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NORTH-CENTRAL FLORIDA REGIONAL GROUND-WATER INVESTIGATION AND FLOW MODEL (Final Report)

by

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ABSTRACT

Development of a north-central Florida regional ground-water flow model was authorized by the St. Johns River Water Management District to determine the magnitude and causes of the regional decline in ground-water levels in the upper Floridan aquifer in an area extending westward from Duval County to Alachua County. Regionally, from predevelopment time to 1985, the potentiometric surface of the upper Florida aquifer has declined on the order of 10 to 40 ft in parts of the study area. The USGS modular three-dimensional finite-difference ground-water flow model MODFLOW was used to simulate the ground-water system in the study area. The calibrated May 1985 simulation and the projected pumping rates and boundary conditions for May 2010 were used to predict the potentiometric surface in the upper Floridan aquifer for May 2010 and the drawdowns that will occur from May 1985 to May 2010. The results of the investigation indicate that predicted changes in water levels in the upper Floridan aqufier from May 1985 to May 2010 are negligible (± 1 ft) over a large part of the study area but will range from approximately 12 to 19 ft in other parts of the study area. In the east-central part of the study area, water levels are predicted to <u>increase</u> by as much as 5 ft. Surficial aquifer drawdowns from 1985 to 2010 are predicted to range from -1.6 ft (an <u>increase</u> in the water table) to 1.2 ft. Model results also indicate that presently projected changes in pumping from 1985 to 2010 will not significantly affect lake levels in the Keystone Heights area. Recommendations include requiring commercial and industrial ground-water pumpage to be metered, improving the availability and accuracy of water-use data, and delineating better some of the hydrogeologic regimes in the District.

1.0 INTRODUCTION

1.1 BACKGROUND

Available long-term data for ground-water levels and lake levels in north-central Florida indicate that substantial declines have occurred over the past 20 to 30 years in many parts of the area. For example, water levels in the upper Floridan aquifer in the Keystone Heights area declined more than 15 ft from 1960 to 1991. In response to concerns about declining ground-water and lake levels in the Upper Etonia Creek basin (UECB), the St. Johns River Water Management District (SJRWMD) in 1990 authorized the University of Florida (UF) to investigate long-term changes in rainfall, evapotranspiration, ground-water levels, and water use in the basin. In 1991, SJRWMD authorized a second phase of the investigation, which had as its objective gaining additional insight into the relation between lake levels and the surface-water and ground-water systems in the UECB. The second phase consisted of compiling and evaluating hydrogeologic data, developing a ground-water model for a two-dimensional cross-section, simulating lake stages using water-budget data, and estimating the impacts that drawdowns in the upper Florida aquifer and changes in the surface-water inflow to Brooklyn Lake have had on the stage of Brooklyn Lake.

As a result of the UECB investigation (Motz et al. 1991a and 1993), it was determined, in an overall sense, that below average rainfall over the past several years is the primary cause of declining lake levels in the UECB. For Brooklyn Lake, it was determined that the below average rainfall and declining ground-water levels in the upper Floridan aquifer, vertical leakage from the lake to the upper Floridan aquifer, and cessation of surface-water inflow since 1989 are the major, interrelated factors that have contributed to the lake's recent decline to record low levels (Motz and Fowler 1993). It was recommended that the regional decline in the upper Floridan aquifer and its impact on Brooklyn Lake and other lakes be investigated further by means of a regional ground-water flow model.

1.2 OBJECTIVES

The north-central regional ground-water flow model investigation was authorized by SJRWMD in August 1992. The objective was to determine the magnitude and causes of the regional decline in ground-water levels in the upper Florida aquifer in an area extending westward from Duval County to Alachua County. Recommendations for management strategies that would reduce the regional decline due to present and proposed pumping from the ground-water system also were to be developed.

1.3 TASKS

The investigation consisted of five tasks:

1) compilation and evaluation of hydrologic data,
2) determination of natural effects and pumping effects,
3) development of a regional ground-water flow model,
4) development of recommendations for management strategies, and
5) preparation of a report of findings.

Task 1 consisted of compiling and evaluating hydrologic data to describe conceptually the ground-water and surface-water components of the hydrologic system in the study area. In Task 2, factors that may have contributed to ground-water and lake level declines were investigated, including rainfall, evaporation, and proximity to ground-water pumping centers. In Task 3, a ground-water flow model was developed for the study area, utilizing the U.S. Geological Survey (USGS) modular three-dimensional ground-water flow model called MODFLOW (McDonald and Harbaugh 1988). The impacts of regional pumping on ground-water levels were quantified as part of this task. In Task 4, recommendations were developed for reducing the impacts that pumping has had on ground-water and lake levels in the study area. Task 5 consisted of preparing this report to present to SJRWMD the results of the north-central Florida regional ground-water investigation.

