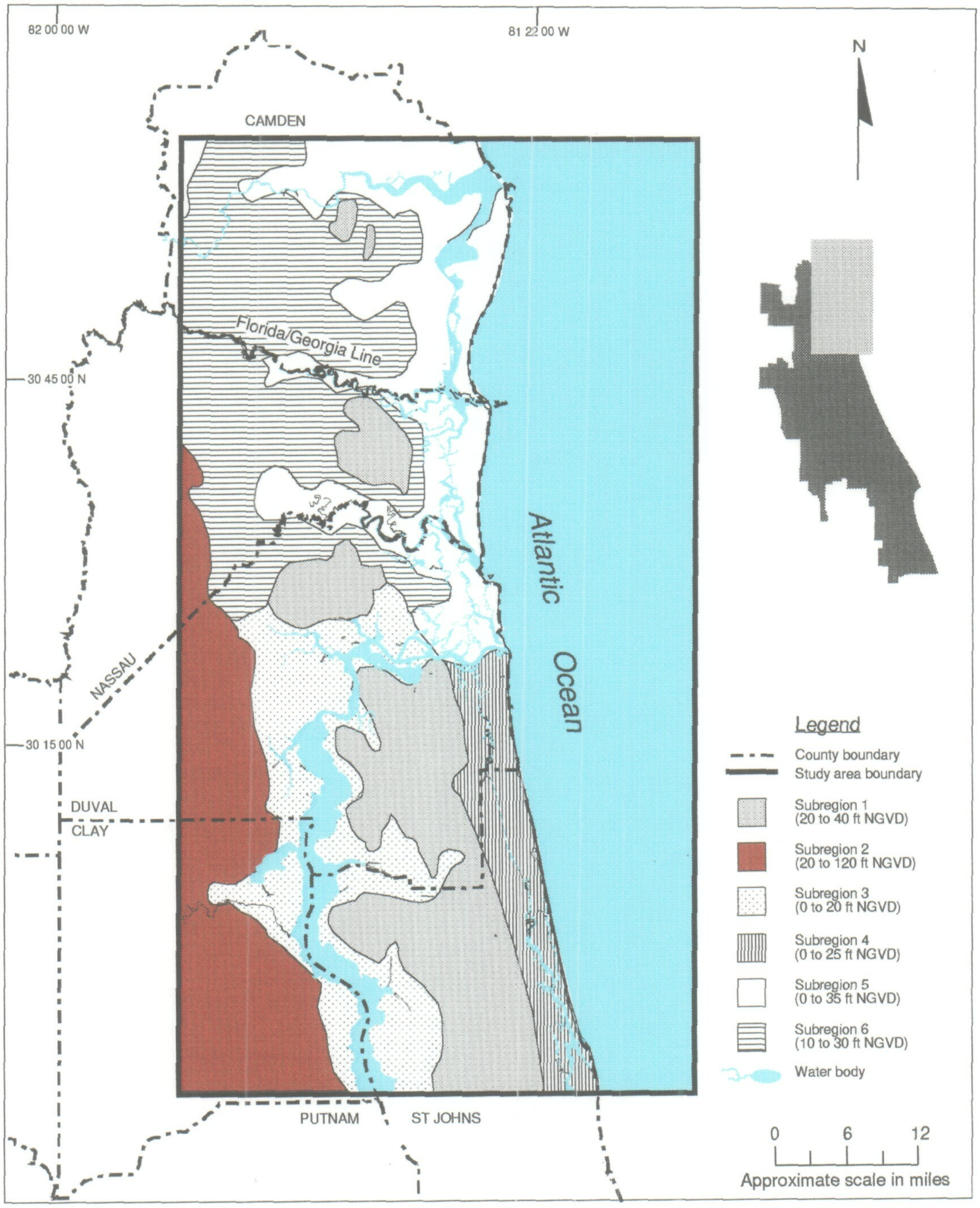


Figure 9. Subregions defined to facilitate the discussion of land-surface topography

generally distinguishable by one or more primary physiographic features.

Subregion one is an area of low to moderately high land surface elevation. The Atlantic Coastal Ridge in central St. Johns County and the Center Park Ridge in eastern Duval County (White 1970) are dominant physiographic features in this subregion (Figure 9). Several relatively small, isolated hills in eastern Nassau and Camden counties also attain moderately high land surface elevations; therefore, outliers of subregion one are shown in these counties as well. Land surface elevations in this subregion range generally from 20 to 40 ft NGVD, and swamps are common. At isolated locations in Duval and St. Johns counties, land surface elevations rise to more than 70 ft NGVD within subregion one.

Subregion two is the area encompassed by Florida's central highlands in the west, primarily in Duval and Clay counties (Figure 9). Land surface elevations in this subregion range generally from 20 to 120 ft NGVD. Deeply eroded stream valleys and steeply sloping hills are common physiographic features within this subregion.

Subregion three consists primarily of areas adjacent to the St. Johns River and its tributaries. Generally, the land surface slopes toward the St. Johns River throughout this subregion. The slope of the land surface in this subregion is relatively gentle along most of the south-north reach of the St. Johns River but is often relatively steep along the west-east reach, particularly along the southern bank of the river where subregion three is bounded by subregion one (Figure 9). The elevation of the land surface in this subregion is usually relatively low, ranging generally from 0 to 20 ft NGVD.

Subregion four lies between the Atlantic Coastal Ridge and the present Atlantic coast in St. Johns and Duval counties. This subregion is characterized primarily by low, swampy areas adjacent to the Intracoastal Waterway. Land surface elevations in areas adjacent to the Intracoastal Waterway range from approximately 0 to 10 ft NGVD. Farther east within this subregion, coastal dunes line the Atlantic coast, and land surface elevations are higher. Land surface elevations in this area range generally from 0 to 25 ft NGVD, or more.

Subregion five encompasses the eastern areas of Nassau and Camden counties and the northeastern area of Duval County within the study area. Most of this subregion is characterized by relatively flat or gently sloping land surfaces. The lack of relief results in extensive coastal marshlands and numerous meandering streams. Land surface elevations in these areas range generally from 0 to 10 ft NGVD. Also included in this subregion are areas of higher elevation and better drainage in the central parts of Amelia and Cumberland islands (Figures 1 and 9). Land surface elevations in these areas range from approximately 10 to 35 ft NGVD.

Subregion six encompasses the western areas of Nassau and Camden counties and northern Duval County. The land surface slopes moderately from west to east throughout most of this subregion. Drainage is generally better than that which occurs in the eastern, coastal areas of Nassau and Camden counties. Land surface elevations range generally from 10 to 30 ft NGVD throughout most of this subregion.

RECHARGE AND DISCHARGE

Surficial Aquifer System

Recharge to the surficial aquifer system within the study area occurs chiefly as downward percolation of rainfall to the water table (Clark et al. 1964). Throughout most of the study area, recharge to the surficial aquifer system occurs also as a result of upward leakage from underlying artesian aquifers (Phelps 1984). Discharge from the surficial aquifer system occurs primarily by evapotranspiration, seepage to streams, withdrawals from wells, and downward leakage to underlying artesian aquifers (Clark et al. 1964). Along the Atlantic coast, ground water from the surficial aquifer system also discharges to the Atlantic Ocean.

Intermediate Aquifer System

Recharge to the intermediate aquifer system within the study area occurs primarily as a result of leakage from either the underlying Floridan aquifer system or the overlying surficial aquifer system; discharge occurs primarily as leakage (Clark et al. 1964).

Floridan Aquifer System

The Floridan aquifer system within the study area is recharged primarily by inflow through the western boundary of the study area. In most of the study area, the potentiometric surface of the Upper Floridan aquifer is higher in elevation than the water table of the surficial aquifer system, resulting in an upward, vertical hydraulic gradient between the two systems. Thus, discharge from the Upper Floridan aquifer to the surficial aquifer system occurs in most areas (Phelps 1984; Clarke et al. 1990) (Figure 10). Withdrawal of water from wells is the other primary mode of discharge.

Recharge from the surficial aquifer system to the Floridan aquifer system occurs in some parts of the study area but is generally in small to moderate amounts (Phelps 1984). Recharge occurs naturally in many areas of relatively high land surface elevation. Within the study area, such areas are found west of the St. Johns River in Duval and Clay counties (Johnston, Krause et al. 1980; Phelps 1984) (Figure 10). Induced recharge to the Upper Floridan aquifer from the surficial aquifer system occurs where withdrawals from wells have resulted in the reversal of the original upward direction of the vertical hydraulic gradient between the Floridan and surficial aquifer systems. Such areas include parts of the Atlantic Coastal Ridge in St. Johns County, parts of the Center Park Ridge in Duval County, and the area of Fernandina Beach in Nassau County (Johnston, Krause et al. 1980; Phelps 1984; Clarke et al. 1990) (Figure 10).

HYDRAULIC CHARACTERISTICS

Estimates of the hydraulic parameters of the Floridan aquifer system, upper confining unit, and overlying surficial aquifer system vary throughout the study area. These estimates have been derived from

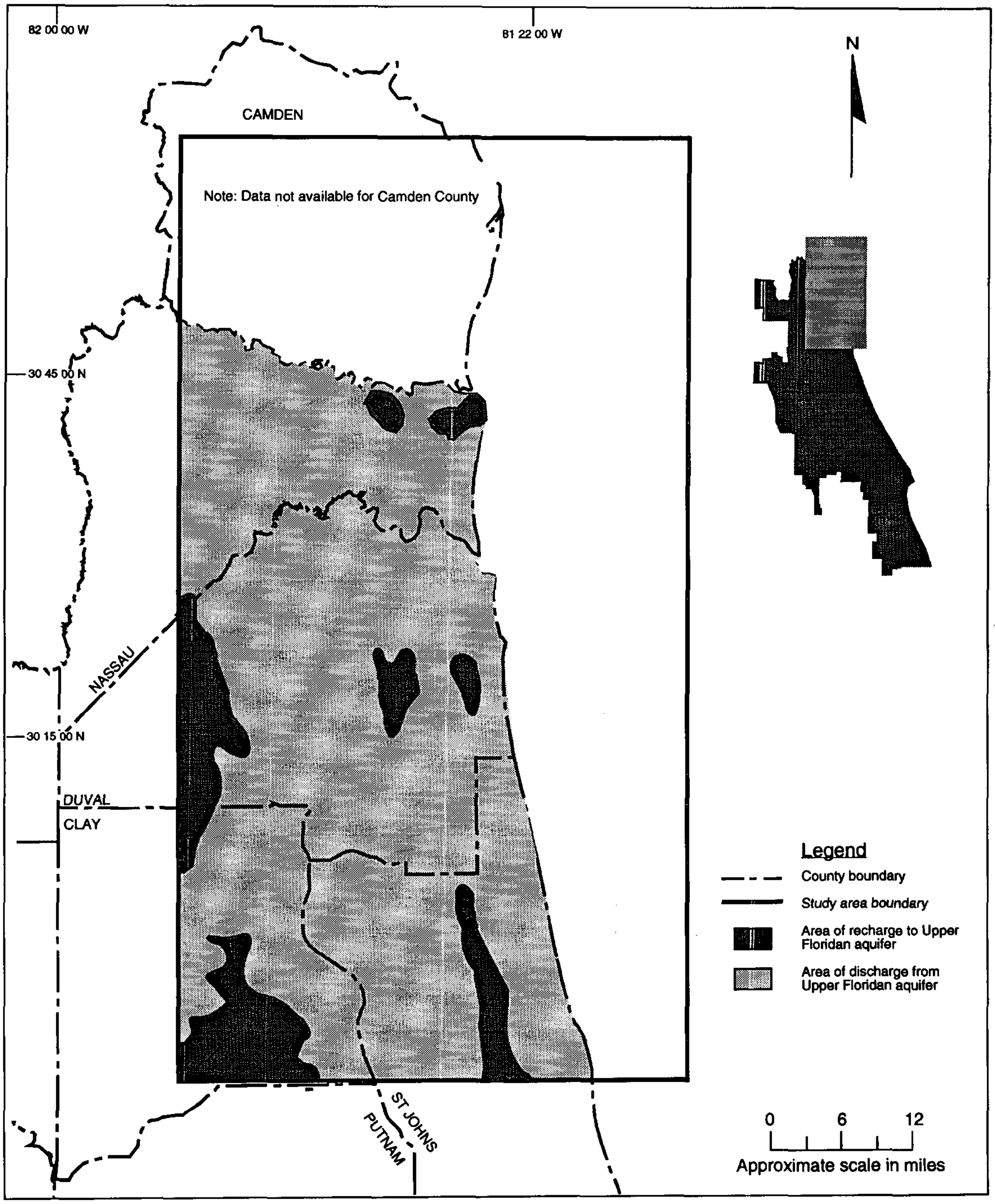


Figure 10. Areas of recharge to and discharge from the Upper Floridan aquifer (modified from Phelps 1984)

aquifer performance tests, permeameter tests of core samples, and numerical modeling studies. Few, if any, aquifer performance tests or permeameter tests have been performed exclusively on the hydrologic units beneath the Upper Floridan aquifer within the study area. Calibration of numerical models of the Floridan aquifer system has resulted in estimates of the hydraulic parameters of the Lower Floridan aquifer and MSCU. These estimates must be viewed cautiously, however, because few, if any, alternate forms of evaluation have been performed.

Transmissivity

Surficial Aquifer System. Relatively few aquifer performance tests have been performed on the surficial aquifer system within the study area, and the surficial aquifer system has not yet been simulated in a regional-scale numerical model. Therefore, estimates of the transmissivity of the surficial aquifer system exist for only a relatively small number of locations within the study area. Aquifer performance tests performed on the shallow-rock zone of the surficial aquifer system in Duval County resulted in estimates of transmissivity of approximately 1,300 square feet per day (ft^2/day) (Causey and Phelps 1978). The transmissivity of the surficial aquifer system is estimated to range from less than 100 to about 1,000 ft^2/day near Fernandina Beach in Nassau County (Brown 1984) and from 2,400 to 3,000 ft^2/day near Mayport in Duval County (Franks 1980). On the Atlantic Coastal Ridge west of St. Augustine in St. Johns County, the transmissivity of the surficial aquifer system is estimated to range from 6,500 to 7,000 ft^2/day (Hayes 1981).

Intermediate Aquifer System. Estimates of the transmissivity of the aquifers of the intermediate aquifer system are not available.

Upper Floridan Aquifer. Estimates of the transmissivity of the Upper Floridan aquifer within the study area have been derived from aquifer performance tests and numerical modeling studies. Krause and Randolph (1989) published estimates of transmissivity resulting from aquifer performance tests performed within the study area and vicinity, several of which were obtained from Bentley (1977,

1979) (Figure 11). These estimates range from 21,000 to 200,000 ft^2/day, with most being less than 50,000 ft^2/day.

Krause and Randolph (1989) also published estimates of the transmissivity of the Upper Floridan aquifer resulting from their calibration of a numerical ground water flow model that encompassed parts of southeast Georgia and northeast Florida, including the present study area. Their results indicate that the transmissivity of the Upper Floridan aquifer varies considerably within the study area but decreases generally from west to east. In Camden County, their results showed that the transmissivity of the Upper Floridan aquifer is generally in excess of 250,000 ft^2/day. In western Nassau, Duval, and northern Clay counties, the estimated transmissivity of the Upper Floridan aquifer ranges from approximately 100,000 to 250,000 ft^2/day. In northern St. Johns, southern Clay, and most of coastal Duval and Nassau counties, the resulting estimates of the transmissivity of the Upper Floridan aquifer range from approximately 50,000 to 100,000 ft^2/day. The transmissivity estimates of the Upper Floridan aquifer are lower in the vicinity of Fernandina Beach, Florida, and St. Marys, Georgia, ranging from approximately 25,000 to 50,000 ft^2/day.

Durden and Motz (1991) estimated transmissivity of the Upper Floridan aquifer in parts of Nassau, Duval, Clay, St. Johns, and Putnam counties as a result of a ground water modeling study. Estimates of transmissivity in central and western Nassau and northern Duval counties range from 300,000 to 450,000 ft^2/day. In most of Clay County within the present study area, the transmissivity estimates range from less than 50,000 to 200,000 ft^2/day. Along the coastal areas of St. Johns, Duval, and Nassau counties, estimates of transmissivity range generally from less than 50,000 to 100,000 ft^2/day; throughout most of St. Johns County, estimates of transmissivity range from 50,000 to 200,000 ft^2/day. Transmissivity estimates in the area of Fernandina Beach range from less than 50,000 to 100,000 ft^2/day.

Relatively low estimates of transmissivity of the Upper Floridan aquifer in the area of Fernandina Beach are supported by the results of several aquifer performance tests (Figure 11). Bentley (1979)

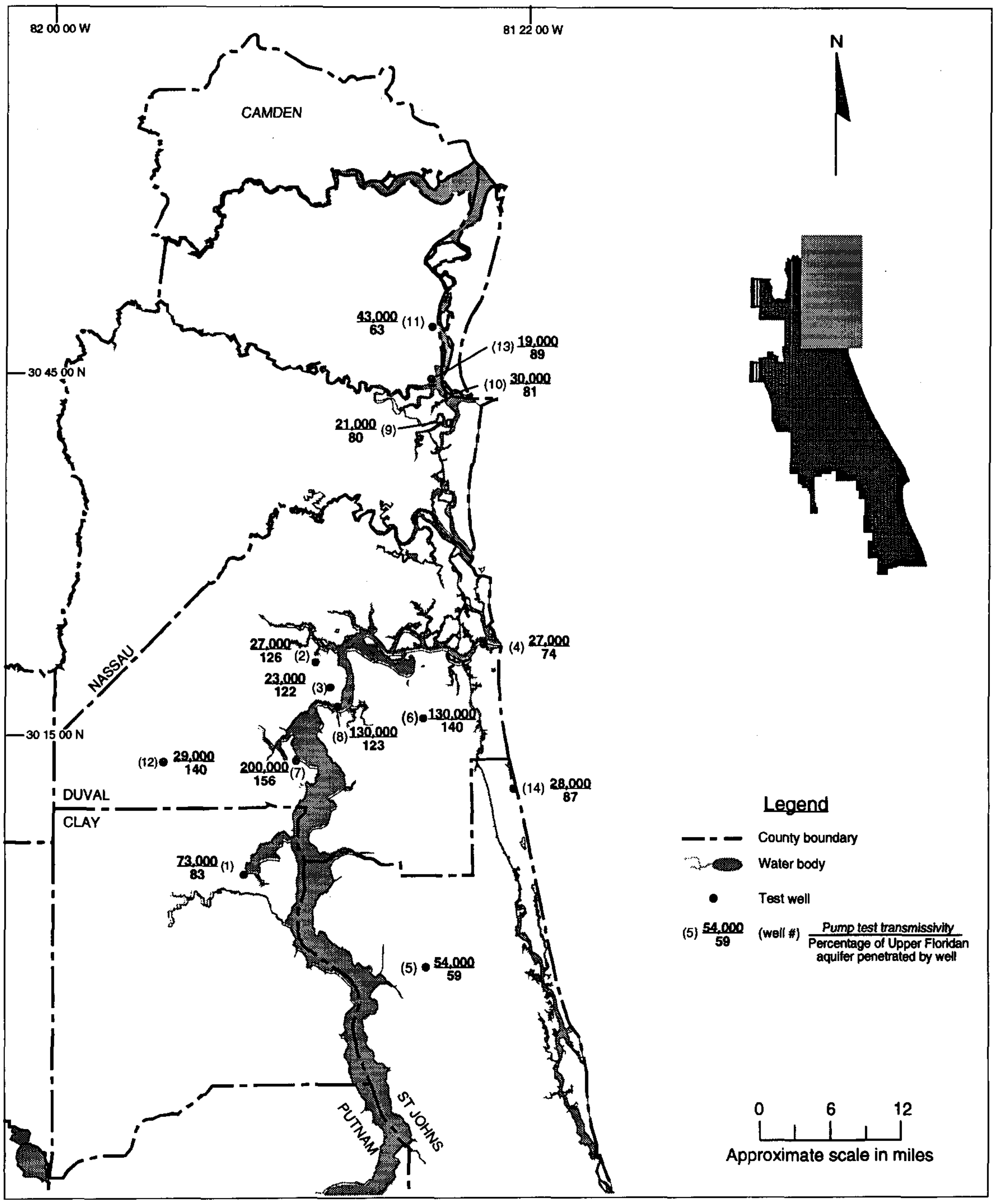


Figure 11. Locations of selected aquifer performance tests in the Floridan aquifer system. *Where percentage of penetration exceeds 100, well terminates beneath the Upper Floridan aquifer.*
(Bentley 1977, 1979; Krause and Randolph 1989; Szell 1993)

estimated the transmissivity of the Upper Floridan aquifer near Fernandina Beach at 30,000 ft^2/day. After reviewing the results of several aquifer performance tests and other studies, Brown (1984) concluded that the transmissivity of the Upper Floridan aquifer in the area of Fernandina Beach ranges from approximately 20,000 to 50,000 ft^2/day.

Lower Floridan Aquifer. No aquifer performance tests are known to have been performed exclusively on the Lower Floridan aquifer within the study area. Therefore, reliable estimates of the transmissivity of the Lower Floridan aquifer are generally not available. Krause and Randolph (1989) state that the transmissivity of the Lower Floridan aquifer beneath Jacksonville is approximately 400,000 ft^2/day.

At least three of the aquifer performance tests within the study area cited in Krause and Randolph (1989) appear to have been performed using test wells that were open to both the Upper and Lower Floridan aquifers (Figure 11, well sites 6, 7, and 12). The transmissivity estimates derived from the aquifer performance tests performed at these three sites are 130,000 ft^2/day, 200,000 ft^2/day, and 29,000 ft^2/day, respectively. A fourth test well (Figure 11, well site 8) may have been open to the Lower Floridan aquifer also. The transmissivity estimate derived from the aquifer performance test performed using that well is 130,000 ft^2/day. Because both the Upper and Lower Floridan aquifers are stressed when such wells are pumped, the transmissivity estimates resulting from aquifer performance tests performed using such wells are composite values that are representative of both aquifers. Three of these four estimates are considerably larger than the estimates obtained from other, nearby sites, where the test wells penetrate through only the Upper Floridan aquifer or MSCU (Figure 11). These results lend support to the possibility that the transmissivity of the Lower Floridan aquifer is higher on average than that of the Upper Floridan aquifer.

The results of the numerical modeling study performed by Durden and Motz (1991) indicate also that the transmissivity of the Lower Floridan aquifer is relatively high in northeast Florida. Throughout most of Duval and Clay counties, estimates of the transmissivity of the Lower Floridan aquifer range from 300,000 to 450,000 ft^2/day. In southeastern Clay, central St. Johns, and coastal Duval counties, estimates of transmissivity of the Lower Floridan aquifer range from 50,000 to 200,000 ft^2/day. In the area of Fernandina Beach, transmissivity estimates of the Lower Floridan aquifer are generally less than 50,000 ft^2/day. Using the results of aquifer performance tests performed with wells that penetrate both the Upper and Lower Floridan aquifers, Brown (1984) estimated that the transmissivity of the Lower Floridan aquifer in the area of Fernandina Beach ranges from approximately 40,000 to 60,000 ft^2/day.

Fernandina Permeable Zone. No aquifer performance tests are known to have been performed on the Fernandina permeable zone within the study area. Brown (1984) estimated the transmissivity of the Fernandina permeable zone at Fernandina Beach to be approximately 75,000 ft^2/day, based on modeling results.

Leakance

Upper Confining Unit. The leakance of the upper confining unit in the area of Fernandina Beach is approximately 2.5×10^{-6} per day (d^{-1}), based on permeameter tests of core samples (Brown 1984). Krause and Randolph (1989) estimated the leakance of the upper confining unit to range from 1.0×10^{-6} to 1.0×10^{-5} d^{-1} throughout most of Duval, Nassau, and Camden counties. In most of Clay and St. Johns counties within the study area, the leakance of the upper confining unit is estimated to range from 1.0×10^{-5} to 1.0×10^{-4} d^{-1} (Krause and Randolph 1989). In the area of Green Cove Springs, the leakance of the upper confining unit is estimated to be in excess of 1.0×10^{-4} d^{-1} (Krause and Randolph 1989).

Middle Semiconfining Unit. Estimates of the leakance of MSCU are not widely available. Durden and Motz (1991) estimated the leakance of MSCU to range from 1.0×10^{-8} to 1.0×10^{-1} d^{-1} throughout most of Nassau, Duval, Clay, and St. Johns counties within the study area. Brown (1984) estimated the leakance of MSCU at 1.0×10^{-5} d^{-1} in the area of Fernandina Beach.

Lower Semiconfining Unit. The leakance of LSCU is approximately 3.3×10^{-6} d^{-1} in the area of Fernandina Beach (Brown 1984).

STORATIVITY AND SPECIFIC YIELD

Surficial and Intermediate Aquifer Systems

The specific yield of the water table zone in Nassau County is approximately 0.2 (Brown 1984). In Duval County, the specific yield of the water table zone ranges from approximately 0.1 to 0.2 (Franks 1980). The storativity of the aquifers of the intermediate aquifer system ranges from approximately 1.0×10^{-5} to 1.0×10^{-3} (Brown 1984).

Upper Floridan Aquifer

Generally, estimates of storativity of the Upper Floridan aquifer range from 1.0×10^{-4} to 1.0×10^{-3} (Johnston and Bush 1988). At Fernandina Beach, the storativity ranges from 2.5×10^{-4} to 4.0×10^{-4} (Bentley 1979). A series of aquifer performance tests performed within the study area and in nearby areas indicate that the storativity of the Upper Floridan aquifer ranges from approximately 1.0×10^{-4} to 1.0×10^{-3} (Bentley 1977).

Lower Floridan Aquifer and Fernandina Permeable Zone

The storativity of the Lower Floridan aquifer is approximately 5.0×10^{-4} (Brown 1984). The storativity of the Fernandina permeable zone is approximately 1.0×10^{-4} (Brown 1984).

AQUIFER WATER LEVELS

Surficial Aquifer System

Causey (1975) described measurements of the depth to the water table obtained during the period of March 3, 1972, to June 30, 1975, at 34 sites throughout Duval County. The maximum and minimum depths to the water table observed during the stated period and the elevation of the water table corresponding to the maximum depth below land surface were reported for each of the 34 observation well sites. During the stated period, the maximum depth to the water table ranged from 3.0 to 14.8 ft below land surface at the 34 sites, and differences in the maximum and minimum depths to the water table ranged from 1.7 to 7.3 ft. The elevation of the water table at maximum depths below land surface ranged from 4 to 84 ft NGVD.

The elevation of the water table tends to fluctuate seasonally in response to seasonal trends in rainfall. Rainfall is usually greater in the late spring and summer months and less in the fall and winter months. Accordingly, water levels in the surficial aquifer system are generally higher in the summer rainy season (June through September) and lower during the dry season (October through May) (Causey and Phelps 1978; Spechler and Hampson 1984).

Floridan Aquifer System

Predevelopment Upper Floridan Aquifer. The Floridan aquifer system prior to the onset of significant withdrawals from wells is referred to herein as the predevelopment Floridan aquifer system. Significant development of the Upper Floridan aquifer within the study area began around the year 1880 (Krause and Randolph 1989). The map of the predevelopment potentiometric surface of the Upper Floridan aquifer used in this study is based on both newer maps of areas where little ground water development has occurred and older maps of areas where much ground water development has occurred (Johnston, Krause et al. 1980) (Figure 12). Because of the limited amount of accurate information concerning the predevelopment ground water system of the Upper Floridan aquifer, this map cannot be used to obtain precise estimates of hydraulic head at specific locations. Rather, it is intended to provide a generalized representation of the potentiometric surface of the predevelopment flow system of the Upper Floridan aquifer (Johnston, Krause et al. 1980). The lines of equal elevation of hydraulic head shown on this map are thought to be accurate at most locations to within about 10 ft (based on Krause 1982).

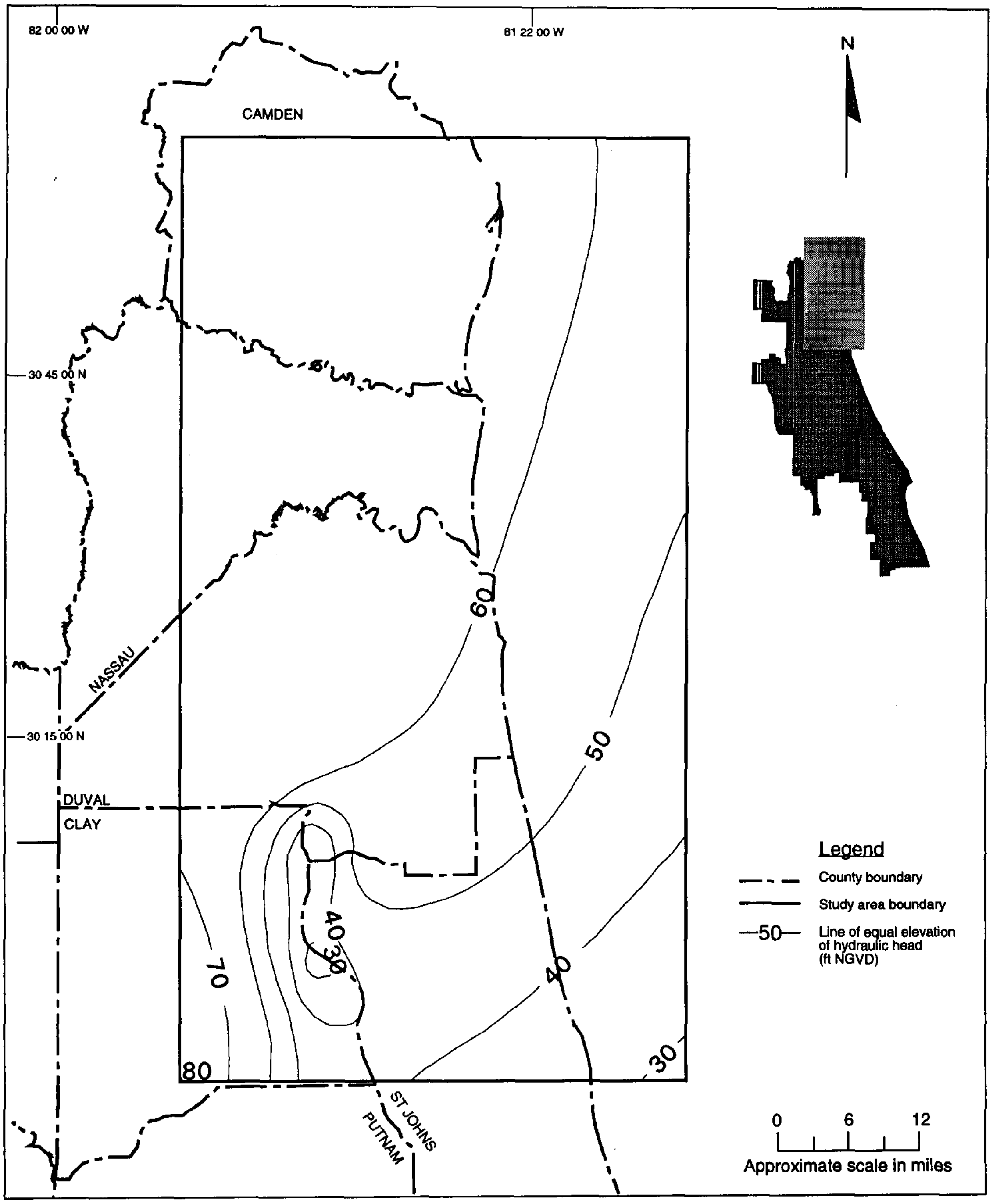


Figure 12. Potentiometric surface of the Upper Floridan aquifer prior to development (Johnston, Krause et al. 1980)

The predevelopment potentiometric surface of the Upper Floridan aquifer sloped downward from the west to the east and south within the study area (Johnston, Krause et al. 1980) (Figure 12). Lines of equal elevation of hydraulic head were oriented approximately from north to south in the northwest part but were bent to the northeast near the Atlantic coast. Therefore, ground water in the Upper Floridan aquifer that entered the northwest portion of the study area flowed eastward initially but then turned toward the southeast, assuming the direction of ground water flow to be normal to lines of equal elevation of hydraulic head (Figure 12). A potentiometric low, caused by discharge at Green Cove Springs and possibly by other unconfirmed, submerged springs in the St. Johns River, occurred in the southwest portion of the study area (Johnston, Bush et al. 1980). The gradient of the potentiometric surface was comparatively small in the northwest portion of the study area but increased towards the southeast. The gradient was relatively steep in the southwest portion of the study area, where a potentiometric high extended into the study area (Johnston, Bush et al. 1980).

Predevelopment Lower Floridan Aquifer. Little or no information exists concerning the potentiometric surface of the Lower Floridan aquifer prior to development.

Predevelopment Fernandina Permeable Zone. Likewise, little or no information exists concerning the potentiometric surface of the Fernandina permeable zone prior to development.

Postdevelopment Upper Floridan Aquifer. The map used to represent the postdevelopment potentiometric surface of the Upper Floridan aquifer was derived from maps of the 1985 potentiometric surface of the Upper Floridan aquifer prepared by Schiner and Hayes (1985) and Clarke (1987) and from data obtained from Johnston, Bush et al. (1980) (Figure 13). This map represents levels of hydraulic head present in the Floridan aquifer system in the study area in September 1985. The map by Schiner and Hayes (1985) was derived from data collected in monitoring wells within SJRWMD in September 1985. The map by Clarke (1987) was derived from data collected in monitoring wells in Georgia in May 1985 (Figure 14).

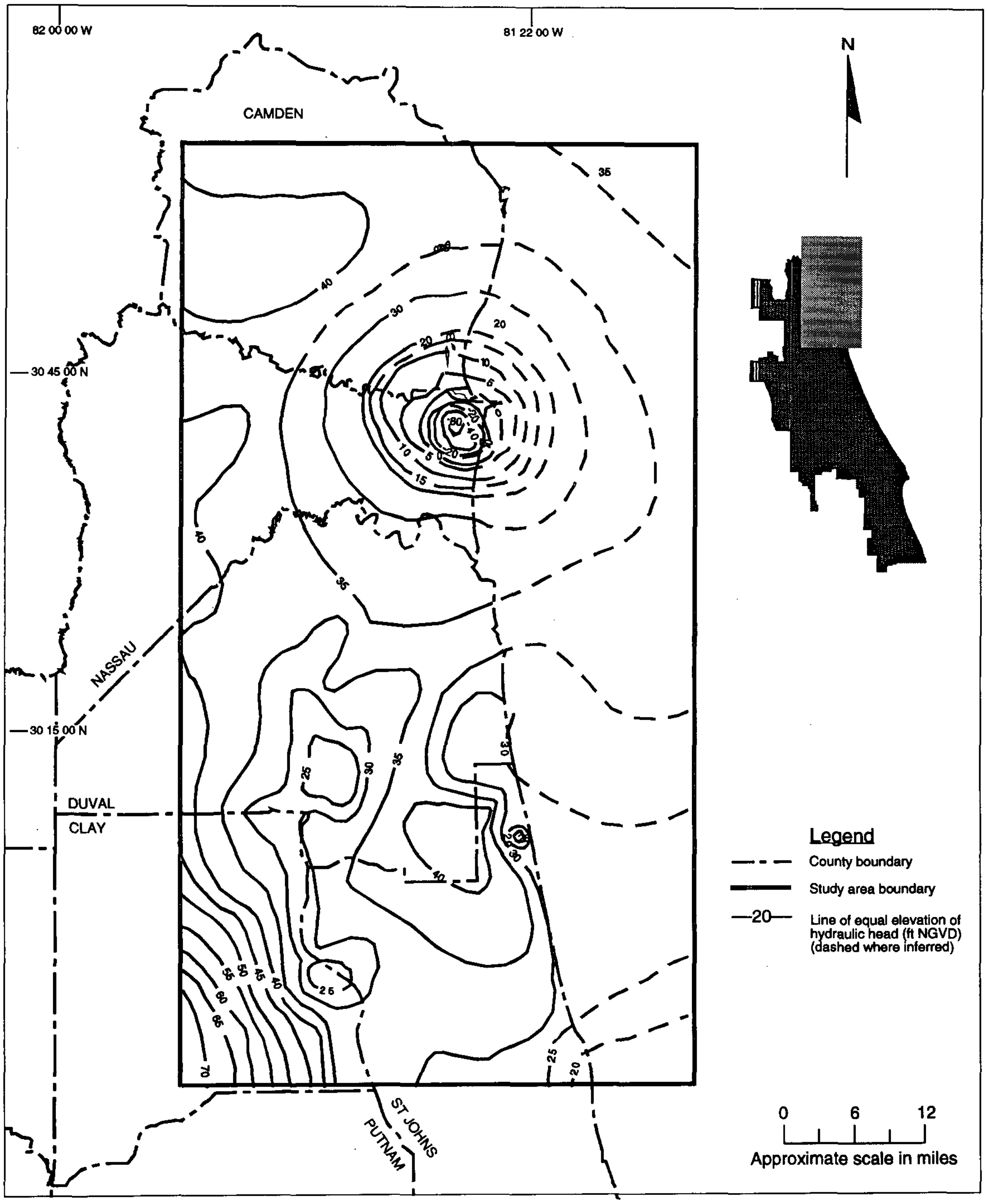


Figure 13. Approximate potentiometric surface of the Upper Floridan aquifer in September 1985 (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987)

Hydraulic head in the Upper Floridan aquifer in Camden County was not measured at most monitoring wells in September 1985. However, comparisons of values of hydraulic head measured in May and September 1985 in observation wells in Nassau County showed that, outside the steepest part of the Fernandina Beach/St. Marys cone of depression, changes in hydraulic head in the Upper Floridan aquifer were generally less than 1 ft. Nassau County is adjacent to Camden County and has similar patterns of aquifer development (Figure 13). The potentiometric surface of the Upper Floridan aquifer in most of Camden County was probably essentially the same in September 1985 as in May.

Accordingly, the map of the May 1985 potentiometric surface of the Upper Floridan aquifer by Clarke (1987) was used to represent the potentiometric surface of the Upper Floridan aquifer in September 1985 in Camden County as well. Because the map of the potentiometric surface of the Upper Floridan aquifer in Georgia (Clarke 1987) was drawn using a 10-ft contour interval, the locations of the 35-, 25-, 15-, and 5-ft lines of equal elevation of hydraulic head in Camden County were interpolated based on the lines of equal elevation of hydraulic head that were shown (Figure 13).

Values of hydraulic head in the Upper Floridan aquifer have been measured at two offshore sites (Johnston, Bush et al. 1980). The first site, the JOIDES J-1 site, is approximately 20 miles (mi) offshore of Fernandina Beach. The equivalent-freshwater head of the Upper Floridan aquifer was estimated to range from 30 to 38 ft NGVD at this site (Johnston, Bush et al. 1980). The second site, the TENNECO LB-427 site, is approximately 55 mi offshore of Fernandina Beach. The equivalent-freshwater head in the Upper Floridan aquifer was estimated to range from 24 to 29 ft NGVD at this site (Johnston, Bush et al. 1980). These hydraulic-head data were used in extrapolating lines of equal hydraulic head of the potentiometric surface of the Upper Floridan aquifer into the part of the study area occupied by the Atlantic Ocean (Figure 13). The results of the extrapolation are similar to those obtained by Brown (1984), who used these data as well.

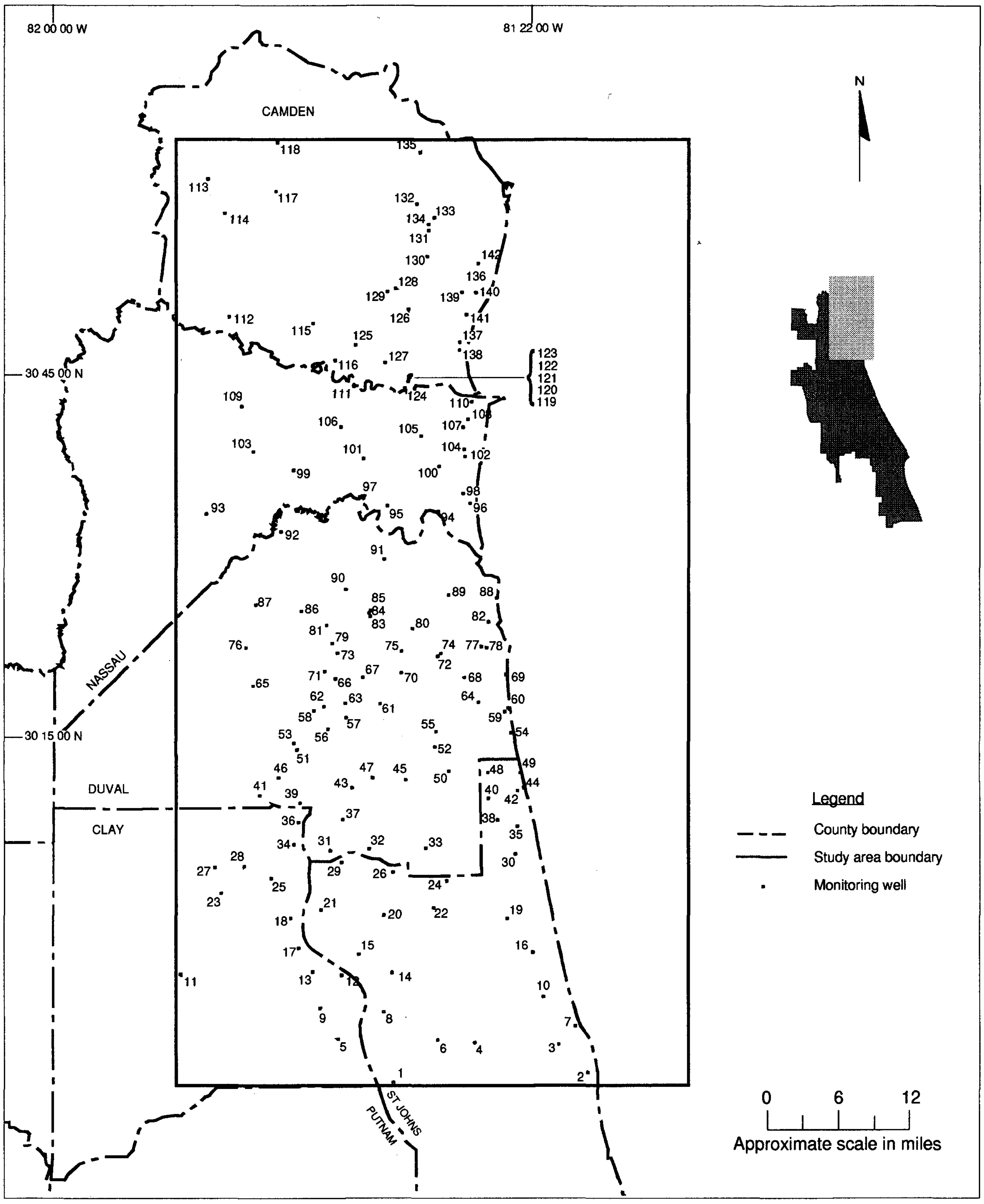


Figure 14. Locations of hydraulic-head monitoring wells in the Upper Floridan aquifer in 1985
(See Table C1 for well descriptions)

Postdevelopment Lower Floridan Aquifer. Values of hydraulic head in wells open only to the Lower Floridan aquifer are being monitored currently at four locations in the study area (USGS 1988) (Figure 15). Measurements did not begin at these sites until October 1986, however. The values of hydraulic head observed at the four sites ranged from approximately 32 to 38 ft NGVD in October 1986. Additionally, hydraulic head was measured as a function of depth in the Lower Floridan aquifer in wells D-2386, D-3060, and SJ-0025 (respectively, Brown et al. 1984, 1985, and 1986).

Postdevelopment Fernandina Permeable Zone. Hydraulic head was measured as a function of depth in the Fernandina permeable zone in wells D-2386, D-3060, and SJ-0025 (respectively, Brown et al. 1984, 1985, 1986) (Figure 16). Comparisons of vertically averaged values of hydraulic head in the Lower Floridan aquifer and the Fernandina permeable zone at these three wells indicate that hydraulic head in the Fernandina permeable zone generally does not differ greatly from that in the Lower Floridan aquifer but is usually higher (Brown et al. 1984, 1985, 1986).

Comparison of Predevelopment and Postdevelopment Potentiometric Surfaces

A comparison of the map of the September 1985 potentiometric surface of the Upper Floridan aquifer (based on Johnston, Krause et al. 1980; Schiner and Hayes 1985; Clarke 1987) with the map of the predevelopment potentiometric surface (Johnston, Bush et al. 1980) indicates that many characteristics of the predevelopment flow system still exist (Figures 12 and 13). Much ground water still enters through the western boundary of the study area, and discharges to the east and southeast, though to a lesser extent (Figure 13). The potentiometric low in the southwest portion of the study area is still present, although it appears to extend farther northward, probably due to withdrawals from wells in Jacksonville. This potentiometric low now provides a more extensive hydraulic barrier to the eastward flow of ground water entering the Upper Floridan aquifer in the recharge areas west of the St. Johns River (Figures 10, 12, and 13).

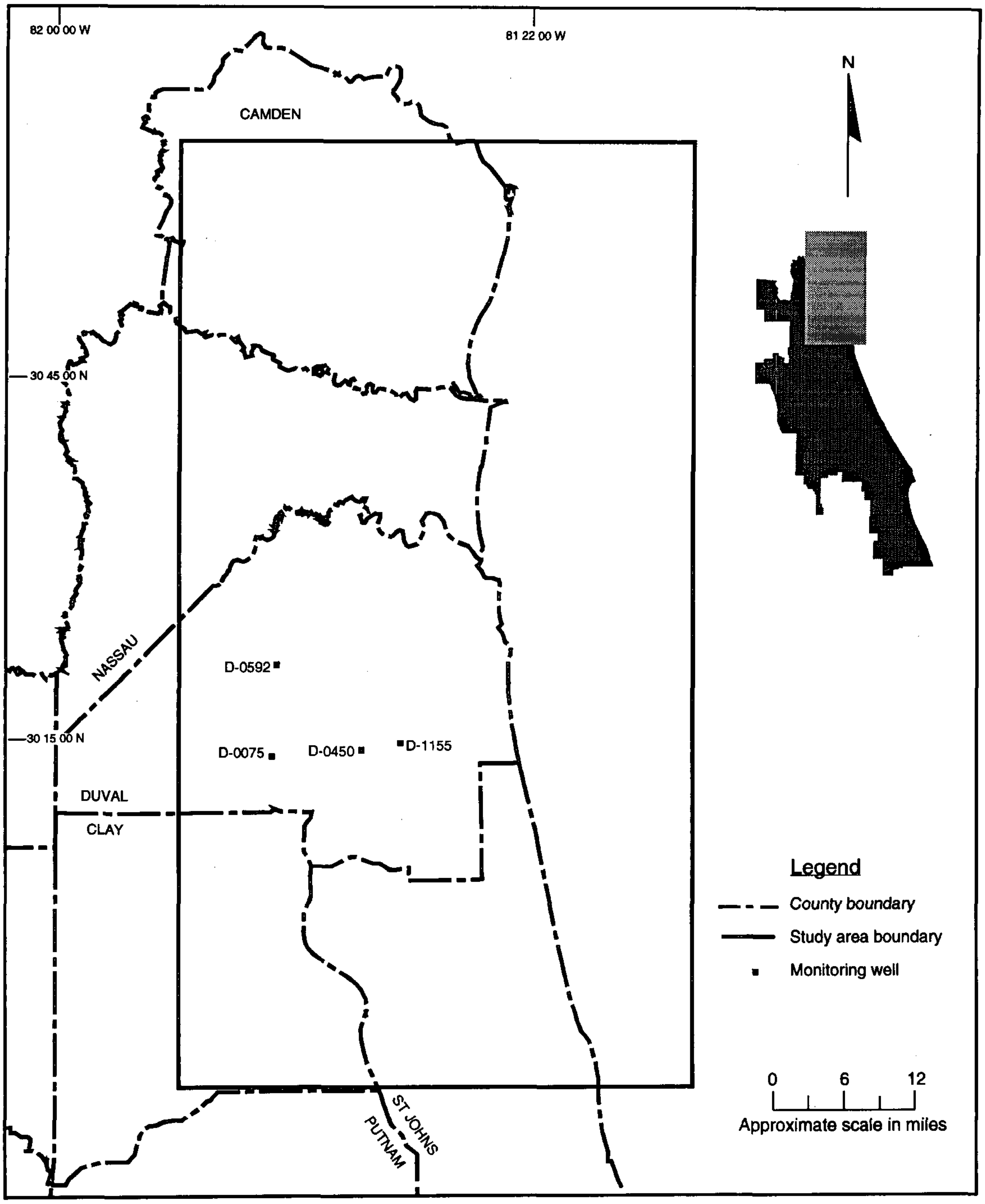


Figure 15. Locations of hydraulic-head monitoring wells in the Lower Floridan aquifer in 1986 (See Table 10 for well descriptions)

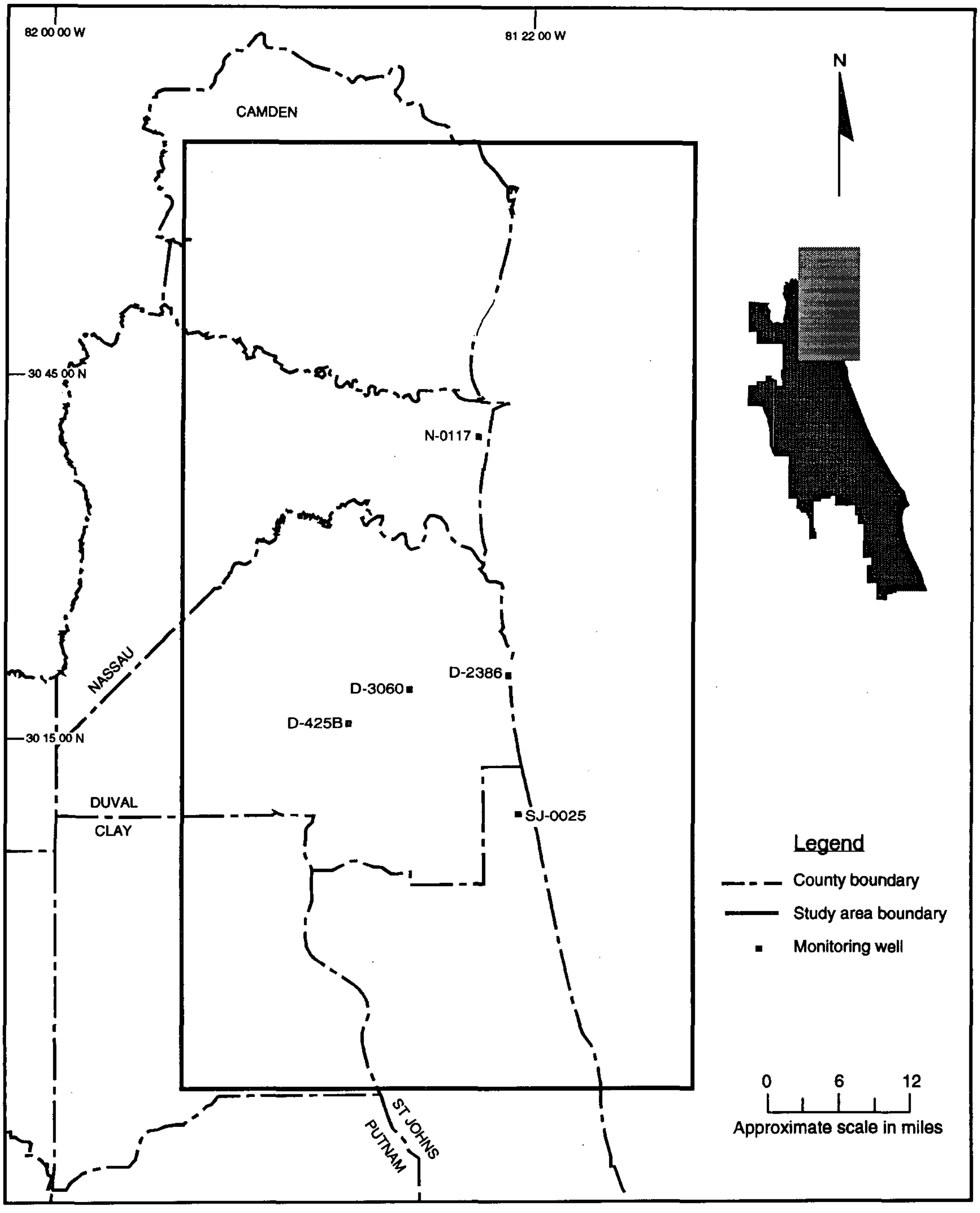


Figure 16. Locations of hydraulic-head monitoring wells in the Fernandina permeable zone in 1985 (See Table 11 for well descriptions)

Changes in water levels average approximately 25 ft over the study area and are attributable primarily to steady increases in withdrawals from wells since the 1880s (Figure 17). Withdrawals in the areas of Fernandina Beach, Florida, and St. Marys, Georgia, have resulted in a deep, areally extensive cone of depression in the potentiometric surface of the Upper Floridan aquifer (Schiner and Hayes 1985; Clarke 1987) (Figures 13 and 17). As a result of this cone of depression and ones centered on the areas of Jacksonville and the Atlantic coast to the south, the flow system of the Upper Floridan aquifer within the study area is now divided into northern and southern ground water subbasins in the area of northern Duval County (Figure 13). A local potentiometric high centered on the county line between St. Johns and Duval counties is now present and is perhaps being maintained primarily by upward leakage from the Lower Floridan aquifer (Durden and Motz 1992) (Figure 13).

FRESHWATER/SALTWATER INTERFACE

Saline water underlies the freshwater flow system of the Upper Floridan aquifer throughout the study area. The boundary between fresh and saline water is referred to as the freshwater/saltwater interface (Bear 1979). Presently, five monitoring wells in the study area penetrate the Floridan aquifer system to the freshwater/saltwater interface (Figure 16). At each of these wells, chloride concentrations have been observed as a function of depth (Leve and Goolsby 1966; Brown 1980; Brown et al. 1984, 1985, 1986).

The results of these investigations indicate that the transition zone from fresh to saline water is apparently relatively narrow (i.e., the interface is sharp) in most of the onshore part of the study area. The measurements also show that the interface is approximately 2,000 ft bNGVD near the Atlantic coast in the parts of the study area north of Ponte Vedra Beach (Figure 1). Therefore, the interface is generally located in the Fernandina permeable zone in parts of the study area near the coast.