2.0 REGIONAL SETTING

2.1 LOCATION

The study area covers approximately 3,540 square miles in north-central Florida (see Figure 2-1). It is centered on the Keystone Heights lake region in southwestern Clay County, and it lies between 29°15′ and 30°12′ north latitude and approximately 81°35′ and 82°30′ west longitude. The study area extends from the north in the southern part of Baker County to the south in northern Marion County and from the east approximately along the St. Johns River to the west in the western part of Alachua County. All or parts of twelve counties are in the study area: all of Bradford and Clay counties, most of Alachua, Putnam, and Union counties, and smaller parts of Baker, Columbia, Duval, Levy, Marion, St. Johns, and Volusia counties.

2.2 PREVIOUS INVESTIGATIONS

2.2.1 Regional and State-Wide Investigations

A number of state-wide and regional investigations have included some aspects of the physiography, geology, hydrogeology, and hydrology of north-central Florida. MacNeil (1950) described Pleistocene shores lines in Florida and Georgia, including those that occur in north-central Florida. Puri and Vernon (1964) summarized the geology of Florida, and White (1970) described the geomorphology of the Florida peninsula. Scott (1983 and 1988) studied and mapped the Hawthorn Formation in northeastern Florida. Rosenau et al. (1977) published a comprehensive report