The area of St. Johns County south of Ponte Vedra Beach may be an exception to this, however. In St. Johns County, chloride concentrations in the Upper Floridan aquifer increase from less than

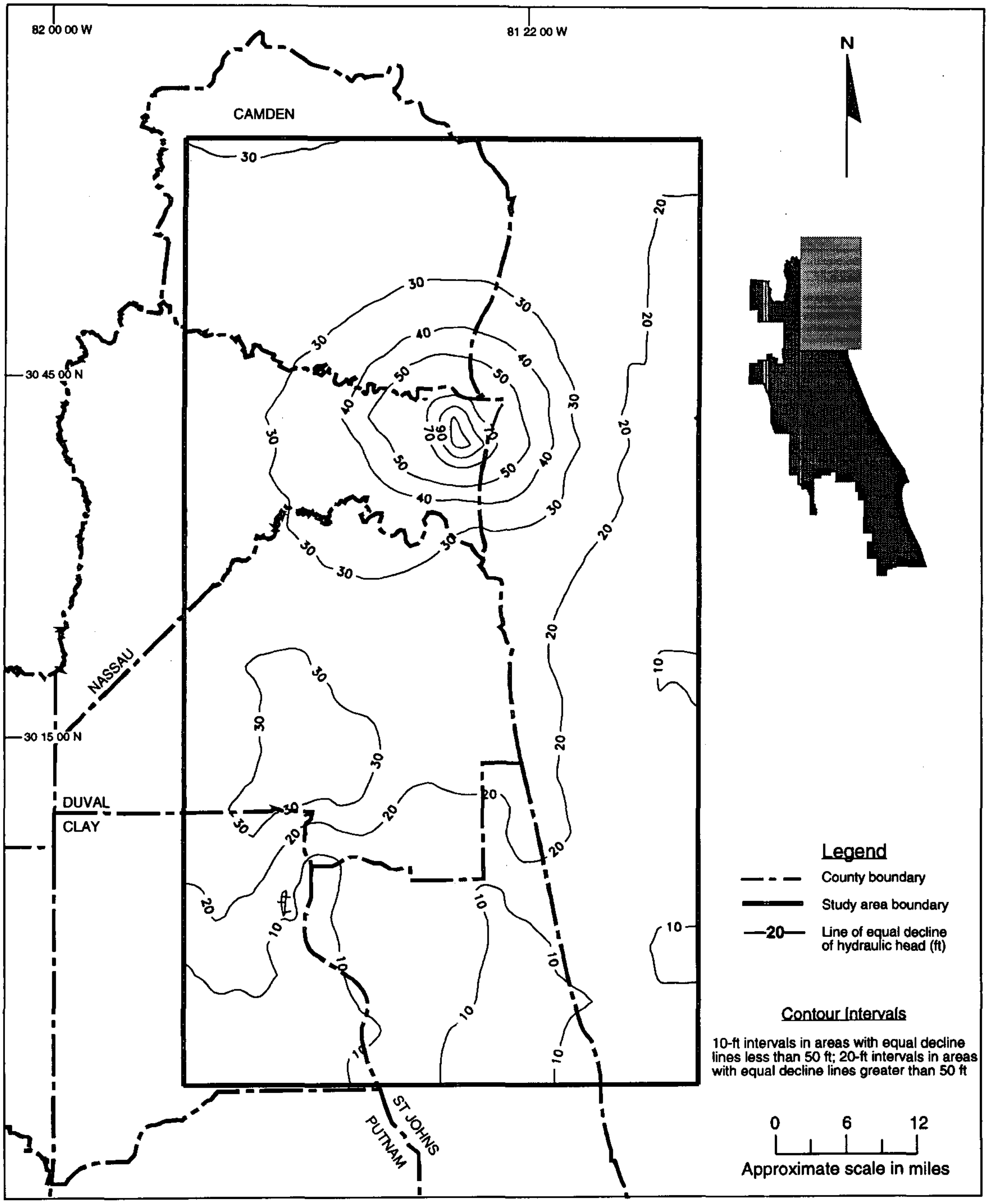


Figure 17. Approximate declines in the potentiometric surface of the Upper Floridan aquifer between predevelopment times and 1985

50 milligrams per liter (mg/L) in the northern part of the county to as much as 250 mg/L in the east-central part of the county (Toth 1990) (Figure 18). Unlike most of the rest of the onshore part of the study area, the vertical transition from fresh to saline water in this area probably cannot be characterized accurately as sharp. No known water quality monitoring wells that penetrate the Lower Floridan aquifer exist in this area, so it is not possible to characterize the vertical transition with certainty.

Offshore, chloride concentrations in the Floridan aquifer system were measured at the JOIDES J-1, JOIDES J-2, and TENNECO LB-427 test wells (Johnston, Bush et al. 1980). Water samples were collected at each of the sites at approximately 1,000 ft bNGVD. Chloride concentrations of these samples at the JOIDES J-1 site ranged from approximately 675 to 1,025 mg/L and at the TENNECO LB-427 site from approximately 1,000 to 7,000 mg/L. The chloride concentration at the JOIDES J-2 site was 19,600 mg/L (Johnston, Bush et al. 1980), which is the concentration of chloride found in seawater.

Taken together, these data indicate that the sample from the JOIDES J-1 site was obtained above the freshwater/saltwater interface and landward of it; the sample from the TENNECO LB-427 site was obtained at the interface; and the sample from the JOIDES J-2 well was obtained below the interface and seaward of it (Johnston, Bush et al. 1980) (Figure 19).

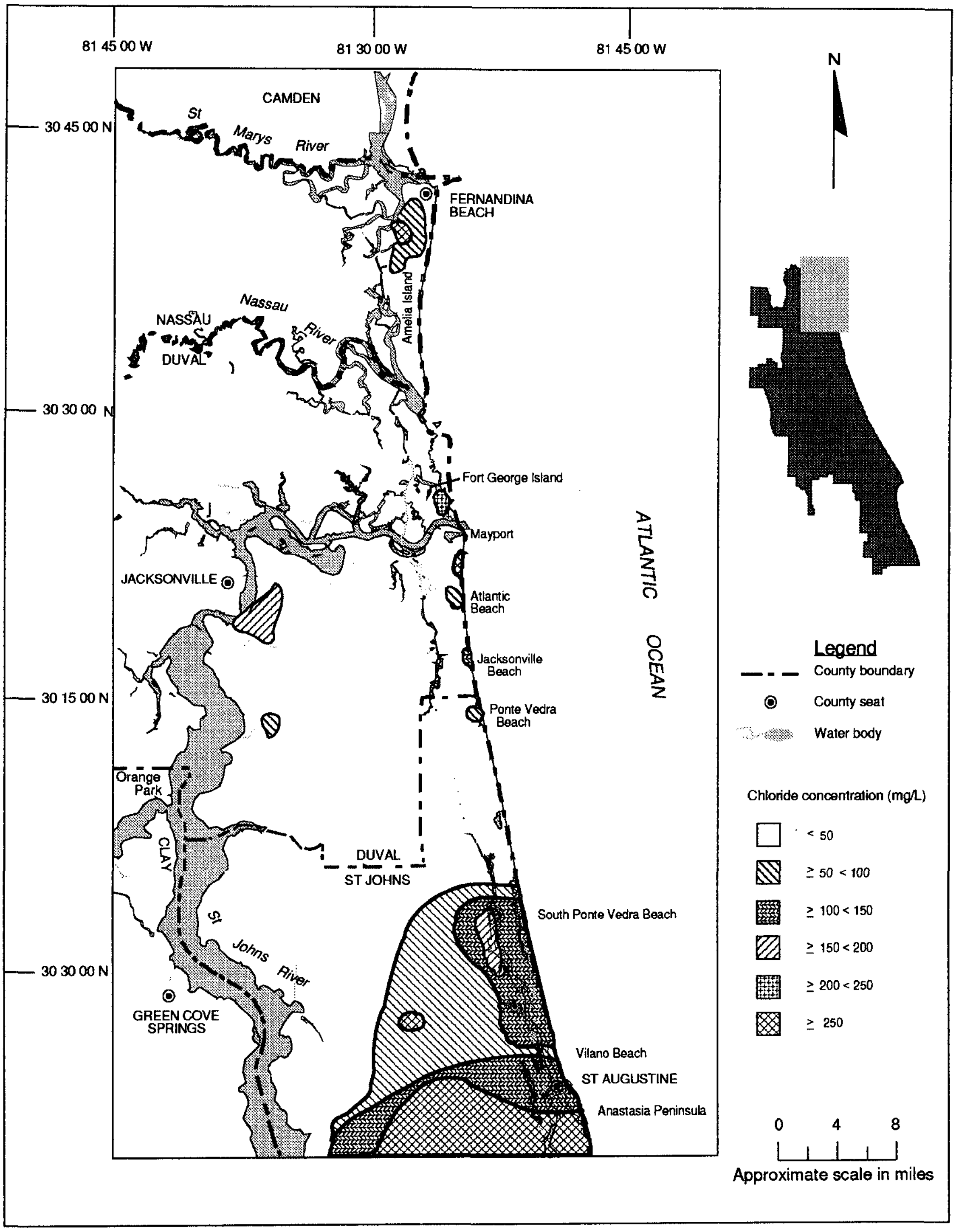


Figure 18. Concentration of chloride in the Upper Floridan aquifer based on data collected after 1979 (modified from Toth 1990)

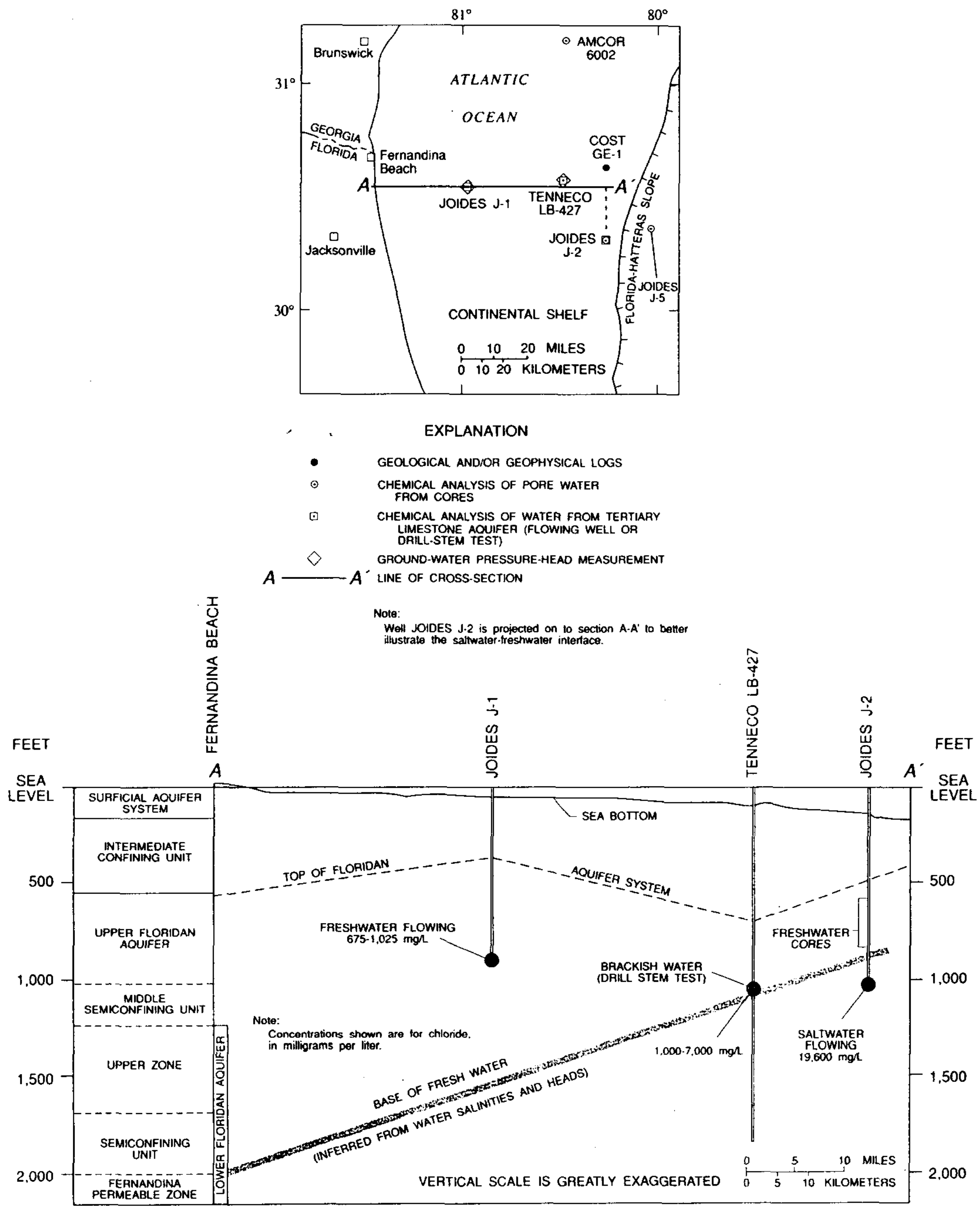


Figure 19. Estimated location of the freshwater/saltwater interface in the offshore Floridan aquifer system. *Hydrogeologic nomenclature does not match that used in this report.* (Spechler 1994 modified from Johnston, Bush et al. 1980)

GROUND WATER WITHDRAWALS

The Floridan aquifer system is the primary source of potable water in the study area. Points of withdrawal from the Floridan aquifer system are most concentrated in Duval County but occur throughout the study area (Figure 20). Due to the regional scale of the study area, consideration was limited primarily to withdrawals from the Floridan aquifer system that were in excess of an average of 100,000 gallons per day (gpd), although some withdrawals less than this were considered.

The postdevelopment ground water flow model was calibrated primarily by comparing simulated values of hydraulic head in the Floridan aquifer system to values representing conditions in September 1985. Consideration in this study was limited to withdrawals made from June through September 1985. Withdrawals made in the period of June through August were included for consideration with those made in September to account approximately for the effects of variations in withdrawal rates and locations that occurred prior to September. In the Floridan aquifer system, the major portion of water level changes in response to changes in withdrawal rates occurs over a period of several months, based on analyses performed using the modified leaky-aquifer equation (Hantush 1960) and representative hydraulic parameters. Conceivably, then, water levels observed in September 1985 may still have been affected significantly by changes in withdrawal rates that occurred as early as June 1985. To account for this possibility, albeit in an approximate fashion, average rates of withdrawals observed between June and September were used to simulate September water levels in the postdevelopment flow model.

Withdrawals from the Floridan aquifer system in the study area can be classified broadly as nonagricultural or agricultural. Nonagricultural withdrawals include public supply, institutional, commercial/industrial, and domestic self-supply. Between June and September, agricultural water use in the study area typically includes withdrawals for irrigation of cabbage, corn, vegetables, blueberries, golf course turf, landscape, and nursery plants (Lynne and Kiker

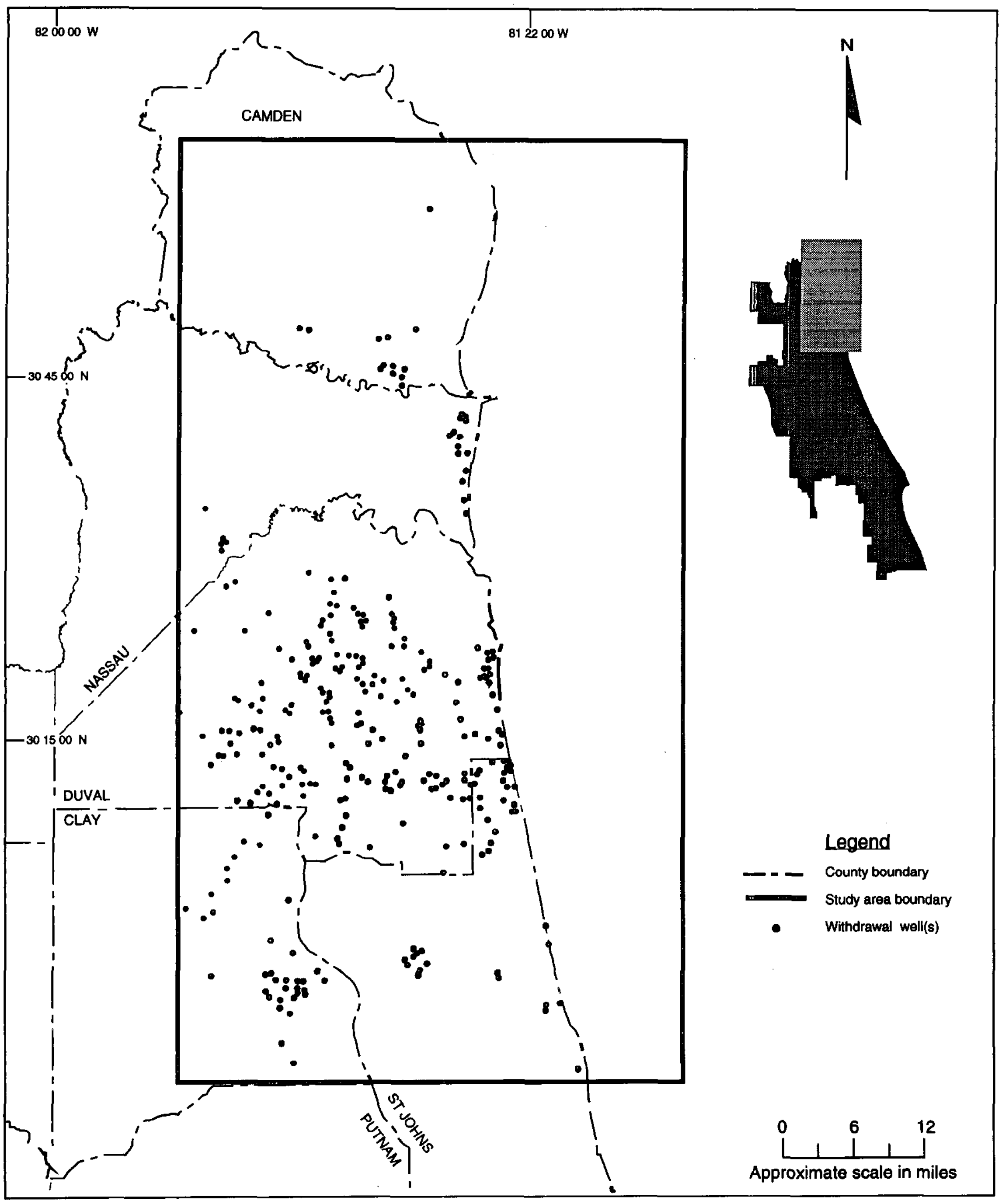


Figure 20. Locations of individual and groups of withdrawal wells in the Floridan aquifer system in 1985

1991). Withdrawals used to supply dairy and beef operations are classified herein as agricultural withdrawals also.

NONAGRICULTURAL WITHDRAWALS

Estimates of the magnitudes of monthly withdrawals made by public supply, commercial/industrial, and institutional water users located in SJRWMD were obtained primarily from Marella (1986a), which lists magnitudes of public supply exceeding an annual average of 10,000 gpd or more (B.L. Florence, pers. com. 1992). Estimates of monthly withdrawal magnitudes in Camden County were obtained primarily from the USGS office in Doraville, Georgia (Fanning, pers. com. 1990) and from a publication of the Georgia Department of Natural Resources (Turlington et al. 1987). In some cases, estimates of withdrawal magnitudes were obtained directly from water users (Appendix A and Table A5).

Domestic Self-Supply

Withdrawal amounts attributed to domestic self-supply in Duval, Clay, St. Johns, and Nassau counties in 1985 are 15.5, 2.7, 2.1, and 4.0 million gallons per day (mgd), respectively (Marella 1986b). The withdrawal amount attributed to domestic self-supply in Camden County in 1985 is 0.5 mgd (Fanning, USGS, Doraville, Georgia, pers. com. 1992). Withdrawals for domestic self-supply in Clay, St. Johns, Nassau, and Camden counties were ignored because domestic self-supply in these four counties represented only a relatively small percentage of total water use within the study area.

In Duval County, most domestic self-supply wells tap the shallow-rock zone of the surficial aquifer system rather than the Upper Floridan aquifer (D.J. Toth, pers. com. 1992). Therefore, withdrawals for domestic self-supply in Duval County were ignored also.

Public, Commercial/Industrial, and Institutional Supply

Estimates of total monthly withdrawals obtained from the Floridan aquifer system were available for most public supply, commercial/industrial, and institutional water users within the study area in the months of June through September 1985. Average rates of withdrawal were determined for individual users by summing the total volume of water used in June, July, August, and September and then dividing by the total number of days (122) in those 4 months. The sum of the average rates of withdrawal from the Floridan aquifer system of all public supply, commercial/industrial, and institutional water users withdrawing an average of 100,000 gpd or more in 1985 was 219.2 mgd (Table 5).

AGRICULTURAL WITHDRAWALS

Generally, direct measurements of agricultural withdrawals within the study area are not available. Therefore, estimation of the magnitudes and schedules of agricultural withdrawals involved the use of various indirect methods and was generally more complex and less reliable than the estimation of the magnitudes of nonagricultural withdrawals. The total average rate of agricultural withdrawals from the Floridan aquifer system for June through September 1985 was approximately 9.8 mgd within the study area (Table 6).

The methods used for estimating schedules and magnitudes of agricultural withdrawals depended on which agricultural product was being considered and on the availability of data. Estimates of withdrawals by dairies were based on estimates of the number of cattle present in 1985. Estimates of irrigation requirements for most crops were obtained from a study performed by the Institute of Food and Agricultural Sciences (IFAS) at the University of Florida (Lynne and Kiker 1991).

The IFAS study estimates were based partly on simulations performed using the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model (Smajstrla 1990). Estimates of the irrigation requirements of golf course turf and landscape were obtained by applying the AFSIRS model independently of the IFAS study (Lynne and Kiker 1991).

The AFSIRS model enables estimates to be made of the monthly irrigation requirements of crops grown commonly in Florida. In

Table 5. Summary of nonagricultural withdrawals represented in the postdevelopment flow model

County	Type of Use	Average* Withdrawal Rate (mgd)	Percent of Total
Duval	Municipal	87.49	39.9
	Commercial/ Industrial	37.55	17.1
	Institutional	6.81	3.1
Nassau	Municipal	3.14	1.4
	Commercial/ Industrial	38.83	17.7
	Institutional	0.00	0.0
Camden	Municipal	0.93	0.4
	Commercial/ Industrial	30.80	14.1
	Institutional	0.75	0.3
Clay	Municipal	7.67	3.5
	Commercial/ Industrial	2.49	1.1
	Institutional	0.00	0.0
St. Johns	Municipal	2.66	1.2
	Commercial/ Industrial	0.00	0.0
	Institutional	0.08	0.0
Total		219.20	99.8

Note: mgd = million gallons per day

*Average daily use in period June through September 1985

Table 6. Summary of agricultural withdrawals represented in the postdevelopment flow model

County	Type of Use	Average* Withdrawal Rate (mgd)	Percent of Total
Duval	Golf course irrigation	1.97	20.0
	Dee Dot Ranch water use	1.64	16.7
	Dairy operations water use	0.42	4.3
	Landscape irrigation	1.23	12.5
	Nursery irrigation	0.11	1.1
	Sod irrigation	0.44	4.5
Nassau	Golf course irrigation	0.70	7.1
Camden	Negligible agricultural water use	0.00	0.0
Clay	Golf course irrigation	0.46	4.7
	Dairy operations water use	1.02	10.4
	Landscape irrigation	0.11	1.1
	Blueberry irrigation	0.24	2.4
St. Johns	Golf course irrigation	1.43	14.5
	Vegetable irrigation	0.06	0.6
	Blueberry irrigation	0.01	0.1
Total		9.84	100.0

Note: mgd = million gallons per day

*Average daily use in period June through September 1985 doing so, it takes account of several critical factors, including soil type, irrigation technique, and climatological conditions.

Crop Irrigation Based on IFAS Data

Monthly withdrawal magnitudes of Consumptive Use Permit (CUP) holders were derived in the IFAS study by multiplying monthly irrigation rates obtained from the AFSIRS model by the number of permitted acres of the crop being considered (Lynne and Kiker 1991). Well locations were reported as latitude/longitude coordinates obtained from CUP files at SJRWMD (Lynne and Kiker 1991).

In the present study, IFAS irrigation estimates were obtained for vegetables, blueberries, and nursery plants. Withdrawals for potato irrigation were not represented because potato irrigation occurs in February through May (Lynne and Kiker 1991). Withdrawals for corn irrigation were not represented because corn is not a widely irrigated crop (V. Singleton, SJRWMD, pers. com. 1992). Withdrawals for cabbage irrigation were not represented because cabbage irrigation probably did not begin until the latter half of September (V. Singleton, pers. com. 1992), after the ground water levels used to draw the map of the September 1985 potentiometric surface had already been measured.

The IFAS data were sorted to obtain a subset of data pertaining only to the present study area. CUP allocations issued by SJRWMD after 1985 were sorted out. Withdrawal estimates for the months of June through September for each of the CUP holders were summed and divided by 122 days to obtain estimates of average daily use. The locations of these withdrawals were determined from the latitude/longitude coordinates stated in the IFAS report (Lynne and Kiker 1991).

Golf Course Turf and Landscape Irrigation

The irrigation requirements of golf courses were determined using the AFSIRS model (Smajstrla 1990) independently of the IFAS report (Lynne and Kiker 1991), because final IFAS estimates were unavailable at the time. The numbers of irrigated acres of each of the golf courses were obtained from CUP files at SJRWMD and confirmed by telephone conversations with golf course representatives and SJRWMD consumptive use permitting personnel. Soil types were approximated using Soil Conservation Service surveys (Stem et al. 1978; Readle 1983; Weatherspoon et al. 1989; Watts 1991). Estimates of average rates of withdrawal for June through September were obtained by summing the estimated withdrawal magnitudes for June, July, August, and September and dividing the result by 122 days (Table 6). Estimates of withdrawals for urban landscape were obtained using the same procedure.

Dairy Operations Water Use

Seven dairies were known to be present in the study area in 1985 (Appendix A, Table A2). Dairy withdrawal estimates (Table 6) were derived by multiplying estimates of daily water requirements per dairy cow by estimates of the numbers of cattle present. The herds of each dairy operation were delineated according to the numbers of milking cows, dry cows, and calves, because each type of cow uses considerably different amounts of water.

The majority of water used by dairy operations is for cleaning milking cows and the barns and for providing the cows with drinking water. The amount of water needed for these activities ranges from approximately 100 to 150 gpd per milking cow (Nordstedt and Baldwin 1975). In the present study, a median value of 125 gpd per milking cow was used.

Dry cows are dairy cows not being used to produce milk. Dry cows consume approximately 18 gpd per cow on average in summer months (H. Van Horn, University of Florida, pers. com. 1991). Calves consume only about 3 gpd of water per calf on average (Hembry, pers. com. 1991). In some cases, beef cows were present at dairy operations as well; they consume about 13 gpd per cow on average (F. Hembry, University of Florida, pers. com. 1991).

Dee Dot Ranch Water Use

Dee Dot Ranch is a private wildlife preserve that encompasses thousands of acres in southeastern Duval and northern St. Johns counties. At least 35 wells that penetrate the Floridan aquifer system are located there. Direct measurements of withdrawal magnitudes from the Floridan aquifer system at Dee Dot Ranch in 1985 are unavailable. However, compliance reports submitted to the SJRWMD Department of Resource Management by Dee Dot Ranch indicate that withdrawals from the Upper Floridan aquifer were made primarily by four wells in 1985, all of which are located in Duval County. Three of the wells were operated continuously; one was operated for 8 hours per 24-hour period in the months of June through September 1985, according to the compliance reports.

The pump capacities of several wells at Dee Dot Ranch, including these four, were determined by SJRWMD personnel in December 1990 and April 1991 (V. Singleton, pers. com. 1992). For the three wells used continuously, the average rates of withdrawal in the period June through September 1985 were assumed to be equivalent to respective pump capacities as measured in 1990 and 1991 by SJRWMD personnel (V. Singleton, pers. com. 1992). For the well used 33% of the time, the average withdrawal rate in June through September of 1985 was assumed to be equivalent to one-third of the pump capacity. The total average daily withdrawal rate for Dee Dot Ranch, therefore, was approximately 1.6 mgd for June through September 1985 (Table 6).

WELL INFORMATION

Other essential data related to water use include well locations, well depths, well diameters, and well pump capacities. These data are collectively referred to herein as well information. Well information for SJRWMD was obtained from CUP files at SJRWMD or directly from users. Well information for Camden County, Georgia, was obtained from the USGS office in Doraville, Georgia (Fanning, pers. com. 1990) or directly from users.

Well-depth data were used to determine whether wells penetrated both the Upper and Lower Floridan aquifers or just the Upper Floridan aquifer. Well-diameter and discharge-capacity data were used to distribute the total discharge from a given wellfield to the individual wells within the wellfield.

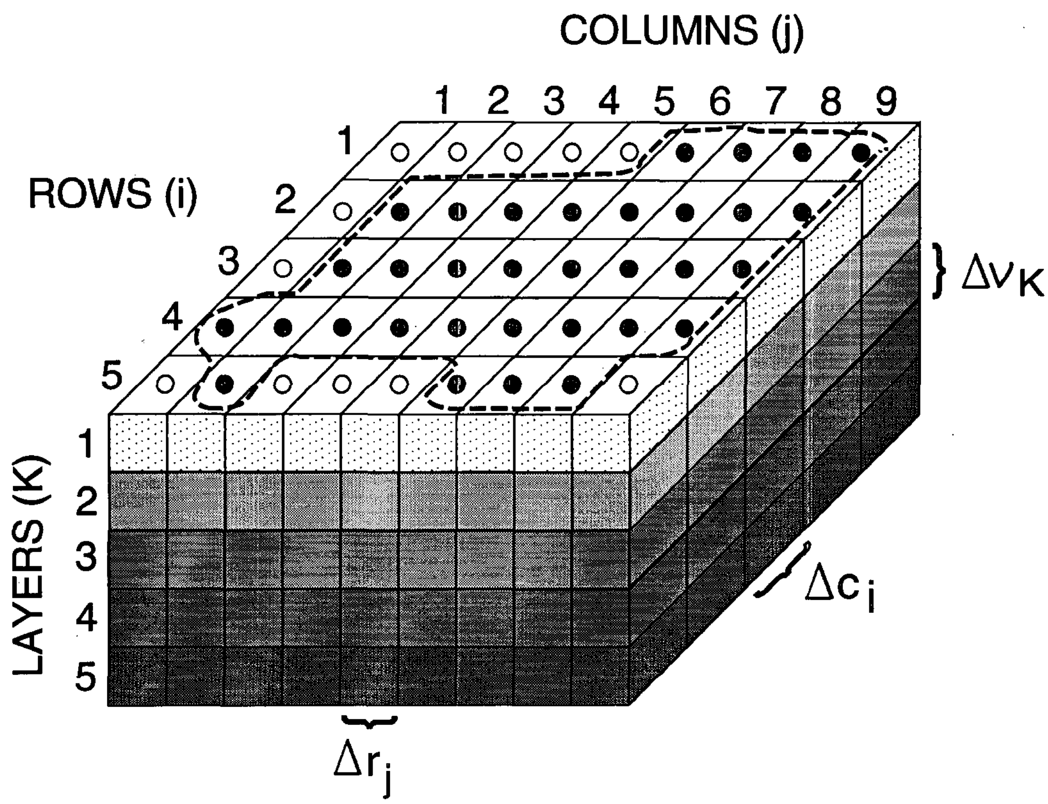
In many cases, some or all of these data were not available, and simplifying assumptions were made. See page 123 for details regarding the distribution of withdrawals between the Upper and Lower Floridan aquifers and to individual wells within wellfields.

MODEL CODE AND CONFIGURATION

CODE SELECTION

The model code used in the study is the McDonald and Harbaugh (1988) modular, three-dimensional, finite-difference, ground water flow model (MODFLOW). A number of criteria were considered in selecting MODFLOW. The ability to account for multiple aquifers and semiconfining units was a primary consideration. This ability was necessary to account for the interaction between the aquifers that comprise the Floridan aquifer system as well as the interaction between the Floridan aquifer system and the overlying surficial aquifer system. Other essential requirements included the ability to account for the spatial distribution of withdrawals from wells, the ability to account for heterogeneity in the physical properties of the aquifers and semiconfining units of the Floridan aquifer system and of the upper confining unit, and the ability to represent complex lateral boundary conditions. In addition to meeting all of these criteria, MODFLOW is well documented and has been applied successfully in numerous other ground water modeling studies.

In general, MODFLOW is a fully three-dimensional ground water flow model. Aquifer systems in MODFLOW are discretized into a mesh of blocks called cells, the locations of which are described in terms of rows, columns, and layers (Figure 21). Values of hydraulic head are determined at points called nodes, which are located at the centers of the cells (McDonald and Harbaugh 1988). Horizontal flow components are based on head differences between adjacent nodes within a given model layer and assigned values of transmissivity or hydraulic conductivity. Vertical flow components are based on head differences between corresponding nodes of adjacent model layers and assigned values of vertical conductance (also called VCONT). VCONT incorporates both the vertical hydraulic conductivity and thickness of the interval between the points in the actual aquifer system that correspond to vertically adjacent model nodes (McDonald and Harbaugh 1988).



<u>Legend</u>

----	Aquifer boundary
●	Variable–head cell
○	Inactive cell
Δr_j	Dimension of cell along the row direction. Subscript (j) indicates the number of the column.
Δc_i	Dimension of cell along the column direction. Subscript (i) indicates the number of the row.
Δv_K	Dimension of cell along the vertical direction. Subscript (K) indicates the number of the layer.

Figure 21. Hypothetical MODFLOW model domain (modified from McDonald and Harbaugh 1988)

In general, VCONT is not the same as leakance, the ratio of the vertical hydraulic conductivity of a semiconfining unit and its thickness. Rather, VCONT values represent the *entire* interval of the aquifer system—not just the interval occupied by the semiconfining unit—between points corresponding to vertically adjacent model nodes. In the specific case in which the nodes in question correspond to the midpoints of two aquifers separated by a semiconfining unit with vertical hydraulic conductivity much less than that of the two aquifers, the value of VCONT will be approximately equal to the leakance of the semiconfining unit. If, furthermore, the horizontal component of flow and storage capacity of the semiconfining unit are relatively small, then the semiconfining unit can be represented effectively in MODFLOW by a single array of VCONT. Such a representation constitutes a "quasi-three-dimensional" rather than fully three-dimensional model because the horizontal component of flow within the semiconfining unit and the storage capacity of the semiconfining unit are discounted entirely (McDonald and Harbaugh 1988).

The cells that comprise a MODFLOW finite-difference grid may be designated as variable-head, constant-head, or inactive (McDonald and Harbaugh 1988). Variable-head cells are those for which calculations of hydraulic head are performed during model simulations. Variable-head cells correspond generally to areas of the aquifer system where magnitudes of changes in hydraulic head in response to anticipated changes in stresses must be determined. Constant-head cells are those in which the initial estimates of hydraulic head are unchanged during the model simulation. Constant-head cells correspond generally to areas of the aquifer system where values of hydraulic head are not expected to change significantly in response to anticipated changes in stresses. Inactive cells are those for which values of hydraulic head are neither specified by the modeler nor calculated by the program. Inactive cells correspond generally to areas of the aquifer system where estimates of the magnitudes of changes in hydraulic head are not required. Although such areas lie within the overall area to which the finite-difference grid corresponds, they lie outside of the area of interest or outside of the boundaries of the aquifer system being modeled.

MODEL CONFIGURATION

Model Layering

Three ground water flow models were developed as a result of the present study: the predevelopment, postdevelopment, and revised predevelopment flow models. All three models are quasi-three-dimensional and steady-state. The aquifers comprising the Floridan aquifer system (the Upper Floridan aquifer, the Lower Floridan aquifer, and the Fernandina permeable zone) are each represented by a single model layer. These model layers are referred to hereafter as aquifer layers. Simulated flow within the aquifer layers is entirely horizontal. The internal semiconfining units and the upper confining unit are each represented by a single VCONT array. These VCONT arrays are referred to hereafter as semiconfining unit layers. Simulated flow across the semiconfining unit layers is entirely vertical (Figure 22). The lower confining unit of the Floridan aquifer system, which is assumed to be completely impermeable, is not represented by a VCONT array, as simulated leakage through the bottom of the lowermost model layer of all MODFLOW models is zero by default. In this study, the term *leakance* will be used in lieu of *VCONT* hereafter because the two are assumed to be approximately equal due to large contrasts in the vertical permeabilities of the represented aquifers and semiconfining units.

Aquifer layer 1 represents the surficial aquifer system in the models of the study. Aquifer layer 1 functions as a constant-head, source/sink boundary for the underlying aquifer layers, which represent the aquifers of the Floridan aquifer system. All grid cells of aquifer layer 1 are designated as constant-head in all three of the models. This representation enables accurate simulation of vertical leakage between the Floridan aquifer system and the surficial aquifer system without requiring simulation of ground water flow within the surficial aquifer system.

Aquifer layers 2, 3, and 4 represent the aquifers of the Floridan aquifer system. Aquifer layers 2 and 3 represent the Upper and Lower Floridan aquifers, respectively, and consist entirely of variable-head cells. Aquifer layer 4 represents the Fernandina

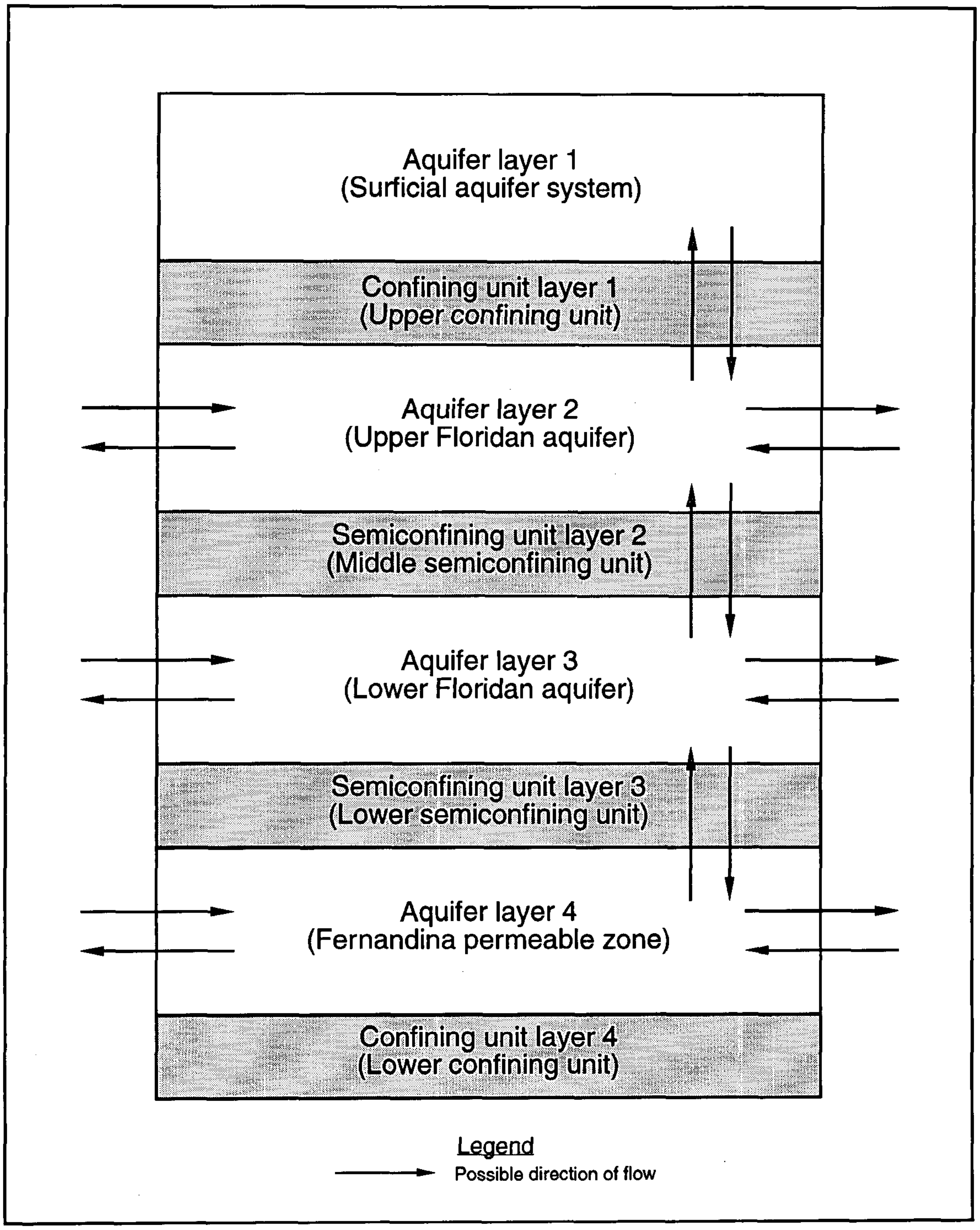


Figure 22. General configuration of the models of the study

permeable zone. In the predevelopment flow model, the cells of aquifer layer 4 were designated as either inactive or constant-head. In the postdevelopment flow model, the cells of aquifer layer 4 that were designated as constant-head in the predevelopment flow model were designated initially as constant-head also. Later, however, the cells were redesignated as variable-head to enable the simulation of changes in water levels in aquifer layer 4 in response to changes in withdrawals from wells in aquifer layers 2 and 3. The designations of the grid cells of aquifer layer 4 in the revised predevelopment flow model were consistent with those in the postdevelopment flow model.

In all three models, many cells of aquifer layer 4 corresponding to the northeast and southeast corners of the portion of the Fernandina permeable zone within the study area were designated as inactive because these areas of the Fernandina permeable zone are probably seaward of the intersection of the freshwater/saltwater interface with the top of the Fernandina permeable zone (i.e., the tip of the interface in the Fernandina permeable zone). The same cells were designated as no-flow in both the predevelopment and postdevelopment versions of the model because the freshwater/saltwater interface was assumed to have moved only a small amount in response to the ground water withdrawals that have occurred since predevelopment times. Later model simulations performed using a regional sharp-interface ground water model of the Floridan aquifer system of northeast Florida supported this assumption (Durden and Huang 1997, draft).

Semiconfining unit layers 1, 2, 3, and 4 represent the upper confining unit, the middle and lower semiconfining units, and the lower confining unit, respectively, in the models of the study (Figure 22).

Lateral Boundary Conditions

Lateral boundary conditions were specified for aquifer layers 2 and 3 in all three models and for aquifer layer 4 in the postdevelopment and revised predevelopment flow models. The lateral boundary conditions prescribed for cells in the outermost rows and columns of the models were either general-head boundary (GHB) or no-flow boundary conditions.

The GHB condition is a head-dependent-flux boundary condition. At each of the cells for which GHB conditions are prescribed, the rate of flux into or out of the model domain varies linearly in proportion to the difference between the hydraulic head specified at a point outside the model domain (the source head) and the value of hydraulic head calculated at the node of the cell.

The distance from the node of the cell to the point at which the source head is specified may vary from one cell to the next. Ideally, the corresponding point in the actual aquifer system is far enough from centers of withdrawal so that the hydraulic head at that point would not be expected to change significantly in response to anticipated changes in withdrawal rates.

Prescription of a no-flow lateral boundary condition for a given cell means that the side of the cell that faces outward from the finite-difference grid is represented as being impermeable in model simulations. This is the default lateral boundary condition in MODFLOW.

In the models of the present study, the type of lateral boundary condition prescribed for a given cell depended on the apparent or assumed direction of ground water flow relative to the orientation of the finite-difference grid at the location of the cell. Where the direction of ground water flow was primarily perpendicular to the outward face of a cell on an outermost row or column of a model grid, a GHB condition was prescribed; where the direction of ground water flow was primarily parallel to the outward face of such a cell, a no-flow boundary condition was prescribed.

For aquifer layer 2, directions of ground water flow were inferred from the configurations of the lines of equal elevation of hydraulic head shown on the maps of the potentiometric surfaces of the predevelopment (Johnston, Krause et al. 1980) and postdevelopment (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987) Upper Floridan aquifer (Figures 12 and 13).

Maps of the potentiometric surfaces of the Lower Floridan aquifer and Fernandina permeable zone were unavailable. Therefore, to specify appropriate lateral boundary conditions, the directions of ground water flow were assumed near the locations of the lateral boundaries of aquifer layer 3 in all three models and in aquifer layer 4 in the postdevelopment and revised predevelopment models.

In the Lower Floridan aquifer, the patterns of ground water flow were assumed to be similar to those observed in the Upper Floridan aquifer. Based on this assumption, cells in aquifer layer 3 were prescribed with the same boundary-condition types as those of corresponding cells in aquifer layer 2.

In the Fernandina permeable zone, a general pattern of west to east flow was assumed to exist in both the postdevelopment and predevelopment ground water flow systems. Accordingly, in the postdevelopment and revised predevelopment flow models, the cells along the western and eastern boundaries of aquifer layer 4 that were not designated as inactive cells due to the presence of saline water were prescribed with GHB conditions, while the cells along the southern and northern boundaries were prescribed with no-flow boundary conditions.

Lateral boundary conditions were not specified for aquifer layer 1 in any of the three models or in aquifer layer 4 in the predevelopment model because grid cells in these layers were designated either as constant-head or inactive. Consequently, finite-difference equations were not assembled for the grid cells of these layers, and lateral boundary conditions were not required.

Withdrawals from Wells

More than 400 wells that penetrate the Floridan aquifer system are present in the study area and are represented in the postdevelopment flow model (Appendix A). In MODFLOW, the locations of points of discharge are specified by layer, row, and column of the finite-difference grid. Several of the wells represented in the domain of the postdevelopment flow model are open to both the Upper and Lower Floridan aquifers and thus obtain water from both aquifers. Such wells are represented as well pairs in the postdevelopment flow model, with one well of the pair open exclusively to the Upper Floridan aquifer and the other open exclusively to the Lower Floridan aquifer. The total discharge from such wells was distributed between the model wells in proportion to the estimated transmissivities of the Upper and Lower Floridan aquifers.

Required Data Input

Aquifer Layers

For aquifer layer 1, the primary input data are estimates of the elevation of the water table (Table 7). These data were required for accurate determination of vertical leakage between aquifer layers 1 and 2. Proper formatting of the MODFLOW input file in which hydraulic parameters are submitted requires specification of a value of hydraulic conductivity and bottom elevation for aquifer layer 1. However, because aquifer layer 1 is a constant-head boundary, the values entered have no effect on the results of the model simulations.

Required input data were the same for aquifer layers 2 and 3 in all three models and in aquifer layer 4 in the postdevelopment and revised predevelopment models. All three layers required estimates of transmissivity and initial estimates of hydraulic head. Estimates of conductance were required as well for each of the GHB conditions prescribed to grid cells in these layers. In addition, an estimate of the ratio of the transmissivity or hydraulic conductivity along a model column to the transmissivity or hydraulic conductivity along a model row (the anisotropy factor) was required for each aquifer layer. As with the hydraulic conductivity and bottom-elevation values assigned to aquifer layer 1, the value of the anisotropy factor assigned to aquifer layer 1 has no effect on the results of the model simulations. Likewise, the value assigned to aquifer layer 4 of the predevelopment flow model also has no effect on model simulations.

Conductance is derived from Darcy's equation and is the product of hydraulic conductivity and cross-sectional area of flow divided by the length of the flow path (McDonald and Harbaugh 1988). This

Table 7. Summary of model configurations

Hydrologic Unit	Model Representation	Required Input Data
Surficial aquifer system	Aquifer layer 1	Hydraulic conductivity, aquifer bottom elevation, water table elevation, and anisotropy factor
Upper confining unit	Semiconfining unit layer 1	Leakance
Upper Floridan aquifer	Aquifer layer 2	Transmissivity, conductance, hydraulic head, and anisotropy factor
Middle semiconfining unit	Semiconfining unit layer 2	Leakance
Lower Floridan aquifer	Aquifer layer 3	Transmissivity, conductance, hydraulic head, and anisotropy factor
Lower semiconfining unit	Semiconfining unit layer 3	Leakance
Fernandina permeable zone	Aquifer layer 4	Predevelopment flow model: hydraulic head; postdevelopment and revised predevelopment flow models: transmissivity, conductance, hydraulic head, and anisotropy factor
Lower confining unit	Semiconfining unit layer 4	None (zero leakance implied)

may be written as

$$C = \frac{KA}{L} \tag{1}$$

where:

C = conductance
K = hydraulic conductivity
A = the cross-sectional area perpendicular to the direction of flow
L = the length of the flow path

Within model layers, conductance may be expressed in terms of transmissivity as

$$C = \frac{TW}{L} \tag{2}$$

where:

C = conductance
T = transmissivity, which equals the product of hydraulic conductivity and the saturated thickness of the aquifer
W = the width of the cross-sectional area normal to the direction of flow
L = the length of the flow path

In the predevelopment flow model, aquifer layer 4 was represented as a constant-head boundary, except in cells corresponding to locations that were judged to be seaward of the tip of the interface in the Fernandina permeable zone. Therefore, estimates of hydraulic head were required as data input. Proper formatting of the MODFLOW input file in which hydraulic parameters are submitted required the specification of a transmissivity value for aquifer layer 4. However, the value entered had no effect on the model simulations because the grid cells of aquifer layer 4 were designated as either constant-head or inactive in the predevelopment flow model.

Semiconfining Unit Layers

Semiconfining unit layers 1, 2, and 3 required estimates of leakance. Semiconfining unit layer 4 did not require data input. The assumption that this layer is impermeable is implicit in MODFLOW; therefore, leakance is specified by default as zero for this layer.

THE PREDEVELOPMENT FLOW MODEL

The model of the predevelopment Floridan aquifer system was developed primarily to provide initial estimates of transmissivity and leakance for the calibration of the postdevelopment flow model. Initial calibration to predevelopment conditions is advantageous because estimates of transmissivity and leakance can be obtained independently of the estimates of well locations and rates of withdrawals. The absence of withdrawals from wells however is a disadvantage because calibrations performed to unstressed conditions are more likely to result in inaccurate estimates of transmissivity and leakance. In many cases, a lack of predevelopment hydraulic-head data represents an additional disadvantage, also limiting the accuracy of the calibration results.

In the present study, observations of hydraulic head in the predevelopment Lower Floridan aquifer and Fernandina permeable zone were unavailable altogether. Observations of hydraulic head in the predevelopment Upper Floridan aquifer were scarce. As a result, the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) is accurate in the study area only to within about ±10 ft (based on Krause 1982).

Because of the unavailability of hydraulic-head observations in the Lower Floridan aquifer and Fernandina permeable zone, adjustments in aquifer parameters were limited primarily to the estimates of transmissivity of aquifer layer 2 (i.e., the representation of the Upper Floridan aquifer) and estimates of leakance of semiconfining unit layer 1 (i.e., the representation of the upper confining unit) (Figure 22). When adjustments were made to the estimates of transmissivity or leakance of other aquifer or semiconfining unit layers, the effectiveness of the adjustments was determined primarily by evaluating the response of the simulated potentiometric surface of the Upper Floridan aquifer.

FINITE-DIFFERENCE GRID

The finite-difference grid of the predevelopment flow model consists of 68 rows and 35 columns (2,380 finite-difference cells per aquifer layer) (Figure 23). The rows of the grid are oriented approximately along lines of latitude, and the columns of the grid are oriented approximately along lines of longitude. The width of the grid corresponds approximately to 44 mi, and the length corresponds approximately to 83 mi.

In designing the finite-difference grid, an attempt was made to minimize the number of grid cells. Therefore, the dimensions of the rows and columns of the grid are smaller in areas that are of greater interest in the study. The smallest grid cells correspond approximately to 1 mi^2 of area. These cells are concentrated in the parts of the grid that correspond to the areas of Jacksonville, Fernandina Beach, and the Atlantic coast (Figures 1 and 23). From these parts of the grid, the dimensions of the rows and columns were increased in all directions except toward the north. Toward the western edge of the grid, the column dimensions were increased to correspond to a maximum width of 2.0 mi. Toward the eastern edge of the grid, the column dimensions were increased to correspond to a maximum width of 4.4 mi. Toward the southern edge of the grid, the row dimensions were increased to correspond to a maximum width of 3.5 mi (Figure 23). The largest grid cells correspond approximately to 15 mi^2 of area.

LATERAL BOUNDARY CONDITIONS

Aquifer Layer 1

Lateral boundary conditions for aquifer layer 1 (i.e., the model representation of the surficial aquifer system) (Figure 22) were not required because the cells in this layer were all designated as constant-head.

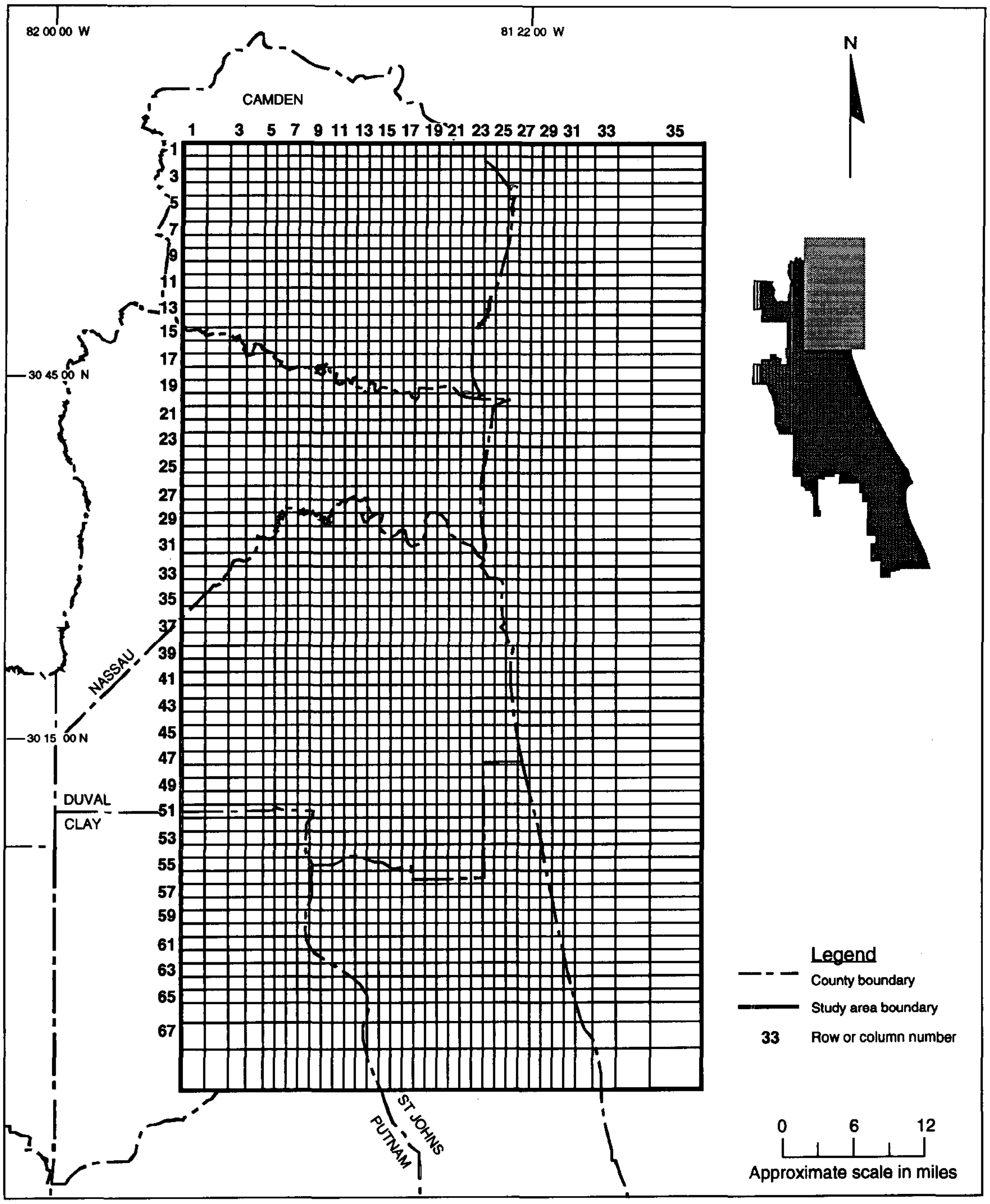


Figure 23. Numbering convention of the rows and columns of the finite-difference grid

Aquifer Layer 2

Lateral boundary conditions for aquifer layer 2 (i.e., the model representation of the Upper Floridan aquifer) (Figure 22) were established by first superimposing a representation of the finite-difference grid of the model (Figure 23) onto the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 12). This enabled the directions of ground water flow to be inferred in areas to which the cells of the outermost rows and columns correspond. GHB conditions were prescribed at most of the 202 cells on the outermost rows and columns of the finite-difference grid. Two lateral boundary conditions were prescribed for corner cells of the finite-difference grid, one for each of the two outward cell faces (Figure 24).

On the westernmost column of the grid, GHB conditions were prescribed at all but four of the cells, reflecting the general pattern of west to east flow that existed in the western portion of the study area (Figure 24). On the northernmost row of the grid, no-flow lateral boundary conditions were prescribed at all of the cells, also reflecting a general pattern of west to east flow. A combination of GHB and no-flow lateral boundary conditions was prescribed in cases in which the general direction of ground water flow was neither predominantly perpendicular nor parallel to the direction of orientation of an outermost row or column of the finite-difference grid. This phenomenon occurred with respect to the easternmost column and southernmost row of the grid. In areas corresponding to those parts of the model domain, the direction of ground water flow was primarily to the southeast. This phenomenon occurred also with respect to the southern part of the westernmost column. In the area corresponding to that part of the model domain, the direction of ground water flow was primarily to the northeast.

The distance between the edge of the finite-difference grid and the points at which the GHB-condition source heads are specified corresponds to 6.6 mi along the western boundary, 3.5 mi along the southern boundary, and 2.0 mi along the eastern boundary of the model (Figure 24). Uniform distances were specified within each of the boundary segments to simplify calculation of the conductance of

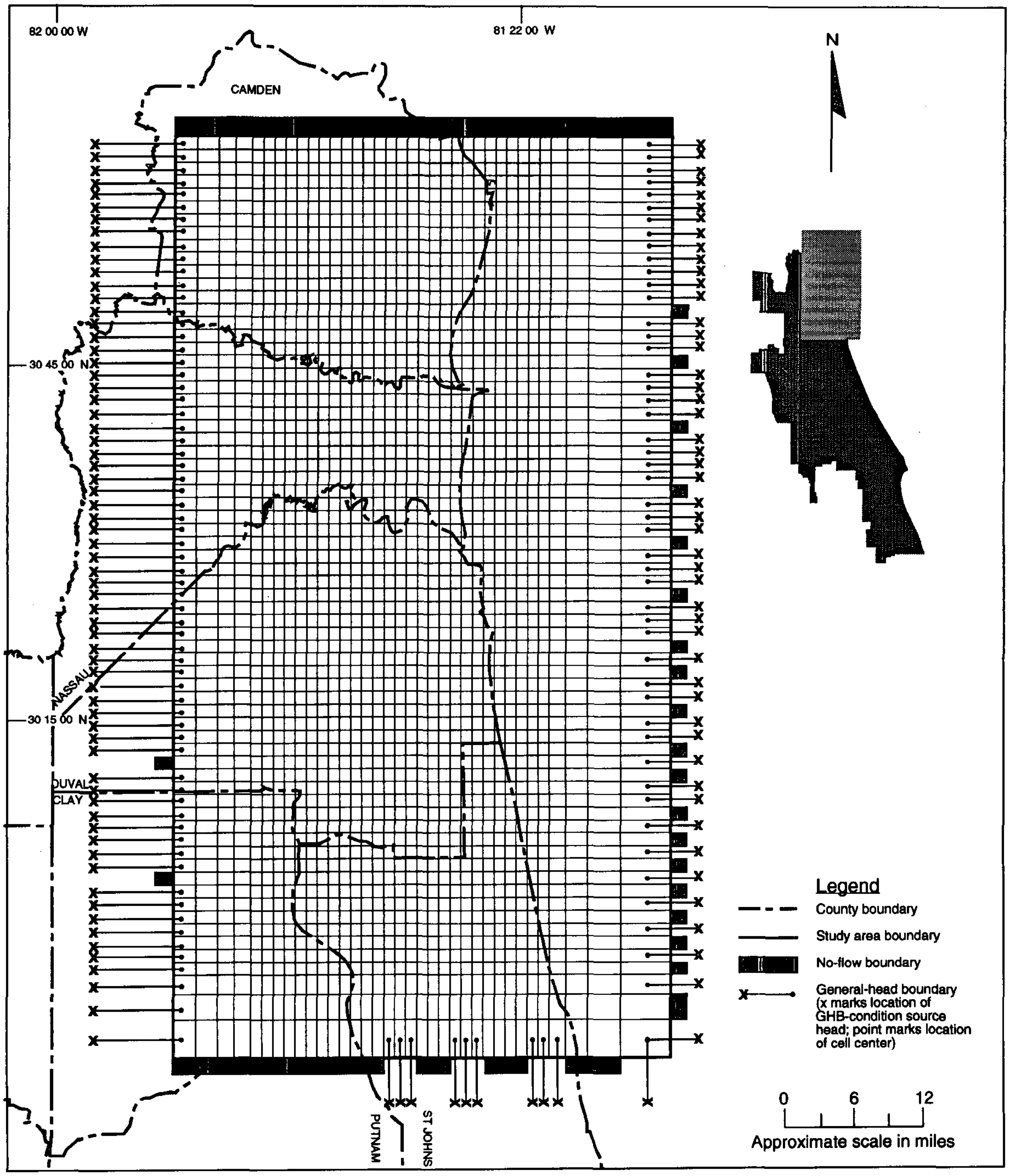


Figure 24. Lateral boundary conditions of aquifer layers 2 and 3 of the predevelopment flow model

the GHB conditions. The distances between nodes and corresponding GHB-condition source heads were chosen to be as great as was felt possible without violating the assumption of linearity in the distribution of hydraulic head between nodes and corresponding GHB-condition source heads. Thus, along a boundary segment in which the slope of the potentiometric surface of the Upper Floridan aquifer tended to change at a generally greater rate, a smaller distance was specified. The distances specified were meted out in increments of latitudinal or longitudinal minutes. As a result, the fractional portions of the distances correspond in some cases to values other than 0.0 or 0.5 mi. Once the locations of the source heads were determined, values of hydraulic head of the Upper Floridan aquifer were estimated by interpolating between the lines of equal elevation of hydraulic head shown on the map of the predevelopment potentiometric surface (Figure 12) (Johnston, Krause et al. 1980).

Aquifer Layer 3

In aquifer layer 3, the distances between the edges of the finite-difference grid and the points at which the GHB-condition source heads are specified are the same as for corresponding cells in aquifer layer 2. The values of hydraulic head specified at these locations were obtained by subtracting or adding a foot of hydraulic head from or to the values of hydraulic head specified at corresponding points in aquifer layer 2. A foot of hydraulic head was added if the grid cell to which the GHB condition was prescribed corresponded to a grid cell in aquifer layer 2 at which there was an upward vertical hydraulic gradient between the Upper Floridan aquifer and the surficial aquifer system. Likewise, a foot of hydraulic head was subtracted if the grid cell to which the GHB condition was prescribed corresponded to a grid cell in aquifer layer 2 at which there was a downward vertical hydraulic gradient between the Upper Floridan aquifer and the surficial aquifer system.

The direction of the vertical hydraulic gradient between the Upper Floridan aquifer and the surficial aquifer system was determined by taking the difference in estimated elevations of the water table of the surficial aquifer system and corresponding estimates of the hydraulic head of the Upper Floridan aquifer, as determined from the Johnston, Krause et al. (1980) map of the predevelopment potentiometric surface (Figure 12). Implicit to this procedure is the assumption that the direction of the vertical hydraulic gradient between the Lower and Upper Floridan aquifers was the same as that between the Upper Floridan aquifer and surficial aquifer system.

The difference of 1 ft that was applied to the predevelopment flow model is based indirectly on observations made in the postdevelopment flow system. Recently, measurements of hydraulic head were made as a function of depth within the Floridan aquifer system of the study area in three different monitoring wells, wells D-3060, D-2386, and SJ-0025 (Figure 16). Differences in the vertically averaged hydraulic head of the Upper and Lower Floridan aquifers were between 2 and 3 ft at the locations of wells D-3060 and D-2386 and 7 ft at the location of well SJ-0025 (respectively, Brown et al. 1985, 1984, and 1986). While no actual data concerning differences in hydraulic head between the predevelopment Upper and Lower Floridan aquifers are available, the differences were undoubtedly smaller on average than those of the postdevelopment flow system due to the absence of ground water withdrawals from the Upper Floridan aquifer. The assumed difference of 1 ft, therefore, is smaller than the lower end of the range of difference estimated, based on the head observations in the postdevelopment flow system. It is, nevertheless, generally on a par with those differences. More precise estimates probably cannot be made due to the lack of data.

Aquifer Layer 4

Lateral boundary conditions were not specified for aquifer layer 4 (i.e., the representation of the Fernandina permeable zone) (Figure 22) in the predevelopment flow model because the cells in this model were designated as either constant-head or inactive.

MODEL DATA REQUIREMENTS

Estimated Water Table Elevations

Prior to beginning the calibration, average elevations of the water table over the areas corresponding to the cells of the finite-difference grid were estimated. The resulting estimates of the elevation of the water table were used in both the predevelopment and postdevelopment flow models. This approach was based on the assumption that water levels in the surficial aquifer system of the study area were not affected significantly by the advent of ground water withdrawals from the Floridan aquifer system due to the relative impermeability of the upper confining unit.

Estimates of the elevation of the water table were based on correlations established between the elevation of the water table and the corresponding elevation of the land surface. The data used to establish the correlations were obtained from well sites in Duval and Clay counties and were published in reports by Causey (1975, Duval) and Clark et al. (1964, Clay).

Causey (1975) reported minimum and maximum depths to the water table relative to land surface as observed between March 21, 1972, and June 30, 1975, at well locations scattered throughout Duval County. The elevations of the water table corresponding to the maximum depths below land surface at each of the well sites were reported as well.

In the present study, land surface elevations were established at each of the well sites by adding the reported maximum depth below land surface to the corresponding water table elevation. The minimum and maximum depths to the water table corresponding to each of the well locations were averaged to obtain an estimate of the long-term, average depth to the water table. The estimated average depth to the water table was subtracted from the land surface elevation to establish the estimated average water table elevation at each well site.

The water table data reported in Clark et al. (1964) are point values shown on a map of the water table. The locations of the data points were scaled from the map, and the corresponding elevations of the land surface were estimated from USGS 1:24,000-scale topographic maps. Most of these data points were located just to the west of the present study area but are, nevertheless, representative of the land surface physiography of parts of the present study area.

Once compiled, all the data points were plotted in cartesian format as water table elevation versus land surface elevation, and a regression analysis was performed to fit a smooth curve through the data points (Figure 25). The program used to perform the regression analysis was CFIT, which is included in the Hewlett-Packard (HP) Advantage Pac accessory for the HP 41CV model calculator. The equation of the resulting curve is

$$\begin{aligned} we &= 0.903(lse) - 0.088 \\ R^2 &= 0.97 \end{aligned} \tag{3}$$

where:

we = the water table elevation (ft NGVD)
lse = the land surface elevation (ft NGVD)
R^2 = the coefficient of determination

Once this equation was determined, average land surface elevations were estimated over areas corresponding to each grid cell located on land, using either USGS 1:100,000- or 1:24,000-scale topographic maps. The equation was used with careful consideration of physical features represented on the topographic maps, such as water bodies and wetlands. A map of the average elevation of the water table throughout the study area was thus produced (Figure 26).

Grid cells located in the ocean were necessarily treated differently. Hydraulically, the effect of the ocean surface on rates of discharge from the part of the Floridan aquifer system located beneath the ocean is similar to the effect of the water table on the part of the Floridan aquifer system located beneath the land surface. However, because ocean water is saline, the level of the ocean surface was adjusted to an equivalent freshwater head, which was approximated

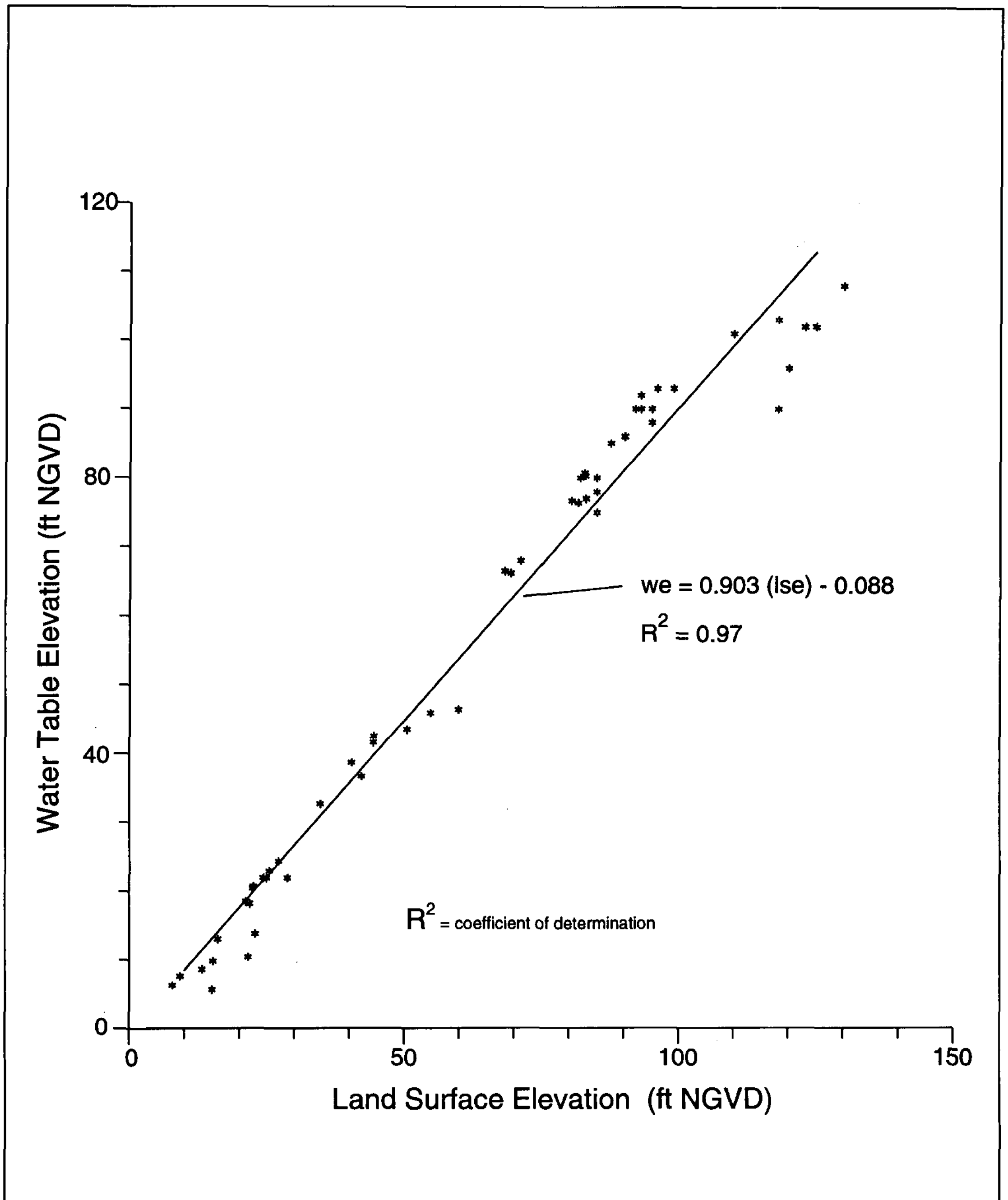


Figure 25. Water table elevation (we) versus land surface elevation (lse) (modified from Clark et al. 1964 and Causey 1975)

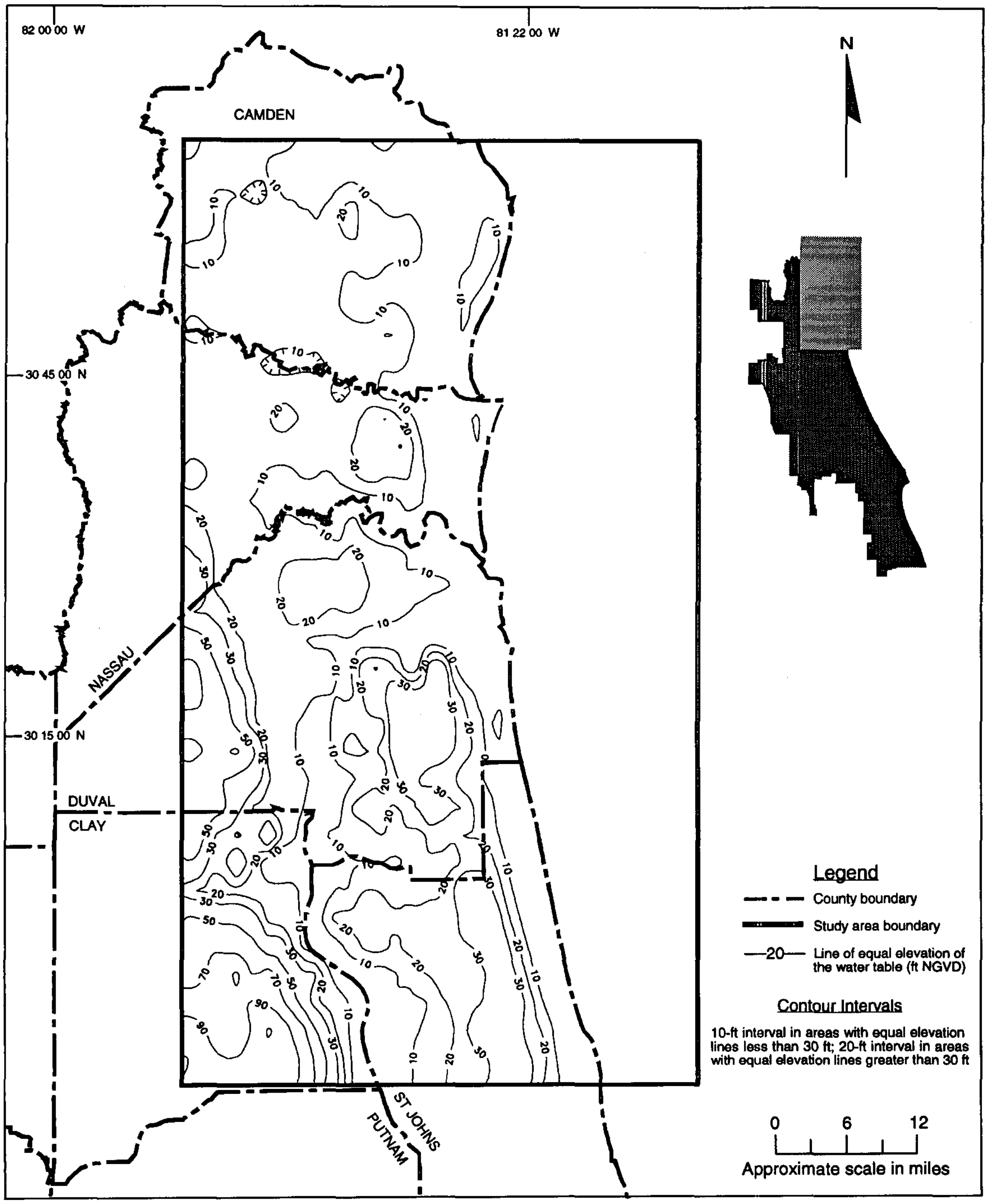


Figure 26. Estimated average elevations of the water table of the surficial aquifer system

according to the following equation:

$$h_f = d_s\left(\frac{Y_s}{Y_f} - 1\right) \tag{4}$$

where:

h_f = the equivalent freshwater head of the ocean, relative to NGVD
d_s = the depth of the ocean
Y_s = the specific weight of seawater
Y_f = the specific weight of freshwater

Use of Equation 4 results in values of hydraulic head that approach zero near the coast and become greater as the distance from the coast increases. The average depth of the ocean over the areas corresponding to each of the grid cells was estimated from bathymetric contours shown on USGS 1:100,000-scale topographic maps.

Delineation of the Freshwater/Saltwater Interface

Grid cells in the northeast and southeast corners of aquifer layer 4 were found to correspond to areas of the Fernandina permeable zone that are seaward of the intersection of the freshwater/saltwater interface with the top of the Fernandina permeable zone (i.e., the tip of the interface) (Figure 27). The area of saline water to which the northeast corner of aquifer layer 4 corresponds was delineated by comparing the estimated position of the top of the Fernandina permeable zone to the estimated vertical position of the interface. The onshore vertical position of the interface was approximated from chloride concentration data obtained from deep-test wells N-0117, D-2386, and SJ-0025 (respectively, Brown 1980; Brown et al. 1984; Brown et al. 1986) (Figure 16). The offshore vertical position of the interface tip was approximated using data and conclusions from Johnston, Bush et al. (1980) (Figure 19).

Data collected at the deep-test wells indicate that the vertical position of the interface along the Atlantic coast between Fernandina Beach

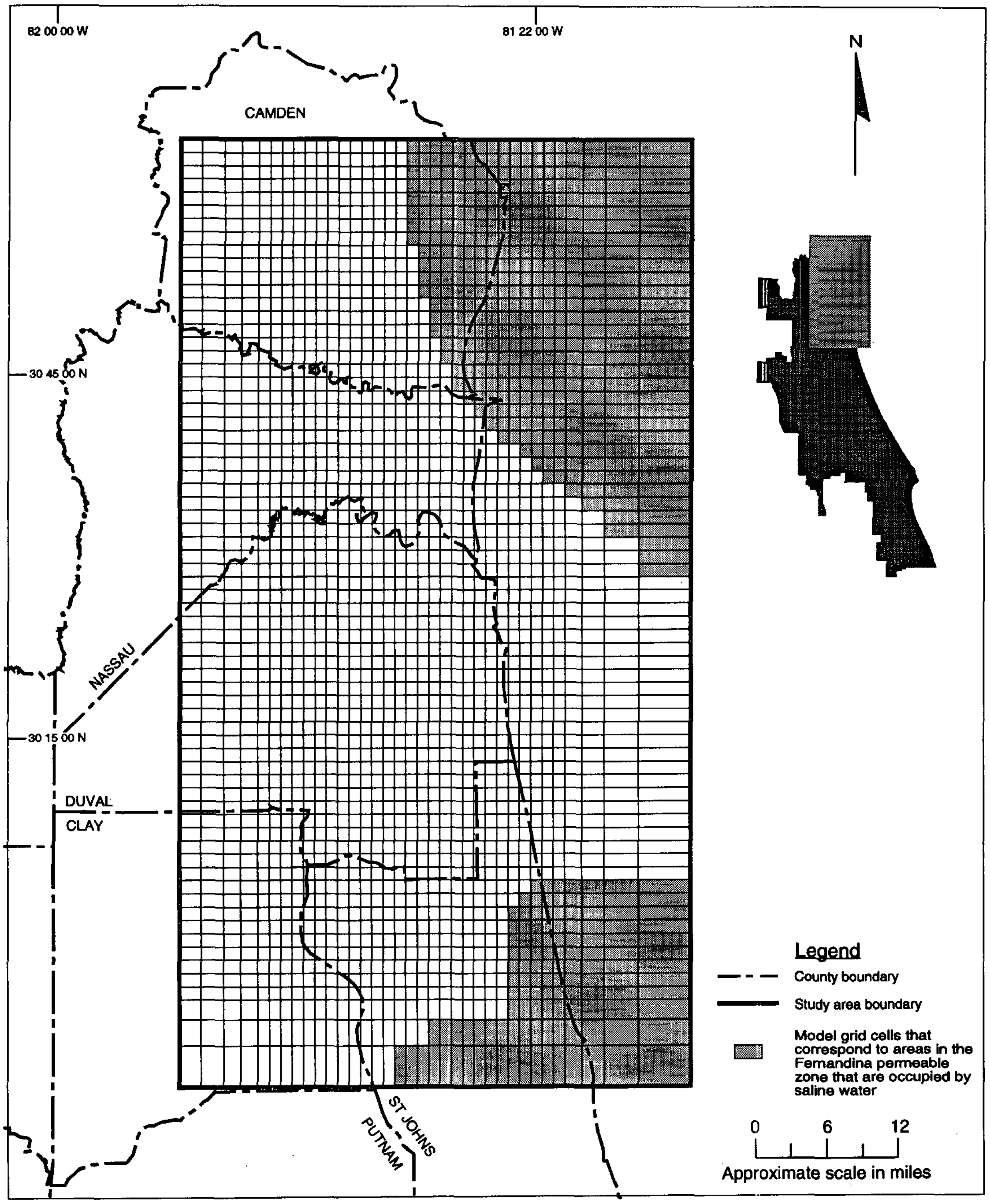


Figure 27. Locations of model grid cells in aquifer layer 4 occupied entirely by saline water

and Ponte Vedra Beach is approximately 2,000 ft bNGVD. At Fernandina Beach, the top of the Fernandina permeable zone is approximately 2,000 ft bNGVD as well (Miller 1986). In the coastal areas of Camden County to the north of Fernandina Beach, the top of the Fernandina permeable zone is between 2,000 and 2,100 ft bNGVD (Miller 1986). In the coastal areas to the south of Fernandina Beach, the top of the Fernandina permeable zone slopes upwardly; it is approximately 1,700 ft bNGVD at the site of deep-test well D-2386 and 1,600 ft bNGVD at the site of deep-test well SJ-0025 (Miller 1986) (Figure 16). Based on these considerations, the position of the interface tip in the Fernandina permeable zone was approximated as being coincident with the Atlantic coast in the vicinity of Fernandina Beach, somewhat west of the Atlantic coast to the north of Fernandina Beach and east of the Atlantic coast to the south of Fernandina Beach.

The position of the interface tip in the Fernandina permeable zone to the south of Fernandina Beach and east of the Atlantic coast was estimated by first determining the elevation of the top of the Fernandina permeable zone at the mouth of the Nassau River (Figure 1) to be approximately 1,800 ft bNGVD (Miller 1986). The elevation of the top of the Fernandina permeable zone was assumed to be constant at all points along an imaginary east-west segment connecting the mouth of the Nassau River to the eastern boundary of the study area, a distance of approximately 16 mi. A horizontal line representing the top of the Fernandina permeable zone at this elevation was superimposed onto the plot of the offshore position of the interface (Johnston, Bush et al. 1980) (Figure 19) and was found to intersect with the line representing the interface at a distance of 14 mi to the east of the Atlantic coast.

The intersection of the two lines was taken as the approximate position of the interface tip in the Fernandina permeable zone to the east of the mouth of the Nassau River. A straight line between Fernandina Beach and this point was then plotted onto a base map of the study area and was assumed to coincide with the approximate line of the interface tip in the Fernandina permeable zone. The line was extended to the southeast until it intersected with a line representing the eastern boundary of the study area. The area of saline water in the Fernandina permeable zone in the northeast corner of the model domain was thus delineated fully (Figure 27).

Grid cells in aquifer layer 4 that correspond to areas that are seaward of the line of the interface tip were designated as inactive because these cells correspond to areas that are presumably outside the freshwater flow system in the Fernandina permeable zone.

The line representing the interface did not intersect with the assumed offshore position of the top of the Lower Floridan aquifer along the imaginary east-west segment between the mouth of the Nassau River and the eastern edge of the model grid. Therefore, this area of the Upper and Lower Floridan aquifers was assumed to be occupied by freshwater. Consequently, grid cells corresponding to this area in aquifer layers 2 and 3 were designated as variable-head rather than inactive.

Delineation of the area of saline water in the southeast corner of the model domain involved overlaying a representation of the finite-difference grid of the model onto a map of chloride concentrations in the Upper Floridan aquifer, as shown in a report by Toth (1990) (Figure 18). Ground water in the Fernandina permeable zone was assumed to be saline in areas of St. Johns County in which chloride concentrations in the Upper Floridan aquifer were shown to exceed 100 mg/L (Toth 1990) (Figure 18). Ground water was assumed to be saline to the east of this area as well (Figure 27).

The approximate position of the line of the interface tip in the Fernandina permeable zone was assumed to coincide with the western boundary of the resulting area. Grid cells in aquifer layer 4 that corresponded to areas east of this boundary were designated as inactive because those areas are presumably seaward of the boundary of the freshwater flow system in the Fernandina permeable zone. Ground water in the Lower Floridan aquifer was assumed to be relatively fresh in this area as well; therefore, no grid cells in aquifer layer 3 were designated as inactive. No wells are known to penetrate the Lower Floridan aquifer or Fernandina permeable zone in this area; therefore, more exact estimates of the horizontal and vertical positions of the interface could not be determined.

Initial Hydraulic-Head Distributions

Initial values of hydraulic head must be specified to initiate the iterative solving procedure used in the models of the study. In variable-head cells of the model, the same simulated values of hydraulic head will result from model simulations regardless of the specified initial values. The same values result because the models of the study simulate steady-state conditions, which are the same regardless of specified initial conditions. The accuracy of the initial values of hydraulic head assigned to variable-head cells of the models is therefore not critical, though a degree of accuracy is desirable to minimize the convergence time of the iterative solver.

The initial values of hydraulic head assigned to constant-head cells, of course, stay the same throughout the simulation. Therefore, these values can affect significantly the results of the model simulation. In recognition of this effect, efforts were made to estimate, as accurately as possible, the initial values of hydraulic head to be assigned to constant-head cells.

Aquifer Layer 1

The initial values of hydraulic head specified in aquifer layer 1 were the estimates of the elevation of the water table and the equivalent-freshwater head of the ocean, as discussed previously.

Aquifer Layer 2

The initial values of hydraulic head assigned to the grid cells of aquifer layer 2 were interpolated from lines of equal elevation of hydraulic head shown on the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 12). These values were used to calculate hydraulic-head residuals in aquifer layer 2.

Aquifer Layer 3

Initial values of hydraulic head were specified for the grid cells of aquifer layer 3 by either subtracting or adding a foot of hydraulic head to corresponding estimates of hydraulic head in the grid cells of aquifer layer 2. A foot of hydraulic head was added if the vertical hydraulic gradient between the Upper Floridan aquifer and surficial aquifer system was upward at the corresponding grid cell in aquifer layer 2. A foot of hydraulic head was subtracted if the vertical hydraulic gradient between the Upper Floridan aquifer and surficial aquifer system was downward at the corresponding grid cell in aquifer layer 2.

Aquifer Layer 4

The cells of aquifer layer 4 were designated as constant-head, unless they corresponded to areas of the Fernandina permeable zone that were determined to be occupied with saline water (Figure 27). The approach used to specify initial values of hydraulic head for aquifer layer 3 would have resulted in the presumption of a potentiometric low in aquifer layer 4 corresponding to the potentiometric low in the Upper Floridan aquifer between Green Cove Springs and the Duval-Clay county line (Figures 1 and 12). Because such a potentiometric low may not have existed in the predevelopment Fernandina permeable zone, the approach used for aquifer layer 3 was not used for aquifer layer 4.

In the approach that was used, the predevelopment flow model was reconfigured temporarily to consist of only three aquifer layers instead of four, with aquifer layers 3 and 4 being replaced by a single aquifer layer representing a composite of the predevelopment Lower Floridan aquifer and Fernandina permeable zone. Values of hydraulic head simulated in this aquifer layer were assumed to be intermediate to values that would have been observed in the predevelopment Lower Floridan aquifer and Fernandina permeable zone.

Then, similar to the procedure used for aquifer layer 3, a foot of hydraulic head was either subtracted from or added to the simulated values of hydraulic head in the grid cells of the composite aquifer layer that corresponded to the constant-head grid cells of aquifer layer 4. Whether a foot of hydraulic head was subtracted or added depended on the direction of the vertical hydraulic gradient between the Upper Floridan aquifer and the surficial aquifer system. The resulting values of hydraulic head were specified as initial values in the corresponding cells of aquifer layer 4 of the predevelopment flow model. The reconfigured model was discarded at this point. As the calibration of the predevelopment flow model progressed, the values of hydraulic head assigned to aquifer layer 4 were updated periodically by subtracting or adding a foot of hydraulic head from or to values of hydraulic head simulated in corresponding cells in aquifer layer 3.

TRANSMISSIVITY

Aquifer Layer 2

Transmissivity in the Upper Floridan aquifer was estimated primarily from the results of ground water modeling studies performed by Durden and Motz (1991) and Krause and Randolph (1990).

Aquifer Layer 3

Transmissivity in the Lower Floridan aquifer was estimated initially from the results of the ground water modeling study performed by Durden and Motz (1991). Transmissivity estimates obtained from that study were extrapolated or interpolated in the present study area. Estimates from the modeling study performed by Krause and Randolph (1989) also were used.

LEAKANCE

Semiconfining Unit Layer 1

Leakance of the upper confining unit was estimated primarily from the ground water modeling studies of Durden and Motz (1991) and Krause and Randolph (1989).

Semiconfining Unit Layer 2

Leakance of MSCU was estimated initially from the ground water modeling study of Durden and Motz (1991). As with the initial transmissivity estimates of the Lower Floridan aquifer, leakance estimates of MSCU were extrapolated into parts of the present study area as necessary.

Semiconfining Unit Layer 3

Initial leakance estimates of LSCU were based on estimates used in the ground water flow model of the Floridan aquifer system developed by Krause and Randolph (1989).

ANISOTROPY FACTOR

An anisotropy factor of 1 was assigned to all four aquifer layers of the predevelopment flow model.

MODEL CALIBRATION

In calibrating the predevelopment flow model, the primary goal was to minimize the differences between the estimated and simulated potentiometric surfaces of the Upper Floridan aquifer using physically realistic estimates of transmissivity and leakance. The calibration procedure involved using trial transmissivity and leakance distributions to simulate the predevelopment potentiometric surface of the Upper Floridan aquifer.

Calibration progress was monitored using several different techniques. Progress was monitored quantitatively by calculating the mean and standard deviation of the hydraulic-head residuals in aquifer layer 2 at the end of each simulation. Hydraulic-head residuals were computed as the differences in elevation between simulated values of hydraulic head and values interpolated from the map of Johnston, Krause et al. (1980) at points corresponding to the nodes of the model grid cells. Progress in the calibration was monitored also by determining the percentages of the absolute values of the hydraulic-head residuals in aquifer layer 2 less than or equal to 5 and 10 ft and by calculating the mean of the absolute values.

Progress was monitored qualitatively by visually comparing maps of the simulated potentiometric surface of the Upper Floridan aquifer to the map of the estimated potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 12). Progress was monitored as well by visually inspecting maps of the hydraulic-head residuals of aquifer layer 2.

Residual Statistics

The final mean of the hydraulic-head residuals in aquifer layer 2 was -1.1 ft, the negative sign indicating that simulated values of hydraulic head were higher on average than interpolated values. The standard deviation of the hydraulic-head residuals in aquifer layer 2 was 2.3 ft. The mean of the absolute values was 2.0 ft. The range of the hydraulic-head residuals in aquifer layer 2 was from -10.0 to 5.4 ft. Thus, 100% of the absolute values in aquifer layer 2 were less than or equal to 10 ft, while 93% were less than or equal to 5 ft. As stated earlier, the map of the potentiometric surface of the predevelopment Upper Floridan aquifer is accurate in the study area only to within ±10 ft (based on Krause 1982). Therefore, the final mean, standard deviation, and range of the hydraulic-head residuals resulting from the calibration of the predevelopment flow model are apparently within reason.

Comparison of Estimated and Simulated Potentiometric Surfaces and Inspection of Residual Maps

A comparison of maps of the estimated and simulated potentiometric surfaces of the predevelopment Upper Floridan aquifer indicates the degree to which the basic features of the predevelopment flow system in the Upper Floridan aquifer were simulated by the predevelopment flow model (Figure 28). Maps of hydraulic-head residuals of aquifer layer 2 represent a spatial distribution of error in the model simulation. During calibration, both types of plots were used to determine the level of agreement between the estimated and simulated potentiometric surfaces in various subregions of the model

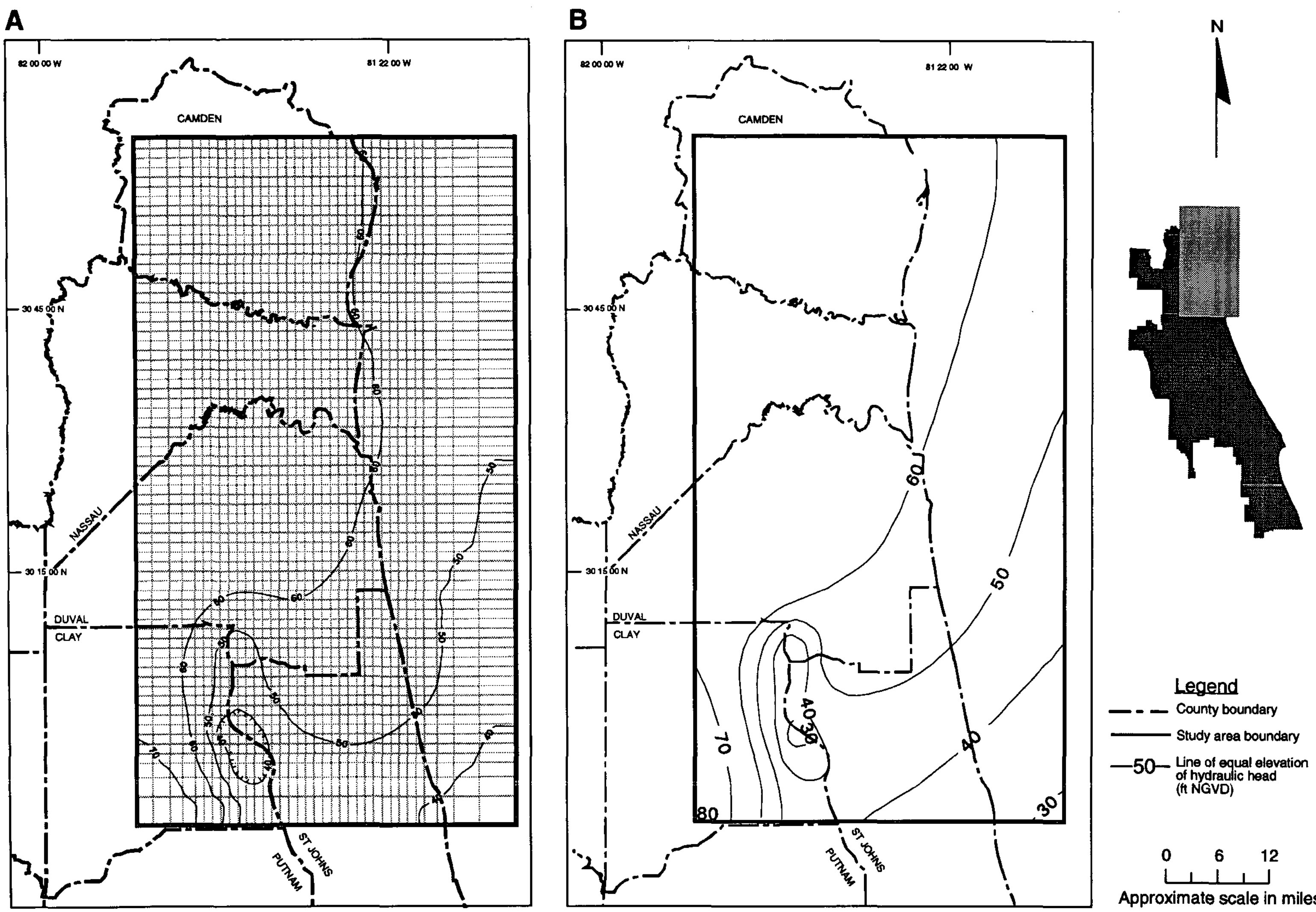


Figure 28. Simulated (A) and estimated (B) predevelopment potentiometric surfaces of the Upper Floridan aquifer

domain, thereby indicating where the greatest amount of additional calibration was needed.

Lines of Equal Elevation of Hydraulic Head

The essential shapes and positions of the lines of equal elevation of hydraulic head of the estimated potentiometric surface (Johnston, Krause et al. 1980) were simulated by the model, despite some deviations (Figure 28). The close agreement between the estimated and simulated potentiometric surfaces indicates that the essential features of the predevelopment flow system were simulated successfully by the predevelopment flow model.

Map of Hydraulic-Head Residuals

A map of hydraulic-head residuals of aquifer layer 2 shows that the simulated potentiometric surface of the Upper Floridan aquifer is 0 to 5 ft higher than the estimated potentiometric surface in most of the model domain (Figure 29). In the southeast corner of the model domain, the simulated potentiometric surface is 5 to 10 ft higher than the estimated potentiometric surface (Johnston, Krause et al. 1980). The simulated potentiometric surface is 0 to 5 ft lower in most of the southwest corner of the model domain but is as much as 5 to 10 ft lower in isolated areas (Figure 29). These results are acceptable, especially given the uncertainties concerning the estimated potentiometric surface of the predevelopment Upper Floridan aquifer and the limited objectives in developing the predevelopment model.

RESULTANT DISTRIBUTIONS OF HYDRAULIC PARAMETERS

Transmissivity

Aquifer Layer 2. Calibration of the predevelopment flow model was attained without making substantial changes in the initial estimates of transmissivity. The resulting estimates of transmissivity of the Upper Floridan aquifer ranged from 2,400 ft^2/day to 540,000 ft^2/day (Figure 30). The arithmetic mean was 159,000 ft^2/day. Estimates tended to decrease from west to east.

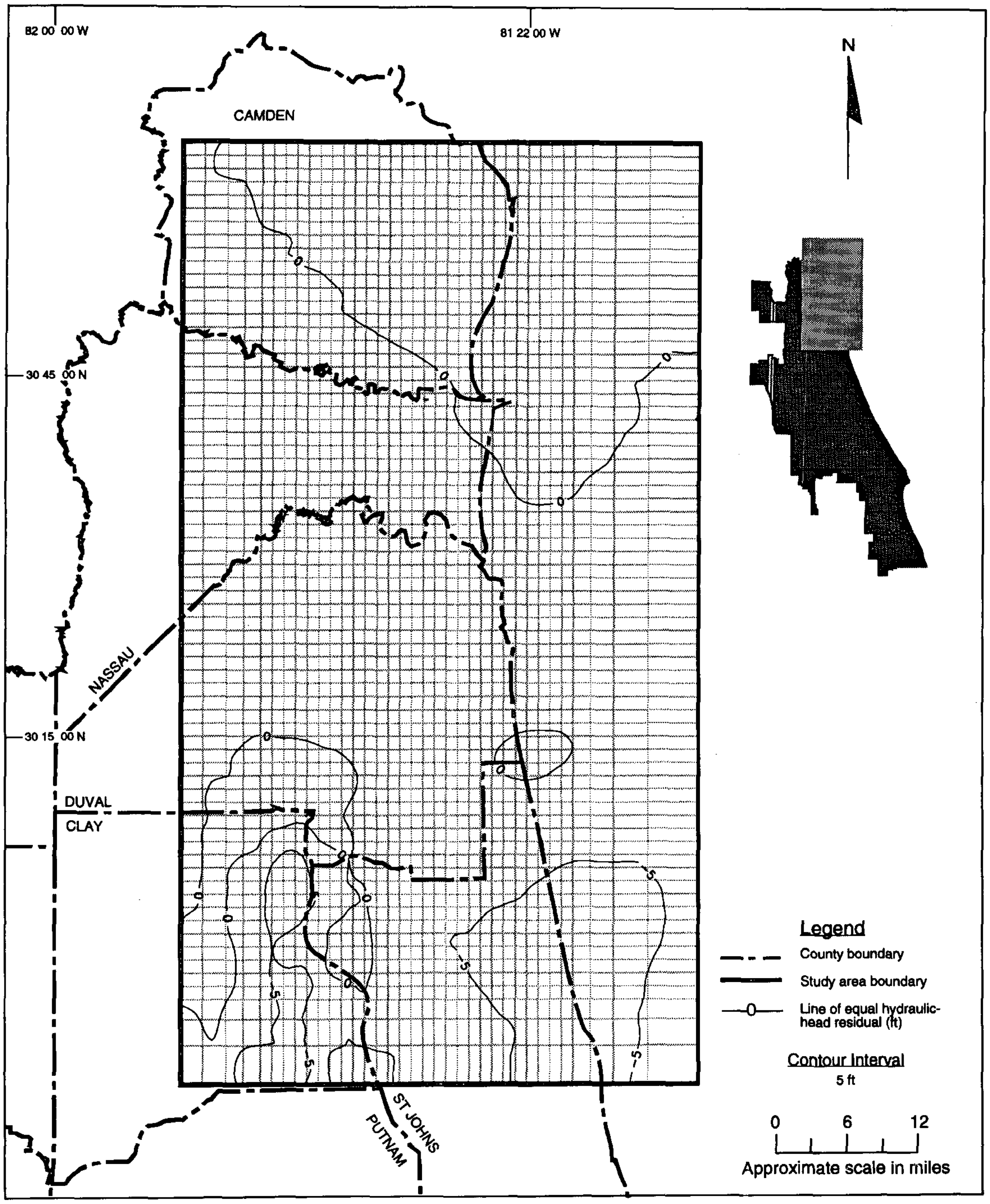


Figure 29. Hydraulic-head residuals in aquifer layer 2 of the predevelopment flow model. *Negative residuals indicate areas in which simulated hydraulic heads are greater than estimated values. Positive residuals indicate areas in which simulated hydraulic heads are less than estimated values.*

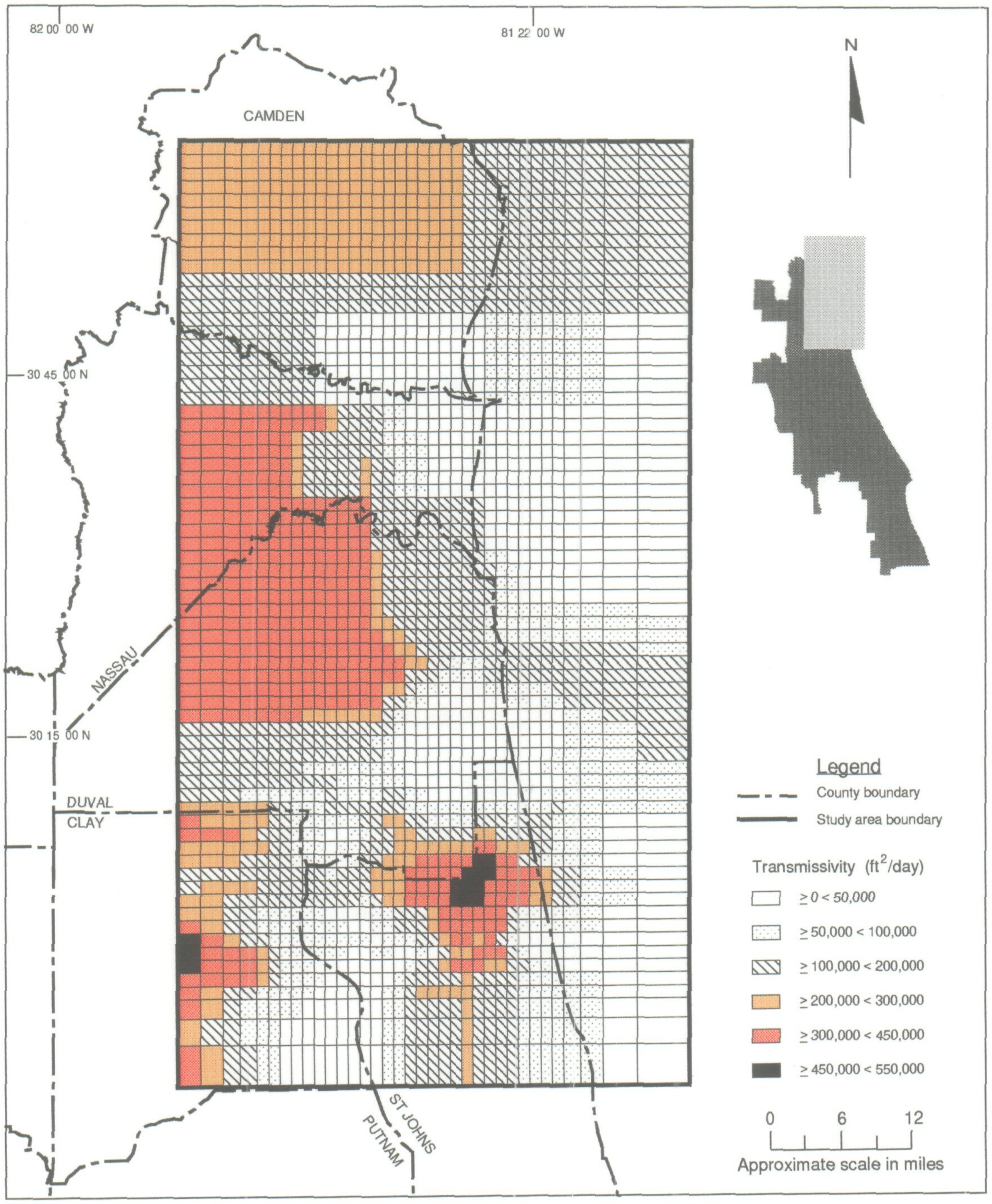


Figure 30. Transmissivity distribution of the Upper Floridan aquifer resulting from the calibration of the predevelopment flow model

Aquifer Layer 3. The resulting estimates of transmissivity of the Lower Floridan aquifer ranged from 18,000 ft^2/day to 420,000 ft^2/day (Figure 31). The arithmetic mean was 216,000 ft^2/day. Estimates also tended to decrease from west to east.

Leakance

Semiconfining Unit Layer 1. The resulting estimates of leakance of the upper confining unit ranged from 4.0×10^{-9} to 5.0×10^{-2} d^{-1} (Figure 32). In most of the model domain, the estimates were relatively low, ranging from 5.0×10^{-8} to 5.0×10^{-6} d^{-1}. The higher estimates were generally concentrated in parts of the grid that correspond to the area encompassed by the potentiometric low between Green Cove Springs and the Duval-Clay county line (Figures 1 and 12); leakance values in grid cells corresponding to that area ranged generally from 5.0×10^{-6} to 5.0×10^{-3} d^{-1}.

Semiconfining Unit Layer 2. The resulting estimates of leakance of MSCU ranged from 1.0×10^{-8} to 1.0×10^{-3} d^{-1} (Figure 33). The higher values were generally in grid cells that correspond to the middle and south-central areas of the model domain; leakance values in grid cells corresponding to those areas ranged from 1.0×10^{-5} to 1.0×10^{-3} d^{-1}. Values were low or moderately low in the remaining grid cells of the model domain, ranging from 1.0×10^{-7} to 1.0×10^{-5} d^{-1}.

Semiconfining Unit Layer 3. The resulting estimates of leakance of LSCU ranged from 1.0×10^{-8} to 1.0×10^{-5} d^{-1} (Figure 34). Generally, the resulting estimates ranged upward from 1.0×10^{-7} d^{-1}.

Sensitivity Analysis

The sensitivity of the model to changes in model parameters was analyzed to ascertain relative degrees of influence of individual parameter distributions on the simulated potentiometric surface of the Upper Floridan aquifer. The results of the sensitivity analysis provided a preliminary indication of which parameters should receive the most attention in calibrating the postdevelopment model.