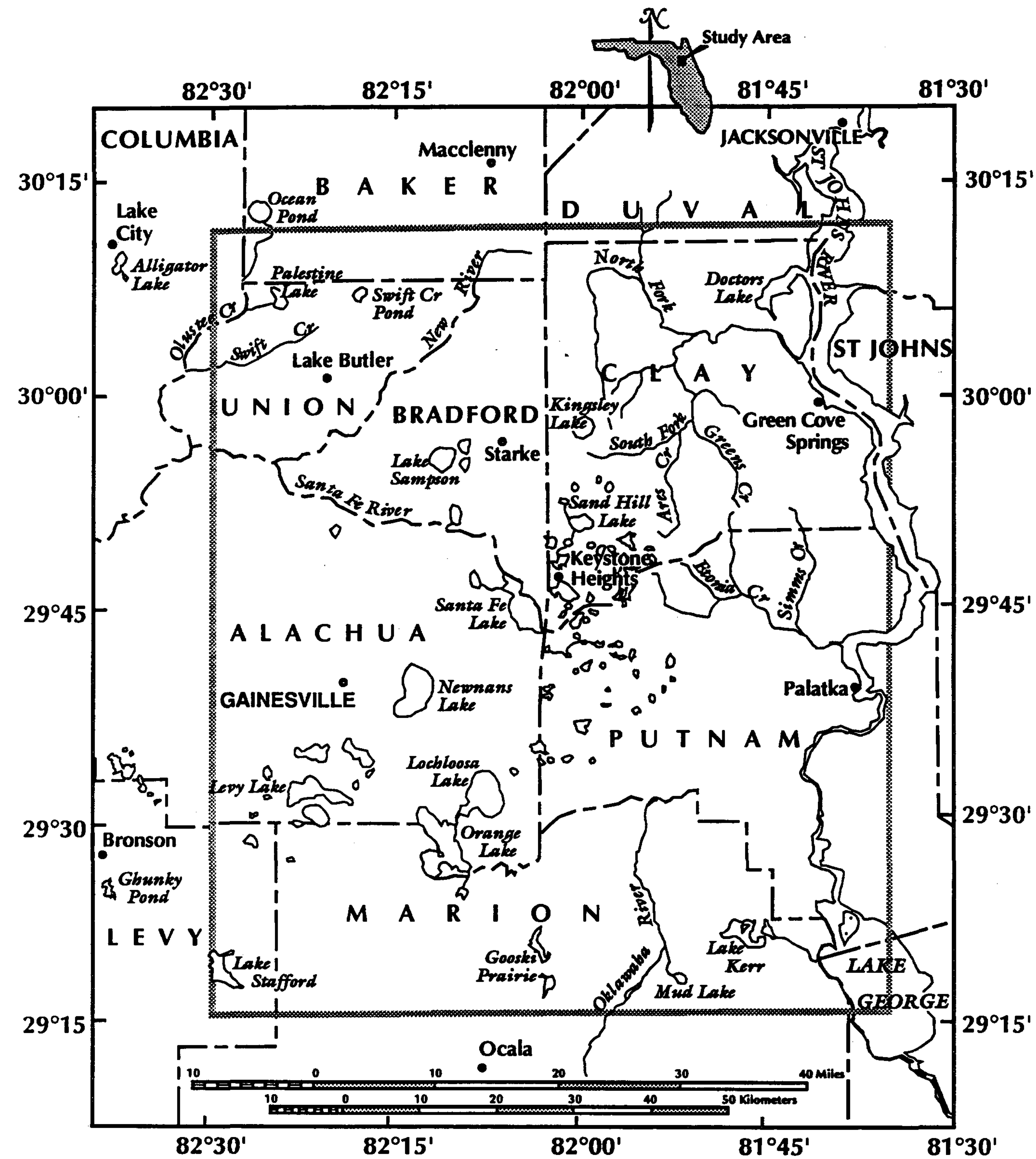


Figure 2-1. North-Central Florida Regional Study Area

describing the springs of Florida, and Fernald and Patton (1984) edited a comprehensive summary of the water resources of Florida. As part of the USGS Regional Aquifer System Analysis (RASA) program, Johnston and Bush (1988) summarized aspects of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama, including the hydrogeologic framework, hydraulic properties of aquifers, regional flow system, effects of ground-water development, and geochemistry. Miller (1986) described in detail the hydrogeologic framework of the regional aquifers and confining units that comprise the Florida aquifer system.

2.2.2 Investigations in North-Central Florida

Clark et al. (1964) investigated the water-resources of Alachua, Bradford, Clay, and Union counties, which includes a large part of the north-central Florida study area. Hunn and Slack (1983) investigated the water resources of the Santa Fe River basin, including parts of Alachua, Bradford, Columbia, and Union counties and smaller parts of Baker and Clay counties. The geologic and ground-water investigation by Bermes et al. (1963a) included Putnam and St. Johns counties, and Faulkner's (1973) investigation of the geohydrology of the proposed Cross-Florida Barge Canal area included the northern part of Marion County and the southern parts of Alachua and Putnam counties. Snell and Anderson (1970) studied the water resources of northeast Florida with an emphasis on the St. Johns River basin and adjacent coastal areas. Bentley (1977) investigated the surface-water and ground-water features of Clay County, and Yobbi and Chapel (1979) investigated and summarized the hydrology of the Upper Etonia Creek basin (UECB). Pirkle et al. (1977) described Trail

Ridge, and Arrington (1985) investigated the geology of the Interlachen Karstic Highlands, which is in the UECB. Detailed investigations of the hydrology and declining lake levels that occurred during 1954-1958 in Brooklyn Lake near Keystone Heights were conducted by Clark et al. (1962 and 1963). Investigations of leakage from Brooklyn Lake and other lakes in UECB also were reported by Motz et al. (1991a, 1991b, and 1993) and Motz and Fowler (1993). Also, Phelps (1987) studied the effects of surface runoff and treated wastewater recharge on the quality of water in the Floridan aquifer system in the Gainesville area in Alachua County.

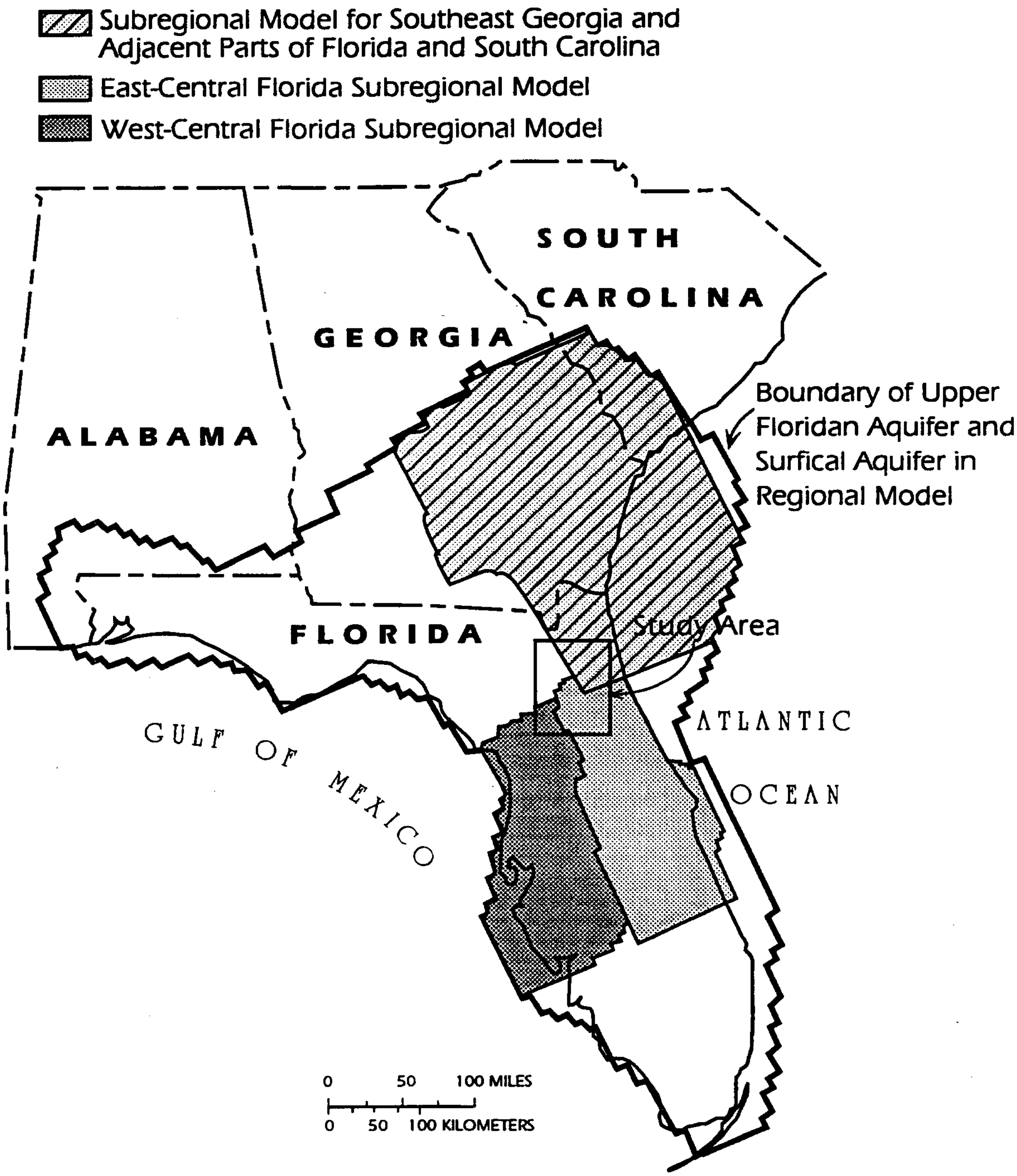
2.2.3 Ground-Water Models

As part of the RASA program, a regional ground-water flow model and three subregional ground-water flow models were developed by the USGS (see Figures 2-2 and 2-3). Bush and Johnston (1988) described the ground-water hydraulics of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama based on the results of a computer simulation of the regional flow system. Krause and Randolph (1989) modeled the Floridan aquifer system in southeast Georgia, including adjacent parts of South Carolina and northeast Florida, and Tibbals (1990) modeled the Floridan aquifer system in east-central Florida. Ryder (1986) modeled the Floridan aquifer system in west-central Florida.

Ground-water flow models of the Floridan aquifer system in and adjacent to the north-central Florida study area also have been developed by SJRWMD (see Figure 2-4). Durden and Motz (1991) developed a ground-water flow model of the Floridan aquifer system in the Jacksonville area of northeast Florida, and Durden (1994a)

Source: Bush and Johnston 1988.

Figure 2-2. USGS Regional Ground-Water Flow Model



Source: Bush and Johnston 1988.