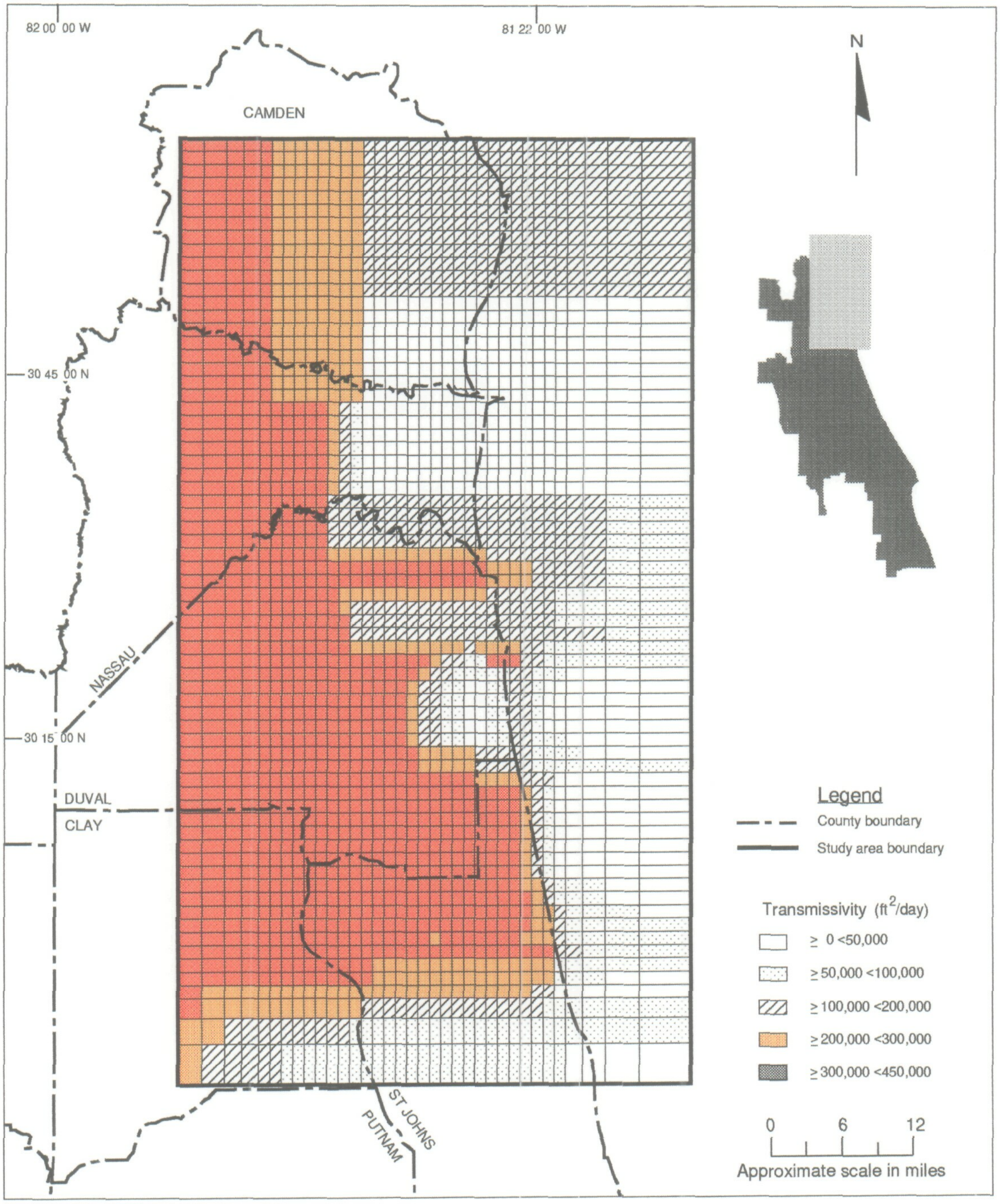


Figure 31. Transmissivity distribution of the Lower Floridan aquifer resulting from the calibration of the predevelopment flow model

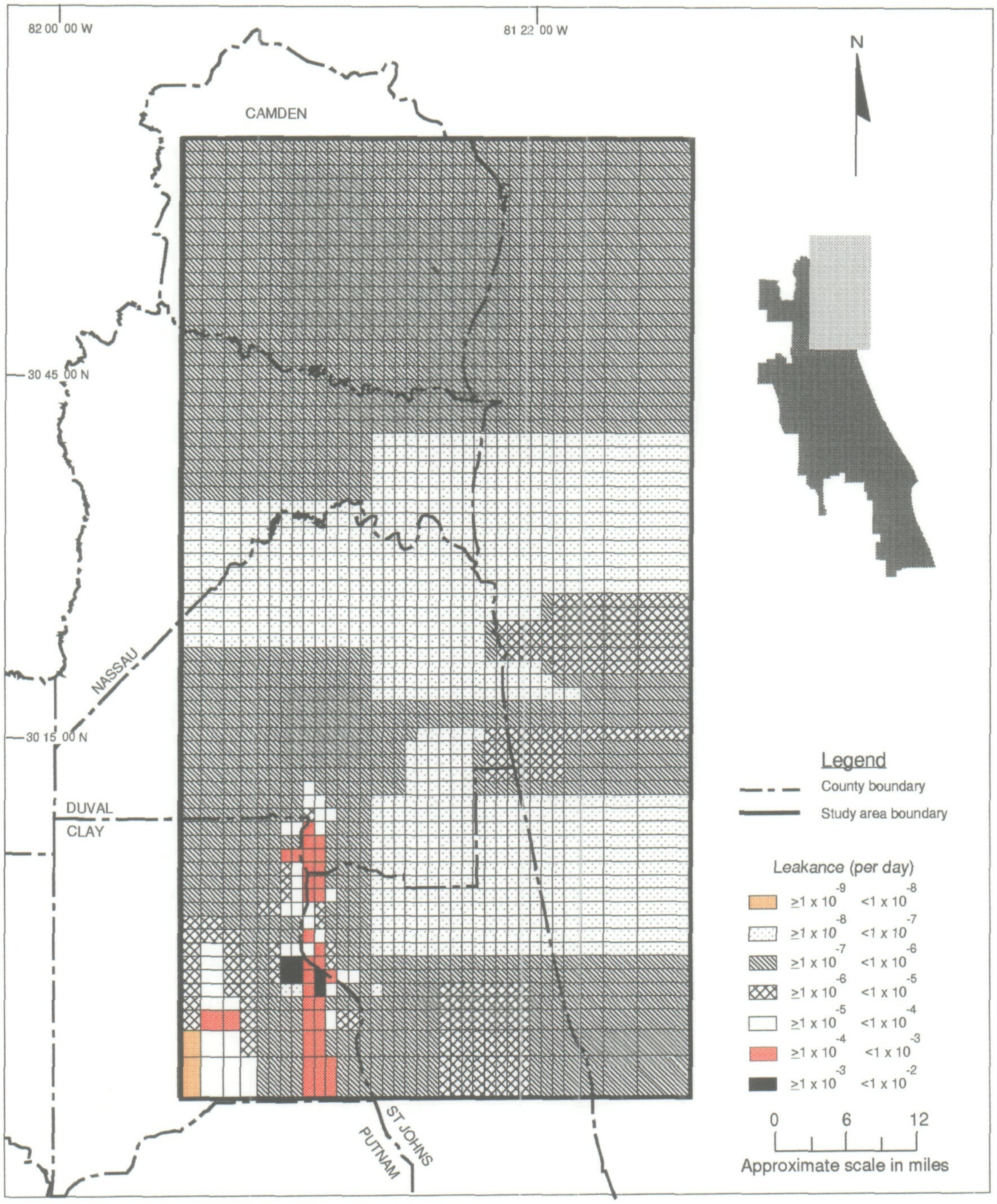


Figure 32. Leakance distribution of the upper confining unit resulting from the calibration of the predevelopment flow model

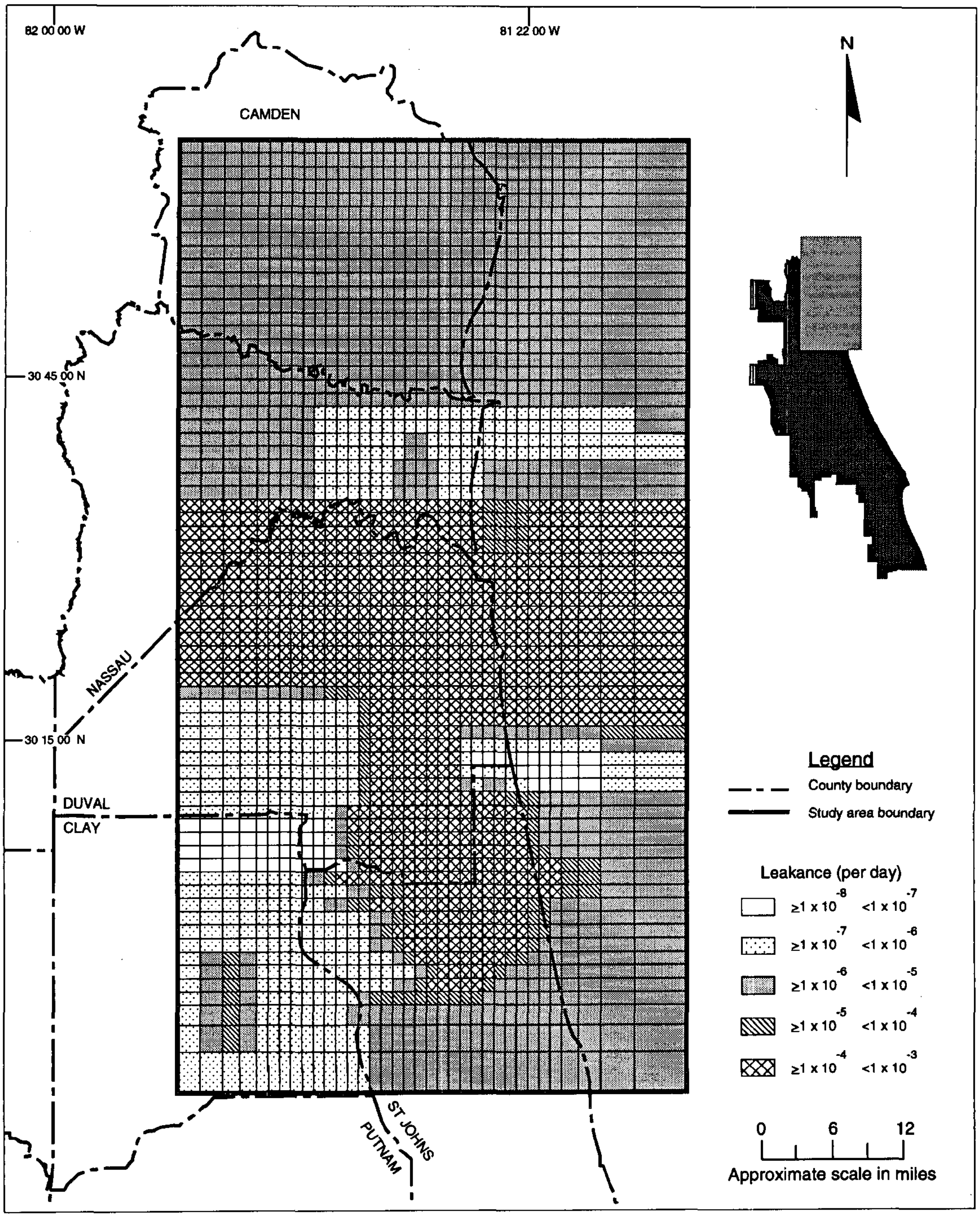


Figure 33. Leakance distribution of the middle semiconfining unit resulting from the calibration of the predevelopment flow model

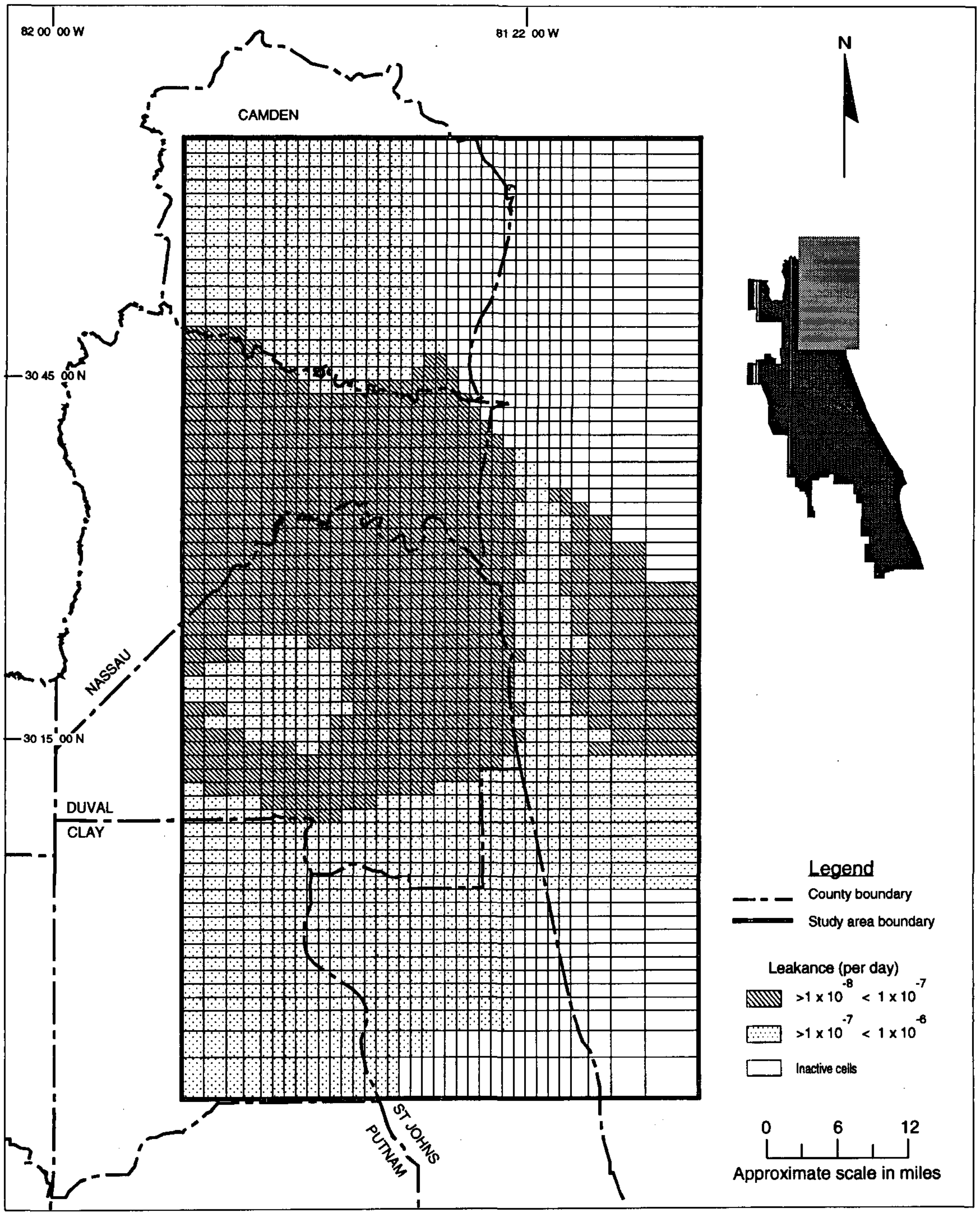


Figure 34. Leakance distribution of the lower semiconfining unit resulting from the calibration of the predevelopment flow model

The results were also useful in calibrating the revised predevelopment flow model.

In the analysis used, every member of a given parameter distribution in the model was multiplied by the same factor (first by 2.0, then by 0.5), while the members of all other parameter distributions were unchanged from calibrated values. The mean, standard deviation, and maximum of the absolute values of the hydraulic-head residuals of aquifer layer 2 were then determined. The percent change of these statistics from the corresponding calibration values was used to indicate the relative degree of influence of the parameter being considered.

The parameter distributions considered in the analysis were as follows:

- Leakance distributions of the upper confining unit and the middle and lower semiconfining units (LK1, LK2, and LK3, respectively)
- Transmissivity distributions of the Upper and Lower Floridan aquifers (T2 and T3, respectively)
- Distribution of water table elevations (WTE)
- Source heads of the GHB conditions of the Upper and Lower Floridan aquifers (LBH2 and LBH3, respectively)
- Distribution of constant heads assigned to the Fernandina permeable zone (HFPZ) (Tables 8 and 9).

Changes in the transmissivity distributions were accompanied by proportional changes in distributions of the conductance of the GHB conditions.

In this sensitivity analysis, the predevelopment flow model was evaluated from a purely mathematical perspective without regard to the hydrological limits on variations in the various model parameters. Consequently, the percentage of change applied to several of the parameters is, from a hydrological perspective, outside the plausible range of variation of those parameters. Examples of such parameters are the GHB-condition source heads and the water table elevations. An alternative approach would be to vary the parameters within a range that is dictated solely by hydrological considerations. In such an approach, the size of the percentage of change applied to each of the parameters would vary depending on a subjective estimate of the plausible range of that parameter. The primary drawback of this approach, however, is that the determination of the relative degree of influence of the parameters is also a matter of subjectivity, due to the nonuniformity of the percentages of change applied to the input parameters. The advantage of the approach that was used, however, is that it provides a completely objective evaluation of the relative degree of influence of the parameters.

The results of the sensitivity analysis indicate that changes in the source heads of the GHB conditions of aquifer layers 2 and 3 have the greatest influence on the simulated potentiometric surface of the Upper Floridan aquifer. Changes in estimates of the elevations of the water table and leakance of the upper confining unit have significant influence as well on the simulated potentiometric surface of the Upper Floridan aquifer. Changes in estimates of transmissivity of the Upper and Lower Floridan aquifers have moderate influence, while the changes in estimates of the leakance of the middle and lower semiconfining units and the values of hydraulic head assigned to the Fernandina permeable zone have only a minor influence (Tables 8 and 9).

Table 8. Results of sensitivity analysis of the predevelopment flow model

Input Data Change	Mean Hydraulic-Head Residual (feet)	Standard Deviation (feet)	Absolute Value of Maximum Hydraulic-Head Residual (feet)
Calibration	-1.1	2.3	10.0
LK1 x 2.0	0.6	2.5	12.9
LK1 x 0.5	-2.5	3.0	15.7
LK2 x 2.0	-1.3	2.3	10.2
LK2 x 0.5	-1.0	2.2	9.7
LK3 x 2.0	-1.1	2.3	10.0
LK3 x 0.5	-1.1	2.3	10.0
T2 x 2.0	-1.2	2.7	12.4
T2 x 0.5	-1.1	2.8	12.2
T3 x 2.0	-2.0	2.9	10.4
T3 x 0.5	-0.2	1.9	9.4
WTE x 2.0	-3.1	5.4	51.9
WTE x 0.5	-0.1	2.7	20.8
LBH2 x 2.0	-35.9	11.9	62.8
LBH2 x 0.5	16.0	7.7	30.2
LBH3 x 2.0	-23.3	10.8	23.3
LBH3 x 0.5	9.9	4.7	16.6
HFPZ x 2.0	-1.3	2.3	10.1
HFPZ x 0.5	-1.1	2.2	10.0

Note: See page 108 for definition of input coding.

Table 9. Percent differences resulting from the sensitivity analysis of the predevelopment flow model

Input Data Change	Percent Change of			Sum of Absolute Values of Percent Differences
	Mean Hydraulic-Head Residual	Standard Deviation	Absolute Value of Maximum Hydraulic-Head Residual	
LK1 x 2.0 LK1 x 0.5	154.5 -124.3	-8.7 -30.4	-29.0 -57.0	406.9
LK2 x 2.0 LK2 x 0.5	-18.2 9.1	0.0 4.3	-2.0 3.0	36.4
LK3 x 2.0 LK3 x 0.5	-0.0 -0.0	0.0 0.0	0.0 0.0	0.0
T2 x 2.0 T2 x 0.5	-9.1 0.0	-17.4 -21.7	-24.0 -22.0	94.2
T3 x 2.0 T3 x 0.5	-81.8 81.8	-26.1 17.4	-4.0 6.0	217.1
WTE x 2.0 WTE x 0.5	-181.8 90.9	-134.8 -17.4	-419.0 -108.0	951.9
LBH2 x 2.0 LBH2 x 0.5	-3,163.6 1,554.5	-417.4 -234.8	-528.0 -202.0	6,100.4
LBH3 x 2.0 LBH3 x 0.5	-2,018.2 1,000.0	-369.6 -104.3	-133.0 -66.0	3,691.1
HFPZ x 2.0 HFPZ x 0.5	-18.2 0.0	0.0 0.0	-1.0 0.0	19.2

Note: See page 108 for definition of input coding.

THE POSTDEVELOPMENT FLOW MODEL

The postdevelopment flow model is a representation of the Floridan aquifer system within the study area in 1985. The primary objective in developing the postdevelopment flow model was to provide a means for predicting changes in levels of hydraulic head in the Floridan aquifer system in response to changes in rates of withdrawals from wells.

Calibration to postdevelopment conditions has several advantages that would be expected to result in increased accuracy in estimates of hydraulic parameters of the aquifer relative to calibration to predevelopment conditions. Perhaps the most important advantage is that the changes in levels of hydraulic head that have occurred within the study area since predevelopment times in response to ground water withdrawals of known magnitude and location have been and continue to be observed. Another advantage is the ability to simulate both the predevelopment and postdevelopment potentiometric surfaces of the Upper Floridan aquifer using the same distributions of transmissivity and leakance. Thus, the postdevelopment flow model can be calibrated to both the postdevelopment and predevelopment conditions. Knowledge of the response of the Floridan aquifer system to known stresses enables important characteristics of the Floridan aquifer system to be inferred more accurately than if information were limited to knowledge of the hydraulic-head levels of the predevelopment (i.e., unstressed) Floridan aquifer system. These characteristics include the sources, paths, and destinations of ground water, the transmissivity and leakance of the Floridan aquifer system, and leakance of the overlying upper confining unit.

Another advantage is the ability to compare the simulated predevelopment and postdevelopment potentiometric surfaces of the Upper Floridan aquifer using the same distributions of transmissivity and leakance to the respective estimated potentiometric surfaces. Thus, the postdevelopment flow model can be calibrated to both the postdevelopment and predevelopment conditions. As detailed later in this chapter and in the next chapter, this approach was used in calibrating the postdevelopment flow model.

Due to the inherent advantages of calibrating to postdevelopment conditions, the estimates of transmissivity and leakance from the calibration of the postdevelopment flow model are felt to be more accurate than those that resulted from the calibration of the predevelopment flow model. Therefore, the estimates of transmissivity and leakance resulting from the postdevelopment calibration were accepted as final results of the study.

Selection of the Calibration Year

The calibration year is defined herein as the year in which the hydraulic-head and water-use data used in the calibration of the postdevelopment flow model were observed. Several criteria were used to determine the most appropriate year for selection as the calibration year. The year meeting all criteria was 1985. The first requirement was that sufficient data regarding the location and rates of withdrawals from wells be available. The reliability and accessibility of well information and withdrawal-rate data collected in the past decade is considerably greater than that of preceding years. Therefore, to meet this criterion, the years considered for selection as the calibration year were limited to 1981 and following years.

The second requirement was that the calibration year be within a period of several years in which water levels in the Upper Floridan aquifer in and near the study area were approximately steady with respect to time. This requirement was necessary because the postdevelopment flow model was to be a steady-state flow model. To identify this period of years, hydrographs of monitoring wells in the Upper Floridan aquifer at 25 locations in and near the study area were compiled. In most of these hydrographs, approximate long-term stability in levels of hydraulic head of the Upper Floridan aquifer was exhibited primarily in the years 1979 through 1986, although fluctuations of 5 to 10 ft above and below average levels in that period were not uncommon (Appendix B). The period of 1979 through 1986, therefore, was determined to be a period in which water levels in the Floridan aquifer system of the study area were approximately steady with respect to time. Because of this requirement and the one discussed in the previous paragraph, the choice of possible calibration years was narrowed to the period of 1981 through 1986.

The third requirement was that rainfall levels in the calibration year and year prior to it be as close to normal as possible to help ensure that water table elevations in the calibration year were near normal. This requirement was imposed because the estimates of water table elevations in the model were intended to be long-term average values, which presumably would be most likely to occur in a normal rainfall year. The requirement that the calibration year follow a normal-rainfall year was intended to reduce the possibility that the water table in the calibration year was affected significantly by an extreme rainfall pattern of the previous year. Analysis of rainfall data showed that during 1981 through 1987, 1984 and 1985 were the two consecutive years in which rainfall levels were closest to normal in the part of the study area within SJRWMD (Durden and Motz 1991). Because 1985 met this criterion and all the other criteria as well, it was chosen to be the calibration year. An additional advantage of calibrating to conditions present in 1985 was that measurements of hydraulic head in the Upper Floridan aquifer were performed throughout Georgia in that year, an event which occurs only once every 5 years.

The September 1985 potentiometric surface of the Upper Floridan aquifer in SJRWMD (Schiner and Hayes 1985) was chosen in favor of the May 1985 potentiometric surface to avoid having to account for spring agricultural withdrawals, which are concentrated in St. Johns County. In St. Johns County, agricultural withdrawal rates are generally less in the summer than in the spring. Because the calibration was to be performed to September data, the calibration results were expected to be less adversely influenced by errors in estimates of agricultural withdrawal rates.

FINITE-DIFFERENCE GRID

The finite-difference grid of the postdevelopment flow model is identical to the finite-difference grid of the predevelopment flow model.

LATERAL BOUNDARY CONDITIONS

Aquifer Layer 1

As in the predevelopment flow model, aquifer layer 1 (i.e., the representation of the surficial aquifer system) (Figure 22) did not require lateral boundary conditions because grid cells in aquifer layer 1 were all designated as constant head.

Aquifer Layer 2

The procedure used to prescribe lateral boundary conditions for aquifer layer 2 (i.e., the representation of the Upper Floridan aquifer) (Figure 22) in the postdevelopment flow model was essentially the same as that used for aquifer layer 2 in the predevelopment flow model. GHB conditions were prescribed at more than half of the 202 cells of the outermost rows and columns of the finite-difference grid, and no-flow lateral boundary conditions were prescribed at the remaining cells (Figure 35). Lateral boundary conditions were prescribed for both faces of corner grid cells.

On the westernmost column of the finite-difference grid, GHB conditions were prescribed at all but a few of the cells (Figure 35), reflecting a general pattern of west to east flow in the part of the study area that corresponds to that part of the model domain. Along the northernmost row, GHB conditions were prescribed at most of the cells, but some no-flow lateral boundary conditions were prescribed as well. The prescription of lateral boundaries along the northernmost row reflects the presence of a northerly component of ground water flow that has been superimposed onto the pattern of west to east flow that existed in the predevelopment flow system (Figure 35). This northerly component of ground water flow is due to withdrawals from wells to the north of the study area.

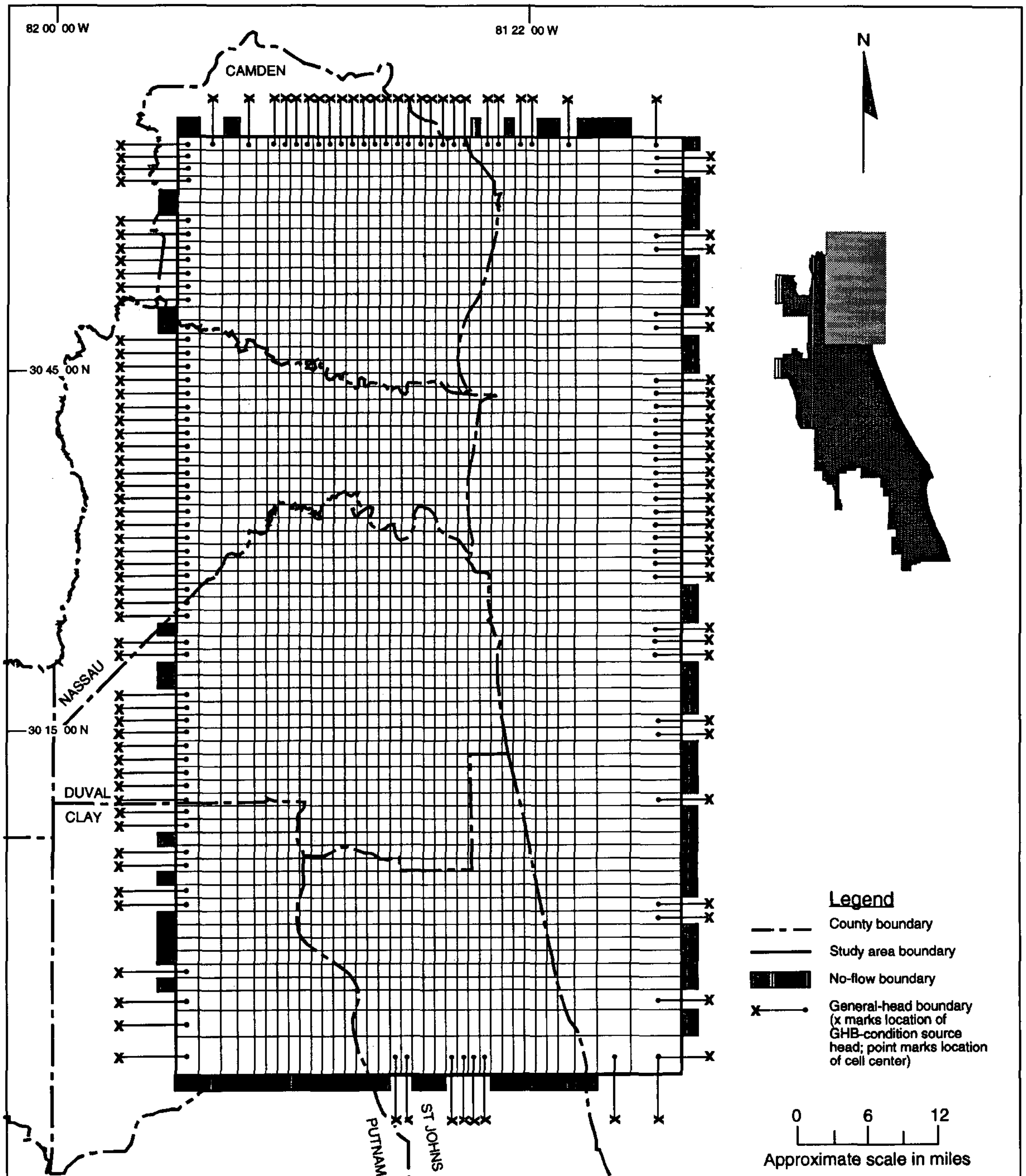


Figure 35. Lateral boundary conditions prescribed for aquifer layers 2 and 3 of the postdevelopment flow model

A combination of GHB and no-flow lateral boundary conditions was prescribed in cases in which the general direction of ground water flow was neither predominantly perpendicular nor parallel to the direction of orientation of an outermost row or column of the finite-difference grid. As was the case in the predevelopment flow system, this phenomenon occurs with respect to the easternmost column and southernmost row of the grid; in areas corresponding to those parts of the model domain, the direction of ground water flow is primarily to the southeast. This phenomenon occurs also with respect to parts of the westernmost column (Figure 35).

In aquifer layer 2, the distance between the edge of the finite-difference grid and the points at which the GHB-condition source heads are specified corresponds to 4.4 mi along the western boundary, 3.5 mi along the southern boundary, 2.0 mi along the eastern boundary, and 3.5 mi along the northern boundary (Figure 35). Uniform distances were specified within each of the boundary segments to simplify the calculation of the conductances of the GHB conditions. The source heads of the GHB conditions were estimated by interpolating between lines of equal elevation of hydraulic head shown on the map of the estimated postdevelopment potentiometric surface (Figure 13).

Aquifer Layer 3

Grid cells in the outermost rows or columns of aquifer layer 3 were prescribed with the same boundary-condition types as for corresponding grid cells in aquifer layer 2. The distances between the edges of the finite-difference grid and the points at which the GHB-condition source-heads are specified are the same as for corresponding cells in aquifer layer 2.

The procedure used to estimate hydraulic-head levels at locations corresponding to the positions of the GHB-condition source heads of aquifer layer 3 involved estimation of hydraulic-head levels in the pre- and postdevelopment Upper and Lower Floridan aquifers at the sites of wells D-2386, D-3060, and SJ-0025 (respectively, Brown et al. 1984; Brown et al. 1985; Brown et al. 1986) (Figure 16). Estimates of hydraulic head in the postdevelopment Upper and Lower Floridan aquifers at these three sites were obtained by vertically averaging values of hydraulic head observed as a function of depth in the Upper and Lower Floridan aquifers in the three wells. Estimates of hydraulic head in the predevelopment Upper Floridan aquifer were obtained by interpolating between lines of equal elevation of hydraulic head shown on the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 12). Estimates of hydraulic head in the predevelopment Lower Floridan aquifer were obtained by extraction of simulated values of hydraulic head from grid cells of the predevelopment flow model that correspond to the locations of the sites.

The ratio of the decline in hydraulic head in the Upper Floridan aquifer to that in the Lower Floridan aquifer was calculated for the respective sites. The calculation was performed by dividing the differences in the estimates of the pre- and postdevelopment hydraulic head in the Upper Floridan aquifer by the respective differences in estimates of the pre- and postdevelopment hydraulic head in the Lower Floridan aquifer. The average of the three ratios was 1.02.

Estimated decline in hydraulic head in the Upper Floridan aquifer at the locations corresponding to the positions of the GHB-condition source heads were obtained by subtracting the hydraulic-head values interpolated from the maps of the estimated pre- and postdevelopment potentiometric surfaces (Figures 12 and 13). The amount of decline in hydraulic head in the Lower Floridan aquifer was estimated by dividing corresponding estimates of the amount of decline in the Upper Floridan aquifer by 1.02. Hydraulic head in the postdevelopment Lower Floridan aquifer at locations corresponding to the positions of the GHB-condition source heads was estimated by subtracting the estimated declines in hydraulic head in the Lower Floridan aquifer from the estimates of hydraulic head in the predevelopment Lower Floridan aquifer. The procedure for estimating hydraulic head in the predevelopment Lower Floridan aquifer at the lateral boundaries of the postdevelopment flow model was described in the previous chapter.

Aquifer Layer 4

Initially, the grid cells of aquifer layer 4 were designated either as constant-head or inactive. Therefore, in the initial stages of the calibration, prescription of lateral boundary conditions for aquifer layer 4 was unnecessary. Once the aquifer layers above semiconfining unit layer 3 were calibrated sufficiently, the grid cells in aquifer layer 4 that were designated initially as constant-head were redesignated as variable-head. At that point, prescription of lateral boundary conditions for aquifer layer 4 became necessary as well.

Because so little is known of the actual patterns of ground water flow in the Fernandina permeable zone, the lateral boundary conditions of aquifer layer 4 were designed to be representative only of a general pattern of west to east flow (Figure 36). Accordingly, no-flow lateral boundary conditions were prescribed at all of the variable-head grid cells of the northernmost and southernmost rows of aquifer layer 4. GHB conditions were prescribed at all of the cells on the westernmost column of aquifer layer 4. GHB conditions were prescribed at all of the variable-head cells on the easternmost column as well. The distance between the edge of the finite-difference grid and the points at which the GHB-condition source heads are specified in aquifer layer 4 corresponds to 6.6 mi along the western boundary and 2.0 mi along the eastern boundary.

The approach used to estimate values of hydraulic head for aquifer layer 4 at the positions of the GHB-condition source heads was essentially the same as that used for aquifer layer 3. The analysis for aquifer layer 4 incorporated measurements of hydraulic head obtained from wells D-2386, D-3060, and SJ-0025 (respectively, Brown et al. 1984; Brown et al. 1985; Brown et al. 1986) (Figure 16). In addition, a value of hydraulic head measured in 1985 in the Fernandina permeable zone in well D-425B (Leve and Goolsby 1966) (Figure 16) and a corresponding value of hydraulic head interpolated from the map of the potentiometric surface of the postdevelopment Upper Floridan aquifer were used in the analysis. Hydraulic-head estimates in the predevelopment Fernandina permeable zone were the same values assigned to the grid cells of aquifer layer 4 in the

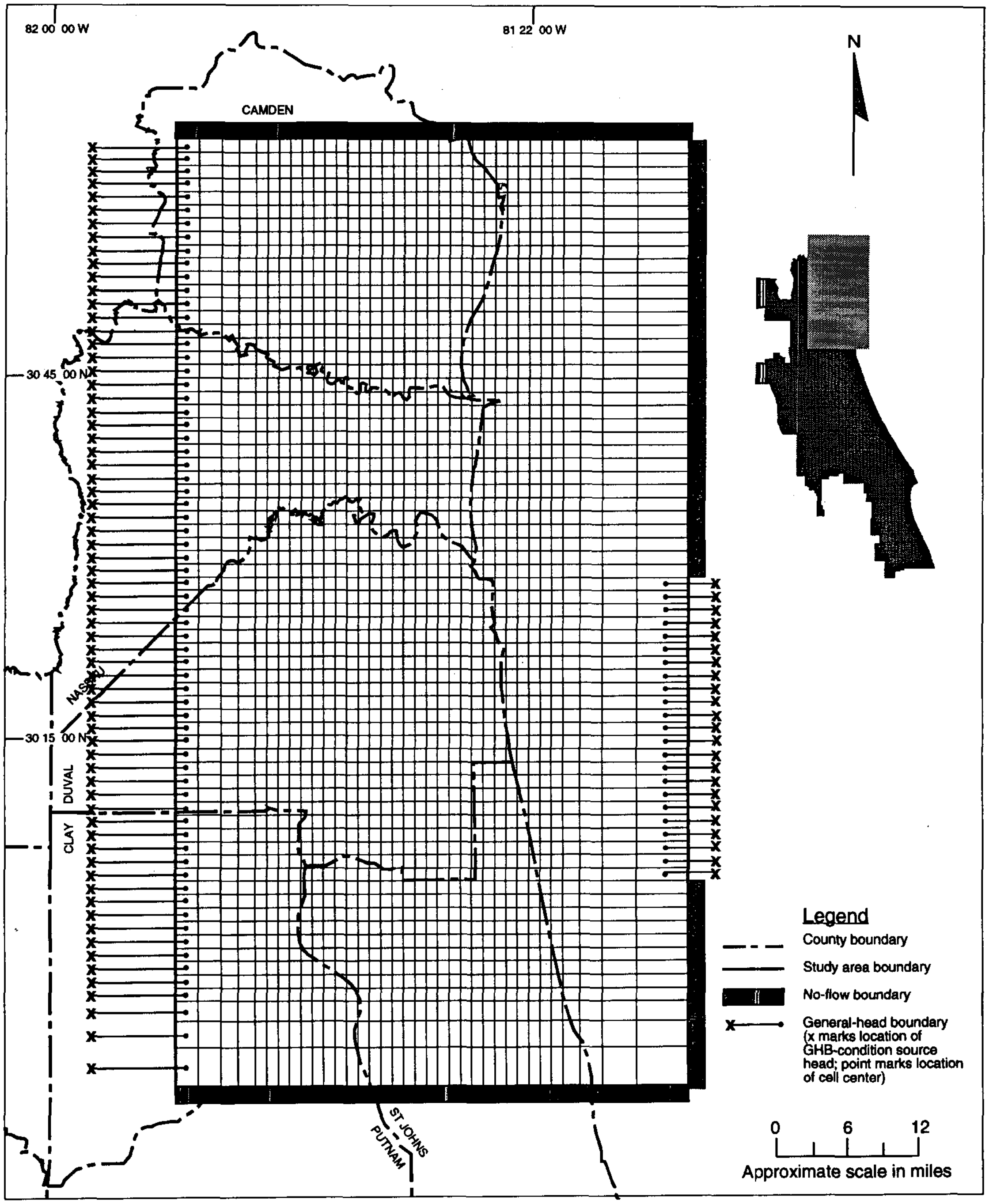


Figure 36. Lateral boundary conditions prescribed for aquifer layer 4 of the postdevelopment flow model

predevelopment flow model that correspond to the locations of the respective test wells. The resulting average of the ratios of decline at the four wells was 1.07.

DATA-INPUT REQUIREMENTS

Water Table Elevations

The distribution of water table elevations used in the postdevelopment flow model is the same as that used in the predevelopment flow model.

Delineation of the Freshwater/Saltwater Interface

The delineation of the tip of the interface in the Fernandina permeable zone was unchanged from that of the predevelopment flow model.

Initial Hydraulic-Head Distributions

Aquifer Layer 2. The initial values of hydraulic head specified for aquifer layer 2 were interpolated from the map of the postdevelopment potentiometric surface of the Upper Floridan aquifer at locations corresponding to the positions of the cell nodes (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987) (Figure 13).

Aquifer Layer 3. The initial values of hydraulic head that were specified for aquifer layer 3 were derived by adding or subtracting a constant value of hydraulic head to or from estimates of hydraulic head already assigned to aquifer layer 2, as in the procedure used in the predevelopment flow model. Later, to decrease the simulation time of the postdevelopment flow model, a distribution of hydraulic head that was simulated for aquifer layer 3 by the postdevelopment flow model was entered and used as the initial hydraulic-head distribution in all subsequent simulations.

Aquifer Layer 4. In the initial stage of model calibration, the grid cells of aquifer layer 4 were designated either as constant-head or inactive. Therefore, these values of hydraulic head affected the interim results of the calibration.

To ensure accuracy, the values of hydraulic head were derived using a simulation procedure similar to that used for aquifer layer 4 in the predevelopment flow model. In the present case, however, the resulting values of hydraulic head in the grid cells that correspond to the locations of the five deep-test wells (Leve and Goolsby 1966; Brown 1980; Brown et al. 1984, 1985, 1986) were replaced by values that were based on observations in the wells. Specified values of hydraulic head in some of the surrounding cells were adjusted to create smooth transitions between the values of hydraulic head based on observations and values obtained using the simulation procedure. Once the aquifer layers above semiconfining unit layer 3 were calibrated substantially, the grid cells in aquifer layer 4 that had been designated as constant-head were redesignated as variable-head.

Transmissivity

The initial estimates of transmissivity of aquifer layers 2 and 3 resulted from the calibration of the predevelopment flow model. Because little information is available regarding the hydraulic properties of the Fernandina permeable zone, the initial estimates of transmissivity for aquifer layer 4 were copied from aquifer layer 3.

Leakance

The initial estimates of leakance for semiconfining unit layers 1, 2, and 3 were obtained from the predevelopment flow model as well.

Anisotropy Factor

An anisotropy factor of 1 was assigned to all four aquifer layers of the postdevelopment flow model.

Distribution of Withdrawals from Wells

Prior to calibrating the postdevelopment flow model, estimates of withdrawal rates (Appendix A) had to be distributed to the grid cells of aquifer layers 2 and 3 (Figures 37 and 38). Typically, the available water use data were indicative only of the total amount obtained from a given wellfield and not of the amounts obtained from the individual wells that comprise the wellfield. This information was required for cases in which the wells of a given wellfield were in locations corresponding to more than one grid cell of the postdevelopment flow model. In a case in which a well penetrated both the Upper and Lower Floridan aquifers, the water use data were also not indicative of the proportion of the withdrawal obtained from the Upper Floridan aquifer versus the Lower Floridan aquifer. Therefore, techniques had to be developed for proportioning to each of the several wells that comprise a given wellfield the total withdrawal obtained from the wellfield. Likewise, techniques had to be developed for proportioning to the Upper and Lower Floridan aquifers the total withdrawal obtained from a well open to both aquifers. The former type of distribution is referred to herein as a horizontal withdrawal distribution, and the latter is referred to herein as a vertical withdrawal distribution.

Horizontal Distribution of Withdrawals from Wells. Three different approaches were used to distribute withdrawals horizontally, depending on the available well information. For a case in which the pump capacities of all the wells in a wellfield were known, the total withdrawal was distributed in proportion to the pump capacity. This approach was based on the assumption that wells with larger pump capacities are generally responsible for larger proportions of a total withdrawal. For a case in which the pump capacity of one or more of the wells in the wellfield was not known but the diameters of all the wells were known, the total withdrawal was distributed in proportion to the squares of the diameters of the wells. This approach was based on the assumption that wells of larger hydraulic area are generally responsible for larger proportions of the total withdrawal. Finally, for a case in which neither the pump capacity nor the casing diameter was known for all the wells, the total withdrawal from the wellfield was divided by the number of wells in the wellfield and distributed equally to each.

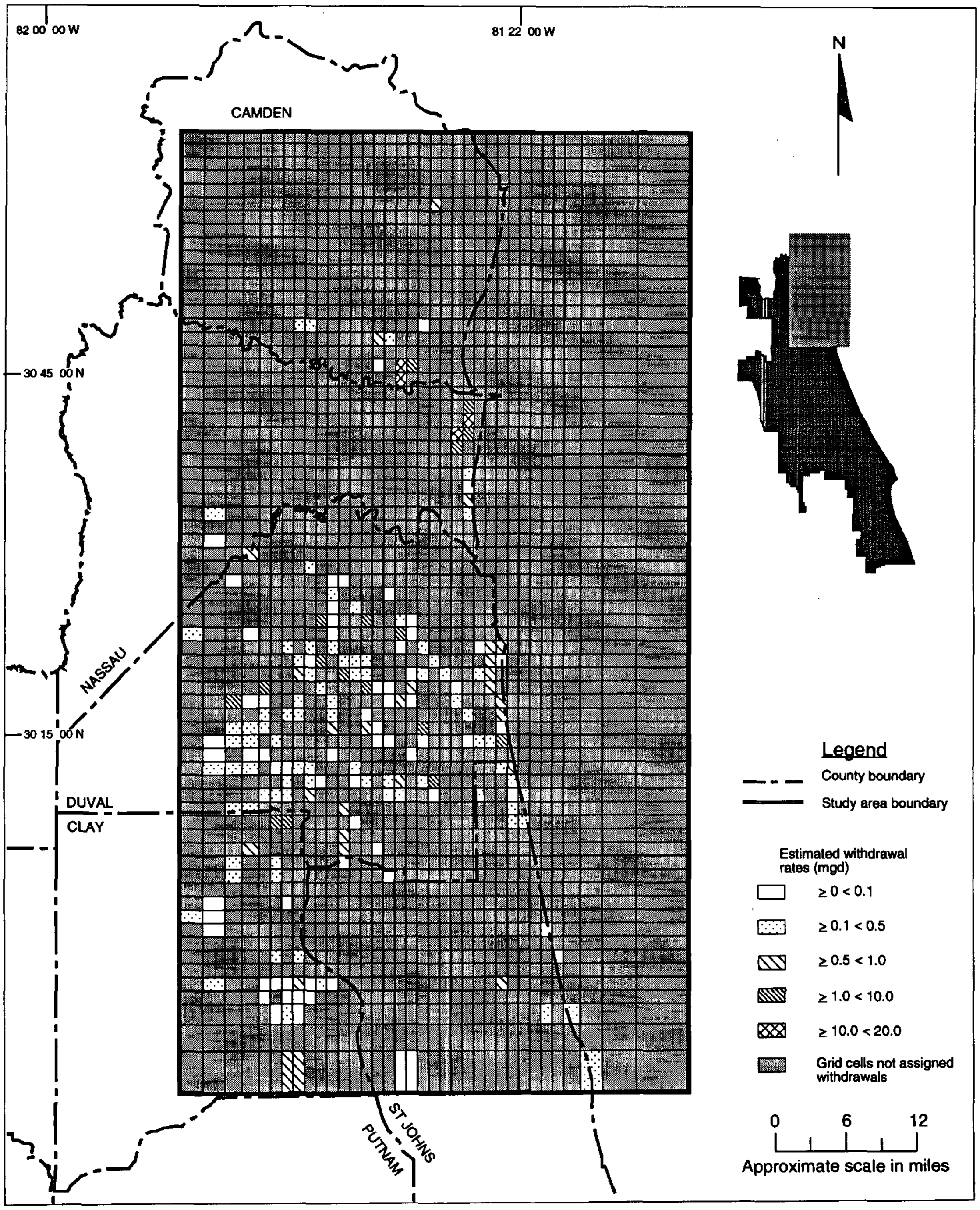


Figure 37. Estimated withdrawal rates prescribed for aquifer layer 2 of the postdevelopment flow model

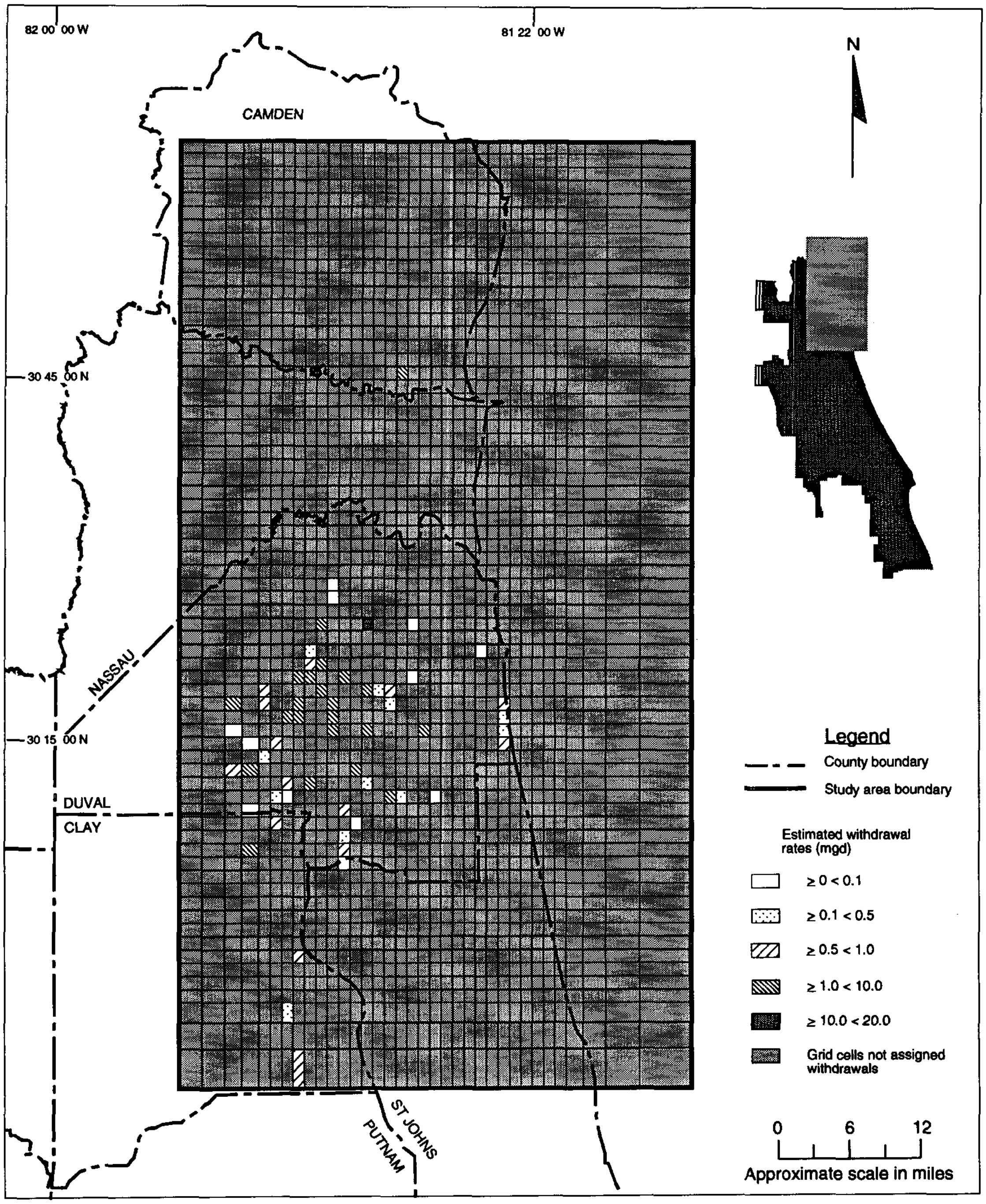


Figure 38. Estimated withdrawal rates prescribed for aquifer layer 3 of the postdevelopment flow model

Vertical Distribution of Withdrawals from Wells. Withdrawals were distributed vertically in proportion to the transmissivity of the Upper Floridan aquifer and the "effective transmissivity" of the Lower Floridan aquifer. Effective transmissivity is defined herein as the product of the depth of penetration into the Lower Floridan aquifer of a given well and the hydraulic conductivity in the Lower Floridan aquifer at the location of the well. Effective transmissivity of the Lower Floridan aquifer was used instead of the actual transmissivity to correct partly for the effects of partial well penetration, as none of the production wells in the study area penetrate the Lower Floridan aquifer fully.

The effective transmissivity of the Lower Floridan aquifer was calculated by first dividing the estimate of transmissivity assigned to the grid cell in aquifer layer 3 that corresponds to the location of the well being considered by the estimated thickness of the Lower Floridan aquifer at that location. The result was an estimate of the hydraulic conductivity of the Lower Floridan aquifer at the location of the well. The effective transmissivity was then obtained by multiplying the estimated hydraulic conductivity of the Lower Floridan aquifer by the depth to which the well penetrates the Lower Floridan aquifer. The underlying assumption in this approach is that, in such cases, a greater proportion of the withdrawal is derived from the aquifer that possesses the greater transmissivity. During the calibration, the vertical distributions of the withdrawals from wells were updated each time the transmissivity distributions of aquifer layers 2 or 3 were modified.

Model Calibration

The primary objective in calibrating the postdevelopment flow model was to minimize the differences in the observed or estimated and simulated values of hydraulic head in aquifer layers 2, 3, and 4 using physically realistic estimates of transmissivity and leakance. The postdevelopment flow model was calibrated using a trial-and-error process that resulted in the development of both the postdevelopment and revised predevelopment flow models.

As a first step in this process, estimates of transmissivity and leakance resulting from the calibration of the predevelopment flow model were entered as initial estimates into the appropriate input file of the postdevelopment flow model. Once a tentative calibration of the postdevelopment flow model was completed, an updated version of the predevelopment flow model (i.e., the revised predevelopment flow model) was constructed using estimates of transmissivity and leakance resulting from the tentative calibration of the postdevelopment flow model.

This process enabled further testing of the tentative calibration of the postdevelopment flow model by comparing the simulated potentiometric surface of the revised predevelopment flow model to that of Johnston, Krause et al. (1980). As necessary, additional adjustments were made in estimates of input parameters. The resulting parameter distributions were then transferred back to the appropriate input file of the postdevelopment flow model, and additional calibration of the postdevelopment flow model was performed. This process was repeated until satisfactory closure was realized. Data representing postdevelopment conditions are more numerous and reliable than data representing predevelopment conditions. Therefore, results obtained from calibration to postdevelopment conditions were given precedence over results obtained from calibration to predevelopment conditions whenever a desirable level of calibration to both pre- and postdevelopment conditions could not be achieved using the same estimates of hydraulic properties. Such instances were unusual, however. The revised predevelopment flow model is described in the next chapter.

Progress in the calibration was monitored using techniques similar to or the same as those used in the calibration of the predevelopment flow model. As before, progress was monitored primarily by calculating at the end of each simulation the mean and standard deviation of the hydraulic-head residuals in aquifer layer 2. Progress was monitored also by determining the percentages of absolute values of the hydraulic-head residuals of aquifer layer 2 less than or equal to 5 and less than or equal to 10 ft and by calculating the mean of the absolute values of the hydraulic-head residuals.

Hydraulic-head residuals were of two types in the postdevelopment calibration. The first type was based on comparisons of simulated values of hydraulic head to values of hydraulic head interpolated between lines of equal elevation of hydraulic head shown on the map of the estimated postdevelopment potentiometric surface of the Upper Floridan aquifer (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987) (Figure 13). Hydraulic-head residuals determined using this approach were of the same type as those determined in calibrating the predevelopment flow model. The second type was based on comparisons of simulated values of hydraulic head to values of hydraulic head observed in 142 monitoring wells in the Upper Floridan aquifer within the study area (Figure 14). A residual of this type was computed as the difference in the value of hydraulic head observed in a given monitoring well and the value of hydraulic head simulated in the grid cell that corresponds to the location of the monitoring well.

The progress of the calibration was monitored also by comparing the simulated potentiometric surface of the Upper Floridan aquifer to the map of the estimated potentiometric surface of the Upper Floridan aquifer (Figure 13) and by visually inspecting maps of hydraulic-head residuals in aquifer layer 2 that were based on interpolated values of hydraulic head. Measurements of hydraulic head in the Lower Floridan aquifer and the Fernandina permeable zone were available from several sites within the study area as well (Tables 10 and 11; Figures 15 and 16). These data enabled comparisons of simulated and observed values of hydraulic head. Due to the small number of these data, however, residual statistics based on them were not calculated.

Residual Statistics

Residuals Based on Interpolated Values of Hydraulic Head. The mean of the hydraulic-head residuals based on interpolated values of hydraulic head was +0.06 ft, the positive sign indicating that simulated values of hydraulic head were lower on average than interpolated values. The corresponding standard deviation was 3.6 ft.

Table 10. Hydraulic-head residuals in aquifer layer 3 of the postdevelopment flow model in grid cells that encompass observation wells

USGS Well Identifier	SJRWMD Well Identifier	Location		Model Coordinates		Date of Observation	Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
302227081435001	D-0592	30 22 27	81 43 50	40	6	10/06/86	39.1[a]	39.6	-0.5
301537081441901	D-0075	30 15 37	81 44 19	47	5	10/06/86	32.3[a]	42.1	-9.8
301604081361501	D-0450	30 16 04	81 36 15	47	14	10/06/86	38.1[a]	37.5	0.6
301639081330802	D-1155	30 16 39	81 33 08	46	17	10/06/86	35.7[a]	36.3	-0.6
301132081225801	SJ-0025	30 11 32	81 22 58	51	27	---[b]	38.1[b]	35.7	2.4
302159081235601	D-2386	30 21 59	81 23 56	41	26	---[c]	34.9[c]	34.5	0.4
302052081323201	D-3060	30 20 52	81 32 32	42	17	---[d]	33.7[d]	35.4	-1.7

Note: USGS = U.S. Geological Survey
SJRWMD = St. Johns River Water Management District
ft = feet
NGVD = National Geodetic Vertical Datum

[a]Source: USGS 1988
[b]Weighted average of vertically distributed observations made during drilling, August to October 1985. Observations reported in Brown et al. 1986.
[c]Weighted average of vertically distributed observations made during drilling, November 1980 to July 1981. Observations reported in Brown et al. 1984.
[d]Weighted average of vertically distributed observations made during drilling, October 1982 to February 1983. Observations reported in Brown et al. 1985.

The mean of the absolute values was 2.4 ft. Approximately 92% of the residuals were 5 ft or less, and approximately 99% were 10 ft or less.

The extreme values of the hydraulic-head residuals were 44.4 and -48.4 ft. These residuals corresponded to grid cells located near the center of the areally extensive cone of depression in the potentiometric surface of the Upper Floridan aquifer located in the area of Fernandina Beach and St. Marys (Figures 1 and 13). The relatively large sizes of these residuals reflect difficulty encountered in matching simulated and interpolated values of hydraulic head near the center of the cone of depression. The slope of the potentiometric surface near the center of the cone of depression is so great that the finite-difference grid of the postdevelopment flow

Table 11. Hydraulic-head residuals in aquifer layer 4 of the postdevelopment flow model in grid cells that encompass observation wells

USGS Well Identifier	SJRWMD Well Identifier	Location		Model Coordinates		Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column			
301132081225801	SJ-0025	30 11 32	81 22 58	51	27	38.6[a]	37.0	-1.6
302159081235601	D-2386	30 21 59	81 23 56	41	26	34.6[b]	37.4	-2.8
302052081323201	D-3060	30 20 52	81 32 32	42	17	32.8[c]	40.1	-7.3
304001081280301	N-0117	30 40 01	81 28 03	23	22	47.0[d]	38.6	8.4
301817081374902	D-425B	30 18 17	81 37 49	44	12	38.2[e]	42.0	-3.8

Note: USGS = U.S. Geological Survey
SJRWMD = St. Johns River Water Management District
ft = feet
NGVD = National Geodetic Vertical Datum

[a]Weighted average of vertically distributed observations made during drilling, August to October 1985. Hydraulic-head values corresponding to chloride concentrations in excess of 1,000 mg/L were excluded in calculating the average. Observations reported in Brown et al. 1986.
[b]Weighted average of vertically distributed observations made during drilling, November 1980 to July 1981. Hydraulic-head values corresponding to chloride concentrations in excess of 1,000 mg/L were excluded in calculating the average. Observations reported in Brown 1984.
[c]Weighted average of vertically distributed observations made during drilling, October 1982 to February 1983. Hydraulic-head values corresponding to chloride concentrations in excess of 1,000 mg/L were excluded in calculating the average. Observations reported in Brown et al. 1985.
[d]Approximate average equivalent-freshwater head in the period of January through September 1980. Derived from Brown 1984, Figure 10.
[e]Single observation of hydraulic head made in September 1985. Reported in USGS 1986.

model would have to be considerably finer to achieve a significantly better match between simulated and interpolated values of hydraulic head.

Residuals Based on Observed Values of Hydraulic Head. The mean of the hydraulic-head residuals based on observed values of hydraulic head was −0.6 ft (Appendix C). The corresponding standard deviation was 9.9 ft. The mean of the absolute values of the hydraulic-head residuals was 4.6 ft. Approximately 82% of the residuals were 5 ft or less, and approximately 92% were 10 ft or less.