Figure 2-3. USGS Subregional Ground-Water Flow Models

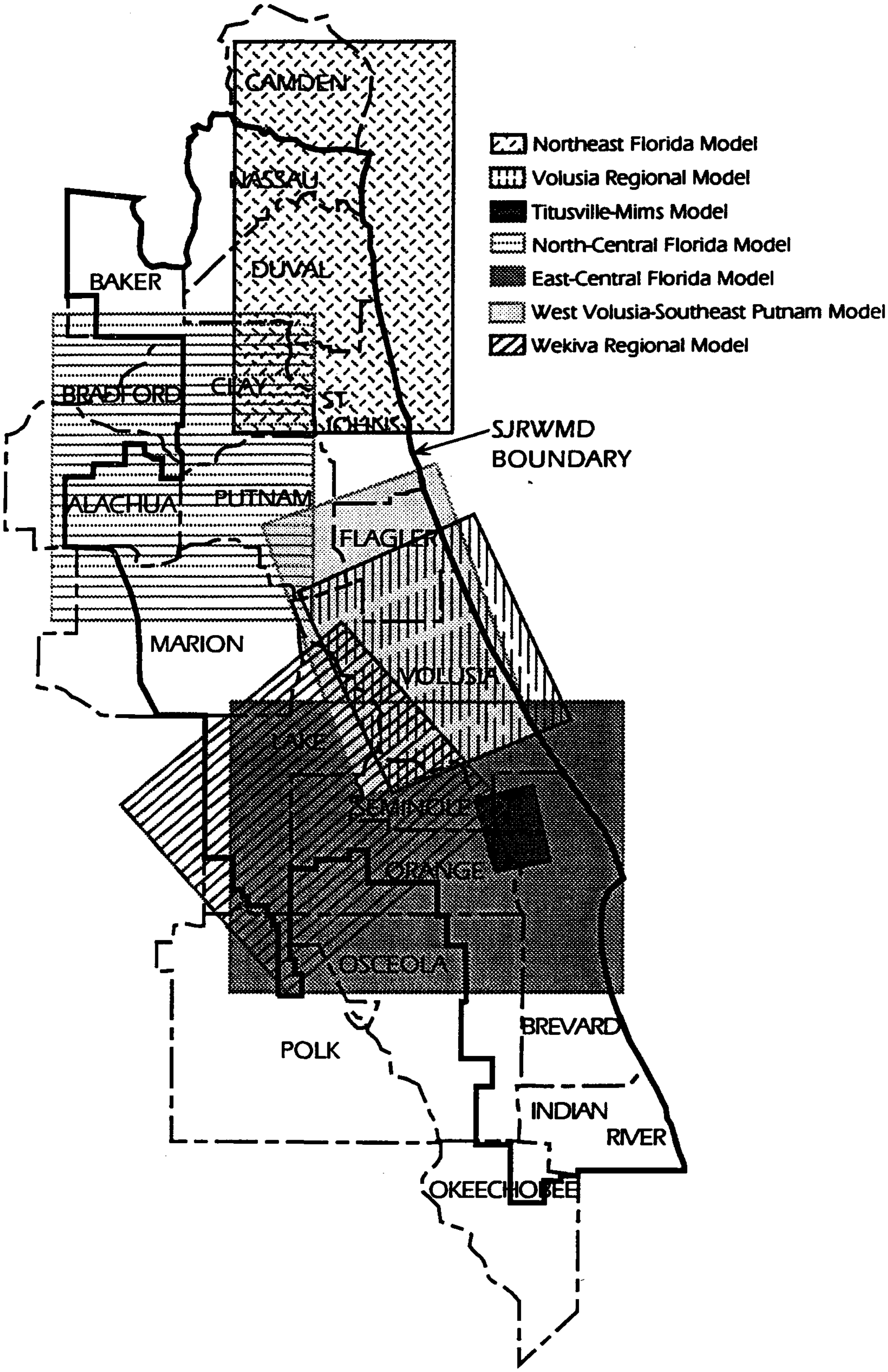


Figure 2-4. SJRWMD Ground-Water Flow Models In and Adjacent to the North-Central Florida Study Area

developed a northeast Florida regional ground-water flow model. Geraghty & Miller (1991) developed a Volusia County regional model that was revised by Williams (1992a). Also, Williams (1992b) modeled the Titusville-Mims area in northern Brevard County, and Blandford and Birdie (1992) modeled the east-central Florida area. McGurk (1992) modeled the west Volusia - southeast Putnam counties area, and GeoTrans (1992) developed a model of the Wekiva Springs area that has been partially modified by Huang (1994).

2.2.4 Water-Use Studies

Water use for Florida has been summarized by the USGS at approximately five-year intervals (Pride 1973; Leach 1978 and 1983; Leach and Healy 1980; and Marella 1985 and 1990). Water use in the St. Johns River basin is compiled by SJRWMD on an annual basis, and annual reports for 1979-1990 have been prepared by Marella (1981-1986b and 1988a-1992a); and Florence (1990-1992).

2.3 PHYSIOGRAPHY AND TOPOGRAPHIC FEATURES

The study area is in the physiographic division of Florida known as the Central Highlands, except for the eastern edge, which is in the Coastal Lowlands division (Clark et al. 1964). The principal topographical features in the study area include Trail Ridge, which extends in a north-south direction through the center, swampy plains in the north, rolling plains in the west and south, and rolling, downward sloping lands in the eastern part. Trail Ridge is a 130-mile long sand ridge that extends from the lake region in the vicinity of Keystone Heights northward to southern Georgia (Pirkle et al. 1977).

The center of the study area is an area of high sand hills and many lakes. These lakes have developed in the numerous karst depressions that occur in the area (Motz et al. 1993). Some of the lakes are connected by perennial and intermittent streams to form the Etonia Creek drainage basin, which drains into the St. Johns River. The west and northwest areas slope downward from Trail Ridge to the swampy plain, dropping as much as 100 ft per mile in places (Clark et al. 1964). The southwest area is characterized by rolling plains and an absence of stream channels. The eastern section slopes downward for 20 to 25 miles, decreasing in elevation from a range of 100 to 200 ft, National Geodetic Vertical Datum of 1929 (ft, NGVD, formerly called mean sea level) to approximately 35 ft, NGVD (Tibbals 1990), or less along the St. Johns River.

2.4 CLIMATE

2.4.1 Temperature and Precipitation

The climate of north-central Florida is classified as humid subtropical, and it is characterized by warm, normally wet summers and mild, relatively dry winters (Yobbi and Chappell 1979). The average temperature is about 73°F (Miller 1986). In the winter and early spring, precipitation is widespread and usually associated with frontal activity, while in the summer most of the rainfall is in the form of isolated showers and thunderstorms (Clark et al. 1964).

There are six rain gages in and adjacent to the study area: Gainesville, Jacksonville, Lake City, Palatka, Ocala, and Starke (see Figure 2-1 for locations and Table 2-1). Gainesville is the most centrally located rain gage in the study area, and it has a long period of record from 1897 to the present (Jenab et al. 1986 and SJRWD 1995). The mean annual rainfall for Gainesville from 1897 to 1993 is 51.05 inches (see Figure 2-5), and over fifty percent of the annual rainfall occurs during the four months from June to September. The driest year in the 1897-1992 period of record is 1917 with 32.79 inches, and the wettest year is 1964 with 76.95 inches of rainfall. A plot of the cumulative departure from the mean annual rainfall indicates that three major trends have occurred in the long-term annual rainfall at Gainesville (see Figure 2-6). Based on the changing slope of the cumulative departure curve, rainfall was significantly below average during 1897-1943, significantly above average during 1944-1972, and below average during 1973-1992.

2.4.2 Evaporation and Evapotranspiration

Pan evaporation is measured at the weather station in Gainesville, and the mean annual pan evaporation from 1954 to 1989 was 61.63 inches (Motz et al. 1993). In north-central Florida, mean annual lake evaporation is approximately 45 inches, and the mean annual evapotranspiration ranges from 33.5 to 35.4 inches (Fernald and Patton 1984).

Table 2-1 Rainfall in North-Central Florida

Location	Latitude Longitude	Annual Average Rainfall (inches)	Annual Standard Deviation (inches)	Annual Maximum Rainfall (inches)	Annual Minimum Rainfall (inches)	Period of Record
Gainesville	29°38'N 82°22'W	50.91	8.61	76.95 (1962)	32.79 (1917)	1/1897-12/1992
Jacksonville	30°30'N 81°42'W	51.78	9.83	82.27 (1947)	30.44 (1927)	1/1867-12/1992
Lake City	30°11'N 82°36'W	52.22	9.75	84.47 (1964)	29.83 (1908)	1/1893-12/1992
Palatka	29°39'N 81°39'W	52.60	9.49	74.61 (1948)	29.22 (1954)	1/1923-12/1984
Ocala	29°12'N 82°05'W	52.84	8.74	74.71 (1982)	34.00 (1990)	1/1891-12/1992
Starke	29°56'N 82°06'W	52.57	8.88	70.08 (1959)	40.10 (1976)	2/1958- 4/1985