These statistics seem to indicate that the simulated values of hydraulic head compared much more closely to the interpolated values than to the observed values of hydraulic head. However, the statistics are skewed by the relatively large hydraulic-head residuals corresponding to grid cells that are located near the center of the Fernandina Beach/St. Marys cone of depression (Figures 1 and 13). The relatively large sizes of the hydraulic-head residuals in that area are, as stated before, attributable to the steepness of the slope of the potentiometric surface of the Upper Floridan aquifer and to the level of discretization of the finite-difference grid. The relatively small number of affected hydraulic-head residuals influences the mean, standard deviation, and other stated statistics of the residual distribution more strongly, however. The effect is stronger in this case because the statistics are based on a total of only 142 residual values, whereas in the comparison to the interpolated values of hydraulic head, the statistics were based on 2,380 residual values.

This point is underscored by noting that the locations of 5 of the 142 monitoring wells in the Upper Floridan aquifer within the study area correspond to the cell at row 19, column 17 (cell R19/C17) (Figure 23) and that the absolute values of the hydraulic-head residuals corresponding to these five wells range from 4.6 to 68.3 ft. Obviously, simulation of hydraulic head to within 5 to 10 ft of the observed values at all 5 wells would be impossible unless the model grid were discretized more finely.

To alleviate the skewing of the residual statistics, the five hydraulic-head residuals corresponding to cell R19/C17 and one each corresponding to cells R2/C23 and R22/C23 were removed from consideration in the calculation of the residual statistics. These residuals were excluded because of the proximity of the corresponding grid cells to the center of the Fernandina Beach/St. Marys cone of depression (Figures 1, 13, and 23).

The mean and standard deviation of the remaining hydraulic-head residuals were calculated, and the results were comparable to the statistics resulting from the comparison of the simulated and interpolated values of hydraulic head. The resulting mean was 0.2 ft. The corresponding standard deviation was 4.2 ft. The mean of the absolute values of the hydraulic-head residuals was 3.1 ft. Approximately 87% of the residuals were less than or equal to 5 ft, and 96% of the residuals were less than or equal to 10 ft.

These comparisons indicate that an acceptable match between simulated and estimated or observed values of hydraulic head has been achieved everywhere in the model domain except possibly near the center of the Fernandina Beach/St. Marys cone of depression.

The results indicate further that the large sizes of the hydraulic-head residuals in grid cells corresponding to the area of the Fernandina Beach/St. Marys cone of depression are related to the level of discretization of the existing finite-difference grid and that the sizes of the residuals could perhaps be reduced if the finite-difference grid were discretized more finely in that area. However, rediscretization of the entire finite-difference grid merely to accommodate such a small proportion of the study area is beyond the scope of the present study. The grid resolution required to improve substantially the simulation of ground water flow in that area would best be met by development of a subregional ground water flow model that corresponds specifically to the Fernandina Beach/St. Marys area.

Comparisons of Estimated and Simulated Potentiometric Surfaces and Inspection of Residual Maps

Lines of Equal Elevation of Hydraulic Head. Comparisons of estimated and simulated lines of equal elevation of hydraulic head were used to check the ability of the postdevelopment flow model to simulate the dominant features of the postdevelopment potentiometric surface of the Upper Floridan aquifer (Figure 39). These features include the Fernandina Beach/ St. Marys cone of depression, the potentiometric low along the St. Johns River between Green Cove Springs and Jacksonville, the potentiometric high that straddles the Duval-St. Johns county line, and the potentiometric high that protrudes into the southwest corner of the study area (Figures 1 and 13).

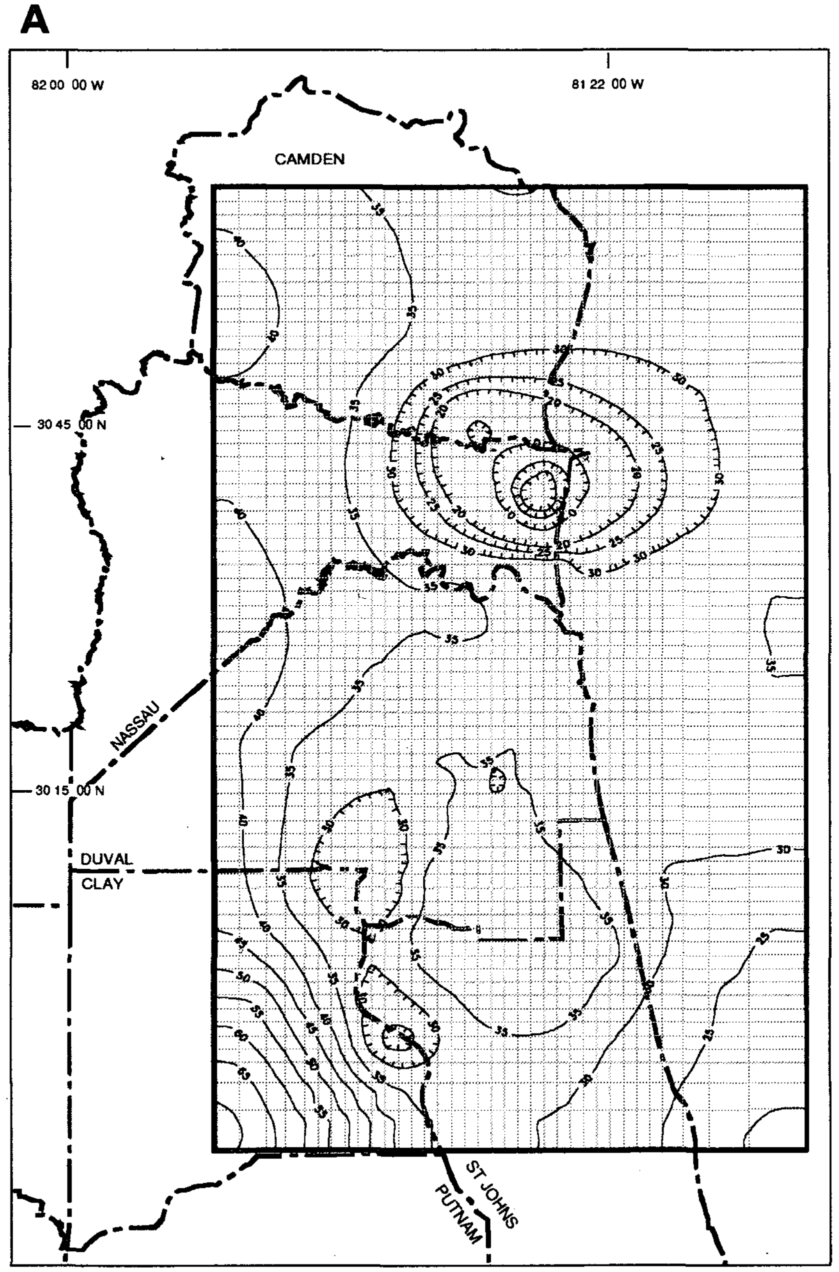
A comparison of maps of the estimated and simulated potentiometric surfaces of the Upper Floridan aquifer shows that the shapes and locations of the lines of equal elevation of hydraulic head are quite similar (Figure 39). Regionally, all of the dominant features of the estimated postdevelopment potentiometric surface of the Upper Floridan aquifer appear to be simulated adequately.

Maps of Hydraulic-Head Residuals. Based on the map of interpolated hydraulic-head residuals, the simulated potentiometric surface of the Upper Floridan aquifer is within 5 ft of the estimated potentiometric surface in most of the study area (Figure 40). Isolated areas are apparent in which the residuals exceed absolute values of 5 ft. The map shows that hydraulic-head residuals in excess of 10 ft are confined primarily to the central part of the Fernandina Beach/St. Marys cone of depression. Given the regional scale of the postdevelopment flow model, these results appear to be acceptable.

Comparisons of Estimated or Observed and Simulated Values of Hydraulic Head in the Lower Floridan Aquifer and Fernandina Permeable Zone

Lower Floridan Aquifer. Comparison of values of hydraulic head observed in the Lower Floridan aquifer to corresponding simulated values shows that a close agreement was achieved at cells corresponding to the locations of wells D-0592, D-0450, and D-1155 (Figure 15 and Table 10). In the cell corresponding to the location of well D-0075, a fair agreement was achieved. Vertically averaged values of hydraulic head that were estimated based on values observed in wells SJ-0025, D-2386, and D-3060 show close agreement also (Table 10 and Figure 16).

Fernandina Permeable Zone. Observations of hydraulic head in the Fernandina permeable zone were made in wells D-0425B, N-0117, D-2386, D-3060, and SJ-0025 (respectively, Leve and Goolsby 1966; Brown 1980; Brown et al. 1984; Brown et al. 1985; Brown et al. 1986) (Figure 16). The values of hydraulic head used in the calibration were either observed or estimated based on the observed values of hydraulic head in these wells (Table 11). Comparisons of these values to corresponding simulated values of hydraulic head indicate fair or good agreement in all five cases (Table 11). The greatest of the five residuals is approximately 8 ft and corresponds to test well



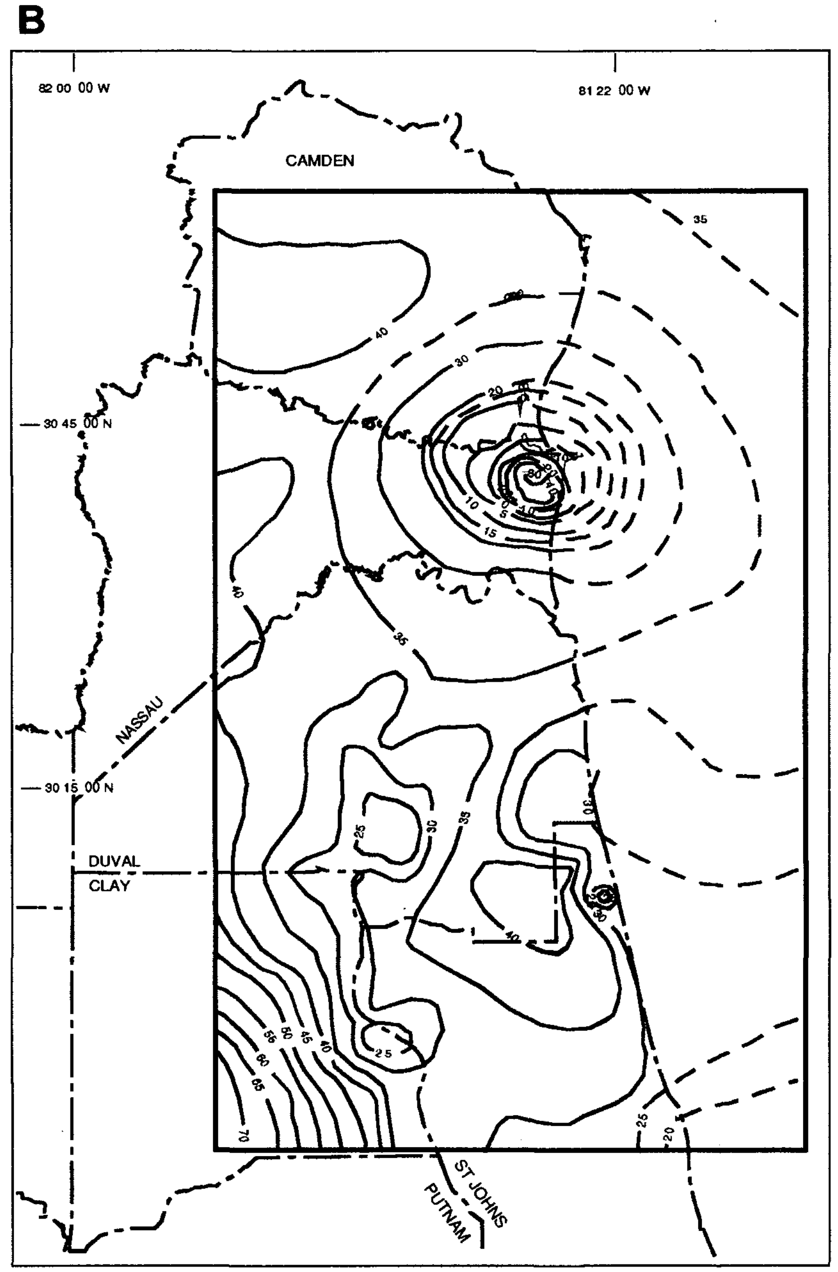
Contour Intervals

Simulated Potentiometric Surface:

20-ft interval in areas with equal hydraulic-head lines less than 20 ft; 5-ft interval in areas with equal hydraulic-head lines greater than 20 ft

Estimated Potentiometric Surface:

5-ft interval in areas with equal hydraulic-head lines greater than 0 ft; 10-ft interval in areas with equal hydraulic-head lines between 0 and -20 ft; 20-ft interval in areas with equal hydraulic-head lines between -20 and -40 ft; 40-ft interval in areas with equal hydraulic-head lines lower than -40 ft



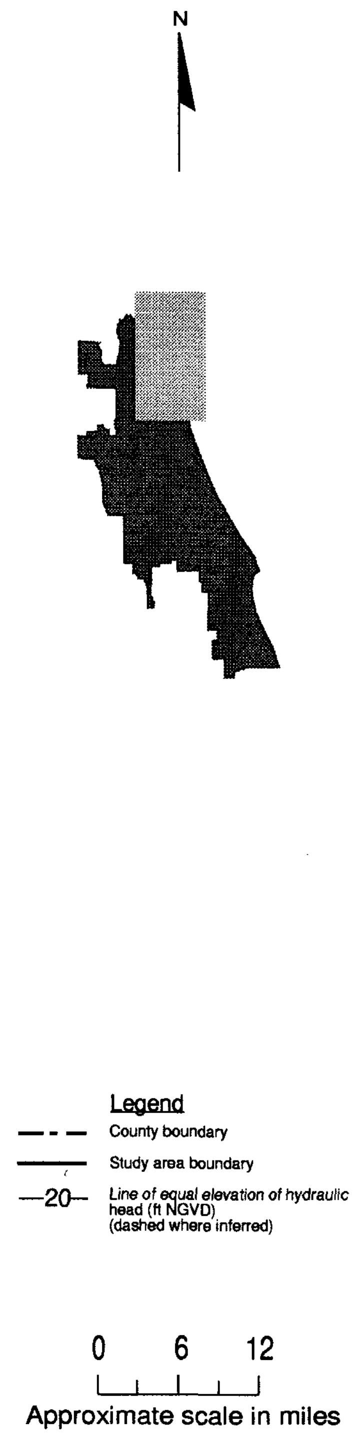


Figure 39. Simulated (A) and estimated (B) postdevelopment potentiometric surfaces of the Upper Floridan aquifer

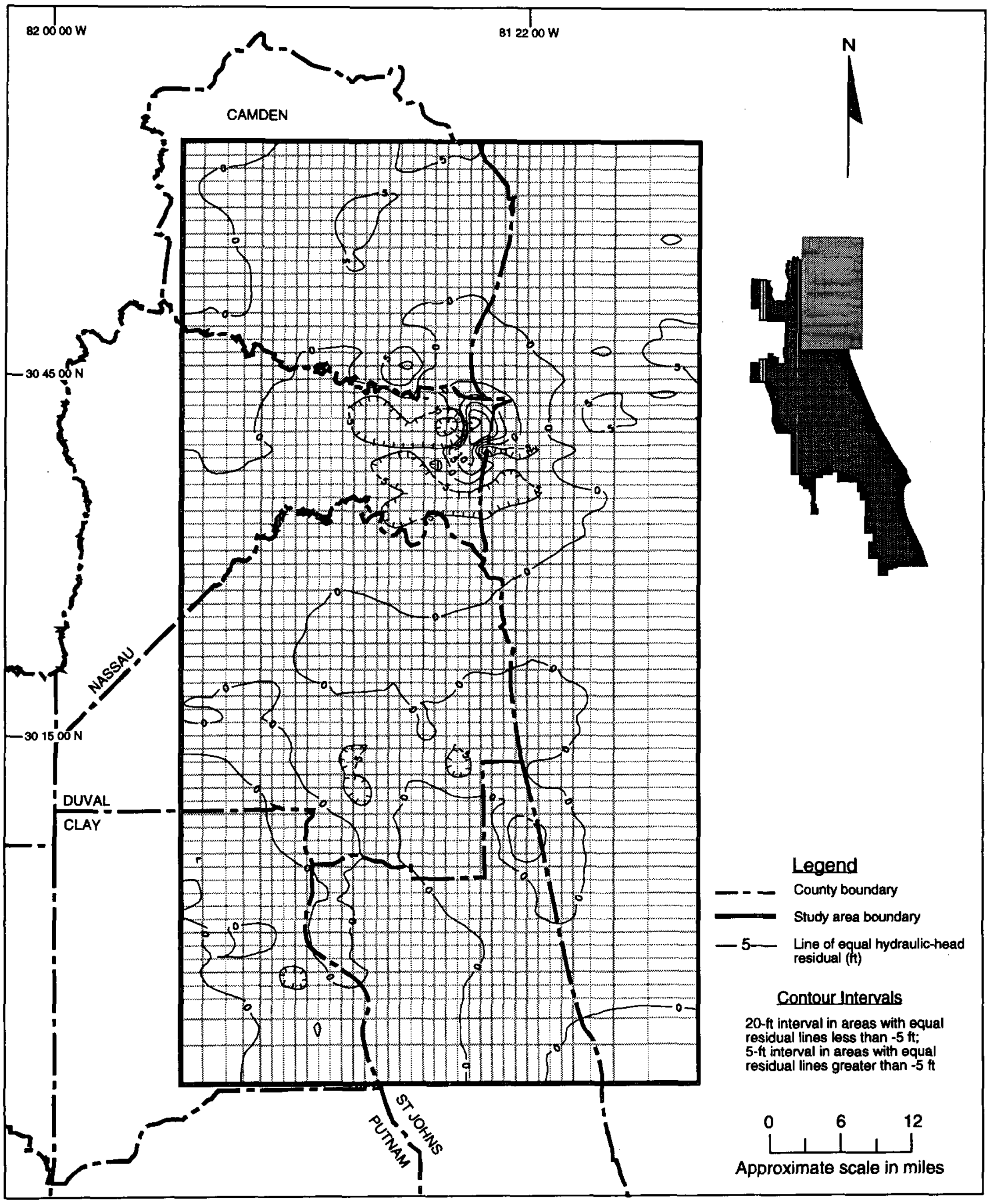


Figure 40. Hydraulic-head residuals of aquifer layer 2 of the postdevelopment flow model. *Negative residuals indicate areas in which simulated hydraulic heads are greater than estimated values. Positive residuals indicate areas in which simulated hydraulic heads are less than estimated values.*

N-0117, which is located near Fernandina Beach (Figure 16 and Table 11).

Plots of the Simulated Potentiometric Surfaces of the Lower Floridan Aquifer and Fernandina Permeable Zone

Lower Floridan Aquifer. A plot of lines of equal elevation of hydraulic head of the simulated potentiometric surface of the Lower Floridan aquifer was created to ensure that the general patterns of simulated ground water flow in aquifer layer 3 are reasonable (Figure 41). A general pattern of ground water flow from west to east can be inferred from the plot, as would be expected. Other aspects of the configuration of the simulated potentiometric surface of the Lower Floridan aquifer cannot be evaluated without additional data.

Fernandina Permeable Zone. A plot of lines of equal elevation of hydraulic head of the simulated potentiometric surface of the Fernandina permeable zone was created to ensure that general patterns of simulated ground water flow in aquifer layer 4 are reasonable (Figure 42). A general pattern of ground water flow from west to east can be inferred from this plot as well. Lines of equal elevation of hydraulic head are generally parallel to the estimated line of the interface tip. This configuration of the simulated potentiometric surface shows that the postdevelopment flow model simulates increasing amounts of upwardly vertical ground water flow as the two areas of saline water in the model domain are approached from the west. In general, the patterns of simulated ground water flow in aquifer layer 4 appear to be reasonable and acceptable.

Simulations of Ground Water Flow in the Lower Floridan Aquifer and Fernandina Permeable Zone

Comparisons of estimated or observed values of hydraulic head from aquifer layers 3 and 4 to corresponding simulated values show that the postdevelopment flow model is doing at least a fair job of simulating ground water flow in aquifer layers 3 and 4 (Tables 10

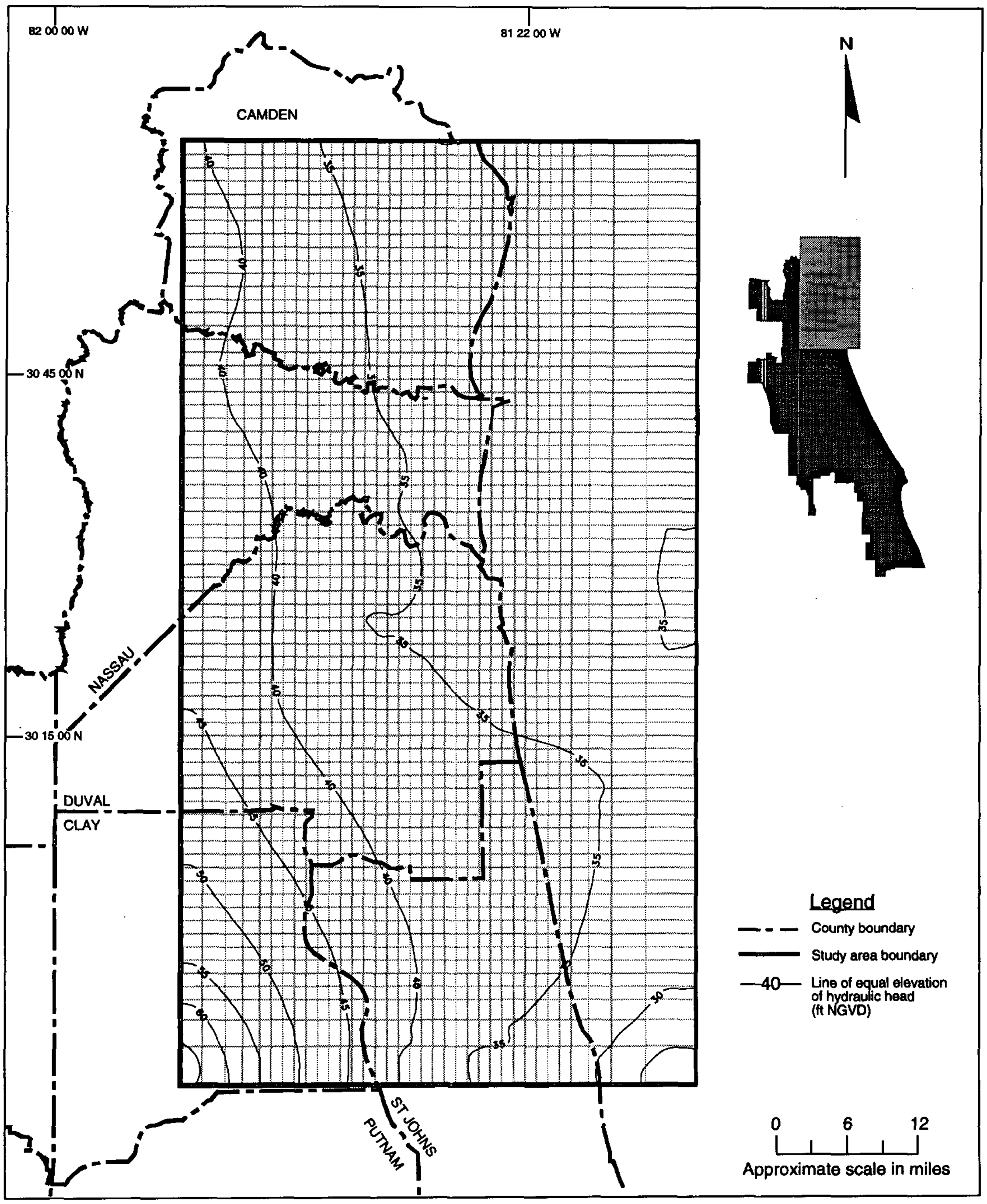


Figure 41. Simulated postdevelopment potentiometric surface of the Lower Floridan aquifer

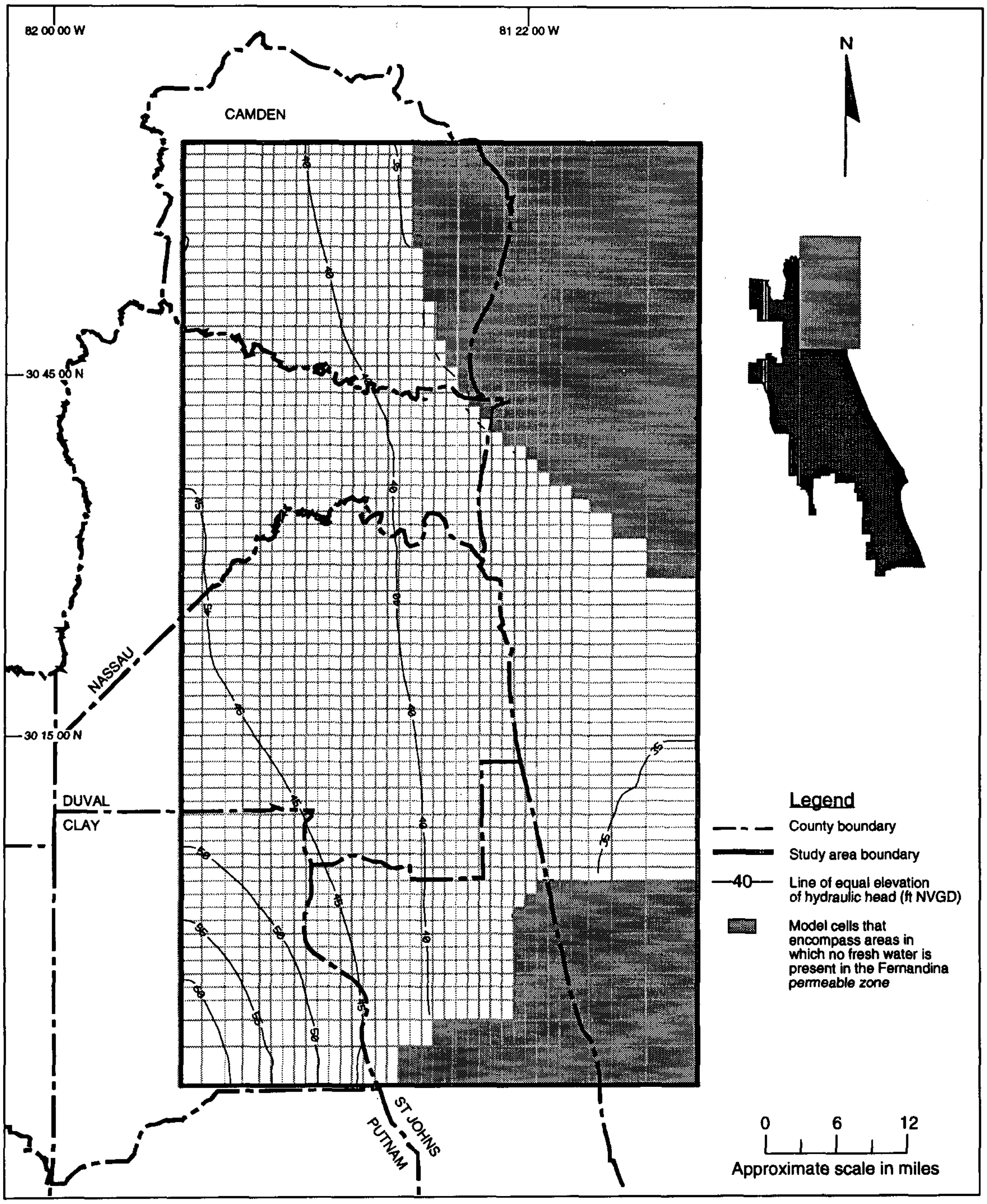


Figure 42. Simulated postdevelopment potentiometric surface of the Fernandina permeable zone

and 11). Because of the scarcity of hydraulic-head data and other aquifer data, however, less confidence should be placed in the results of simulations in aquifer layers 3 and 4 than in the results of simulations in aquifer layer 2. Hydraulic-head data were available from the Lower Floridan aquifer at only seven locations in the study area and from the Fernandina permeable zone at only five locations (Tables 10 and 11). Furthermore, most of these data were not collected in 1985 (Tables 10 and 11).

Final Distributions of Hydraulic Parameters

Transmissivity—Aquifer Layer 2. The transmissivity distribution of aquifer layer 2 resulting from the calibration of the predevelopment flow model was altered substantially with respect to the initial assignments. Initial estimates of transmissivity were lowered in most parts of the model domain. The resulting transmissivity estimates range from 2,000 ft^2/day to 425,000 ft^2/day (Figure 43). The arithmetic mean of the transmissivity distribution is 64,300 ft^2/day. The resulting estimates of transmissivity in the areas of Jacksonville, Fernandina Beach, and St. Marys are generally less than 50,000 ft^2/day. In the west-central and northwest parts of the model domain, estimates of transmissivity exceed 300,000 ft^2/day (Figure 43).

The initial estimates of transmissivity were lowered mainly in parts of the model domain corresponding to areas in the Upper Floridan aquifer that are adjacent to and encompassed by lows in the potentiometric surface. Lowering the transmissivity estimates was necessary because, at the beginning of the calibration, simulated values of hydraulic head in the parts of the model domain corresponding to areas encompassed by lows in the potentiometric surface tended to be higher than corresponding observed or estimated values of hydraulic head. Simulated values of hydraulic head in the parts of the model domain corresponding to areas adjacent to areas encompassed by lows in the potentiometric surface tended to be lower than corresponding observed or estimated values of hydraulic head. Examples of such areas include Jacksonville, Fernandina Beach, and St. Marys. By decreasing the initial estimates of transmissivity assigned to the parts of the model domain

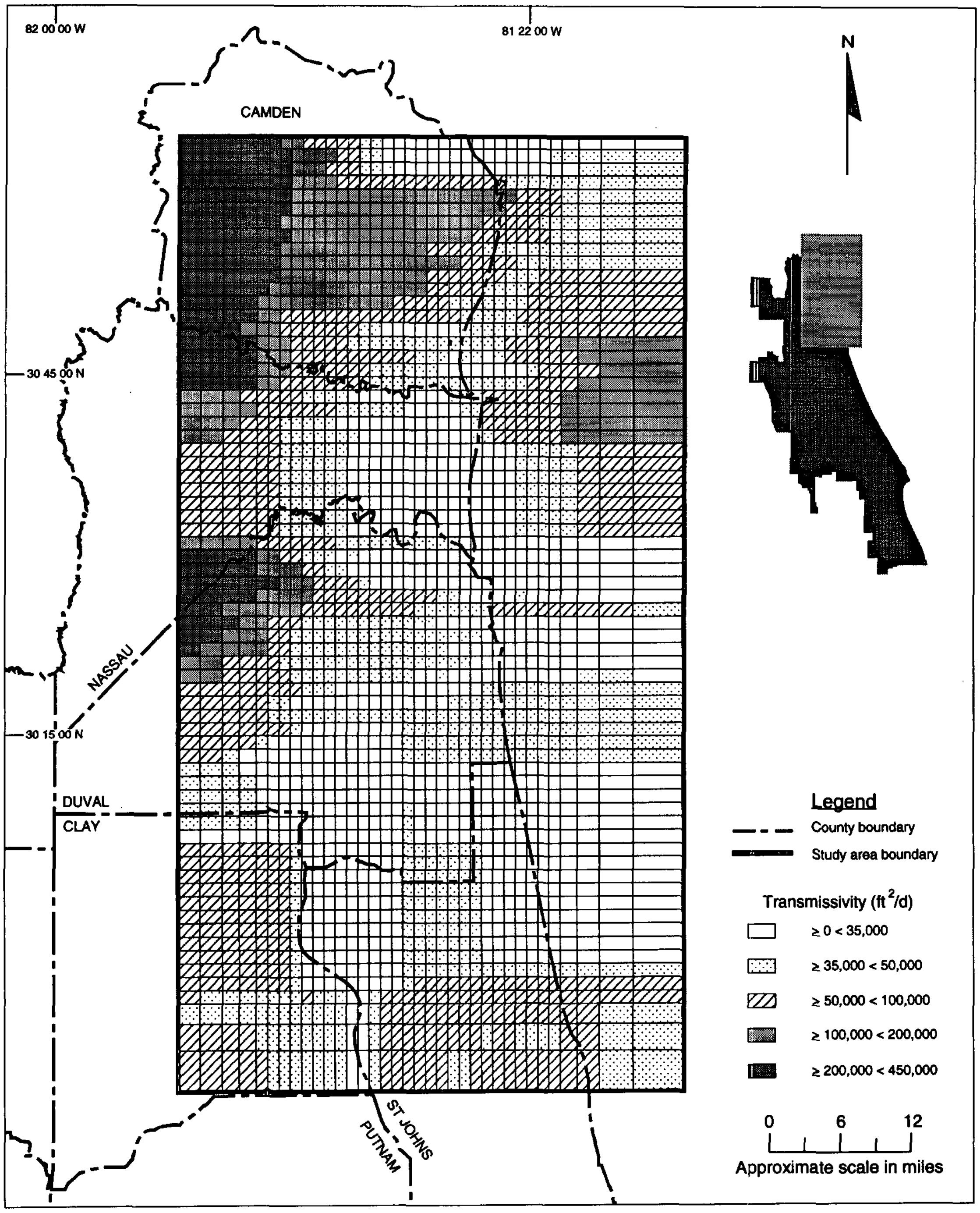


Figure 43. Transmissivity distribution of the Upper Floridan aquifer resulting from the calibration of the postdevelopment flow model

corresponding to such areas, simulated rates of ground water flow toward those parts of the model domain were decreased. As a result, simulated values of hydraulic head in the parts of the model domain corresponding to areas encompassed by lows in the potentiometric surface were decreased. At the same time, simulated values of hydraulic head in parts of the model domain corresponding to areas adjacent to areas encompassed by lows in the potentiometric surface were increased.

The transmissivity estimates of aquifer layer 2 resulting from the calibration were compared to estimates resulting from aquifer performance tests which employed test wells that penetrated through at least 80% of the thickness of the Upper Floridan aquifer or part of MSCU (Figure 11 and Table 12). Because aquifer layer 2 represents the entire thickness of the Upper Floridan aquifer, the results of such aquifer performance tests are more comparable to the results of the calibration than are the results of aquifer performance tests which employed test wells that penetrated only a relatively small percentage of the aquifer thickness. Comparison shows good agreement in all but one case.

Transmissivity—Aquifer Layer 3. The calibration of the postdevelopment flow model resulted in estimates of transmissivity in aquifer layer 3 that in most parts of the model domain were higher than corresponding estimates resulting from the predevelopment calibration. The estimates of transmissivity resulting from the postdevelopment calibration range from 35,000 ft^2/day to 780,000 ft^2/day (Figure 44). The arithmetic mean is 523,000 ft^2/day. The estimates are generally highest in the western parts of the model domain and generally lowest in the eastern and southern parts (Figure 44).

Initial estimates of transmissivity in aquifer layer 3 were increased in most cases so that simulated rates of upward leakage from aquifer layer 3 to aquifer layer 2 would be increased in various subregions of the model domain. These were subregions in which simulated values of hydraulic head in aquifer layer 2 were lower initially than corresponding observed values in the Upper Floridan aquifer. Also, these were subregions corresponding to areas in the Upper Floridan

Table 12. Transmissivity estimates resulting from aquifer performance tests that employed test wells that penetrated at least 80% of the Upper Floridan aquifer

Test Well Identification Number[a]	Location		Model Coordinates		Hydrologic Unit in which Test Well Terminates	Percent Penetration of Upper Floridan Aquifer	Transmissivity Estimate (ft^2/day)	
	Approximate Latitude	Approximate Longitude	Row	Column			Pump Test	Calibration
1	300607	814544	56	4	Upper Floridan aquifer	83	73,000	50,000
2	302158	814035	41	91	MSCU	126[b]	27,000	42,000
3	302022	813823	42	11	MSCU	122[b]	23,000	35,000
4	302348	812425	39	26	Upper Floridan aquifer	89	27,000	21,000
8	301920	813752	43	12	MSCU	123[b]	130,000	25,000
9	304041	812828	22	22	Upper Floridan aquifer	80	21,000	18,000
10	303945	812837	23	21	Upper Floridan aquifer	81	30,000	20,000
14	301019	812234	52	27	Upper Floridan aquifer	87	28,000	27,000

Note: ft^2/day = square feet per day

[a]Refers to the identification number used on Figure 11.
[b]Greater than 100% because the test well terminates in the middle semiconfining unit, which is beneath the Upper Floridan aquifer.

Source: G.Warren Leve, Inc. 1987; Krause and Randolph 1989; Szell 1993

aquifer in which leakage from the Lower Floridan aquifer might represent a significant proportion of the total inflow to the Upper Floridan aquifer. The area encompassed by the potentiometric high that straddles the Duval-St. Johns county line is such an area (Durden and Motz 1992).

By increasing simulated rates of leakage from aquifer layer 3 to aquifer layer 2 in parts of the model domain that correspond to such areas, simulated values of hydraulic head in aquifer layer 2 were increased; the calibration of the model was improved. The upper end of the transmissivity range derived from the postdevelopment calibration for aquifer layer 3 is relatively high. Confirmation of

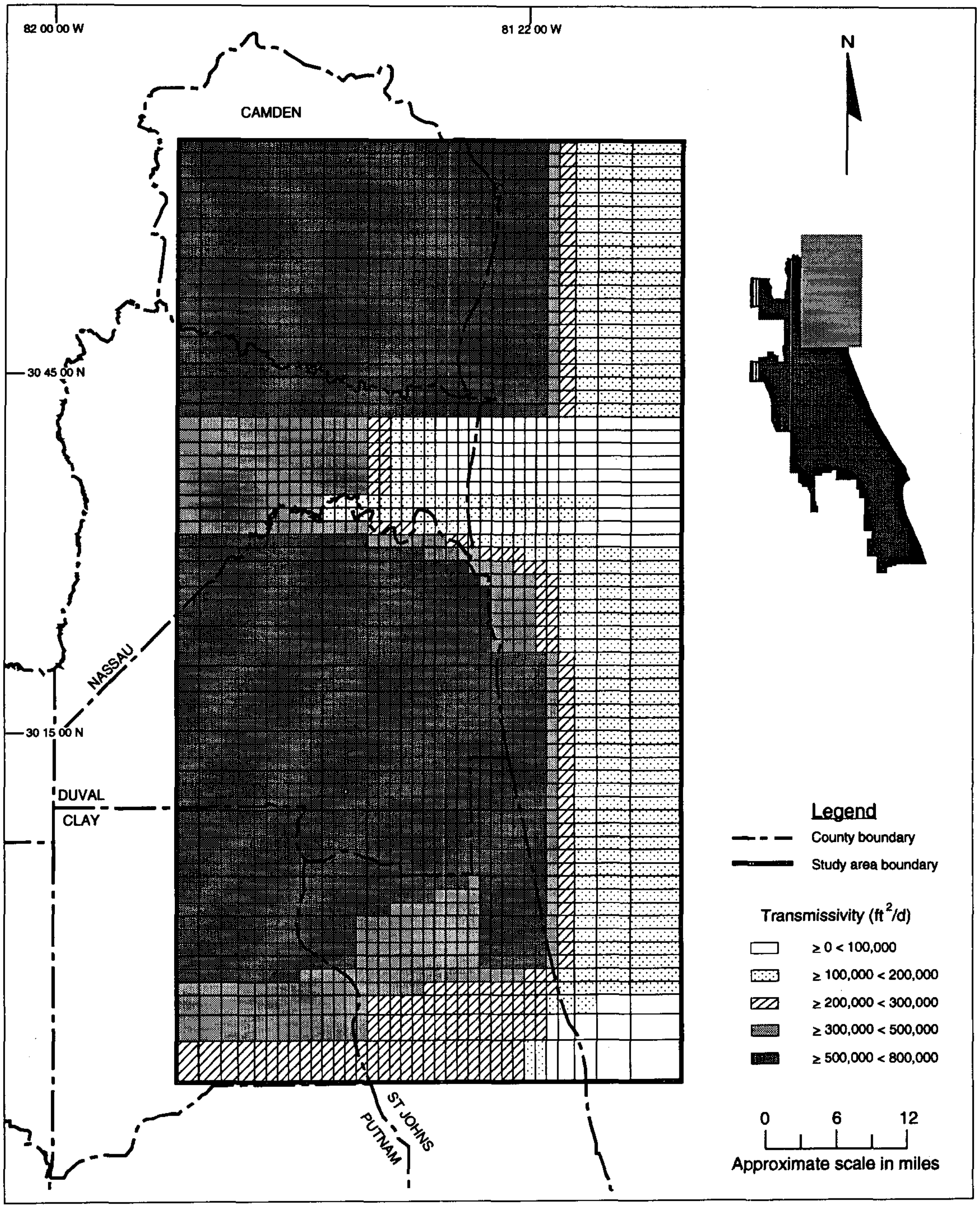


Figure 44. Transmissivity distribution of the Lower Floridan aquifer resulting from the calibration of the postdevelopment flow model

these estimates with results of aquifer performance tests is therefore desirable.

Transmissivity—Aquifer Layer 4. As stated previously, the grid cells of aquifer layer 4 were designated initially as either constant-head or inactive, making accurate estimates of the transmissivity of the Fernandina permeable zone unnecessary. Initially, this approach enabled attention to be focused on adjusting estimates of transmissivity and leakance in the aquifer and semiconfining unit layers, respectively, for which more information was available. Once the model layers above semiconfining unit layer 3 were felt to be calibrated substantially, the grid cells of aquifer layer 4 that had been designated as constant-head were redesignated as variable-head, and the calibration of aquifer layer 4 was undertaken as well.

In calibrating aquifer layer 4, the transmissivity distribution of aquifer layer 4 and the leakance distribution of semiconfining unit layer 3 were adjusted successively. The process was continued until an acceptable match with observed and estimated values of hydraulic head in the Fernandina permeable zone was obtained and a general pattern of flow from west to east was simulated (Table 11).

During this process, the effects of the adjustments on simulated values of hydraulic head in aquifer layers 2 and 3 were being monitored as well. Monitoring of aquifer layers 2 and 3 was necessary to determine if additional adjustments were needed in the hydraulic parameters of the aquifer and semiconfining unit layers above semiconfining unit layer 3 in response to the adjustments in hydraulic parameters of aquifer layer 4 and semiconfining unit layer 3. The adjustments in the hydraulic parameters of aquifer layer 4 and semiconfining unit layer 3 proved to have little effect on the simulated values of hydraulic head in aquifer layers 2 and 3. Additional adjustments in the transmissivity or leakance distributions of the layers above semiconfining unit layer 3 were deemed unnecessary.

The mean of the resulting transmissivity distribution in aquifer layer 4 is 43,300 ft^2/day. The maximum estimate of transmissivity in aquifer layer 4 is 82,500 ft^2/day, and the minimum estimate is

1,000 ft^2/day. The resulting estimates of transmissivity decrease from west to east (Figure 45). The values of transmissivity approach zero in grid cells corresponding to the vicinity of the boundaries of the saline areas because the saturated thickness of the freshwater flow system approaches zero as the boundaries of the saline areas are approached. (Figure 45).

Leakance—Semiconfining Unit Layer 1. The estimates of leakance in the upper confining unit resulting from the calibration of the postdevelopment flow model range from 5.0×10^{-8} d^{-1} to 2.0×10^{-3} d^{-1}. In many parts of the model domain, the resulting estimates were one to two orders of magnitude greater than the estimates resulting from the calibration of the predevelopment flow model (Figure 32). In most cases, the estimates of leakance resulting from the calibration of the predevelopment flow model were increased to make the estimates of leakance in the upper confining unit more consistent with the results of other modeling studies (e.g., Krause and Randolph 1989). These increases did not affect the model simulations greatly because, even after being increased, the estimates of leakance were still relatively small.

In the south-central part of the model domain, the leakance in semiconfining unit layer 1 was increased to induce a greater amount of simulated recharge from aquifer layer 1 to aquifer layer 2. Leakance estimates were increased in the southwest corner of the model domain to induce a greater amount of simulated recharge from aquifer layer 1 to aquifer layer 2. Leakance estimates were altered somewhat in the part of the model domain that corresponds to the area of Green Cove Springs (Figure 1).

In spite of the changes, the general pattern of the leakance distribution is generally similar to the distribution that resulted from the predevelopment calibration (Figures 32 and 46). The estimates of leakance are still low throughout most of the model domain but are relatively high in the parts corresponding to the southwest and south-central subregions of the study area.

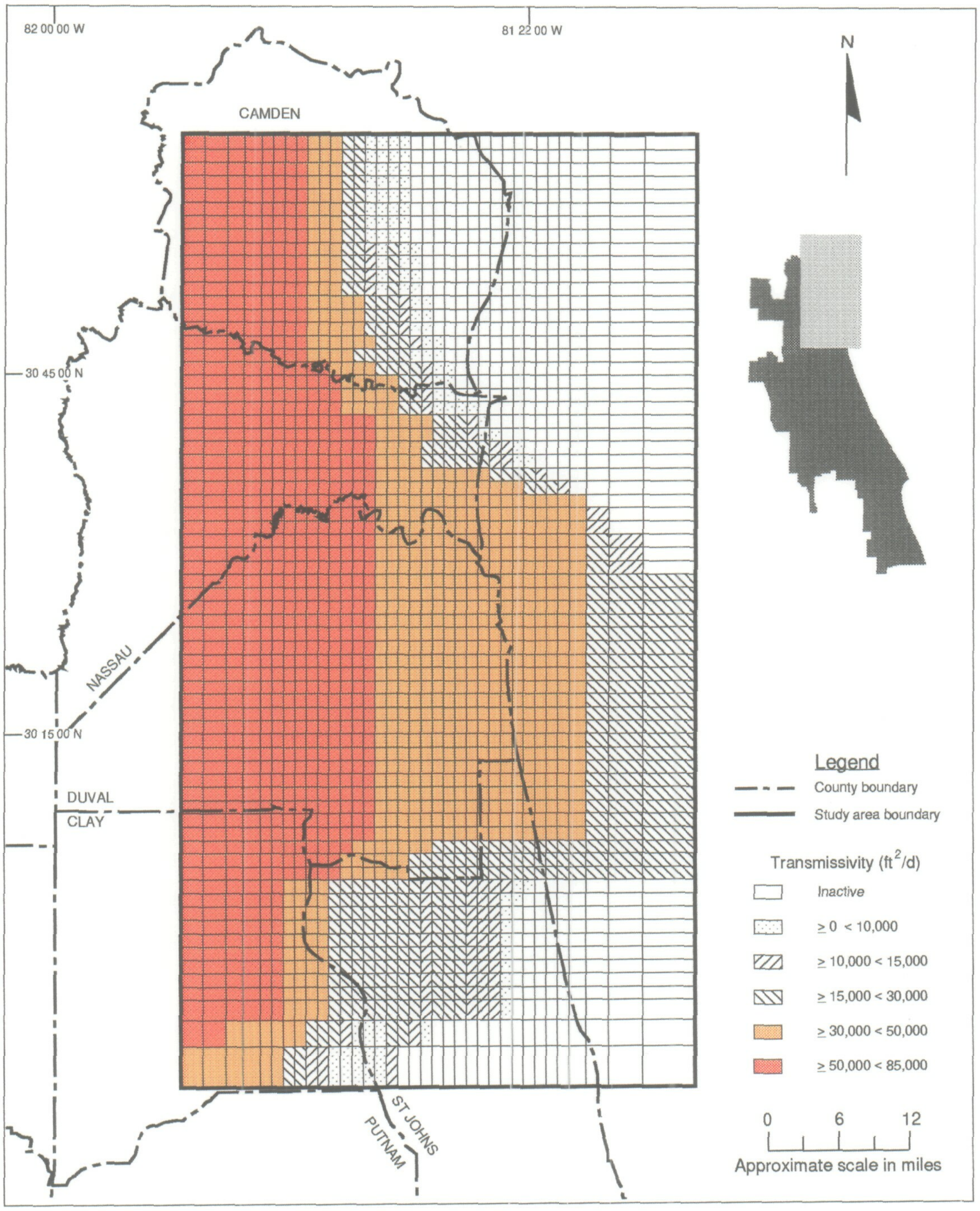


Figure 45. Transmissivity distribution of the Fernandina permeable zone resulting from the calibration of the postdevelopment flow model

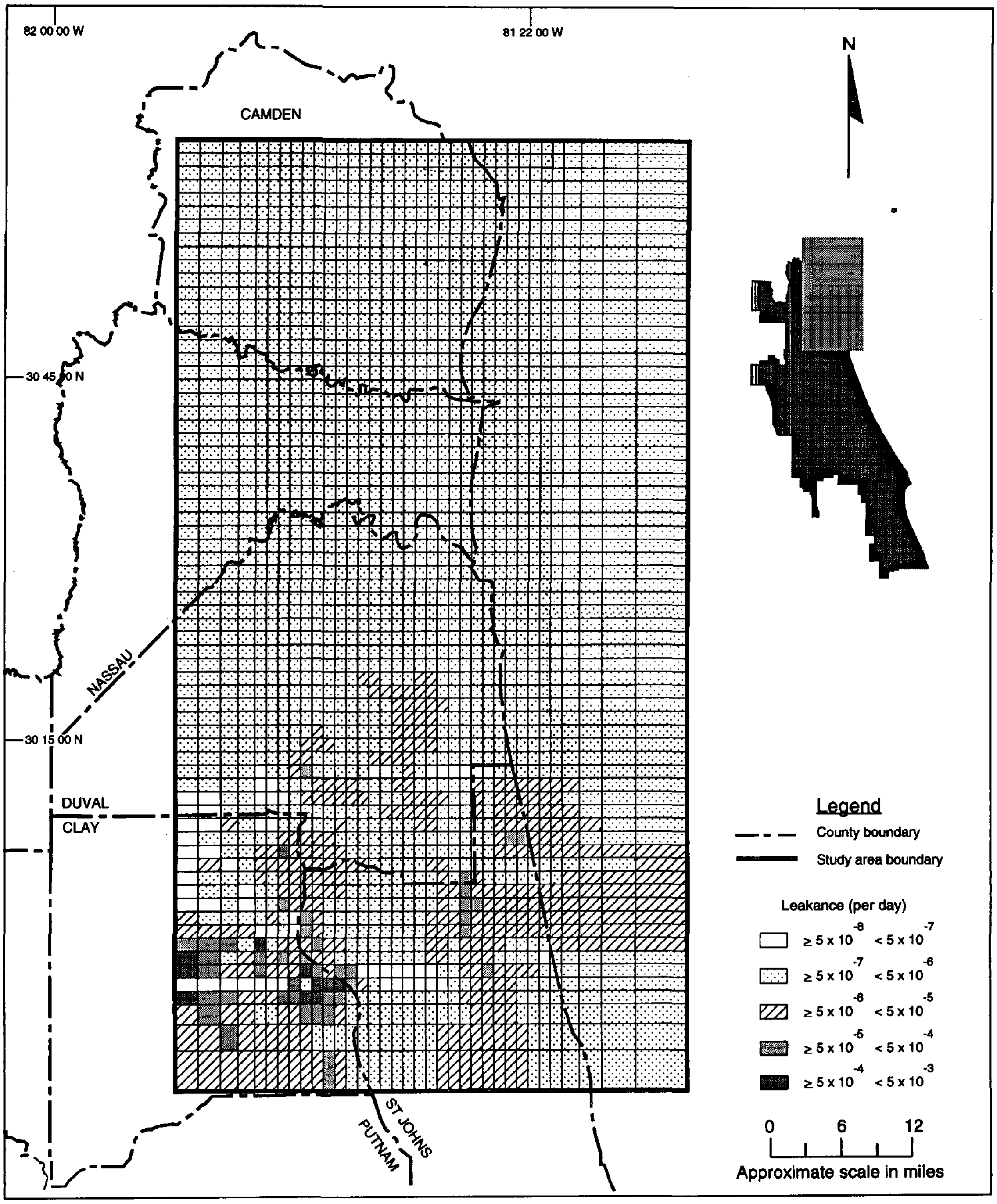


Figure 46. Leakance distribution of the upper confining unit resulting from the calibration of the postdevelopment flow model

Leakance—Semiconfining Unit Layer 2. Estimates of leakance in MSCU resulting from the postdevelopment calibration range from 1.0×10^{-10} d^{-1} to 5.0×10^{-2} d^{-1}. Generally, these estimates were not altered substantially from the initial estimates (Figures 33 and 47). Notable modifications were made in some areas, however.

The initial estimates of leakance were decreased in much of the model domain that corresponds to the area west of the St. Johns River and to the area encompassed by the potentiometric low centered on the St. Johns River between Green Cove Springs and Jacksonville (Figures 1, 13, and 33). The objective was to minimize rates of simulated leakage from aquifer layer 3 to aquifer layer 2 in parts of the model domain corresponding to areas west of and beneath the St. Johns River so that a greater quantity of simulated ground water flow in aquifer layer 3 would be forced to the part of the model domain corresponding to the area east of the St. Johns River. Forcing additional flow to that part of the model domain was necessary to increase values of simulated hydraulic head in aquifer layer 2 there.

In the parts of the model domain corresponding to areas east of the St. Johns River, the initial estimates of leakance in semiconfining unit layer 2 were increased to enable increases in simulated rates of leakage from aquifer layer 3 to aquifer layer 2 (Figures 33 and 47). The initial estimates of leakance in MSCU were increased in the northern and south-central parts of the model domain also to enable increases in simulated rates of leakage from aquifer layer 3 to aquifer layer 2 (Figures 33 and 47).

Leakance—Semiconfining Unit Layer 3. The estimates of leakance in LSCU resulting from the postdevelopment calibration range from 4.3×10^{-6} d^{-1} to 8.1×10^{-5} d^{-1} (Figure 48). In most cases, the initial estimates of leakance in semiconfining unit layer 3 were increased.