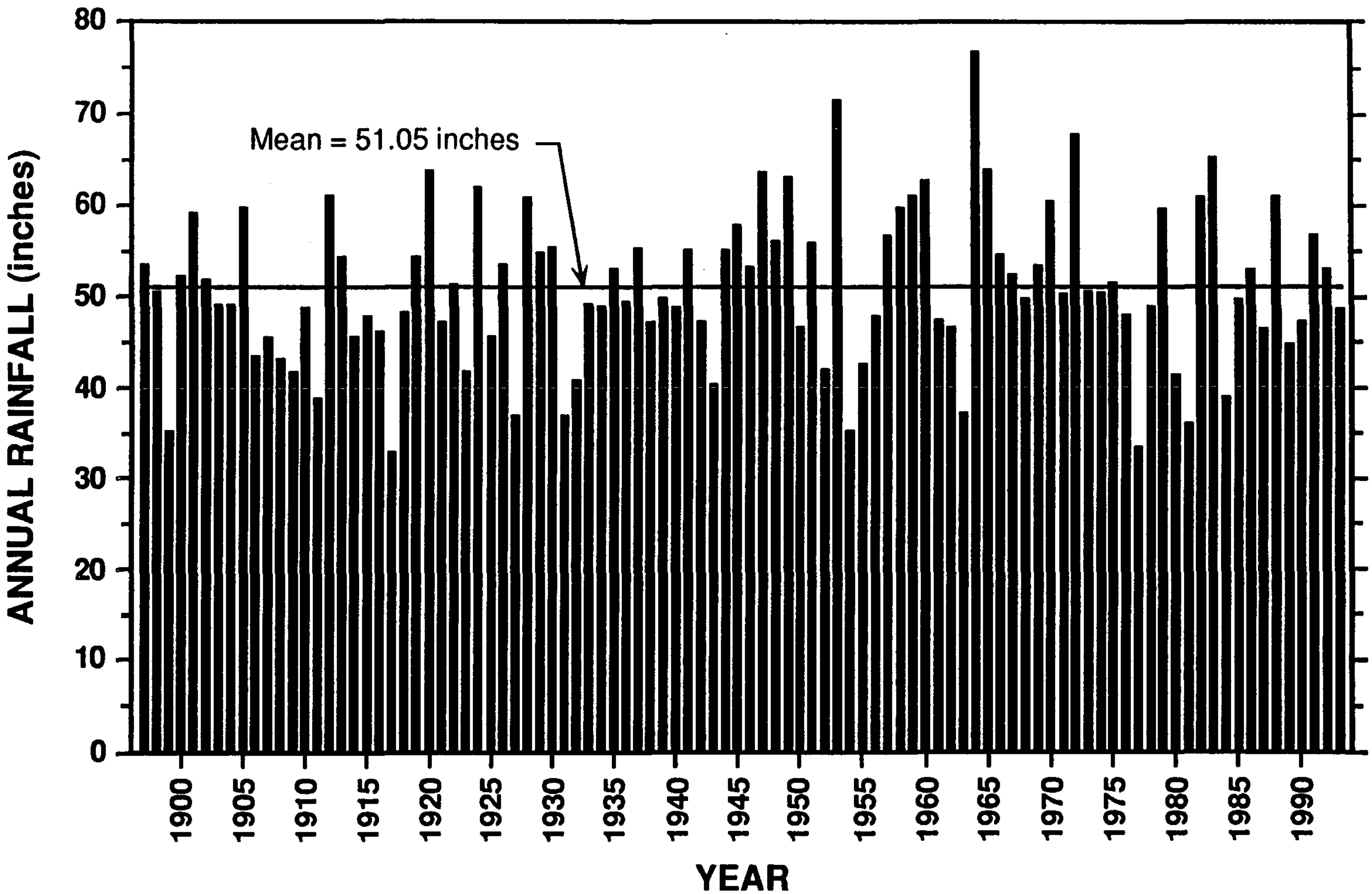


Figure 2-5. Annual Rainfall at Gainesville for 1897-1992

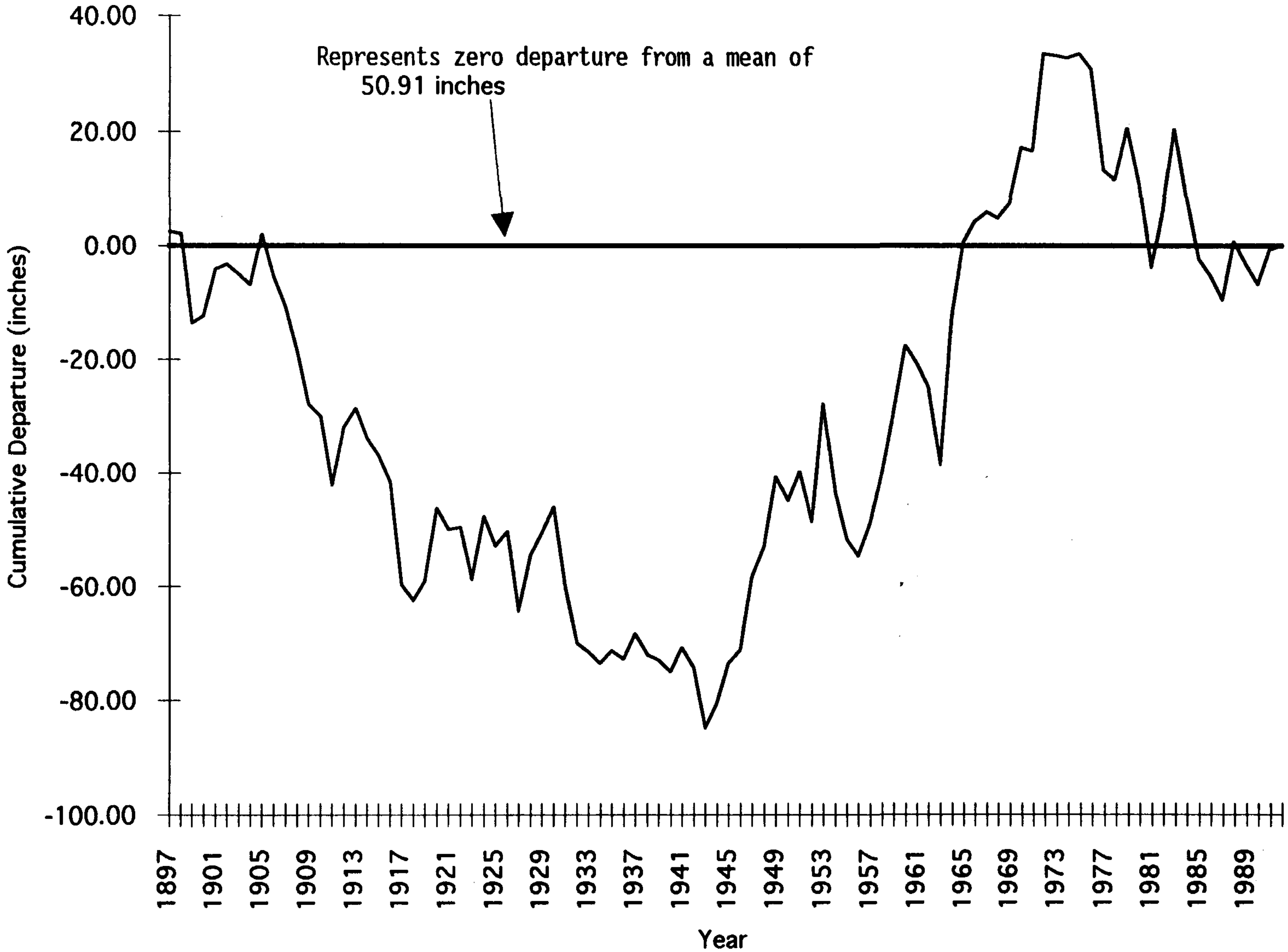


Figure 2-6. Cumulative Departure from Mean Annual Rainfall at Gainesville for 1897-1992

3.0 GEOLOGY

3.1 INTRODUCTION

The geologic units in the north-central Florida area can be divided into pre-Hawthorn Tertiary carbonate formations, the Hawthorn Group, and post-Hawthorn deposits (see Table 3-1). The pre-Hawthorn formations consist of five units that range in age from Paleocene to Oligocene (Miller 1986). The units from oldest to youngest are the Paleocene Cedar Keys Formation, the early Eocene Oldsmar Formation, the middle Eocene Avon Park Formation, the late Eocene Ocala Limestone, and the Oligocene Suwannee Limestone. The Miocene age Hawthorn Group is a very complex formation, consisting of clay, sand, carbonate, and phosphates in heterogeneous patterns and thicknesses throughout (Scott 1983 and 1988). The post-Hawthorn deposits range in age from Pliocene to Holocene. The formations consist of sand, clay, carbonate, clayey sand, sandy clay, and shell (Durden 1990). The ages of these units range from 55 to 65 million years before present for the Paleocene Cedar Keys Formation to 11,000 years before present for the Pleistocene and Holocene deposits (Batten 1987) (see Table 3-2).

3.2 PRE-HAWTHORN TERTIARY CARBONATE FORMATIONS

3.2.1 Paleocene Series

The Cedar Keys Formation contains the rocks of Paleocene age, which consist predominantly of interbedded dolomite and anhydrite. Extensive anhydrite beds,