MASS-BALANCE ANALYSIS

Mass-balance analyses of aquifer layers 2, 3, and 4 of the postdevelopment flow model were performed to gain understanding of the interaction between the aquifers of the Floridan aquifer system

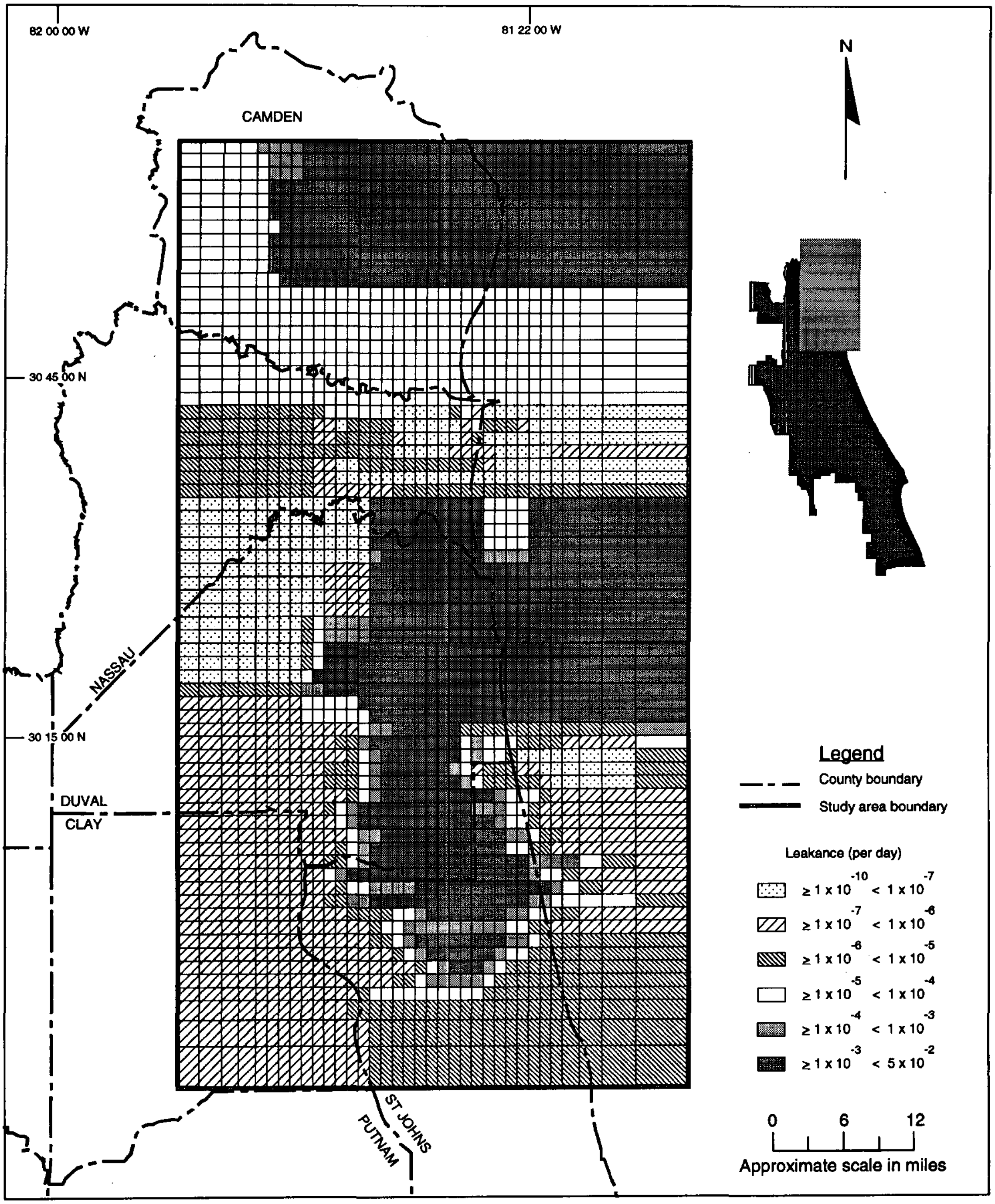


Figure 47. Leakance distribution of the middle semiconfining unit resulting from the calibration of the postdevelopment flow model

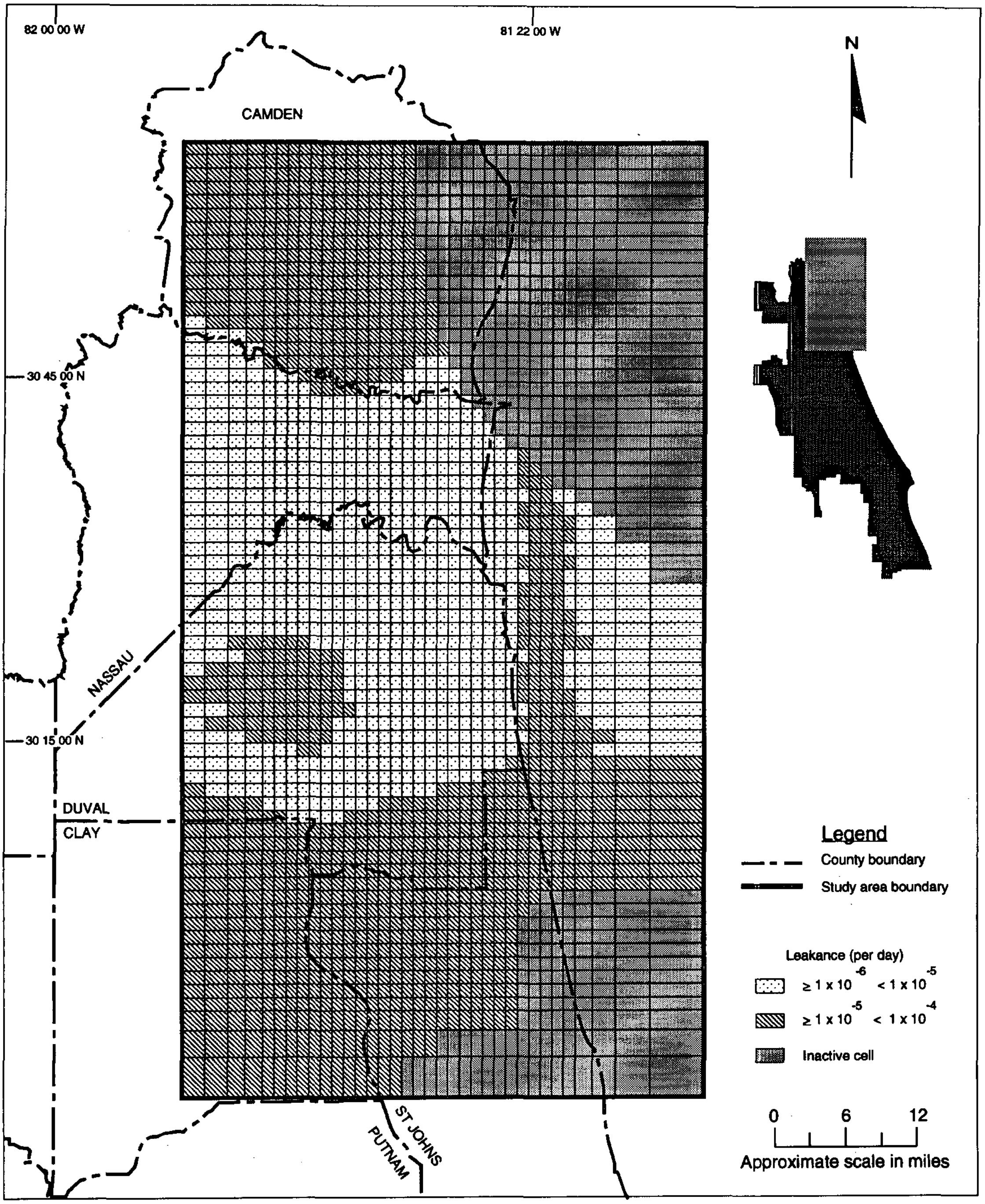


Figure 48. Leakance distribution of the lower semiconfining unit resulting from the calibration of the postdevelopment flow model

and between the Floridan aquifer system and the overlying surficial aquifer system (Tables 13a–15b). The rate of ground water flow is greatest in the Lower Floridan aquifer (1.68 in/yr), somewhat less in the Upper Floridan aquifer (1.25 in/yr), and much less in the Fernandina permeable zone (0.13 in/yr), according to the analyses.

The primary sources of recharge to the Upper Floridan aquifer are the Lower Floridan aquifer and areas west of the western boundary of the model (59 and 26%, respectively) (Table 13a). Only about 12% of recharge to the Upper Floridan aquifer is derived from the surficial aquifer system. The primary source of recharge to both the Lower Floridan aquifer and the Fernandina permeable zone is the area west of the western boundary of the study area (87% and almost 100%, respectively) (Tables 14a and 15a).

Significant proportions of total discharge from the Upper and Lower Floridan aquifers are to wells (65% and 30%, respectively) (Tables 13b and 14b). In addition, a significant proportion of the total discharge from the Upper Floridan aquifer is to the surficial aquifer system (22%). Likewise, a significant proportion of total discharge from the Lower Floridan aquifer is to the Upper Floridan aquifer (43%). Relatively little flow discharges from the Upper and Lower Floridan aquifers laterally via the southern and eastern boundaries of the study area. Almost all discharge from the Fernandina permeable zone occurs as upward leakage to the Lower Floridan aquifer (almost 100%) (Table 15b).

SENSITIVITY ANALYSIS

The sensitivity of the postdevelopment flow model to changes in model parameters was analyzed to ascertain the relative degrees of influence of the different model parameters. The results of the sensitivity analysis help to indicate which parameters are most critical to the accuracy of the postdevelopment flow model and should therefore receive the most attention during the calibration. In addition, the results can be used to help plan for future data collection.

Table 13a. Results of the mass-balance analysis of the postdevelopment Upper Floridan aquifer—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Surficial aquifer system	1.27×10^9	0.15	12.1
Lower Floridan aquifer	6.21×10^9	0.73	58.9
Western boundary	2.75×10^9	0.32	25.8
Eastern boundary	3.45×10^8	0.04	3.2
Southern boundary	0.00	0.00	0.0
Northern boundary	0.00	0.00	0.0
Total	1.06×10^{10}	*1.24	100.0

Table 13b. Results of the mass-balance analysis of the postdevelopment Upper Floridan aquifer—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Surficial aquifer system	2.34×10^9	0.28	22.2
Lower Floridan aquifer	1.80×10^8	0.02	1.6
Western boundary	5.11×10^7	0.01	0.8
Eastern boundary	5.65×10^7	0.01	0.8
Southern boundary	1.86×10^8	0.02	1.6
Northern boundary	8.42×10^8	0.10	7.9
Wells	6.92×10^9	0.82	65.1
Total	1.06×10^{10}	*1.26	100.0

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

*Values are not equal because of rounding error.

Table 14a. Results of the mass-balance analysis of the postdevelopment Lower Floridan aquifer—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Upper Floridan aquifer	1.80×10^8	0.02	1.2
Fernandina permeable zone	1.05×10^9	0.12	7.2
Western boundary	1.24×10^{10}	1.46	87.4
Eastern boundary	5.15×10^8	0.06	3.6
Southern boundary	0.00	0.00	0.0
Northern boundary	8.38×10^7	0.01	0.6
Total	1.42×10^{10}	*1.67	100.0

Table 14b. Results of the mass-balance analysis of the postdevelopment Lower Floridan aquifer—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Upper Floridan aquifer	6.21×10^9	0.73	43.4
Fernandina permeable zone	1.60×10^7	0.00	0.0
Western boundary	0.00	0.00	0.0
Eastern boundary	2.50×10^8	0.03	1.8
Southern boundary	9.92×10^8	0.12	7.1
Northern boundary	2.52×10^9	0.30	17.9
Wells	4.25×10^9	0.50	29.8
Total	1.42×10^{10}	*1.68	100.0

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

*Values are not equal because of rounding error.

Table 15a. Results of the mass-balance analysis of the postdevelopment Fernandina permeable zone—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Lower Floridan aquifer	1.60×10^7	0.00	0.0
Western boundary	1.06×10^9	0.13	100.0
Eastern boundary	1.70×10^7	0.00	0.0
Total	1.09×10^9	*0.13	100.0

Table 15b. Results of the mass-balance analysis of the postdevelopment Fernandina permeable zone—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Lower Floridan aquifer	1.05×10^9	0.12	100.0
Western boundary	8.38×10^6	0.00	0.0
Eastern boundary	3.52×10^7	0.00	0.0
Total	1.09×10^9	*0.12	100.0

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

*Values are not equal because of rounding error.

The procedure used in the analysis was the same as that used in evaluating the predevelopment flow model. As before, every member of each of the parameter distributions in the postdevelopment flow model was multiplied by the same factor (first by 2.0, then by 0.5), while the members of all other parameter distributions were unchanged from the values obtained as a result of the calibration. The mean of the residuals, the standard deviation of the residuals, and the maximum of the absolute values of the residuals of the Upper Floridan aquifer were then determined. The percent change of these statistics from the corresponding calibration values indicated the relative degree of influence of the parameter being considered.

The parameter distributions considered in the analysis were as follows:

- Leakance in the upper confining unit and the middle and lower semiconfining units (LK1, LK2, and LK3, respectively)

- Transmissivity in the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone (T2, T3, and T4 respectively)

- Water table elevations (WTE)

- GHB-condition source heads of the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone (LBH2, LBH3, and LBH4, respectively)

- Withdrawals from wells in the Upper and Lower Floridan aquifers (P2 and P3, respectively) (Tables 16 and 17)

Changes in the transmissivity distributions were accompanied by changes of the same factor in distributions of the conductance of the GHB conditions.

The results are similar to the results of the sensitivity analysis of the predevelopment flow model. As before, changes in the GHB-condition source heads of aquifer layers 2 and 3 had the greatest influence on the simulated potentiometric surfaces of the Upper Floridan aquifer (Tables 16 and 17). The influence of changes made in the GHB-condition source heads of aquifer layer 4 was considerably less but still notable (Tables 16 and 17). Changes in elevations of the water table were quite influential, as were changes in the transmissivity of aquifer layers 2 and 3. Changes in distributions of well withdrawal rates in aquifer layer 2 had significant influence as well. Changes in leakance estimates of semiconfining unit layers 1 and 2 were of moderate influence, as were the changes in the well withdrawal distribution of aquifer layer 3. Changes in estimates of leakance of semiconfining unit layer 3 had only slight influence on the results of the simulations.

The results show that much consideration is warranted in estimating the GHB-condition source heads, rates of withdrawals from wells from the Upper Floridan aquifer, elevations of the water table, and the transmissivity distributions of the Upper and Lower Floridan aquifers. Less consideration is required for estimating the leakance distribution of LSCU and the transmissivity distribution of the Fernandina permeable zone.

Table 16. Results of the sensitivity analysis of the postdevelopment flow model

Input Data Change	Mean Hydraulic-Head Residual (feet)	Standard Deviation (feet)	Absolute Value of Maximum Hydraulic-Head Residual (feet)
Calibration	0.1	3.6	48.8
LK1 x 2.0	0.8	3.8	48.6
LK1 x 0.5	-0.5	3.8	48.9
LK2 x 2.0	-0.6	4.0	54.5
LK2 x 0.5	0.8	3.6	49.0
LK3 x 2.0	0.0	3.6	48.8
LK3 x 0.5	0.1	3.6	48.7
T2 x 2.0	-2.1	5.5	79.3
T2 x 0.5	2.8	7.8	151.0
T3 x 2.0	-2.2	4.2	51.1
T3 x 0.5	3.3	3.8	47.8
T4 x 2.0	-0.1	3.6	48.9
T4 x 0.5	0.2	3.6	48.6
WTE x 2.0	-3.3	8.4	49.5
WTE x 0.5	1.7	4.8	48.6
LBH2 x 2.0	-10.9	9.6	57.8
LBH2 x 0.5	5.5	5.3	49.0
LBH3 x 2.0	-24.0	9.7	76.1
LBH3 x 0.5	12.1	6.0	57.7
LBH4 x 2.0	-1.5	3.9	50.0
LBH4 x 0.5	0.8	3.6	48.1
P2 x 2.0	6.3	9.4	164.0
P2 x 0.5	-3.1	5.9	82.9
P3 x 2.0	1.7	3.5	47.6
P3 x 0.5	-0.8	3.8	49.3

Note: See page 156 for definition of input coding.

Table 17. Percent differences resulting from the sensitivity analysis of the postdevelopment flow model

Input Data Change	Percent Change of			Sum of Absolute Values of Percent Differences
	Mean Hydraulic-Head Residual	Standard Deviation	Absolute Value of Maximum Hydraulic-Head Residual	
LK1 x 2.0	-700.0	-5.6	0.4	
LK1 x 0.5	600.0	-5.6	-0.2	1,311.7
LK2 x 2.0	700.0	-11.1	-11.7	
LK2 x 0.5	-700.0	0.0	-0.4	1,423.2
LK3 x 2.0	100.0	0.0	0.0	
LK3 x 0.5	0.0	0.0	0.2	100.2
T2 x 2.0	2,200.0	-52.8	-62.5	
T2 x 0.5	-2,700.0	-116.7	-209.4	5,341.4
T3 x 2.0	2,300.0	-16.7	-4.7	
T3 x 0.5	-3,200.0	-5.6	2.0	5,529.0
T4 x 2.0	200.0	0.0	-0.2	
T4 x 0.5	-100.0	0.0	0.4	300.6
WTE x 2.0	3,400.0	-133.3	-1.4	
WTE x 0.5	-1,600.0	-33.3	0.4	5,168.5
LBH2 x 2.0	11,000.0	-166.7	-18.4	
LBH2 x 0.5	-5,400.0	-47.2	-0.4	16,632.7
LBH3 x 2.0	24,100.0	-169.4	-55.9	
LBH3 x 0.5	-12,000.0	-66.7	-18.2	36,410.3
LBH4 x 2.0	1,600.0	-8.3	-2.5	
LBH4 x 0.5	-700.0	0.0	1.4	2,312.2
P2 x 2.0	-6,200.0	-161.1	-236.1	
P2 x 0.5	3,200.0	-63.9	-69.9	9,930.9
P3 x 2.0	-1,600.0	2.8	2.5	
P3 x 0.5	900.0	-5.6	-1.0	2,511.8

Note: See page 156 for definition of input coding.

THE REVISED PREDEVELOPMENT FLOW MODEL

INTRODUCTION

As a part of the calibration procedure of the postdevelopment flow model, an updated version of the predevelopment flow model was calibrated. This version is referred to herein as the revised predevelopment flow model. This model incorporates the distributions of leakance and transmissivity resulting from the calibration procedure of the postdevelopment flow model. These distributions are presumably more accurate than those derived from the calibration of the original predevelopment flow model. As a result, the revised predevelopment flow model probably more accurately represents of the predevelopment flow system than the original predevelopment flow model.

The finite-difference grid and GHB-condition source heads of aquifer layers 2 and 3 of the revised predevelopment flow model are identical to those of the original predevelopment flow model. The configuration of the lateral boundary conditions of aquifer layer 4 is the same as that of aquifer layer 4 in the postdevelopment flow model. As with the postdevelopment flow model, the lateral boundary conditions were configured to represent a generalized pattern of ground water flow from west to east. The GHB-condition source heads of aquifer layer 4 were determined using the same procedure as discussed regarding aquifer layer 3 of the predevelopment flow model. The values of conductance assigned to the GHB conditions of all three active aquifer layers were recalculated based on the updated distributions of transmissivity.

COMPARISONS OF ESTIMATED AND SIMULATED POTENTIOMETRIC SURFACES

The hydraulic-head residuals in aquifer layer 2 were based on hydraulic-head values interpolated from the map of the predevelopment Upper Floridan aquifer (Johnston, Krause et al. 1980). The mean of the hydraulic-head residuals in aquifer layer 2 is

-2.0 ft, the negative sign indicating that simulated values of hydraulic head were higher on average than interpolated values. The standard deviation is 2.6 ft. The mean of the absolute values of the residuals is 2.7 ft. Approximately 88% of the residuals were less than or equal to 5 ft, and nearly 100% were less than or equal to 10 ft. The extreme values were 10.0 and -10.1 ft.

These values indicate slightly less agreement between interpolated and simulated values of hydraulic head than was the case in the original predevelopment flow model. As stated previously, however, the map of the predevelopment potentiometric surface of the Upper Floridan aquifer is accurate to only ±10 ft (based on Krause 1982) (Figure 12). Because the residuals at practically all the cells in the model domain are within this error range, the revised predevelopment flow model may conceivably still represent an improvement in the representation of the predevelopment flow system.

Comparison of lines of equal elevation of hydraulic head of the simulated potentiometric surface to the estimated potentiometric surface of the predevelopment Upper Floridan aquifer demonstrates a good agreement with the general features of the estimated surface (Figure 49). Inspection of the lines of equal residual (Figure 50) indicates that residuals in excess of 5 ft were present in only a relatively small proportion of the model domain. Disagreement in interpolated and simulated values of hydraulic head is centered in parts of the model domain that correspond to the areas of St. Johns and Clay counties within the study area.

MASS-BALANCE ANALYSIS

Mass-balance analyses of aquifer layers 2, 3, and 4 of the revised predevelopment flow model were performed. Comparisons to the mass-balance analyses of the postdevelopment flow model indicate significant differences in the predevelopment and postdevelopment flow systems (Tables 13a–15b and 18a–20b).

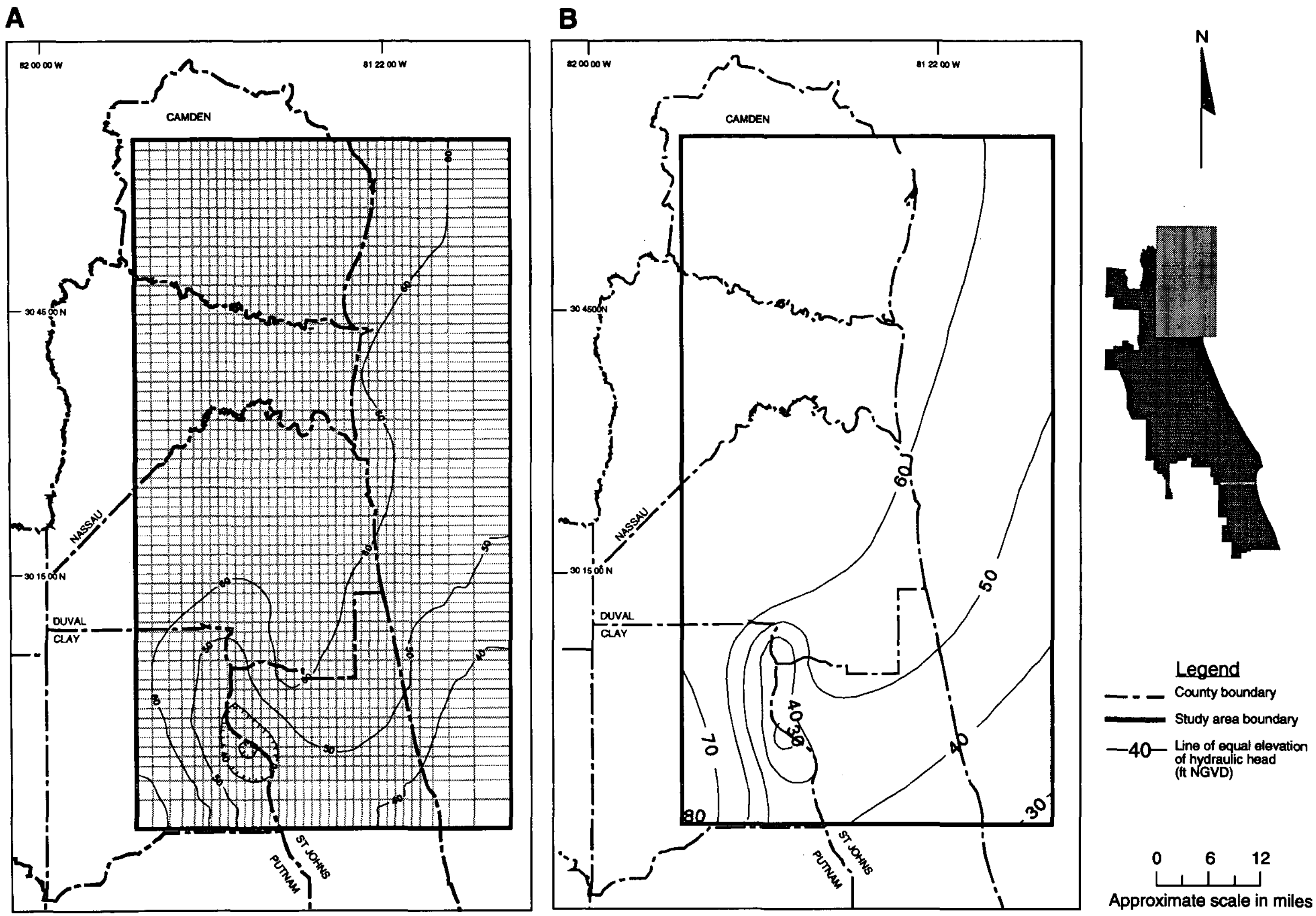


Figure 49. Simulated (A) and estimated (B) potentiometric surfaces of the predevelopment Upper Floridan aquifer (from revised predevelopment flow model)

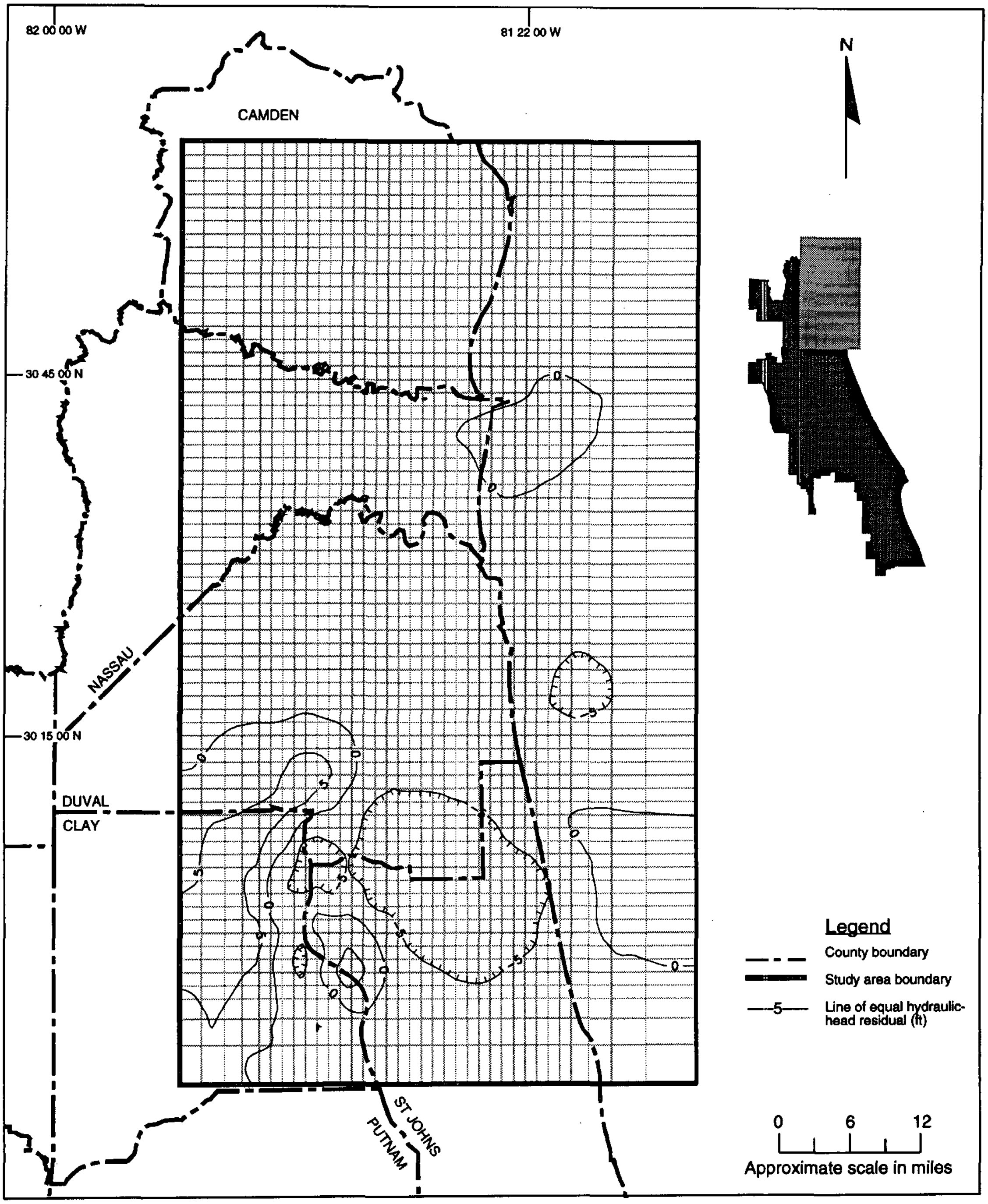


Figure 50. Hydraulic-head residuals of aquifer layer 2 of the revised predevelopment flow model. *Negative residuals indicate areas in which simulated hydraulic heads are greater than estimated values. Positive residuals indicate areas in which simulated hydraulic heads are less than estimated values.*

Table 18a. Results of the mass-balance analysis of the predevelopment Upper Floridan aquifer—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Surficial aquifer system	7.97×10^8	0.09	13.2
Lower Floridan aquifer	3.54×10^9	0.42	61.8
Western boundary	1.48×10^9	0.17	25.0
Eastern boundary	7.17×10^5	0.00	0.0
Southern boundary	0.00	0.00	0.0
Northern boundary	0.00	0.00	0.0
Total	5.82×10^9	*0.68	100.0

Table 18b. Results of the mass-balance analysis of the predevelopment Upper Floridan aquifer—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Surficial aquifer system	4.42×10^9	0.52	75.4
Lower Floridan aquifer	1.05×10^8	0.01	1.4
Western boundary	0.00	0.00	0.0
Eastern boundary	1.07×10^9	0.13	18.8
Southern boundary	2.25×10^8	0.03	4.3
Northern boundary	0.00	0.00	0.0
Total	5.82×10^9	*0.69	†99.9

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

*Values are not equal because of rounding error.
†The total does not equal 100 because of rounding error.

Table 19a. Results of the mass-balance analysis of the predevelopment Lower Floridan aquifer—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Upper Floridan aquifer	1.05×10^8	0.01	1.1
Fernandina permeable zone	5.61×10^8	0.07	7.7
Western boundary	7.03×10^9	0.83	91.2
Eastern boundary	0.00	0.00	0.0
Southern boundary	0.00	0.00	0.0
Northern boundary	0.00	0.00	0.0
Total	7.70×10^9*	0.91	100.0

Table 19b. Results of the mass-balance analysis of the predevelopment Lower Floridan aquifer—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Upper Floridan aquifer	3.54×10^9	0.42	46.2
Fernandina permeable zone	1.93×10^7	0.00	0.0
Western boundary	0.00	0.00	0.0
Eastern boundary	2.52×10^9	0.30	33.0
Southern boundary	1.61×10^9	0.19	20.9
Northern boundary	0.00	0.00	0.0
Total	7.69×10^9*	0.91	†100.1

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

*Values are not equal because of rounding error.
†The total does not equal 100 because of rounding error.

Table 20a. Results of the mass-balance analysis of the predevelopment Fernandina permeable zone—sources of flow

Flow Source	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Lower Floridan aquifer	1.93×10^7	0.00	0.0
Western boundary	7.38×10^8	0.09	100.0
Eastern boundary	0.00	0.00	0.0
Total	7.57×10^8	0.09	100.0

Table 20b. Results of the mass-balance analysis of the predevelopment Fernandina permeable zone—destinations of flow

Flow Destination	Flow Rate (ft^3/yr)	Flow Rate (in/yr)	Percent of Total
Lower Floridan aquifer	5.61×10^8	0.07	77.8
Western boundary	5.89×10^6	0.00	0.0
Eastern boundary	1.90×10^8	0.02	22.2
Total	7.57×10^8	0.09	100.0

Note: ft^3/yr = cubic feet per year
in/yr = inches per year

The rate of flow through the Upper and Lower Floridan aquifers and the Fernandina permeable zone has increased significantly since predevelopment times (0.68 vs. 1.25 in/yr, 0.91 vs. 1.68 in/yr, and 0.09 vs. 0.13 in/yr, respectively). Discharge via the eastern boundary of the study area has decreased significantly since predevelopment times (0.45 vs. 0.04 in/yr). Discharge via the southern boundary has also decreased significantly (0.22 vs. 0.14 in/yr).

Discharge from the Upper Floridan aquifer to the surficial aquifer system has decreased significantly (0.52 vs. 0.28 in/yr). Recharge to the Upper Floridan aquifer from the surficial aquifer system has increased somewhat absolutely (0.09 vs. 0.15 in/yr) but has decreased slightly as a proportion of the overall rate of flow (Tables 13a–15b and 18a–20b).

SIMULATED AREAS OF RECHARGE AND DISCHARGE

The potentiometric surface of the Upper Floridan aquifer has been lowered substantially, an average of about 25 ft, relative to the predevelopment potentiometric surface due to the introduction of withdrawals from wells. This lowering of the potentiometric surface resulted in an increase in the total area of recharge from the surficial aquifer system to the Upper Floridan aquifer within the study area (Figures 51 and 52). The simulated areas of recharge compare well in areal extent, location, and shape with those estimated by Phelps (1984) (Figures 10 and 52).

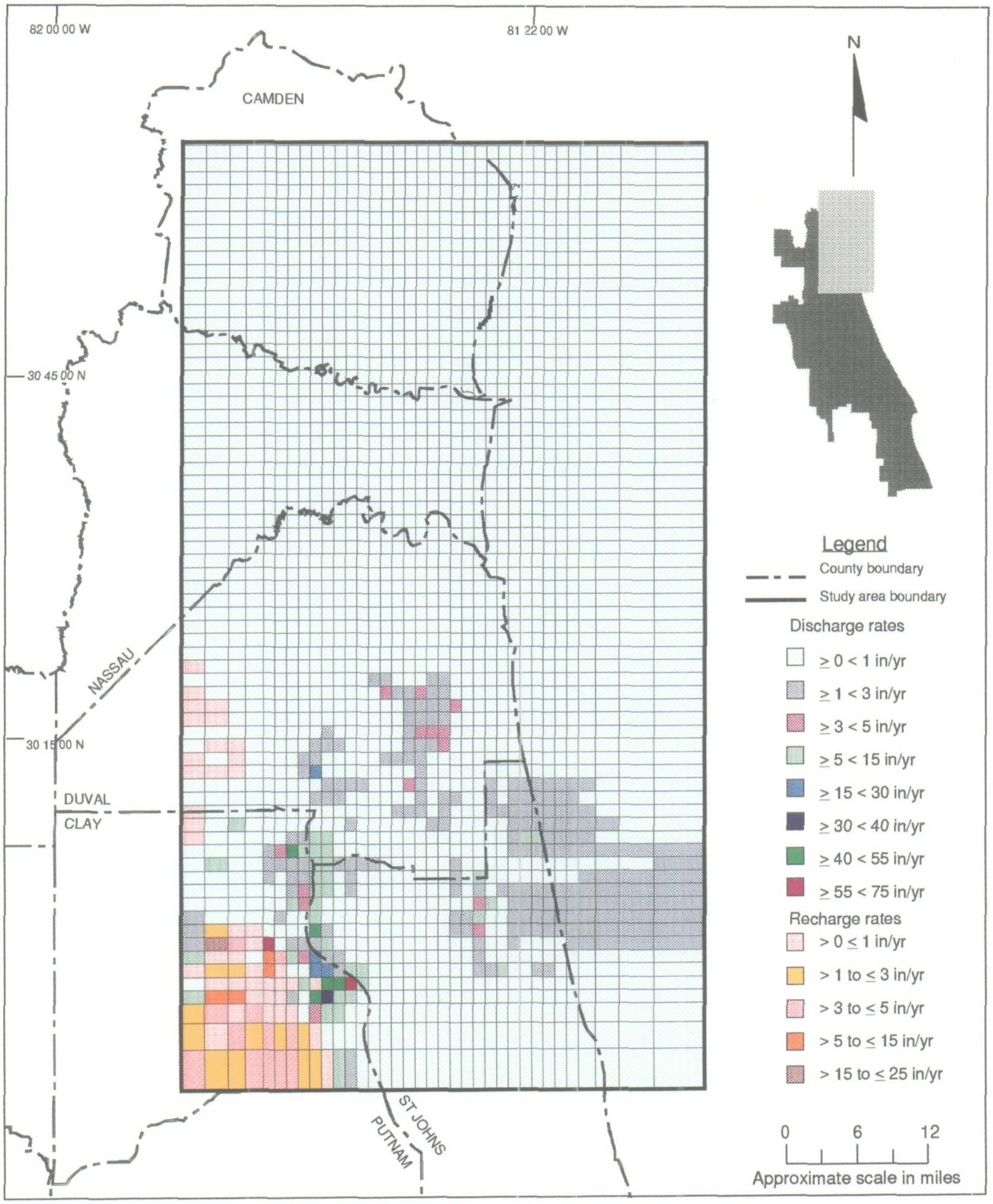


Figure 51. Rates of recharge to and discharge from the Upper Floridan aquifer via the upper confining unit, as simulated by the revised predevelopment flow model

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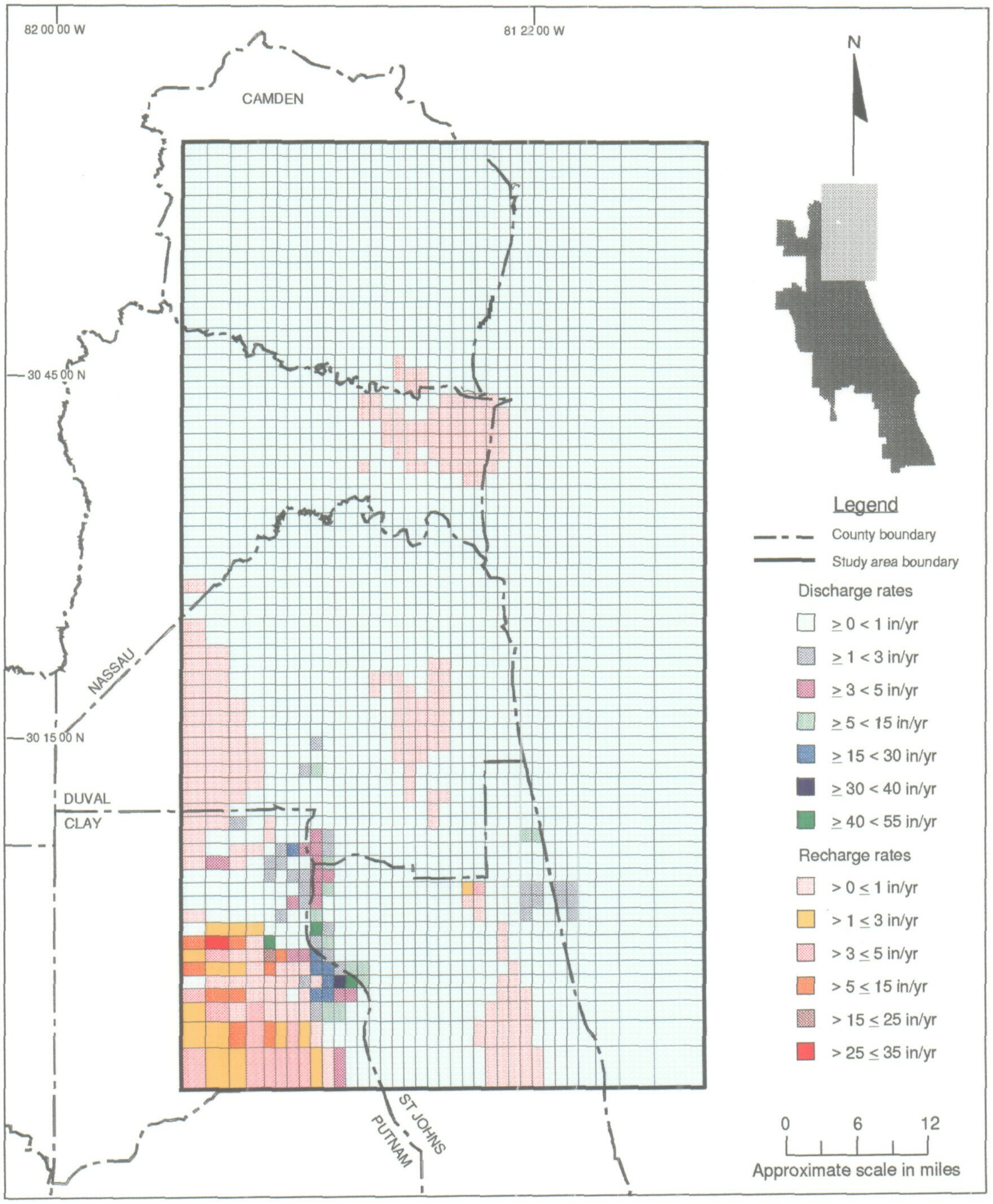

Figure 52. Rates of recharge to and discharge from the Upper Floridan aquifer via the upper confining unit, as simulated by the postdevelopment flow model

EVALUATION OF PROJECTED 2010 WITHDRAWALS

As part of the SJRWMD Water Supply Needs and Sources assessment (Vergara 1994), the postdevelopment flow model was used to simulate the potentiometric surface of the Upper Floridan aquifer in September 2010 (Figure 53). Based on this potentiometric surface, drawdowns in September 2010 relative to the simulated September 1985 potentiometric surface of the Upper Floridan aquifer were determined (Figure 54).

ESTIMATION OF 2010 WITHDRAWAL RATES

In most cases, the 2010 projections of rates of withdrawal for nonagricultural water use were based on trend analyses of past water use. Whenever possible, however, additional information was incorporated. The primary sources of data were SJRWMD annual water-use surveys (Marella 1986a, 1988, 1990; Florence 1990, 1991), comprehensive plans of local governments, and public supply and industrial water users within the study area.

Trend analyses were performed using average-day rates of withdrawal of various years, referred to herein as average annual withdrawal rates. Average annual withdrawal rates were used instead of average June-through-September withdrawal rates because monthly estimates of water use were not readily available for the years following 1986, the last year for which the SJRWMD published monthly water-use estimates. Nevertheless, assuming 1985 was typical, average annual rates of withdrawal for nonagricultural water use appear to be reasonably good estimates of average June-through-September rates of withdrawal in most cases, for the following reasons:

1. Evaluation of monthly water-use estimates corresponding to approximately 99% of the total of the 1985 average June-through-September rates of withdrawal for nonagricultural water use (Table 5) shows that the total of the average June-through-September withdrawal rates exceeds the total of the average annual withdrawal rates by only about 5% (Marella 1986a).

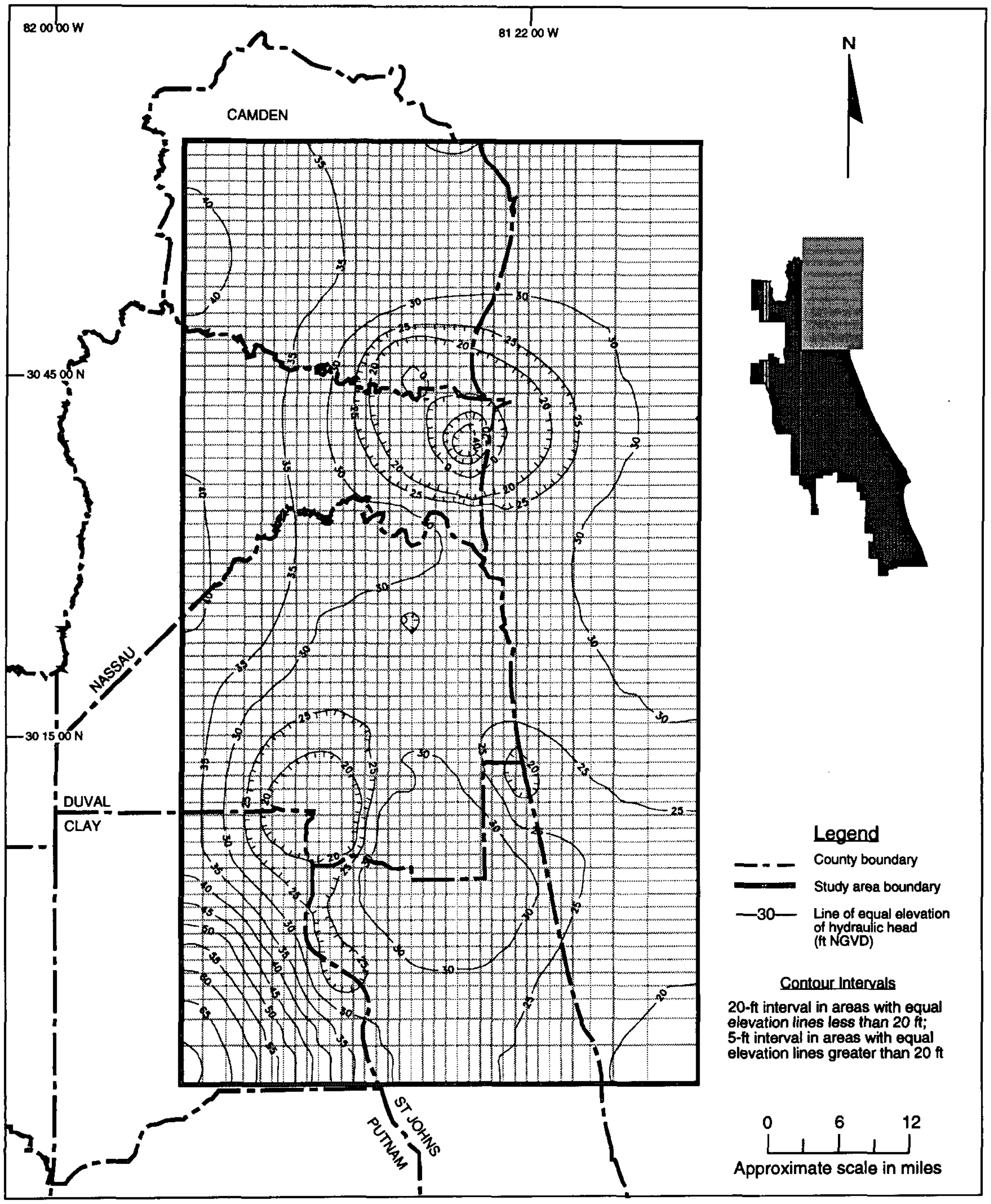

Figure 53. Simulated potentiometric surface of the Upper Floridan aquifer in 2010, as projected by the postdevelopment flow model

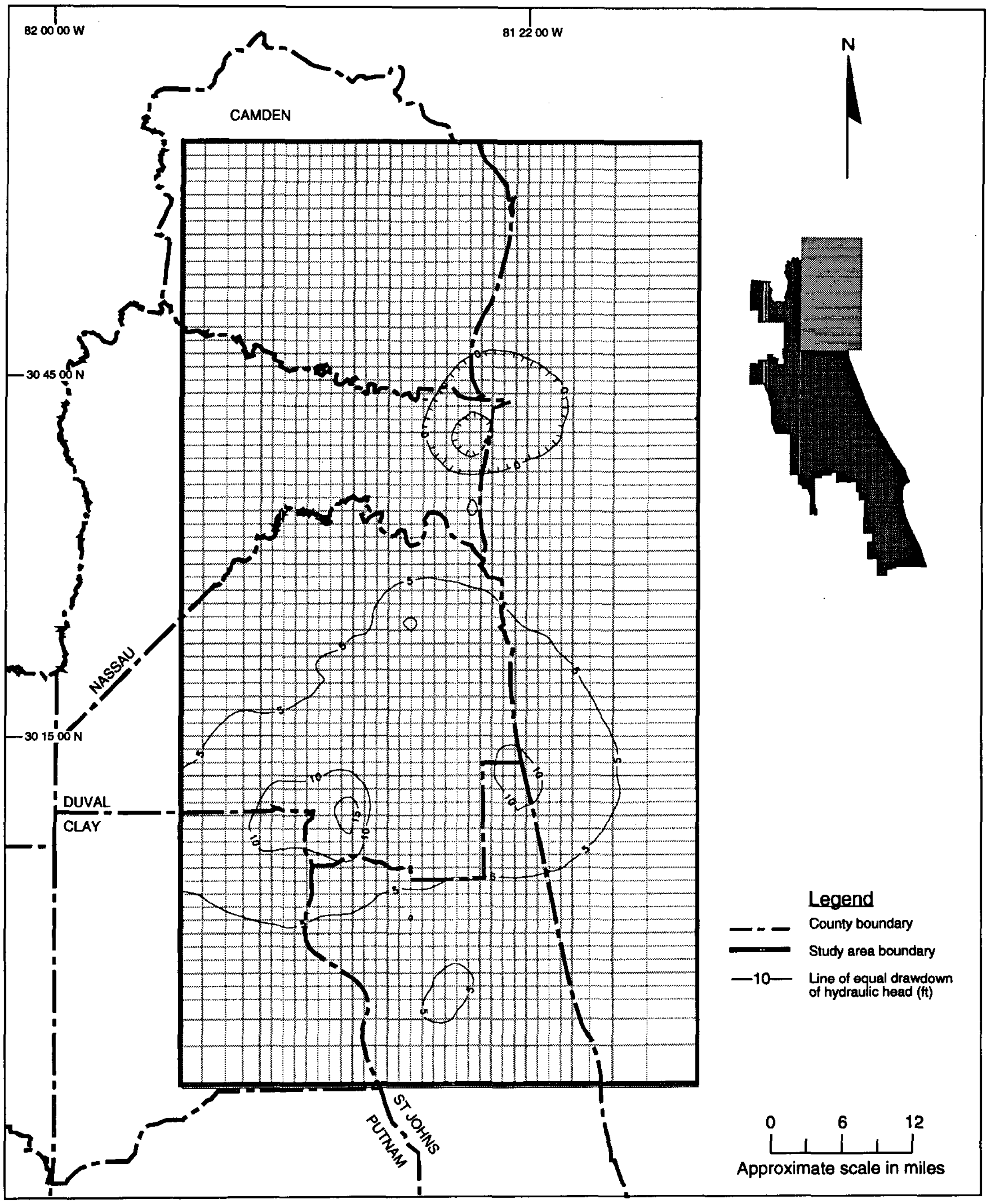

Figure 54. Drawdowns in the simulated potentiometric surface of the Upper Floridan aquifer resulting from projected increases in withdrawal rates of wells between 1985 and 2010. *Negative drawdowns indicate areas of increased hydraulic head.*

2. A plot of 1985 average annual rates of withdrawal from individual wellfields against 1985 average June-through-September withdrawal rates corresponding, again, to approximately 99% of the total of the average June-through-September rates of withdrawal for nonagricultural water use (Table 5) shows that all but one of the corresponding withdrawal rates plot on or very near the line of equivalency (Figure 55).

Except for the irrigation of golf courses constructed after 1985, average rates of withdrawal for agricultural water use in the period of June through September 2010 were assumed to be the same as in 1985, which is generally consistent with Lynne and Kiker (1991). Rates of withdrawal for the irrigation of golf courses constructed between 1985 and 1991 were estimated using the AFSIRS irrigation model (Smajstrla 1990) and are average June-through-September values.

Initial projections of 2010 withdrawal rates were submitted to the water users for review. The water users were thus given the opportunity to suggest improvements in the initial projections. As deemed appropriate, changes in the initial projections were made in accordance with the comments of the users.

The total of the projected 2010 withdrawal rates is 330 mgd, an increase of approximately 44% over the total of the estimated 1985 withdrawal rates (Appendix A). The projected 2010 withdrawal rates were distributed horizontally and vertically within the model domain using the procedures described with respect to the estimated 1985 withdrawal rates (p. 123) (Figures 56 and 57).

ESTIMATION OF 2010 GHB-CONDITION SOURCE HEADS

Failure to account for drawdowns that are expected within the time period represented in a model simulation at locations corresponding to the positions of the GHB-condition source heads will result in a reduction in predicted drawdowns within the model domain. In the present study, projected increases in withdrawals between 1985 and 2010 were considered potentially great enough to cause significant drawdowns in the Floridan aquifer system at locations

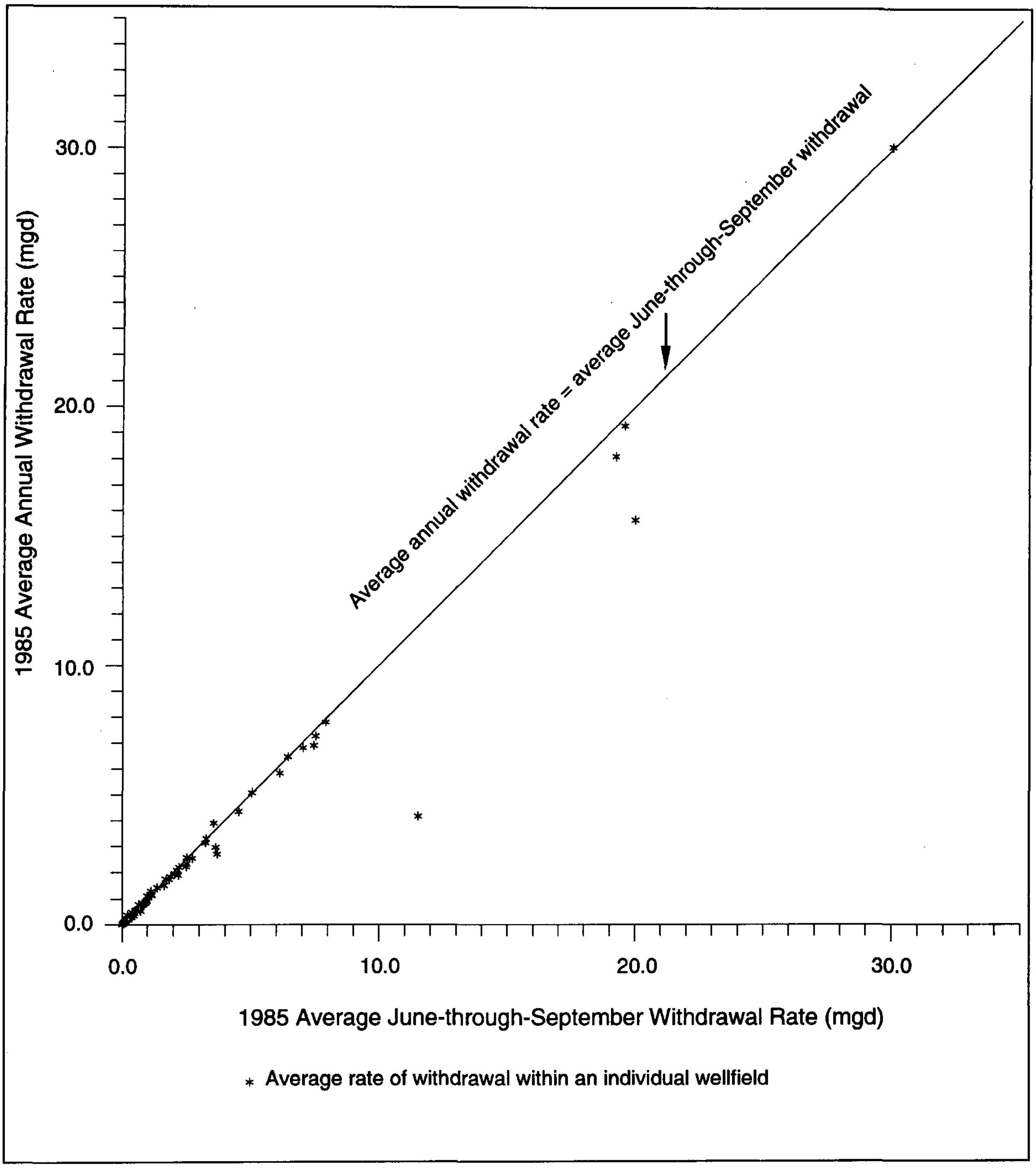

Figure 55. Comparison of average annual and average June-through-September rates of withdrawal for nonagricultural water use in 1985 within the study area

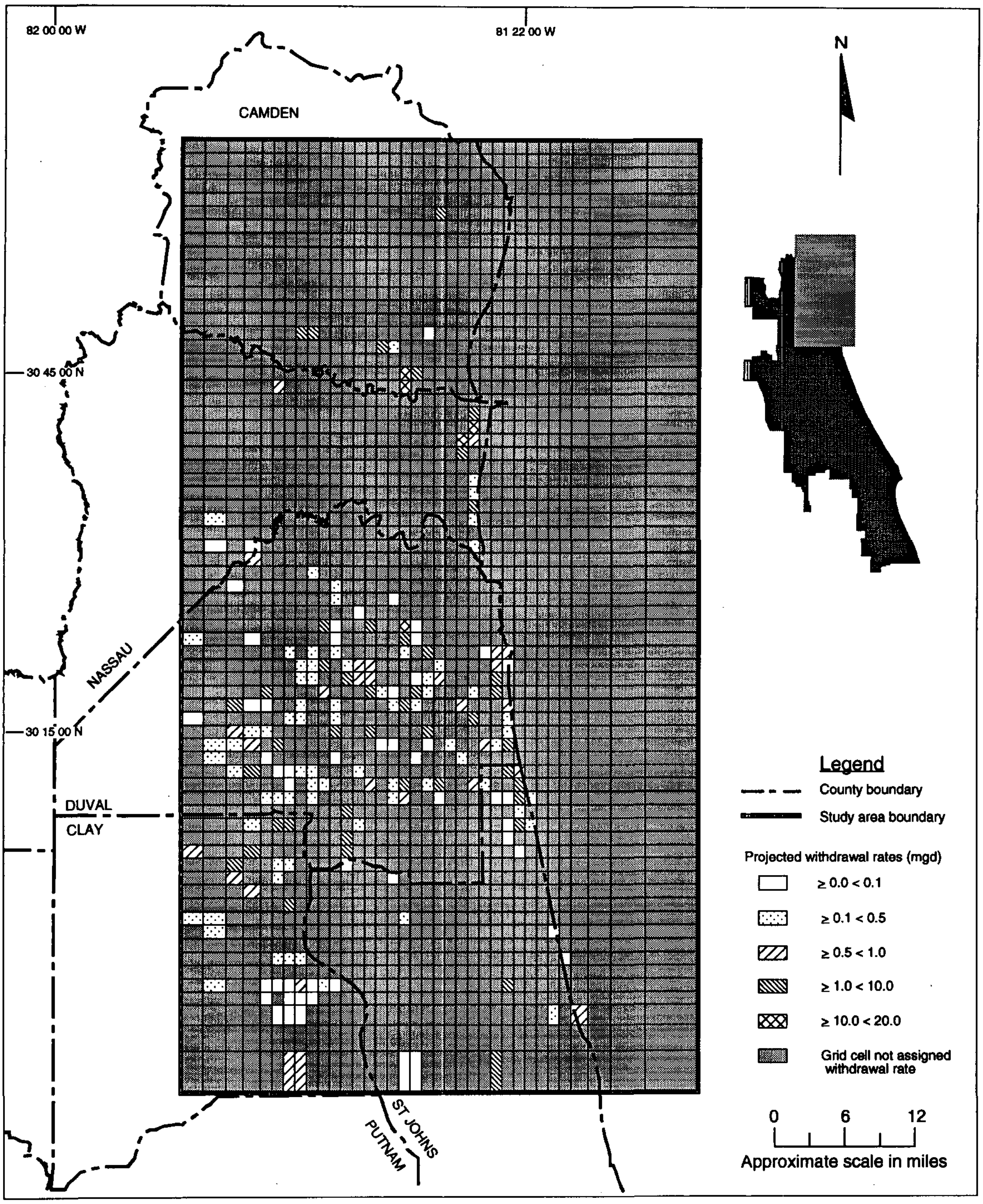

Figure 56. Projected withdrawal rates prescribed for aquifer layer 2 in the 2010 simulation

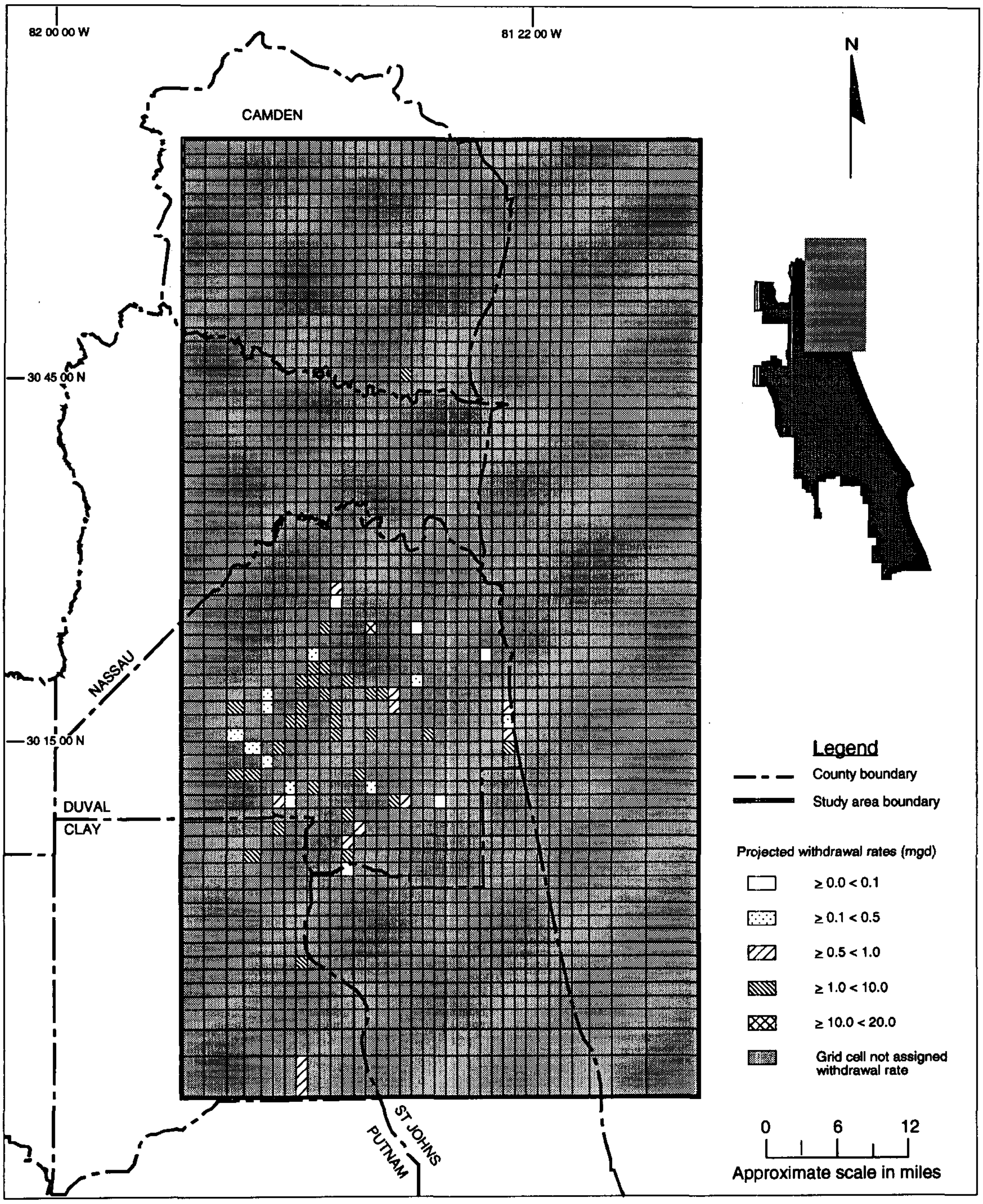

Figure 57. Projected withdrawal rates prescribed for aquifer layer 3 in the 2010 simulation

corresponding to the positions of the GHB-condition source heads. Given the results of the sensitivity analyses of the pre- and postdevelopment flow models, in which the GHB-condition source heads were shown to be the most influential of the model parameters, accurate estimation of the 2010 values of the GHB-condition source heads was considered to be crucial to the accuracy of predicted drawdowns within the study area. Lateral boundary constraints can result in underestimation of the impacts of simulated withdrawals from wells. The degree of underestimation increases with increasing proximity to edges of the finite-difference grid. The effects of boundary constraints in the model are most pronounced in the parts of the model domain corresponding to central Clay and Duval counties. These effects are due primarily to the constraining influence of the western lateral boundary.

The approach used to estimate drawdowns at locations corresponding to the positions of the GHB-condition source heads involved performing a sequence of two model simulations of the effects of projected 2010 withdrawals. The underlying assumption in the approach was that anticipated drawdowns at locations corresponding to the positions of the GHB-condition source heads can be attributed primarily to projected increases in withdrawals within the study area. Drawdowns at these locations due to projected increases in withdrawals outside the study area were assumed to be negligibly small, based on the general lack of aquifer development in areas to the west and north of the study area and on the results of a modeling study performed by Motz et al. (1995).

In the first of the two simulations, the GHB-condition source heads in 2010 were assumed to be the same as corresponding 1985 values, for lack of better information (Figures 58 and 59). This assumption was then tested by extrapolating the lines of equal drawdown resulting from the initial simulation to the areas in which the GHB-condition source heads are specified.

Estimates of drawdowns at the positions of the GHB-condition source heads were interpolated between the extrapolated portions of the lines of equal drawdown. The resulting estimates ranged from 0 to 2.5 ft. The source heads of the GHB conditions in 2010 were then

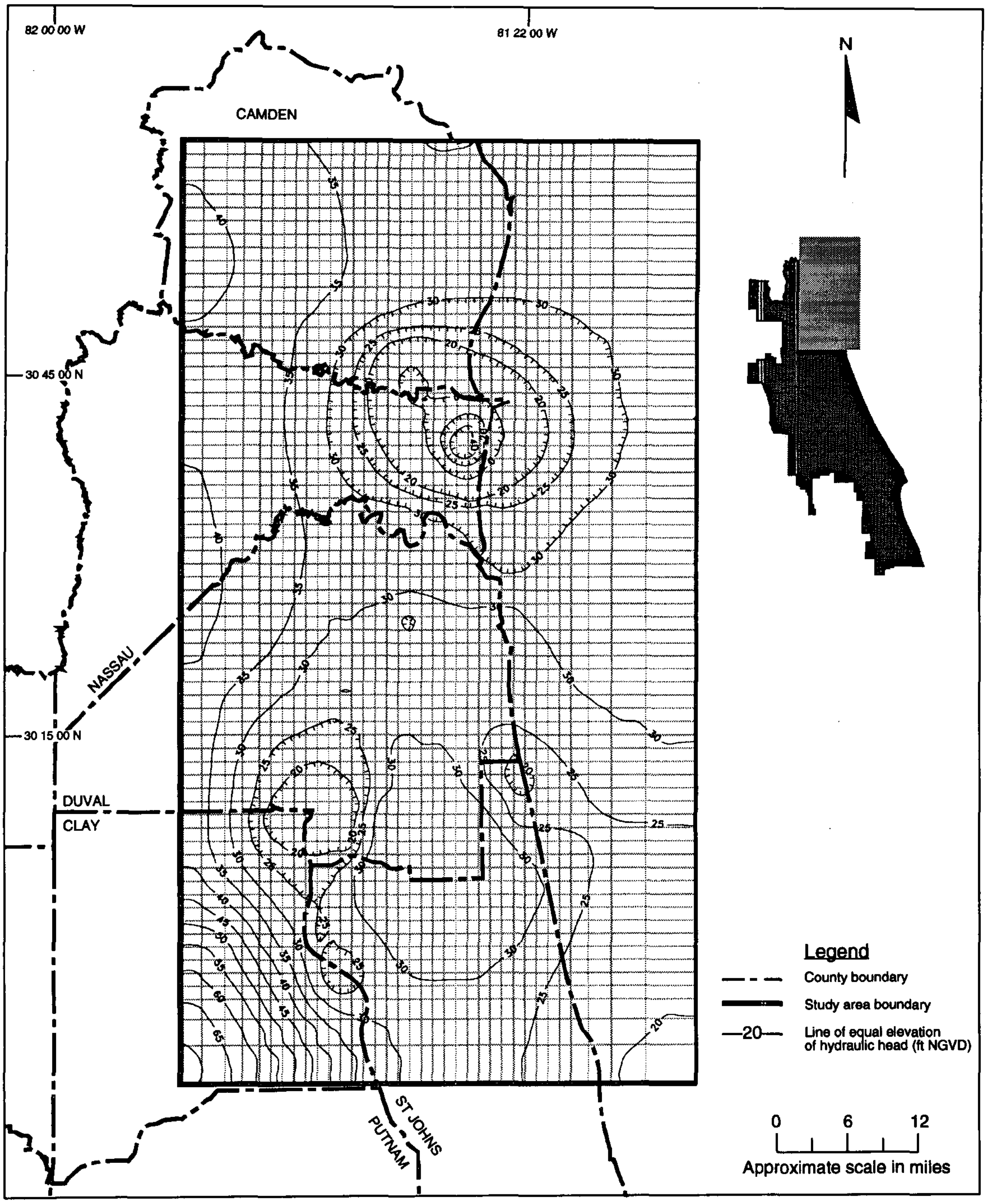

Figure 58. Simulated potentiometric surface of the Upper Floridan aquifer in 2010 based on the use of 1985 GHB–condition source heads as estimates of 2010 GHB–condition source heads

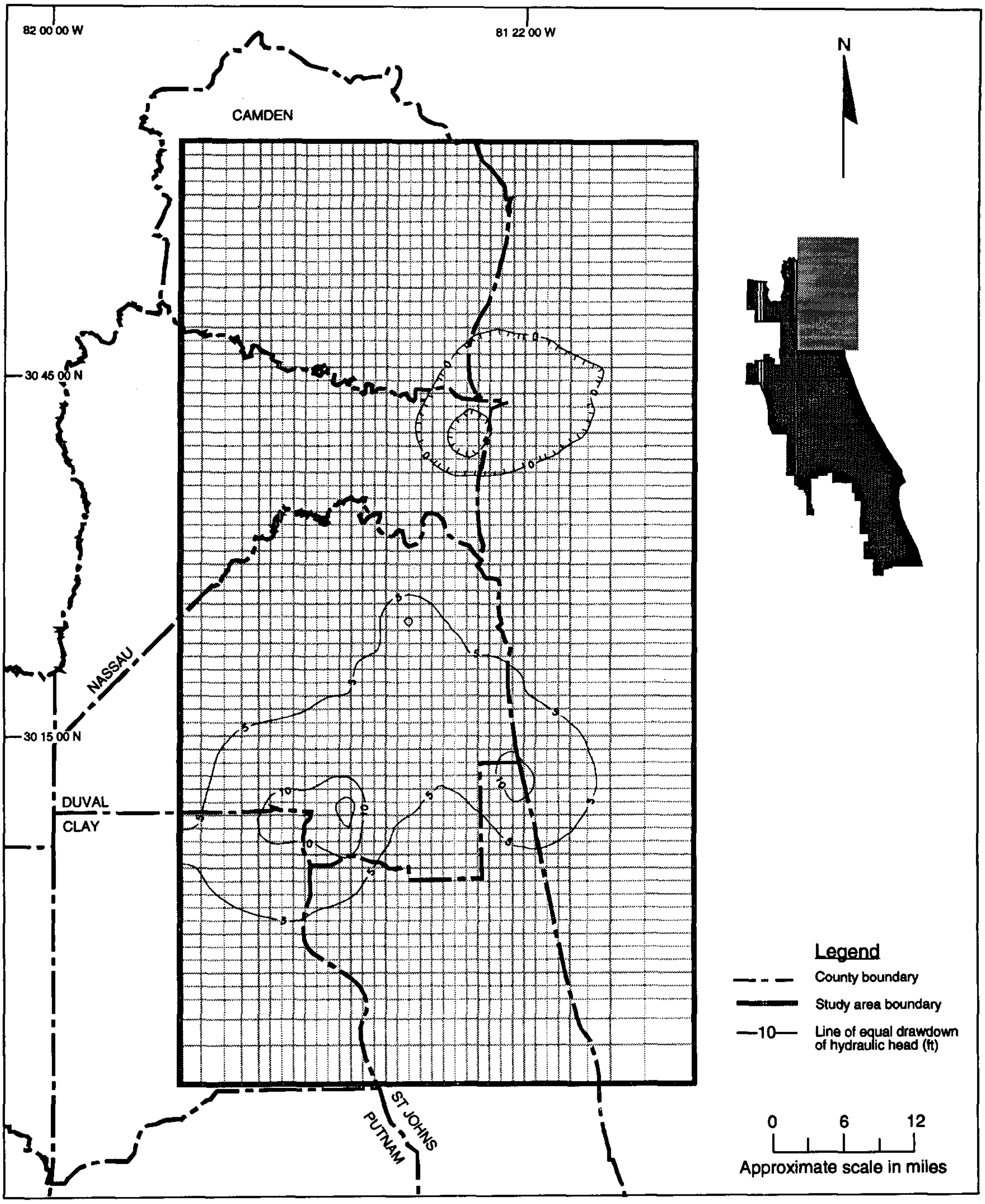

Figure 59. Drawdowns in the 1985 simulated potentiometric surface of the Upper Floridan aquifer resulting from projected increases in withdrawal rates of wells between 1985 and 2010 and use of 1985 GHB–condition source heads as estimates of 2010 GHB–condition source heads. *Negative drawdowns indicate areas of increased hydraulic head.*

re-estimated by subtracting the resulting drawdown estimates from corresponding 1985 GHB-condition source heads. The effects of model boundary constraints were assumed to be addressed adequately at this point, and the second simulation of the effects of 2010 withdrawals was then performed. The results of this simulation were taken as the final prediction of the effects of the projected increases in withdrawals between 1985 and 2010.

The assignment of lateral boundary-condition types was the same in the simulation of projected 2010 ground water withdrawals as in the simulation of the estimated 1985 ground water withdrawals. The same assignments were used in both cases because the essential configurations of the potentiometric surfaces of the Upper and Lower Floridan aquifers and Fernandina permeable zone were assumed to be the same in 2010 as in 1985. Substantial changes in the configurations of the potentiometric surfaces of these aquifers would imply a substantial change in the distribution as well as the magnitude of ground water withdrawals from the Floridan aquifer system within and nearby the study area. The projections of 2010 ground water withdrawals, however, did not indicate a substantial alteration in the distribution of ground water withdrawals within or nearby the study area.

The effects of failing to account for drawdowns in the water table of the surficial aquifer system are similar to those of failing to account for drawdowns at the positions of the GHB-condition source heads. However, due to the relative impermeability of the upper confining unit within the study area, drawdowns in the water table of the surficial aquifer system were assumed to be negligibly small in response to the projected changes in ground water withdrawals from the Floridan aquifer system between 1985 and 2010. This assumption was corroborated by the results of simulations performed using a semi-analytical model called SURFDOWN (Huang and Williams 1996). The results of the SURFDOWN simulations are described in Vergara (1994).

Results of Final 2010 Simulation

The results of the final 2010 simulation (Figures 53 and 54) are presumably more accurate than those of the initial 2010 simulation (Figures 58 and 59), although differences in the predicted potentiometric surfaces of the Upper Floridan aquifer are small, ranging from 0 to only 1.4 ft. The simulated 2010 potentiometric surface of the Upper Floridan aquifer is similar in most of its major features to the simulated 1985 potentiometric surface (Figure 39, Part A, and Figure 53). Drawdowns relative to the simulated 1985 potentiometric surface are predicted to be between 0 and 5 ft throughout most of the study area (Figure 54). In parts of the southern half of the study area, drawdowns in the Upper Floridan aquifer are predicted to be greater, ranging from 5 to 20 ft (Figure 54). In the area of Fernandina Beach, hydraulic head is projected to increase approximately 0–10 ft in response to projected decreases in withdrawal rates (Figure 54).

SUMMARY

This study was performed in support of the Water Supply Needs and Sources Assessment of SJRWMD (Vergara 1994). As such, the primary objective was to predict changes in hydraulic-head levels in the Floridan aquifer system of the study area that will occur in response to projected increases in ground water withdrawals between 1985 and 2010. The study area included parts of northeast Florida and Camden County, Georgia. Ground water flow models of the predevelopment and postdevelopment Floridan aquifer system in northeast Florida and Camden County, Georgia, were developed to fulfill this objective.

The study area includes parts of Duval, Clay, St. Johns, and Nassau counties, Florida; Camden County, Georgia; and a sizable offshore area in the Atlantic Ocean. It lies between latitudes 29°51′ and 31°2′ north and longitudes 81°7′ and 81°52′ west and encompasses approximately 3,660 mi^2.

The geologic units within the study area include the pre-Hawthorn Tertiary carbonate units, the Hawthorn Group, and the post-Miocene deposits. The pre-Hawthorn Tertiary carbonate units include the Cedar Keys Formation of Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, and the Ocala Limestone of late Eocene age. The Hawthorn Group consists of deposits of middle Miocene age. The post-Miocene deposits include the Pliocene, Pleistocene, and Recent deposits.

In descending order, the ground water system of the study area consists of a surficial aquifer system, an intermediate aquifer system, and the Floridan aquifer system. The surficial aquifer system is separated from the Floridan aquifer system by the upper confining unit, which consists of the Hawthorn Group and overlying Pliocene deposits. The intermediate aquifer system is contained in the upper confining unit.

The Floridan aquifer system consists of the Ocala Limestone of late Eocene age, the Avon Park Formation of middle Eocene age, the

Oldsmar Formation of early Eocene age, and the Cedar Keys Formation of Paleocene age. The Floridan aquifer system has been differentiated into three aquifers separated by two semiconfining units. These are, from top to bottom, the Upper Floridan aquifer, the middle semiconfining unit (MSCU), the Lower Floridan aquifer, the lower semiconfining unit (LSCU), and the Fernandina permeable zone. The Floridan aquifer system is bounded at its base by a lower confining unit that consists of low-permeability anhydrite beds in the Cedar Keys Formation.

The transmissivity of the Upper and Lower Floridan aquifers has been estimated to range up to 450,000 ft^2/day for each aquifer within the study area. The transmissivity of the Fernandina permeable zone has been estimated to be 75,000 ft^2/day in the area of Fernandina Beach and St. Marys.

The leakance of the upper confining unit has been estimated to range from 1.0×10^{-6} to 1.0×10^{-4} d^{-1}. The leakance of MSCU has been estimated to range from 1.0×10^{-8} to 1.0×10^{-1} d^{-1} in the study area. The leakance of LSCU is estimated to be approximately 3.3×10^{-6} d^{-1} in the area of Fernandina Beach.

Maps of the predevelopment and postdevelopment potentiometric surfaces of the Upper Floridan aquifer were employed in the present study. The maps of the postdevelopment potentiometric surface of the Upper Floridan aquifer are based on observations of hydraulic head made in 142 monitoring wells in the study area. Observations of hydraulic head in the Lower Floridan aquifer have been made at seven monitoring wells and in the Fernandina permeable zone at five monitoring wells within the study area.

Observations in the five monitoring wells in the Fernandina permeable zone indicate that the vertical transition from fresh to saline water is relatively narrow in much of the onshore part of the study area. In areas north of Ponte Vedra Beach near the coast, it is located about 2,000 ft bNGVD. In central St. Johns County, the vertical transition from fresh to saline water is probably more dispersed and shallower, however. Measurements of chloride concentrations at offshore test wells show that freshwater flow exists in the Floridan aquifer system to at least 55 mi offshore of Fernandina Beach.

Ground water withdrawals made in the period of June through August 1985 were averaged with those made in September 1985 to account approximately for the effects of variations that occurred prior to September in rates and locations of withdrawals. Withdrawals from the Floridan aquifer system in the study area can be classified as nonagricultural or agricultural. Nonagricultural withdrawals include public supply, commercial/industrial, institutional, and domestic self-supply. Agricultural withdrawals relevant to the study include those used to provide irrigation for vegetables, blueberries, golf course turf grass, landscape, and nursery plants. Withdrawals used to supply dairy and beef operations were classified as agricultural also. Withdrawals for nonagricultural use averaged approximately 219.2 mgd in June through September of 1985. Withdrawals for agricultural use averaged approximately 9.8 mgd in June through September of 1985.

The model code selected for use in the study is the McDonald and Harbaugh modular three-dimensional finite-difference ground water flow model (MODFLOW). Three models were developed as a result of the study: the predevelopment, postdevelopment, and revised predevelopment flow models. Ground water flow is represented as being steady state in all three models. All three models consist of four aquifer layers and four semiconfining unit layers. In descending order, the layers represent the surficial aquifer system (aquifer layer 1), the upper confining unit (semiconfining unit layer 1), the Upper Floridan aquifer (aquifer layer 2), MSCU (semiconfining unit layer 2), the Lower Floridan aquifer (aquifer layer 3), LSCU (semiconfining unit layer 3), the Fernandina permeable zone (aquifer layer 4), and the lower confining unit (semiconfining unit layer 4).

All grid cells in aquifer layer 1 of the models were designated as constant-head. All grid cells in aquifer layers 2 and 3 were designated as variable-head. Many grid cells in the northeast and southeast corners of aquifer layer 4 correspond to areas in the Fernandina permeable zone that were determined to be seaward of the tip of the freshwater/saltwater interface and were thus designated as inactive. In the predevelopment flow model, grid cells in aquifer layer 4 that were not designated as inactive were designated as constant-head. The same grid cells were designated as variable-head in the postdevelopment flow model to enable simulated water levels in aquifer layer 4 to change in response to changes in simulated stresses.

Lateral boundary conditions of aquifer layers 2, 3, and 4 were prescribed as either GHB or no-flow, depending on apparent or assumed directions of ground water flow relative to the direction of orientation of the rows and columns of the finite-difference grid. Locations of simulated withdrawals from wells within the domain of the postdevelopment flow model were specified by row, column, and aquifer layer. Wells open to both the Upper and Lower Floridan aquifers were represented as well pairs, with one of the pair assigned to aquifer layer 2 and the other assigned to aquifer layer 3.

The finite-difference grid of the predevelopment flow model consists of 68 rows and 35 columns (2,380 grid cells per aquifer layer). The rows of the grid are oriented approximately along lines of latitude, and the columns of the grid are oriented approximately along lines of longitude. The width of the grid corresponds approximately to 44 mi, and the length of the grid corresponds approximately to 83 mi. The smallest grid cells correspond to about 1 mi^2 of area, and the largest correspond to about 15 mi^2 of area.

Estimates of the elevation of the water table were based on a correlation established between the observed elevation of the water table and the corresponding elevation of the land surface. Average land surface elevations were estimated over areas corresponding to the cells of the finite-difference grid using either USGS 1:100,000 or 1:24,000-scale topographic maps. Estimates of the elevation of the water table were then determined using the regression equation, the estimates of land surface elevation, and information concerning the presence of waterbodies and wetlands represented on the topographic maps. In grid cells corresponding to offshore locations, the hydraulic head of the ocean, which is 0 ft NGVD, was converted to an equivalent-freshwater head.

The area of saline water corresponding to the northeast corner of aquifer layer 4 was delineated by comparing the estimated position of the top of the Fernandina permeable zone to the estimated position of the freshwater/saltwater interface. Delineation of the area of saline water corresponding to the southeast corner of the model domain involved overlaying a representation of the finite-difference grid of the model onto a map of chloride concentrations in the Upper Floridan aquifer, as shown in a report by Toth (1990).

The procedure for calibrating the predevelopment flow model involved using trial transmissivity and leakance distributions to simulate the predevelopment potentiometric surface of the Upper Floridan aquifer for comparison to an estimated predevelopment potentiometric surface of the Upper Floridan aquifer. Initial estimates of transmissivity and leakance were obtained primarily from previous ground water modeling studies. Progress in calibrating the predevelopment flow model was monitored primarily by calculating the mean and standard deviation of the hydraulic-head residuals in aquifer layer 2 at the end of each simulation. The final mean of the residuals was -1.1 ft in aquifer layer 2. The standard deviation of the residuals was 2.3 ft. The mean of the absolute values of the residuals was 2.0 ft. The range of the residuals was -10.0 to 5.4 ft.

The sensitivity of the predevelopment flow model to changes in model parameters was analyzed to ascertain the relative degrees of influence of model parameters on the simulated potentiometric surfaces of the Upper Floridan aquifer. The results of the sensitivity analysis indicate that changes in the GHB-condition source heads of aquifer layers 2 and 3 have the greatest influence on the simulated potentiometric surfaces of the Upper Floridan aquifer. Changes in estimates of the leakance of the middle and lower semiconfining units and values of hydraulic head assigned to the Fernandina permeable zone have the least influence.

The postdevelopment flow model was calibrated primarily to conditions observed in 1985. The finite-difference grid of the postdevelopment flow model is identical to that of the predevelopment flow model. The grid cells of aquifer layer 4 that were designated as constant-head in the predevelopment flow model were designated as variable-head in the postdevelopment flow model. The lateral boundary conditions of aquifer layer 4 were configured to represent a generalized pattern of west to east flow, because little detailed information is available concerning actual directions of ground water flow in the Fernandina permeable zone. Observations of hydraulic head in four deep-test wells were used to specify the source heads of the GHB conditions of the postdevelopment flow model.

The distribution of water table elevations used in the postdevelopment flow model is the same as that used in the predevelopment flow model. Initial estimates of transmissivity and leakance were generally those resulting from the calibration of the predevelopment flow model. Initial estimates of transmissivity of aquifer layer 4 were obtained by copying estimates used in aquifer layer 3, because better estimates were not available.

Withdrawals from individual wellfields were distributed to each of the several wells comprising the wellfields whenever the locations of the wells corresponded to more than one grid cell of the postdevelopment flow model. Withdrawals were proportioned according to pump capacities of the wells if pump capacities of all wells were known. Withdrawals were proportioned according to the squares of well diameters if the pump capacity of one or more of the wells were unknown but the diameters of all of the wells were known. Withdrawals were divided equally among the wells if the pump capacity and/or diameter of one or more wells were unknown.

Withdrawals from individual wells that are open to both the Upper and Lower Floridan aquifers were distributed between aquifer layers 2 and 3. In such cases, the withdrawals were distributed in proportion to the transmissivity of the Upper Floridan aquifer and "effective transmissivity" of the Lower Floridan aquifer. The effective transmissivity is defined herein as the product of the hydraulic conductivity in the Lower Floridan aquifer and the depth of well penetration into the Lower Floridan aquifer.

Progress in calibrating the postdevelopment flow model was monitored primarily by calculating the mean and standard deviation of the hydraulic-head residuals in aquifer layer 2. Hydraulic-head residuals used in the statistical calculations were of two types: (1) those calculated using values of hydraulic head interpolated from the map of the estimated postdevelopment potentiometric surface of the Upper Floridan aquifer at locations corresponding to the centers of the model grid cells and (2) those calculated using values of hydraulic head observed in 142 monitoring wells within the study area.

The mean of the hydraulic-head residuals that were based on interpolated hydraulic-head values was +0.06 ft, the positive sign indicating that simulated values of hydraulic head were lower on average than observed values. The corresponding standard deviation was 3.6 ft; the mean of the absolute values of the residuals was 2.4 ft.

The mean of the hydraulic-head residuals that were based on the observed hydraulic-head values was -0.6 ft. The corresponding standard deviation was 9.9 ft, and the mean of the absolute values was 4.6 ft. These results were skewed somewhat by several relatively large residual values corresponding to locations in the potentiometric cone of depression in the area of Fernandina Beach and St. Marys.

After removing from the statistical calculations seven of the hydraulic-head residual values corresponding to locations in this area, the results were similar to the results of the comparisons to the interpolated values of hydraulic head. The resulting mean was 0.2 ft. The corresponding standard deviation was 4.2 ft, and the mean of the absolute values of the residuals was 3.1 ft.

The estimates of transmissivity in the Upper Floridan aquifer resulting from the calibration of the postdevelopment flow model range from 2,000 ft^2/day to 425,000 ft^2/day, and the arithmetic mean is 64,300 ft^2/day. The resulting estimates of transmissivity are usually less than 50,000 ft^2/day. Good agreement was achieved with the results of aquifer performance tests which employed test wells that penetrated at least 80% of the thickness of the Upper Floridan aquifer.

Estimates of transmissivity in the Lower Floridan aquifer resulting from the calibration of the postdevelopment flow model range from 35,000 ft^2/day to 780,000 ft^2/day, and the arithmetic mean is 523,000 ft^2/day. The resulting estimates of transmissivity in the Fernandina permeable zone range from 1,000 ft^2/day to 82,500 ft^2/day, and the arithmetic mean is 43,300 ft^2/day. The lowest estimates of transmissivity in the Fernandina permeable zone correspond to grid cells near the estimated location of the tip of the freshwater/saltwater interface, where the thickness of the freshwater flow system approaches zero.

The estimates of leakance in the upper confining unit resulting from the calibration of the postdevelopment flow model range from 5.0×10^{-8} to 2.0×10^{-3} d^{-1}. The estimates of leakance in MSCU resulting from the calibration of the postdevelopment flow model range from 1.0×10^{-10} d^{-1} to 5.0×10^{-2} d^{-1}. The estimates of leakance in LSCU resulting from the calibration of the postdevelopment flow model range from 4.3×10^{-6} d^{-1} to 8.1×10^{-5} d^{-1}.

A sensitivity analysis of the postdevelopment flow model to changes in model parameters was analyzed also. Changes in the GHB-condition source heads of aquifer layers 2 and 3 have the greatest influence on the simulated potentiometric surfaces of the Upper Floridan aquifer. Changes in the GHB-condition source heads of aquifer layer 4 have less influence but are still notably influential. Changes in the elevations of the water table are quite influential, as are the changes in the transmissivity of aquifer layers 2 and 3. Changes in the distributions of rates of withdrawals from wells from aquifer layer 2 were of significant influence as well. Changes in the leakance estimates of semiconfining unit layers 1 and 2 were of moderate influence, as were the changes made in rates of withdrawals from wells from aquifer layer 3. Changes in the estimates of leakance of semiconfining unit layer 3 and aquifer layer 4 were of only slight influence.

As a part of the calibration procedure of the postdevelopment flow model, an updated version of the predevelopment flow model was calibrated and is referred to herein as the revised predevelopment flow model. The revised predevelopment flow model incorporates the estimates of leakance and transmissivity resulting from the postdevelopment calibration procedure. These distributions are presumably more accurate than those derived from the calibration of the original predevelopment flow model. Assuming this is indeed the case, the revised predevelopment flow model enables the attainment of a more accurate representation of the predevelopment flow system than did the original predevelopment flow model.

The finite-difference grid and the GHB-condition source heads of aquifer layers 2 and 3 of the revised predevelopment flow model are identical to those of the original predevelopment flow model. As with the postdevelopment flow model, the lateral boundary conditions of aquifer layer 4 in the revised predevelopment flow model were configured to represent a generalized pattern of ground water flow from west to east. The GHB-condition source heads prescribed for aquifer layer 4 were determined using the same procedure as was discussed with regard to aquifer layer 3 of the predevelopment flow model. The values of conductance assigned to the GHB conditions were calculated based on the distributions of transmissivity used in the model.

The mean of the hydraulic-head residuals in aquifer layer 2 of the revised predevelopment flow model is -2.0 ft, the negative sign indicating that simulated values of hydraulic head were higher on average than interpolated values. The corresponding standard deviation is 2.6 ft. The mean of the absolute values of the residuals is 2.7 ft.

Conclusions and Recommendations

The results of the study indicate that the transmissivity of the Lower Floridan aquifer is considerably higher on average than that of the Upper Floridan aquifer and that upward leakage from the Lower Floridan aquifer accounts for a significant proportion of the total recharge to the Upper Floridan aquifer within the study area (59%). The results of the study indicate also that a significantly greater quantity of ground water flows through the Lower Floridan aquifer than through the Upper Floridan aquifer or the Fernandina permeable zone (1.68 in/yr vs. 1.25 and 0.13 in/yr, respectively).

Withdrawals from wells account for approximately 65% and 30%, respectively, of the total discharge from the Upper and Lower Floridan aquifers and have resulted in significant changes in the Floridan aquifer system since predevelopment times. Levels of hydraulic head in the Upper Floridan aquifer have declined by an average of about 25 ft within the study area. The quantity of ground water flowing through the Upper and Lower Floridan aquifers and the Fernandina permeable zone has increased significantly (respectively, 0.68 vs. 1.25 in/yr; 0.91 vs. 1.68 in/yr; and 0.09 vs. 0.13 in/yr). Discharge from the Floridan aquifer system to the surficial aquifer system has decreased significantly (0.52 vs. 0.28 in/yr), and recharge from the surficial aquifer system to the Floridan aquifer system has increased significantly (0.09 vs. 0.15 in/yr) since predevelopment times

The results of predictive simulations performed using the postdevelopment flow model indicate that by the year 2010, the potentiometric surface of the Upper Floridan aquifer will decline approximately 0–5 ft relative to 1985 water levels throughout most of the study area due to projected increases in withdrawals from wells. In parts of the southern half of the study area, the potentiometric surface of the Upper Floridan aquifer will decline approximately 5–20 ft relative to 1985 water levels, also due to projected increases in withdrawals from wells. In the area of Fernandina Beach, levels of hydraulic head will increase approximately 0–10 ft relative to 1985 levels due to projected decreases in withdrawals from wells. The total of the projected 2010 withdrawal rates is 330 mgd, an increase of approximately 44% over the total of the estimated 1985 withdrawal rates.

Differences in observed or interpolated and simulated values of hydraulic head in the Upper Floridan aquifer are acceptable everywhere in the postdevelopment flow-model domain except possibly near the center of the Fernandina Beach and St. Marys cone of depression. Significant reduction in the differences in the observed or interpolated and simulated values of hydraulic head in that area would require finer discretization in the finite-difference grid of the postdevelopment flow model. The required level of discretization would be met best with a subregional ground water flow model.

Less confidence can be placed in predictions of hydraulic head and drawdowns in the Lower Floridan aquifer and Fernandina permeable zone than in the Upper Floridan aquifer because of the relative scarcity of hydrologic data on those aquifers. Nevertheless, the comparisons of simulation results to available data indicate that the postdevelopment model is capable of simulating ground water flow in the Lower Floridan aquifer and Fernandina permeable zone with at least a fair degree of accuracy.

The results of the model predictions are vulnerable to the effects of lateral boundary constraints. Lateral boundary constraints can result in underestimation of the impacts of simulated withdrawals from wells. The degree of underestimation increases with increasing proximity to edges of the finite-difference grid. The effects of boundary constraints in the model are most pronounced in the parts of the model domain corresponding to central Clay and Duval counties. These effects are due primarily to the constraining influence of the western lateral boundary. In a future revision of the postdevelopment flow model, the influence of the western lateral boundary in Clay and Duval counties can be reduced significantly by moving the western lateral boundary farther to the west. In the meantime, errors in predictions due to lateral boundary constraints can be reduced by approximating the likely drawdowns in aquifer water levels at locations corresponding to the positions of the GHB-condition source heads and then re-estimating the GHB-condition source heads accordingly. In the present study, the likely drawdowns at locations corresponding to the positions of the GHB-condition source heads were estimated iteratively by extrapolating lines of equal drawdown derived from a previous simulation of the effects of the projected changes in ground water withdrawals between 1985 and 2010. In the previous simulation, the drawdowns at locations corresponding to the positions of the GHB-condition source heads were assumed to be 0 ft.

Additional data collection within the study area are needed to improve the ability to simulate ground water flow in the Floridan aquifer system in northeast Florida. The ability to simulate accurately leakage between the surficial aquifer system and the Floridan aquifer system would be improved by increasing the number of monitoring wells in the surficial aquifer system within the study area.

Increases in the number of monitoring wells in the Lower Floridan aquifer and Fernandina permeable zone are needed to improve the calibration of the model layers representing MSCU, Lower Floridan aquifer, lower semiconfining unit, and Fernandina permeable zone. Increasing the number of monitoring wells would increase accuracy in hydraulic-head and drawdown predictions in the Lower Floridan aquifer and the Fernandina permeable zone in response to projected changes in withdrawal rates in either the Upper or Lower Floridan aquifers. In addition, these data could be used to improve estimates of the GHB-condition source heads of aquifer layers 3 and 4. Aquifer performance tests performed using test wells that are both cased to the top of the Lower Floridan aquifer and open from the top to the bottom of the Lower Floridan aquifer are needed to provide reliable estimates of transmissivity of the Lower Floridan aquifer. Such data would enable an improved conceptualization of the Lower Floridan aquifer, which would lead to greater accuracy in future models of the Floridan aquifer system within the present study area.

Additional measurements of hydraulic head in the Floridan aquifer system in offshore areas of the model domain are needed to improve the results of the model calibration in the parts of the model domain corresponding to offshore of the Floridan aquifer system. Improved knowledge of the location of the freshwater/saltwater interface in onshore and offshore areas would result in improvements of model accuracy as well. Accuracy in estimates of offshore hydraulic head and of the location of the freshwater/saltwater interface will be particularly critical in future water quality models.

The postdevelopment ground water flow model should be revised, updated, and recalibrated periodically. This procedure will ensure that new information is incorporated into the model as it becomes available and will enable needed improvements to be implemented as they become apparent. In each of the future recalibrations, the calibration year should be as current as is acceptable. However, comparisons should be made to each of the preceding calibration years and to predevelopment conditions. Such an approach should result in successive improvements in the estimates of transmissivity and leakance in the model.

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APPENDIX A—WATER USE DATA BY USER NAME FOR 1985 AND 2010

Table A1. Public supply water use data by user name, 1985

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Anastasia Sanitary District	Anastasia Island WTP	68 68	33 33	10,986 10,986
Anheuser Busch, Inc.	Wellfield name not available	36	11	877
Associated Minerals	Wellfield name not available	68	7	75,438
		68	8	211,228
Atlantic Beach, City of	Buccaneer SA/Assisi Lane WTP; WTP No. 3	41 41	25 25	19,889 19,889
	WTP No. 2	42	25	125,471
	WTP No. 1	43 43	26 26	83,118 83,118
Atlantic Utility Corporation	Ortega Hills Subdivision	50 50	7 7	7,740 12,094
	Bon Air	38	11	210
	River View	39	9	3,616
	West Wood	43	4	958
	Milmar Manor	44	14	1,497
	Ridgeland Gardens	45	15	6,575
	Brackridge	46	16	8,438
	Greenfield Estates	46	15	1,707
	Oak Harbor	41	25	16,985
Beauclerc Utility, Inc.	Wellfield name not available	49 49	14 14	40,162 40,162
Callahan, City of	Wellfield name not available	29 29	2 2	9,643 9,643
Canal Utilities, Inc.	Sunni Pines	44 44	23 23	44,359 8,872
	Beach Haven	46	23	13,308
	Arbor Point (Joeandy WTP)	43	22	44,359
Castleton Beverages	Wellfield name not available	35	11	19,286
Celotex Corporation	Wellfield name not available	39	17	10,958
Clay Utility	Greenwood	56	3	24,546
	Tanglewood	55	3	36,710
	Rideaught	55	3	4,712

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Colony Mobile Home Park	Wellfield name not available	47 47	2 2	2,988 8,299
Container Corporation of America	Wellfield name not available	22 22	23 23	363,883 614,962
		21	23	363,883
		22 22	23 23	614,962 614,962
Dulay Utility	Argyle Forest	51 51	4 4	22,574 22,574
Duval Utility	Indian Trails	51 51	3 3	5,917 9,862
	Blackhawk Bluff	42	22	4,164
	S.W. Villa	48	2	14,684
	McRae Landing	58	2	4,164
El Agua Utilities	Wellfield name not available	46 46	24 24	18,483 36,966
Florida Department of Corrections	Dinsmore Community Corrections Center	34 34	3 3	200 1,003
Florida Public Utilities	Wellfield name not available	22 22	23 23	80,347 79,290
		22 22	23 23	84,576 88,805
Gilman Paper Co.	Wellfield name not available	18 18	17 17	812,776 704,279
	Wellfield name not available	19 19	17 17	808,969 824,197
	Wellfield name not available	18	18	847,038
	Bag Division	18	15	12,834
Green Cove Springs, City of	Wellfield name not available	62	8	99,172
ITT Rayonier	Wellfield name not available	24 24	22 22	420,794 244,573
		24	22	420,794
		23	23	115,872
		23	22	115,872

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
ITT Rayonier—*continued*	Wellfield name not available	23 23 23 23	22 22 22 22	213,842 420,794 244,573 420,794
J-M Manufacturing Co.	Wellfield name not available	64 64	9 9	3,068 3,068
Jacksonville, City of	Dinsmore School	38	4	264
	Beauclerc Gardens	51	12	26,912
	Hilliard	49	13	4,708
	Mayport	39	24	13,537
	Fairfax	41 41	8 8	86,761 92,958
		41 41 41	8 8 8	123,944 154,930 61,972
		41 41	9 9	86,761 123,944
		41	9	86,761
	Highlands	37	10	264,421
		37	10	264,421
		37	10	264,421
		37	10	264,421
	Lake Shore	46 46 46 46	6 6 6 6	24,797 20,664 20,664 20,664
	Main Street	42 42 42	10 10 10	91,961 125,402 117,042
		42 42	10 10	83,601 64,791
		43 43 43 43	11 11 11 11	64,791 66,881 79,421 83,601
		43	11	83,601

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville, City of—*continued*	Marietta	43	3	234,834
		43	3	234,834
		43	3	234,834
		43	3	234,834
	McDuff	44	8	115,685
		44	8	154,247
		44	8	154,247
		44	7	192,809
		44	7	146,535
		43	8	231,371
	Norwood	40	10	84,077
		40	10	84,077
		40	10	84,077
		40	9	84,077
	Southwest	48	4	145,780
		48	4	145,780
		48	3	145,780
	Arlington	42	14	183,965
		42	14	147,171
		42	14	275,947
	Hendricks	44	11	34,452
		44	11	57,420
		44	11	57,420
		44	11	39,045
		44	11	39,045
	Love Grove	45	14	127,609
		45	14	100,264
		45	14	113,936
		45	14	91,149
	Oak Ridge	45	19	158,292
		45	19	179,877
		45	19	179,877
		45	19	158,292
	River Oaks	45	11	76,425
		45	11	96,805
		45	11	35,665
		45	11	25,475

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville, City of—*continued*	River Oaks—*continued*	45 45	11 11	56,045 127,375
		44	11	76,425
	Mandarin/Community Hall	54 54 54	12 12 12	24,157 24,157 60,392
	Mandarin/Hood Landing	54	15	9,862
	Mandarin/Julington Hills	54	12	41,751
	Mandarin/Mandarin Point	53 53	12 12	29,423 29,423
	Mandarin/Mandarin Terrace	53 53	12 12	26,245 26,245
	Mandarin/Pickwick	51 51 51 51	12 12 12 12	23,061 39,204 46,122 46,122
	Mandarin/Southwood	52	13	13,917
	Bennett Estates	41 41	21 21	13,013 13,013
	Hanna Park	41	25	15,791
	Ocean Manor	34 34	12 12	6,529 3,264
	Zoo	39	11	48,654
Jacksonville Beach, City of	Wellfield name not available	45	26	52,021
	Wellfield name not available	46 46	26 26	52,021 52,021
	Wellfield name not available	46 46 46	26 26 26	92,481 92,481 92,481
Jacksonville Electrical Authority	Power Park (Eastport Power Plant)	37	17	5,114
		37	17	5,114
		37	17	5,114

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville Electrical Authority—*continued*	Northside Generating Plant	38	17	53,284
		38	17	53,284
		38	17	53,284
		38	17	53,284
		38	17	53,2834
		38	17	4,795
Jacksonville International Airport	Wellfield name not available	33	9	11,780
		33	9	11,780
Jacksonville Naval Air Station	Wellfield name not available	49	9	38,134
		49	9	85,803
		49	9	85,803
		49	9	62,024
		49	9	16,116
		49	7	93,692
		50	9	80,543
		49	10	4,946
		48	9	19,251
Jacksonville Port Authority	Blount Island	38	18	858
	Wellfield name not available	37	18	4,292
		37	18	858
		37	18	4,292
Jacksonville University	Wellfield name not available	41	13	41,531
Jacksonville Suburban Utilities	Alderman Park	43	16	28,382
		43	16	28,382
	Holly Oaks	41	18	658
	Columbine	42	15	48,106
	Elvia	42	16	104,870
	Lake Lucina	42	14	90,186
	University Park	41	14	55,996
	Oak Hill	47	5	29,258
	Magnolia Gardens	40	8	30,025
	Lake Forest	39	9	38,134
	Hyde Grove	45	4	17,423
	Green Forest	48	4	27,286
	Wheat Road	48	4	97,528

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville Suburban Utilities—*continued*	Forest Brook	48	6	6,137
	Venetia Terrace	48	7	6,904
	Royal Lakes Onsite	50	16	164,970
	Royal Lakes Offsite	50	16	79,069
	San Jose	48 48	13 13	127,060 127,060
	Green Fern	41	15	Unknown
	Colony Manor	47	4	9,534
	Monument Road	42	18	78,680
	Queen Akers	43	18	3,069
Jacksonville Shipyards	Wellfield name not available	43	11	50,517
Jefferson Smurfit Corporation	Alton Packaging	41 41 41	12 12 12	189,556 236,945 236,945
	Wellfield name not available	41 41 41	12 12 12	94,778 94,778 94,778
		41	12	56,867
Kings Bay Naval Base	No. 1	16	15	67,731
	No. 2	16	16	28,988
	No. 4	15	19	3,364
Kingsland, City of	Wellfield name not available	15	8	32,086
		15	9	32,086
Kingsley Service Company	Meadowbrook	52 52 52	6 6 6	50,261 50,261 50,261
	Lucy Branch	52 52 52	6 6 6	43,723 43,723 43,723
	Ridgecrest	54 54	4 4	168,263 168,263
	Fleming Oaks	58	7	13,040

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Lake Asbury Utilities	Dow Court	59 59	2 2	9,150
	Branscomb Road	60	2	9,150
Lamplighter Mobile Home Park	Wellfield name not available	45 45	3 3	6,849 6,849
London Town Apartments	Wellfield name not available	46	6	17,862
Magnolia Springs Apartments	Wellfield name not available	62	8	13,479
Mayport Naval Station	Wellfield name not available	39 39	25 25	75,753 55,655
	Wellfield name not available	40	25	98,943
	Wellfield name not available	39	26	98,943
	Naval Housing	41	24	34,957
Neighborhood Utilities	Wellfield name not available	46	2	3,904
Neptune Beach, City of	Wellfield name not available	44 44 44 44	26 26 26 26	42,516 38,041 26,852 46,991
Normandy Village Apartments	Wellfield name not available	46 46	4 4	23,779 23,779
North Beach Utilities	Usinas	66 66	32 32	6,982 12,413
Oaks of Atlantic Beach	Wellfield name not available	41 41	25 25	13,259 13,259
Orange Park, City of	Wellfield name not available	52	7	183,330
Ortega Utility Company	Airport	34	11	17,314
	Blanding System	50 50	6 6	38,134 38,134
	Herlong System	45	3	12,492
Penney Retirement Community	Wellfield name not available	64 64	2 2	8,957 5,041
Ponte Vedra Utilities	Ponte Vedra No. 1	48	27	61,914
	Ponte Vedra No. 3	50	28	61,914
	S. Ponte Vedra (North)	60	30	4,219
	S. Ponte Vedra (South)	62	31	4,219

Table A1—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Reynold's Industrial Park	Wellfield name not available	64 64	10 10	19,834 19,834
Rhone-Poulenc (Union Carbide)	Wellfield name not available	6	20	106,952
St. Augustine, City of	Wellfield name not available	64 64	26 26	36,074 32,966
St. Augustine, City of—*continued*	Wellfield name not available	64	26	33,299
St. Johns Service Co.	Marsh Landing	48	26	14,939
	DeLeone Shores	49	27	10,374
	Inlet Beach No. 1	50	27	10,374
	Inlet Beach No. 2	49	27	14,939
St. Marys, City of	Wellfield name not available	19	17	29,813
		18	17	29,813
Southern States Utilities	Amelia Island Water Works	28 28	23 23	24,064 42,780
	Woodmere	40 40	13 14	24,071 48,143
	Beacon Hills	39 39	19 19	26,464 26,464
Southside Utilities	Wellfield name not available	50 50	17 17	21,129 54,089
	Wellfield name not available	49	17	54,089
Union Camp	Wellfield name not available	42 42 42 42	5 5 5 5	147,969 147,969 147,969 32,553
U.S. Gypsum	Wellfield name not available	40	12	35,395
Wesley Manor Retirement Center	Wellfield name not available	55	12	11,287

Note: ft^3/day = cubic feet per day
WTP = water treatment plant

Table A2. Dairy and ranch water use data by user name, 1985

Dairy Farm/Beef Ranch Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
ASB Carter Dairies	34 34	3 3	2,020 3,591
Cloverdale Farms	31 31	2 2	9,358 2,339
Dee Dot Ranch	49	20	67,861
	49	23	102,995
	51	24	33,690
	50	20	14,246
Gustafson Farms	64	6	39
	64 64	5 5	39 39
	65	5	39
	66	6	39
	66	7	39
	66	7	560
	65 65 65 65	7 7 7 7	39 39 39 39
	66 66 66	8 8 8	39 39 39
	66	8	39
	64 64 64 64	8 8 8 8	21,074 79,158 280 140
	64	9	280
	65	8	280
	65 65 65	8 8 8	280 280 280
	65 65	9 9	280 280

Table A2—*Continued*

Dairy Farm/Beef Ranch Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Gustafson Farms—*continued*	65 65	9 9	280 280
	64	7	39
	64	7	39
Pine Grove Dairies	38	1	15,294
M and M Dairy	35 35 35 35 35 35 35	16 16 16 16 16 16 16	1,723 1,723 1,7223 1,7223 1,7223 1,7223 1,7223
Meadowbrook Farms	47	18	11,471
Wright's Clay Co. Farms	62 62 62	6 6 6	10,758 10,758 10,758

Note: ft^3/day = cubic feet per day

Table A3. Golf course water use data by user name, 1985

Golf Course Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Amelia Island Plantation	29	23	49,740
Baymeadows Country Club	49	16	11,885
	49	16	11,885
Deerwood Golf Course	49	17	21,393
	49	17	9,508
Dunes Golf Course	41	19	22,2845
Fernandina Beach Golf Course	27	23	12,361
	26	23	23,295
	26	23	7,607
Hidden Hills	40	20	44,570
Hyde Park Golf/Country Club	45	5	16,936
Jacksonville Beach Golf Course	46	25	20,086
Mayport Naval Station	40	26	4,457
PGA Tours—TPC	51	27	32,090
Ponte Vedra Corporation, Ocean Course North	48	27	10,153
	48	27	10,153
Ponte Vedra Corporation, Ocean Course South	48	27	9,954
	48	27	9,954
Ponte Vedra Corporation, Lagoon Course	48	27	9,657
	48	27	9,657
Ponce de Leon Golf Course	66	30	4,120
	66	30	16,481
	66	30	16,481
Ravines Development Corporation	59	1	25,672
	59	1	25,672
Reynold's Golf Course	64	11	9,984
San Jose Country Club	48	13	17,115
	48	13	7,607

Table A3—*Continued*

Golf Course Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Sawgrass Country Club	52	28	31,347
	52	27	31,347
Timuquana Country Club	48	8	14,114
University Golf Club	40	13	18,541
Willow Lakes Golf Course	50	5	27,522
	50	6	14,819

Note: ft^3/day = cubic feet per day

Table A4. Turfgrass or nursery water use data by user name, 1985

User Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Anheuser Busch, Inc.	37	11	4,145
Florida Jr. College, South	45 45	19 19	3,438 13,751
Oaklawn Cemetery	47	11	11,450
Skinner's Tree Nursery	49	19	14,438
University of North Florida	46 46	19 19	2,433 9,732

Note: ft^3/day = cubic feet per day

Table A5. Public supply water use data by user name, 2010

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Anastasia Sanitary District	Anastasia Island WTP	68	33	On Standby
Associated Minerals	Wellfield name not available	68	7	75,007
	Wellfield name not available	68	8	210,020
Atlantic Beach, City of	Buccaneer SA/Assisi Lane WTP No. 3	41 41	25 25	147,059 147,0589
	WTP No. 2	42	25	236,631
	WTP No. 1	43 43	26 26	82,487 82,4867
Atlantic Utility Corporation	Ortega Hills Subdivision	50 50	7 7	8,953 13,989
	Bon Air	38	11	242
	River View	39	9	4,183
	West Wood	43	4	1,108
	Brackenridge	46	16	9,762
	Greenfield Estates	46	15	1,975
Beauclerc Utility Inc.	Wellfield name not available	49 49	14 14	64,171 64,171
Callahan, City of	Wellfield name not available	29 29	2 2	16,110 16,110
Canal Utilities, Inc.	Sunni Pines	44 44	23 23	138,146 27,629
	Arbor Point (Joeandy WTP)	43	22	92,246
Castleton Beverages	Wellfield name not available	35	11	14,438
Celotex Corporation	Wellfield name not available	39	17	35,294
Clay Utility	Greenwood	56	3	81,058
	Tanglewood	55	3	81,058
	Rideaught	55	3	56,290
	Brannan Field	54	1	81,058
Colony Mobile Home Park	Wellfield name not available	47 47	2 2	16,491 45,808
Container Corporation of America	Wellfield name not available	22 22	23 23	272,315 460,212
	Wellfield name not available	21	23	272,315

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Container Corporation of America—*continued*	Wellfield name not available	22 22	23 23	460,212 460,212
Florida Department of Transportation	I-10 Rest Area	44	1	1,738
Florida Public Utilities	Wellfield name not available	22 22	23 23	96,766 95,493
	Wellfield name not available	22 22	23 23	101,859 106,952
Gilman Paper Co.	Wellfield name not available	18 18	17 17	812,462 707,320
	Wellfield name not available	19 19	17 17	812,462 827,755
	Wellfield name not available	18	18	850,696
Green Cove Springs, City of	Wellfield name not available	62	8	208,957
Harbor View Utilities	Wellfield name not available	39	7	26,337
Intercoastal Utilities	Wellfield name not available	52 52	27 27	139,037 139,037
ITT Rayonier	Wellfield name not available	24 24	22 22	398,468 231,597
	Wellfield name not available	24	22	398,468
	Wellfield name not available	23	23	109,724
	Wellfield name not available	23	22	109,724
	Wellfield name not available	23 23 23 23	22 22 22 22	202,496 398,468 231,597 398,468
J-M Manufacturing Co.	Wellfield name not available	64 64	9 9	5,348 5,348
Jacksonville, City of	Dinsmore School	38	4	2,139
	Mayport	39	24	15,642
	Fairfax	41 41	8 8	57,186 39,712
		41 41 41	8 8 8	128,669 128,669 39,713
		41 41	9 9	57,186 57,186

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville, City of—*continued*	Fairfax—*continued*	41	9	57,186
	Highlands	37	10	299,733
		37	10	299,733
		37	10	299,733
		37	10	299,733
		37	10	299,733
	Lake Shore	46	6	163,865
		46	6	136,555
		46	6	136,555
		46	6	136,555
	Main Street	42	10	98,943
		42	10	134,923
		42	10	125,928
		42	10	89,949
		42	10	69,710
		43	11	69,710
		43	11	71,959
		43	11	85,451
		43	11	89,949
		43	11	89,949
	Marietta	43	3	363,971
		43	3	363,971
		43	3	363,971
		43	3	363,971
	McDuff	44	8	102,133
		44	8	136,177
		44	8	136,177
		44	7	170,221
		44	7	129,368
		43	8	204,266
	Norwood	40	10	239,639
		40	10	239,639
		40	10	239,639
		40	9	239,639
	Southwest	48	4	413,993
		48	4	413,993
		48	3	413,993

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville, City of—*continued*	Arlington	42	14	267,673
		42	14	214,139
		42	14	401,510
		42	14	334,592
	Hendricks	44	11	57,932
		44	11	96,554
		44	11	96,554
		44	11	65,657
		44	11	65,657
	Love Grove	45	14	250,605
		45	14	196,904
		45	14	223,755
		45	14	179,004
	Oak Ridge	45	19	295,106
		45	19	335,348
		45	19	335,348
		45	19	335,348
		45	19	295,106
	River Oaks	45	11	120,528
		45	11	152,668
		45	11	56,246
		45	11	40,1756
		45	11	88,387
		45	11	200,879
		44	11	120,528
	Mandarin/Community Hall	54	12	106,655
		54	12	106,655
		54	12	266,637
	Mandarin/Hood Landing	54	15	0
	Mandarin/Julington Hills	54	12	128,342
	Mandarin/Mandarin Point	53	12	74,198
		53	12	74,198
	Mandarin/Mandarin Terrace	53	12	80,214
		53	12	81,214
	Mandarin/Pickwick	51	12	159,829
		51	12	271,709
		51	12	319,658
		51	12	319,658
	Mandarin/Southwood	52	13	96,257

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville, City of—*continued*	Hanna Park	41	25	9,225
	Zoo	39	11	45,454
Jacksonville Beach, City of	Wellfield name not available	45	26	99,481
		46	26	99,481
		46	26	99,481
		46	26	176,856
		46	26	176,856
		46	26	176,856
Jacksonville Electrical Authority	Power Park (Eastport Power Plant)	37	17	487,433
		37	17	487,433
		37	17	487,433
	Northside Generating Plant	38	17	42,024
		38	17	42,024
		38	17	42,024
		38	17	42,024
		38	17	42,024
		38	17	3,782
Jacksonville International Airport	Wellfield name not available	33	9	33,222
		33	9	33,222
Jacksonville Naval Air Station	Wellfield name not available	49	9	28,095
		49	9	63,214
		49	9	63,214
	Wellfield name not available	49	9	28,095
		49	9	12,487
	Wellfield name not available	49	7	28,095
	Wellfield name not available	50	9	28,095
	Wellfield name not available	49	10	28,095
	Wellfield name not available	48	9	28,095
Jacksonville Port Authority	Blount Island	38	18	836
		37	18	4,178
		37	18	836
		37	18	4,178
Jacksonville University	Wellfield name not available	41	13	66,845
Jacksonville Suburban Utilities	Alderman Park	43	16	53,476
		43	16	53,476
	Holly Oaks	41	18	36,631
	Columbine	42	15	215,374

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Jacksonville Suburban Utilities—*continued*	Elvia	42	16	94,652
	Lake Lucina	42	14	140,508
	University Park	41	14	81,684
	Oak Hill	47	5	53,476
	Magnolia Gardens	40	8	38,896
	Lake Forest	39	9	49,401
	Hyde Grove	45	4	33,556
	Green Forest	48	4	41,043
	Wheat Road	48	4	145,454
	Forest Brook	48	6	12,299
	Venetia Terrace	48	7	10,695
	Royal Lakes Onsite	50	16	451,872
	Royal Lakes Offsite	50	16	216,577
	San Jose	48 48 48	13 13 13	125,791 125,791 125,791
	Colony Manor	47	4	0
	Monument Road	42	18	168,717
	Queen Akers	43	18	59,358
	El Agua	46 46	24 24	64,572 52,674
Jacksonville Shipyards	Wellfield name not available	43	11	31,150
Jefferson Smurfit Corporation	Alton Packaging	41 41 41	12 12 12	187,595 234,493 234,493
		41 41 41	12 12 12	93,797 93,797 93,797
		41	12	56,278
Kings Bay Naval Base	No. 1	16	15	146,463
	No. 2	16	16	43,897
	No. 4	15	19	5,094
Kingsland, City of	Wellfield name not available	15	8	151,471
		15	9	151,471

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Kingsley Service Company	Meadowbrook	52	6	191,949
		52	6	191,949
		52	6	191,949
	Lucy Branch	52	6	149,960
		52	6	149,960
		52	6	149,960
	Ridgecrest	54	4	251,934
		54	4	251,934
	Fleming Oaks	58	7	124,967
	Dupont	58	7	83,311
	Orange Park South	57	4	124,968
	Pace Island	55	7	14,163
Lake Asbury Utilities	Dow Court	59	2	38,102
	Branscomb Road	60	2	38,102
Lamplighter Mobile Home Park	Wellfield name not available	45	3	23,810
		45	3	23,810
London Town Apartments	Wellfield name not available	46	6	121,102
Mainland Water System	Tillman Ridge	68	25	21,925
		68	25	21,925
Magnolia Springs Apartments	Wellfield name not available	62	8	14,438
Mayport Naval Station	Wellfield name not available	39	25	69,475
		39	25	51,043
	Wellfield name not available	40	25	90,743
	Wellfield name not available	39	26	90,743
Neighborhood Utilities	Wellfield name not available	46	2	20,454
Neptune Beach, City of	Wellfield name not available	44	26	14,163
		44	26	14,163
		44	26	20,395
		44	26	20,395
Normandy Village Apartments	Wellfield name not available	46	4	58,289
		46	4	58,289
North Beach Utilities	Usinas	66	32	36,096
		66	32	64,171
Oaks of Atlantic Beach	Wellfield name not available	41	25	10,094
		41	25	10,094
Orange Park, City of	Wellfield name not available	52	7	248,529

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Ortega Utility Company	Airport	34	11	123,113
	Blanding System	50 50	6 6	69,251 69,251
	Herlong System	45	3	48,091
Penney Retirement Community	Wellfield name not available	64 64	2 2	11,631 11,631
Ponte Vedra Utilities	Ponte Vedra No. 1	48	27	49,227
	Ponte Vedra No. 3	50	28	49,227
	S. Ponte Vedra (North)	60	30	6,923
	S. Ponte Vedra (South)	62	31	6,923
Regency Utilities	Wellfield name not available	43 43 43	17 17 17	58,086 25,816 103,264
Reichold Chemicals	Wellfield name not available	43	5	200,53
Reynold's Industrial Park	Wellfield name not available	64 64	10 10	21,925 21,925
Rhone-Poulenc (Union Carbide)	Wellfield name not available	6	20	160,428
St. Augustine, City of	Wellfield name not available	64 64	26 26	73,021 66,794
	Wellfield name not available	64	26	67,468
St. Marys, City of	Wellfield name not available	19	17	121,992
		18	17	121,992
St. Johns Service Co.	Marsh Landing	48	26	268,256
	DeLeone Shores	49	27	186,289
	Inlet Beach No. 1	50	27	148,757
	Inlet Beach No. 2	49	27	214,211
SCM Glidco Organics	Wellfield name not available	40 40 40 40 40 40	10 10 10 10 10 10	46,867 26,362 46,867 46,867 46,867 46,867
Seminole Kraft Paper Company	Wellfield name not available	37	14	451,002
		37 37 37	14 14 14	473,552 473,542 473,542

Table A5—*Continued*

Wellfield Owner	Wellfield Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
		Row	Column	
Shadowrock Utilities	Springtree Village	46 46	3 3	17,678 7,857
Simplex Products Division	Wellfield name not available	36 36	13 13	3,342 3,342
Southern States Utilities	Amelia Island Water Works	28 28	23 23	75,561 134,331
	Palm Valley, City of	54	27	2,312
		53	26	2,312
		52	26	2,312
		50	26	2,312
		50	25	2,312
	Woodmere	40 40	13 14	53,030 106,061
	Cobblestone	41	20	131,097
	Beacon Hills	39 39	19 19	233,061 233,061
Southside Utilities	Wellfield name not available	50	17	150,401
		49	17	150,401
Union Camp	Wellfield name not available	42 42 42 42	5 5 5 5	50,496 50,496 50,496 22,443
Wesley Manor Retirement Center	Wellfield name not available	55	12	10,561

Note: ft^3/day = cubic feet per day
WTP = water treatment plant

Table A6. Dairy and ranch water use data by user name, 2010

Dairy Farm/Beef Ranch Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
ASB Carter Dairies	34	3	2,020
	34	3	3,591
Cloverdale Farms	31	2	9,358
	31	2	2,339
Dee Dot Ranch	49	20	67,861
	49	23	102,995
	51	24	33,690
	50	20	14,246
Gustafson Farms	64	6	39
	64	5	39
	64	5	39
	65	5	39
	66	6	39
	66	7	39
	66	7	560
	65	7	39
	65	7	39
	65	7	39
	65	7	39
	66	8	39
	66	8	39
	66	8	39
	66	8	39
	64	8	21,074
	64	8	79,158
	64	8	280
	64	8	140
	64	9	280
	65	8	280
	65	8	280
	65	8	280
	65	8	280
	65	9	280
	65	9	280

Table A6—*Continued*

Dairy Farm/Beef Ranch Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Gustafson Farms—*continued*	65	9	280
	65	9	280
	64	7	39
	64	7	39
Pine Grove Dairies	38	1	15,294
M and M Dairy	35	16	1,723
	35	16	1,723
	35	16	1,723
	35	16	1,723
	35	16	1,723
	35	16	1,723
	35	16	1,723
Meadowbrook Farms	47	18	11,471
Wright's Clay Co. Farms	62	6	10,758
	62	6	10,758
	62	6	10,758

Note: ft^3/day = cubic feet per day

Table A7. Golf course water use data by user name, 2010

Golf Course Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Amelia Island Plantation	29	23	49,740
Baymeadows Country Club	49	16	11,885
	49	16	11,885
Cimarrone Golf and Country Club	59	17	40,700
Country Club of Orange Park	64	2	16,000
Deerfield Lakes Country Club	31	4	9,670
Deerwood Golf Course	49 49	17 17	21,393 9,508
Dunes Golf Course	41	19	22,285
Fernandina Beach Golf Course	27	23	12,361
	26 26	23 23	23,295 7,607
Hidden Hills	40	20	44,570
Hyde Park Golf/Country Club	45	5	16,936
Interchange	64	21	85,695
	63	22	85,695
Jacksonville Beach Golf Course	46	25	20,086
Jacksonville Golf and Country Club	52	4	37,082
Long Point Golf Course	31	23	20,800
Magnolia Point	62	7	58,700
Mayport Naval Station	40	26	4,457
Monument Road Golf Course	42	19	27,800
PGA Tours—TPC	51	27	32,090
Ponce de Leon Golf Course	66	30	4,120
	66 66	30 30	16,481 16,481
Ponte Vedra Corporation, Ocean Course North	48	27	10,153
	48	27	10,153

Table A7—*Continued*

Golf Course Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Ponte Vedra Corporation, Ocean Course South	48 48	27 27	9,954 9,954
Ponte Vedra Corporation, Lagoon Course	48 48	27 27	9,657 9,657
Queen's Harbor Yacht and Country Club	42	23	34,000
Ravines Development Corporation	59 59	1 1	25,672 25,672
Reynold's Golf Course	64	11	9,984
San Jose Country Club	48 48	13 13	17,115 7,607
Sawgrass Country Club	52	28	31,347
	52	27	31,347
SHS Jacksonville Golf Inc.	46	21	20,100
Six-Mile Creek	66	19	114,238
	66	20	114,238
Summer Beach	27	23	34,200
Timuquana Country Club	48	8	14,114
University Golf Club	40	13	18,541
White Oak Plantation	19	6	87,400
Willow Lakes Golf Course	50	5	27,522
	50	6	14,819
Windsor Parke	47	22	25,000

Note: ft^3/day = cubic feet per day

Table A8. Turfgrass or nursery water use data by user name, 2010

User Name	Well Location		Estimated Withdrawal Rate (ft^3/d)
	Row	Column	
Anheuser Busch, Inc.	37	11	4,145
Florida Junior College, South	45 45	19 19	3,438 13,751
Oaklawn Cemetery	47	11	11,450
Skinner's Tree Nursery	49	19	14,438
University of North Florida	46 46	19 19	2,433 9,732

Note: ft^3/day = cubic feet per day

Appendix B—Map of Monitoring Well Locations and Selected Hydrographs Within and Near the Study Area

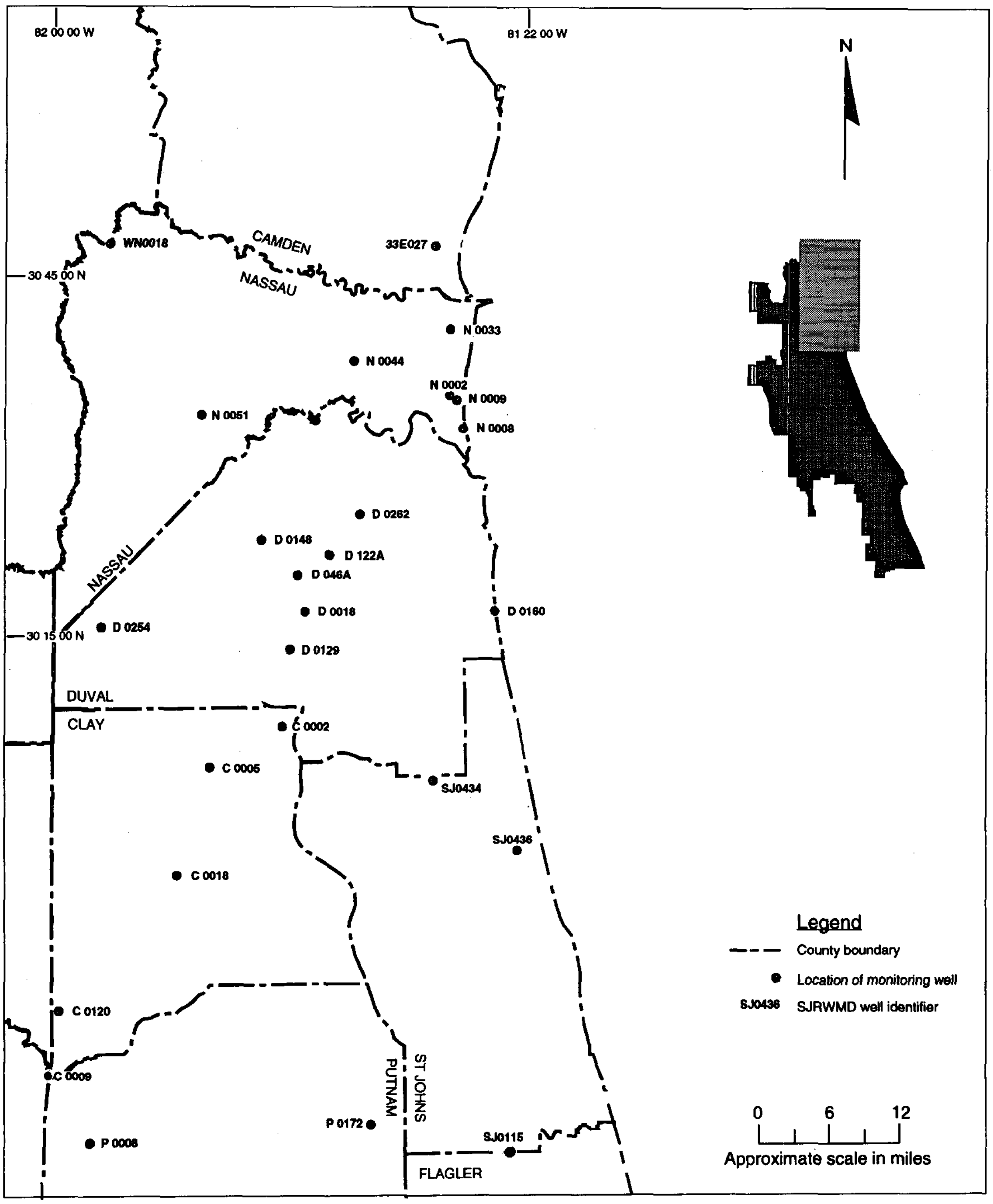

Figure B1. Locations of monitoring wells in the Upper Floridan aquifer for which long-term hydrographs were available

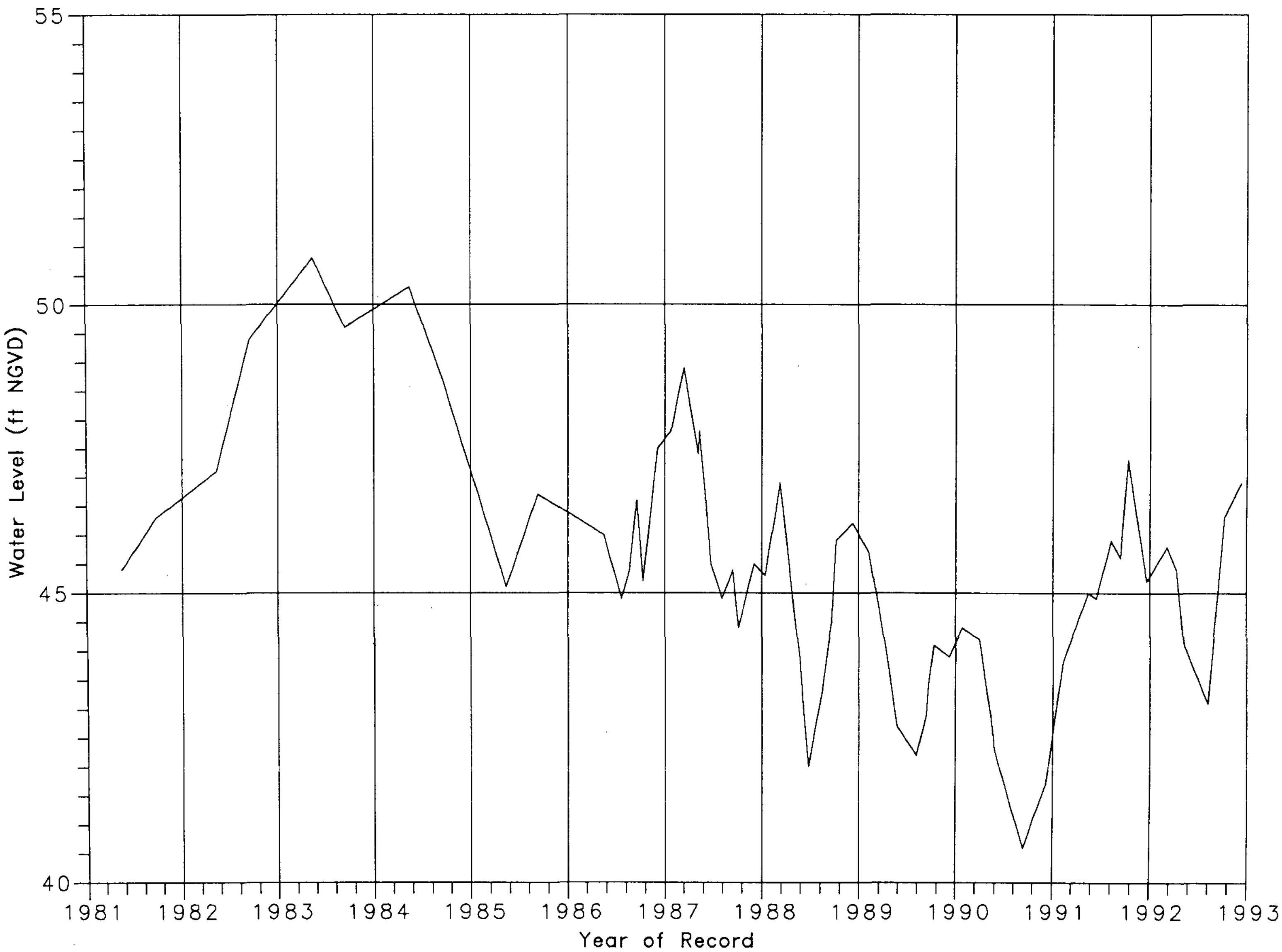

Figure B2. Water level versus time, Well C-0018 (St. Johns River Water Management District)

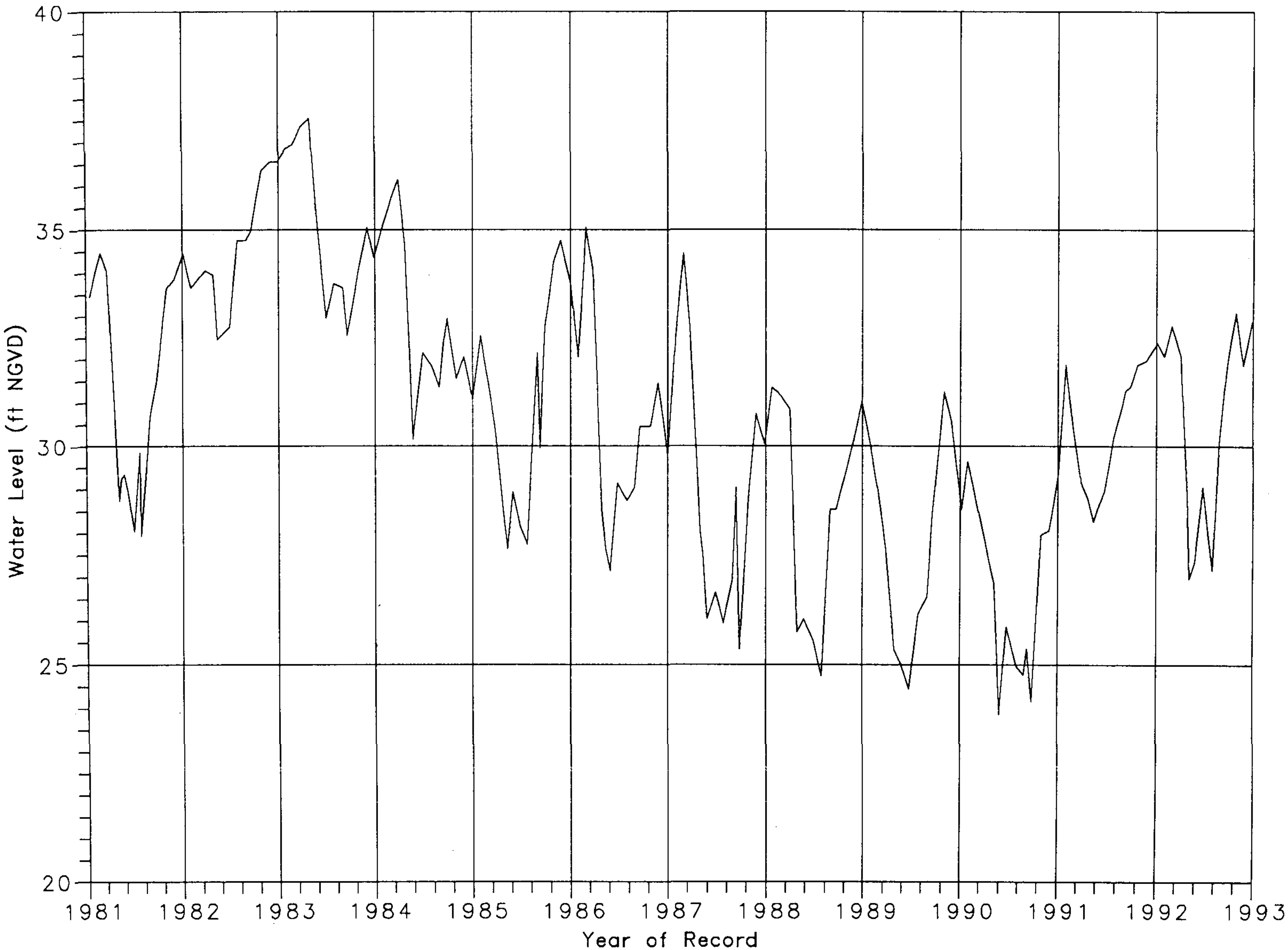

Figure B3. Water level versus time, Well D-0160 (St. Johns River Water Management District)

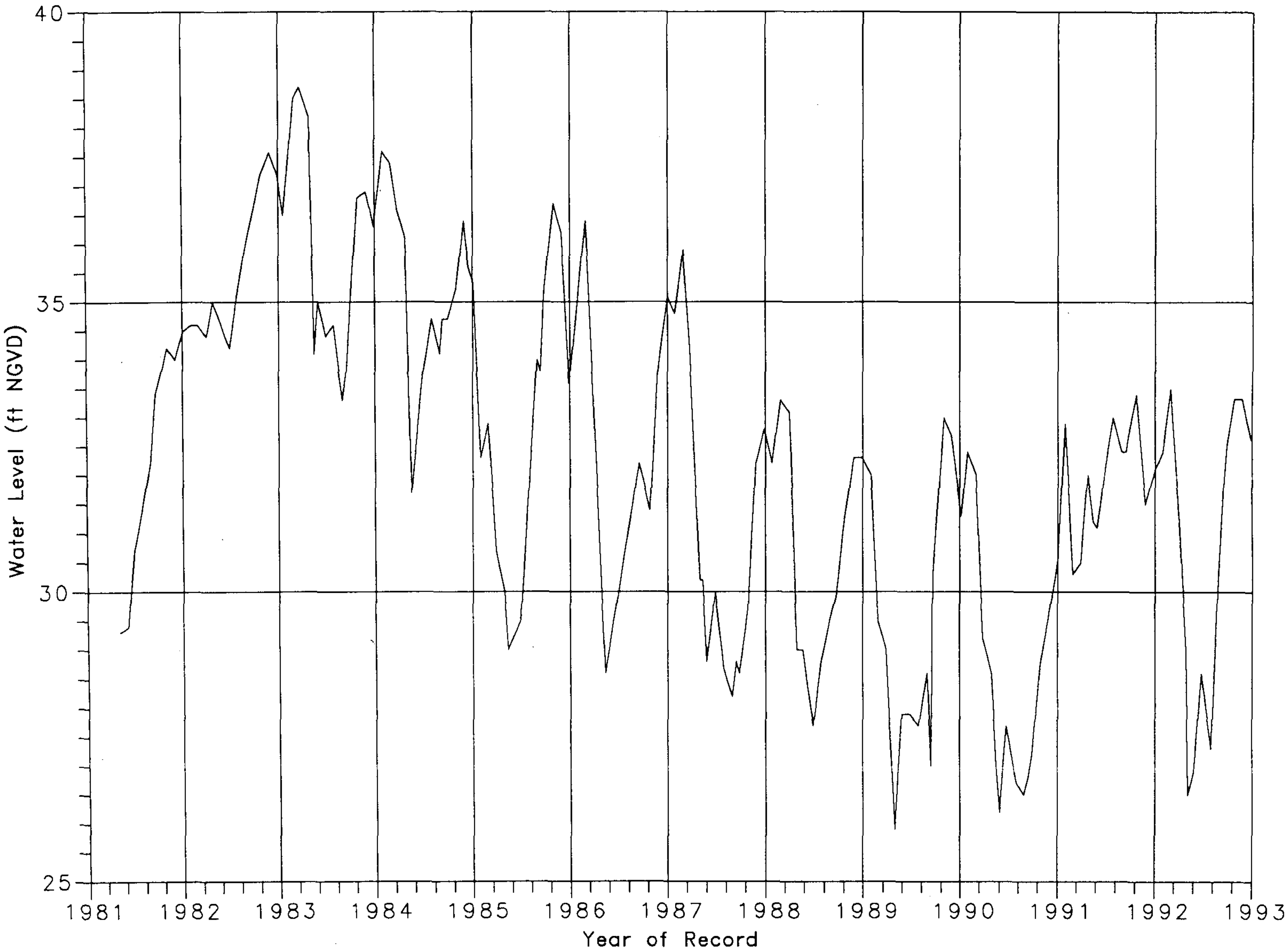

Figure B4. Water level versus time, Well SJ-0436 (St. Johns River Water Management District)

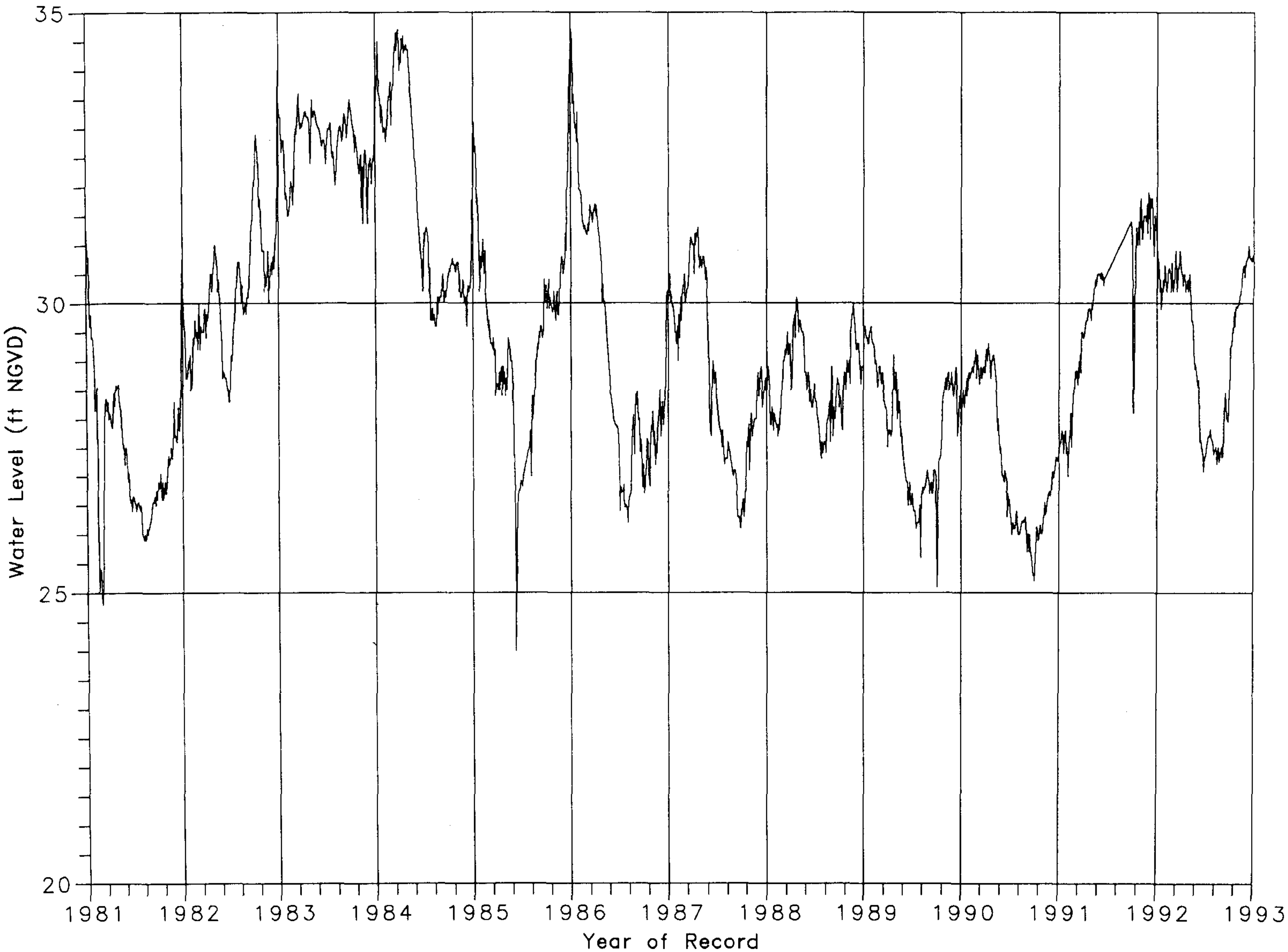

Figure B5. Water level versus time, Well 33E027 (U.S. Geological Survey)

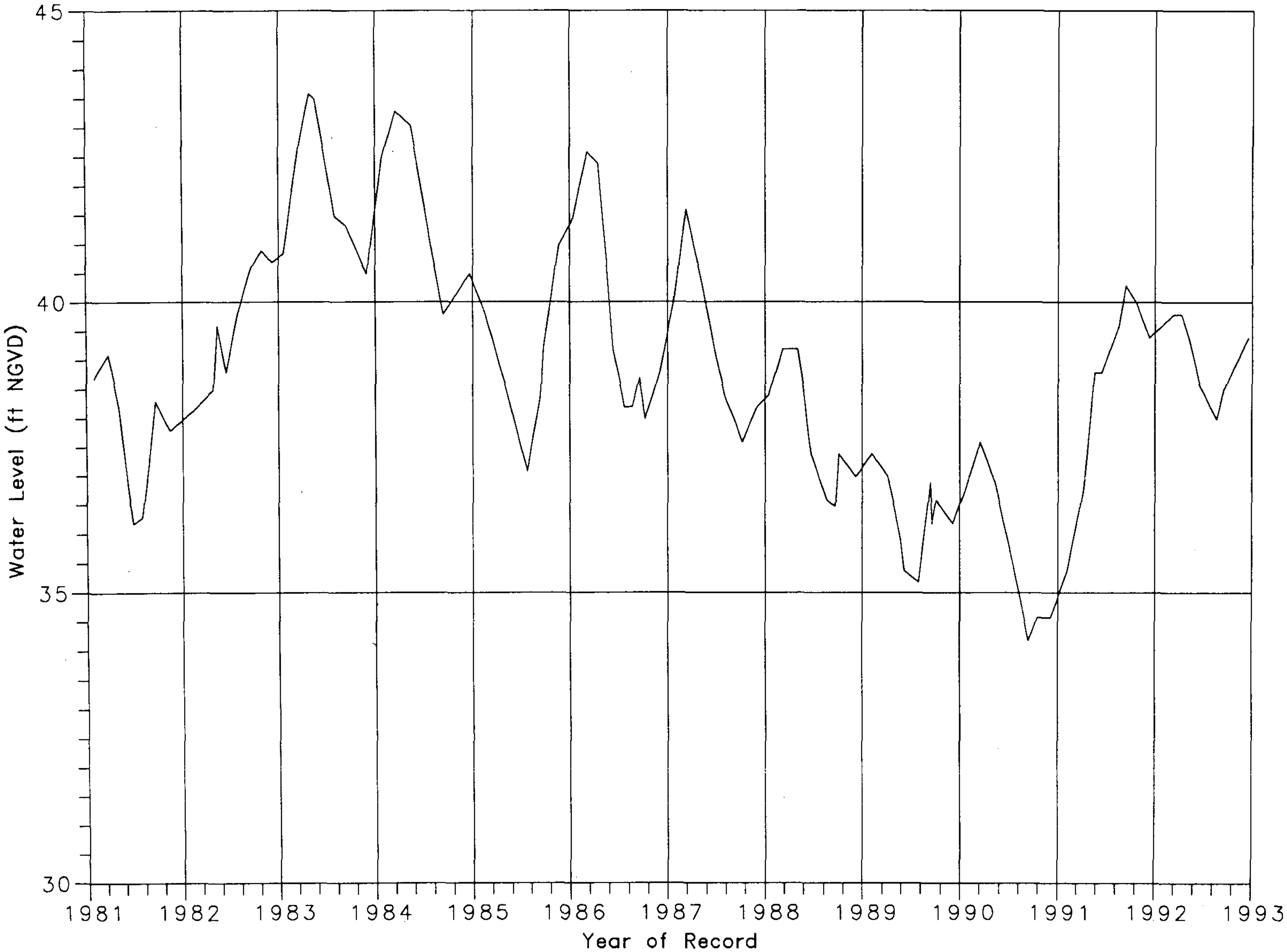

Figure B6. Water level versus time, Well N-0051 (St. Johns River Water Management District)

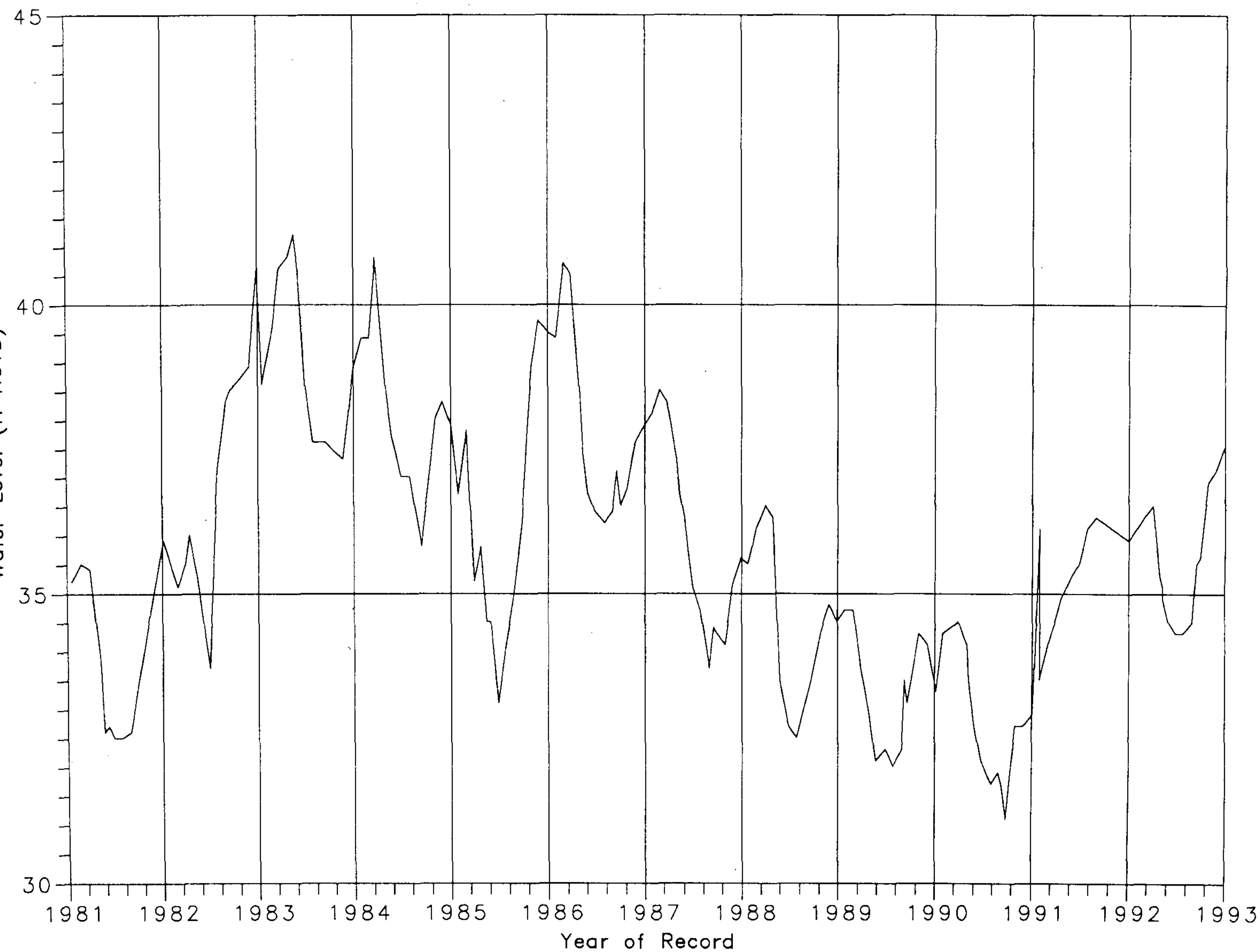

Figure B7. Water level versus time, Well D-0262 (St. Johns River Water Management District)

APPENDIX C—HYDRAULIC-HEAD RESIDUALS BASED ON OBSERVED VALUES OF HYDRAULIC HEAD

Table C1. Hydraulic-head residuals based on observed hydraulic-head values

Identification Number on Figure 14	USGS Well Identifier	Location		Model Location		Date of Observation	Observed Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
1	295040081333201	29 50 40	81 33 32	68	16	9/10/85	31.0	32.7	-1.7
2	295132081164801	29 51 32	81 16 48	68	33	9/11/85	16.5	23.1	-6.6
3	295333081191401	29 53 33	81 19 14	68	31	9/11/85	20.9	25.4	-4.5
4	295341081263705	29 53 41	81 26 37	67	23	9/10/85	30.4	30.8	-0.4
5	295353081381901	29 53 53	81 38 19	67	11	9/10/85	32.8	36.7	-3.9
6	295357081294301	29 53 57	81 29 43	67	20	9/10/85	30.0	31.8	-1.8
7	295502081175401	29 55 02	81 17 54	67	32	9/11/85	22.3	25.2	-2.9
8	295556081342101	29 55 56	81 34 21	66	15	9/10/85	33.6	32.0	1.6
9	295615081394701	29 56 15	81 39 47	66	10	9/10/85	38.5	33.2	5.3
10	295713081203401	29 57 13	81 20 34	65	29	9/11/85	30.5	28.5	2.0
11	295835081515001	29 58 35	81 51 50	64	1	9/10/85	69.7	62.2	7.6
12	295847081380601	29 58 47	81 38 06	64	12	9/10/85	22.8	21.7	1.1
13	295900081403201	29 59 00	81 40 32	64	9	9/10/85	25.8	29.7	-3.9
14	295903081334301	29 59 03	81 33 43	64	16	9/10/85	33.0	32.2	0.8
15	300019081363301	30 00 19	81 36 33	62	13	9/10/85	32.8	28.8	4.0
16	300036081213501	30 00 36	81 21 35	62	28	9/11/85	32.5	31.6	0.9
17	300048081414301	30 00 48	81 41 43	62	8	9/10/85	31.8	32.5	-0.6
18	300300081422501	30 03 00	81 42 25	60	7	9/12/85	29.8	34.4	-4.6
19	300307081234201	30 03 07	81 23 42	60	26	9/10/85	39.2	35.4	3.8
20	300322081342801	30 03 22	81 34 28	59	15	9/13/85	33.6	36.9	-3.3
21	300341081395401	30 03 41	81 39 54	59	10	9/10/85	33.2	29.7	3.5
22	300354081301201	30 03 54	81 30 12	59	20	9/10/85	35.6	38.0	-2.4
23	300450081482801	30 04 50	81 48 28	58	2	9/10/85	46.7	45.9	0.8
24	300555081290601	30 05 55	81 29 06	57	21	9/10/85	38.6	37.7	0.9
25	300604081441501	30 06 04	81 44 15	57	5	9/10/85	33.5	35.6	-2.1
26	300632081334301	30 06 32	81 33 43	56	16	9/10/85	38.1	39.2	-1.1
27	300649081485901	30 06 49	81 48 59	56	2	9/10/85	40.4	42.2	-1.8
28	300656081463401	30 06 56	81 46 34	56	4	9/10/85	36.7	36.4	0.3
29	300717081381001	30 07 17	81 38 10	55	12	9/09/85	33.8	32.9	0.9
30	300758081230501	30 07 58	81 23 05	55	27	9/10/85	34.7	35.4	-0.7
31	300812081390801	30 08 12	81 39 08	54	11	9/09/85	32.1	29.9	2.2
32	300820081354001	30 08 20	81 35 40	54	14	9/09/85	38.4	37.3	1.1

Table C1—*Continued*

Identification Number on Figure 14	USGS Well Identifier	Location		Model Location		Date of Observation	Observed Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
33	300824081305401	30 08 24	81 30 54	54	19	9/10/85	39.7	38.0	1.8
34	300834081421301	30 08 34	81 42 13	54	8	9/10/85	27.8	27.6	0.2
35	301005081225901	30 10 05	81 22 59	53	27	9/09/85	20.2	33.4	-13.2
36	301018081415101	30 10 18	81 41 51	52	8	9/10/85	29.9	25.9	4.0
37	301032081380401	30 10 32	81 38 04	52	12	9/09/85	31.6	30.8	0.8
38	301037081243901	30 10 37	81 24 39	52	25	9/12/85	30.8	35.8	-5.0
39	301144081413801	30 11 44	81 41 38	51	8	9/11/85	29.7	26.2	3.5
40	301212081252401	30 12 12	81 25 24	50	24	9/12/85	39.7	34.9	4.8
41	301216081451201	30 12 16	81 45 12	50	5	9/11/85	27.1	30.0	-2.9
42	301249081225801	30 12 49	81 22 58	50	27	9/09/85	29.0	31.0	-2.0
43	301255081371001	30 12 55	81 37 10	50	13	9/09/85	24.9	32.3	-7.4
44	301304081222701	30 13 04	81 22 27	50	27	9/09/85	23.7	31.0	-7.3
45	301333081324101	30 13 33	81 32 41	49	17	9/09/85	37.3	36.0	1.3
46	301339081433401	30 13 39	81 43 34	49	6	9/11/85	30.7	29.1	1.7
47	301347081353301	30 13 47	81 35 33	49	14	9/09/85	33.1	32.9	0.3
48	301408081253101	30 14 08	81 25 31	49	24	9/12/85	23.5	33.5	-10.0
49	301411081224201	30 14 11	81 22 42	49	27	9/09/85	38.4	30.4	8.0
50	301415081284801	30 14 15	81 28 48	48	21	9/20/85	33.4	36.0	-2.6
51	301551081415701	30 15 51	81 41 57	47	8	9/11/85	27.1	28.9	-1.8
52	301607081301001	30 16 07	81 30 10	47	20	9/09/85	33.3	36.0	-2.7
53	301617081421601	30 16 17	81 42 16	46	8	9/11/85	29.0	30.2	-1.2
54	301712081233301	30 17 12	81 23 33	45	26	9/10/85	28.9	31.6	-2.7
55	301715081300001	30 17 15	81 30 00	45	20	9/09/85	32.8	35.0	-2.2
56	301725081392101	30 17 25	81 39 21	45	10	9/09/85	25.4	30.3	-4.9
57	301817081374901	30 18 17	81 37 49	44	12	9/09/85	35.4	32.4	3.0
58	301844081403801	30 18 44	81 40 38	44	9	9/11/85	29.1	31.3	-2.1
59	301846081240201	30 18 46	81 24 02	44	26	9/10/85	29.4	32.6	-3.2
60	301852081234201	30 18 52	81 23 42	44	26	9/10/85	29.9	32.6	-2.6
61	301900081342801	30 19 17	81 34 54	43	15	9/09/85	31.6	35.5	-3.8
62	301902081394601	30 19 02	81 39 46	44	10	9/09/85	27.2	31.4	-4.2
63	301919081375401	30 19 19	81 37 54	43	12	9/09/85	34.0	33.7	0.3
64	301925081262501	30 19 25	81 26 25	43	23	9/09/85	27.9	34.4	-6.5
65	302037081455301	30 20 37	81 45 53	42	4	9/11/85	35.6	35.1	0.5

Table C1—*Continued*

Identification Number on Figure 14	USGS Well Identifier	Location		Model Location		Date of Observation	Observed Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
66	302112081384701	30 21 12	81 38 47	41	11	9/09/85	35.2	33.8	1.4
67	302120081362201	30 21 20	81 36 22	41	13	9/09/85	32.7	33.6	-0.8
68	302122081274001	30 21 22	81 27 40	41	22	9/10/85	32.2	34.6	-2.4
69	302137081240001	30 21 37	81 24 00	41	26	9/10/85	32.1	33.8	-1.6
70	302142081330701	30 21 42	81 33 07	41	17	9/10/85	31.0	34.9	-3.9
71	302145081394201	30 21 45	81 39 42	41	10	9/12/85	34.9	33.5	1.4
72	302300081295101	30 23 00	81 29 51	40	20	9/10/85	36.3	34.4	1.9
73	302304081383202	30 23 04	81 38 32	40	11	9/10/85	37.4	33.6	3.9
74	302307081293801	30 23 07	81 29 38	40	20	9/10/85	37.0	34.4	2.6
75	302317081330401	30 23 17	81 33 04	39	17	9/11/85	37.5	34.3	3.2
76	302330081463001	30 23 30	81 46 30	39	4	9/12/85	35.9	38.2	-2.3
77	302339081254702	30 23 39	81 25 47	39	24	9/10/85	36.1	34.0	2.1
78	302345081261301	30 23 45	81 26 13	39	24	9/11/85	35.1	34.0	1.1
79	302351081390201	30 23 51	81 39 02	39	11	9/11/85	32.0	33.9	-1.9
80	302502081321001	30 25 02	81 32 10	38	18	9/11/85	35.7	34.2	1.5
81	302514081393701	30 25 14	81 39 37	37	10	9/12/85	33.6	32.5	1.1
82	302538081253101	30 25 38	81 25 31	37	24	9/11/85	38.5	34.5	4.0
83	302608081354901	30 26 08	81 35 49	36	14	9/11/85	35.7	33.7	2.0
84	302608081354902	30 26 08	81 35 49	36	14	9/11/85	36.7	33.7	3.1
85	302608081354903	30 26 08	81 35 49	36	14	9/11/85	35.2	33.7	1.6
86	302616081413901	30 26 16	81 41 39	36	8	9/12/85	38.6	36.6	2.0
87	302641081454201	30 26 41	81 45 42	36	4	9/12/85	38.0	39.4	-1.4
88	302724081244801	30 27 24	81 24 48	35	25	9/11/85	34.6	34.4	0.3
89	302738081290001	30 27 38	81 29 00	35	21	9/11/85	33.4	34.7	-1.3
90	302801081375101	30 28 01	81 37 51	35	12	9/11/85	36.2	34.6	1.6
91	303015081343301	30 30 15	81 34 33	32	15	9/11/85	25.1	35.4	-10.3
92	303216081433301	30 32 16	81 43 33	30	6	9/11/85	36.5	38.2	-1.7
93	303340081500001	30 33 40	81 50 00	29	2	9/11/85	38.3	40.7	-2.3
94	303357081295601	30 33 57	81 29 56	29	20	9/09/85	29.2	33.2	-4.0
95	303417081342201	30 34 17	81 34 22	28	16	9/09/85	30.4	33.2	-2.8
96	303435081271401	30 34 35	81 27 14	28	23	9/09/85	28.4	29.6	-1.2
97	303458081364001	30 34 58	81 36 40	28	13	9/11/85	31.6	33.2	-1.6
98	303518081275001	30 35 18	81 27 50	27	22	9/25/85	20.6	17.5	3.1

Table C1—*Continued*

Identification Number on Figure 14	USGS Well Identifier	Location		Model Location		Date of Observation	Observed Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
99	303658081422601	30 36 58	81 42 26	26	7	9/10/85	34.0	36.4	-2.4
100	303722081295401	30 37 22	81 29 54	25	20	9/09/85	5.9	1.4	4.5
101	303754081362701	30 37 54	81 36 27	25	14	9/10/85	28.6	26.8	1.9
102	303805081273901	30 38 05	81 27 39	25	22	9/09/85	-30.6	-25.3	-5.3
103	303819081455701	30 38 19	81 45 57	24	4	9/09/85	38.8	38.0	0.8
104	303836081274201	30 38 36	81 27 42	24	22	9/09/85	-39.6	-89.9	50.3
105	303939081312601	30 39 39	81 31 26	23	19	9/10/85	0.6	-1.4	2.2
106	304002081381201	30 40 18	81 38 28	22	12	9/10/85	28.6	27.7	0.9
107	304022081275001	30 40 22	81 27 50	22	22	9/09/85	-29.2	-45.3	16.1
108	304055081272002	30 40 55	81 27 20	22	23	9/13/85	-90.8	-55.9	-34.9
109	304150081470301	30 41 50	81 47 03	21	3	9/18/85	39.0	38.3	0.7
110	304213081270801	30 42 13	81 27 08	20	23	9/09/85	-15.9	-5.2	-10.7
111	304317081372301	30 43 17	81 37 23	19	13	9/10/85	25.8	24.4	1.4
112	304830081481201	30 48 30	81 48 12	14	3	5/15/85	40.1	39.4	0.7
113	305854081502201	30 58 59	81 50 10	4	2	5/15/85	36.3	39.3	-3.0
114	305627081473101	30 56 23	81 48 35	6	2	5/15/85	41.0	40.1	0.9
115	304804081405401	30 48 04	81 40 54	15	9	5/15/85	39.3	34.7	4.6
116	304514081390201	30 45 16	81 38 59	17	11	5/15/85	35.9	31.2	4.8
117	305804081441301	30 58 04	81 44 13	4	6	5/15/85	39.5	37.2	2.3
118	310147081440401	31 01 45	81 44 09	1	6	5/15/85	38.2	35.8	2.4
119	304348081323901	30 43 48	81 32 39	19	17	5/15/85	4.6	-9.1	13.7
120	304401081323701	30 44 01	81 32 37	19	17	5/14/85	-60.0	-9.1	-51.0
121	304408081323401	30 44 06	81 32 35	19	17	5/14/85	-15.3	-9.1	-6.3
122	304408081323301	30 44 08	81 32 35	18	17	5/14/85	-15.5	-4.4	-11.1
123	304401081323601	30 44 01	81 32 37	19	17	5/14/85	-79.0	-9.1	-69.9
124	304313081325701	30 43 13	81 32 57	19	17	5/14/85	7.6	-9.1	16.8
125	304627081371201	30 46 27	81 37 12	16	13	5/15/85	28.0	28.5	-0.5
126	304907081323701	30 49 10	81 32 38	13	17	5/15/85	34.0	30.7	3.3
127	304512081343601	30 45 10	81 34 38	17	15	5/15/85	20.7	18.7	2.0
128	305045081334601	30 50 45	81 33 46	12	16	5/15/85	37.0	32.5	4.5
129	305031081342701	30 50 31	81 34 27	12	16	5/15/85	39.0	32.5	6.5
130	305313081310401	30 53 14	81 31 03	9	19	5/15/85	35.0	32.9	2.1
131	305505081305101	30 55 14	81 30 56	7	19	5/21/85	36.3	32.6	3.8

Table C1—*Continued*

Identification Number on Figure 14	USGS Well Identifier	Location		Model Location		Date of Observation	Observed Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (ft)
		Latitude	Longitude	Row	Column				
132	305710081315501	30 57 10	81 31 55	5	18	5/21/85	33.2	32.6	0.6
133	305610081302901	30 56 11	81 30 28	6	20	5/21/85	31.7	32.0	-0.3
134	305538081305401	30 55 38	81 30 54	7	19	5/21/85	38.7	32.6	6.2
135	310106081314501	31 01 06	81 31 45	2	18	5/15/85	37.7	31.2	6.5
136	305122081275601	30 51 22	81 27 55	11	22	5/13/85	30.4	32.1	-1.7
137	304646081280901	30 46 46	81 28 09	16	22	5/13/85	26.5	20.5	6.0
138	304610081280901	30 46 10	81 28 09	16	22	5/13/85	23.6	20.5	3.1
139	305032081280101	30 50 32	81 28 01	12	22	5/13/85	33.4	30.9	2.5
140	305029081265101	30 50 29	81 26 51	12	23	5/13/85	32.4	30.8	1.6
141	304851081274001	30 48 51	81 27 40	14	22	5/13/85	32.1	27.1	5.0
142	305242081263401	30 52 42	81 26 34	10	23	5/13/85	35.0	32.2	2.8

Note: ft = feet
NGVD = National Geodetic Vertical Datum