Table 3-1 Geologic Units in North-Central Florida

Geologic Age	Stratigraphic Unit	Approximate Thickness (feet)	Lithology
Pleistocene and Holocene	post-Hawthorn deposits	10-100	Discontinuous beds of loose sand, clayey sand, sandy clay, marl, and shell
Pliocene	post-Hawthorn deposits	10-110	Clay, clayey sand, sandy clay, shell, and limestone
Miocene	Hawthorn Group	0-350	Interbedded clay, quartz, sand, carbonate, phosphate
Oligocene	Suwannee Limestone	0-100	Carbonate and clastic rocks
Late Eocene	Ocala Limestone	100-300	Porous limestone
Middle Eocene	Avon Park Formation	500-1,000	Interbedded limestone and dolomite
Early Eocene	Oldsmar Formation	300-500	Interbedded limestone and dolomite
Paleocene	Cedar Keys Formation	>1,840	Interbedded dolomite and anhydrite

Sources: Bermes et al. 1963a; Clark et al. 1964; Hoenstine and Lane 1991; Leve 1966; Miller 1986; and Scott 1983 and 1988.

Table 3-2 Time Before Present of Various Geologic Ages

Geologic Epoch	Time Before Present (Years × 10^6)
Pleistocene and Holocene	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.

which are relatively impermeable, 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 top of the Cedar Keys Formation slopes downward from west to east in the study area. The elevation of the top of the Cedar Keys Formation ranges from -1,200 ft, NGVD, in western Alachua County to -1,800 ft, NGVD, in western St. Johns County. Based on a test well in Alachua County that penetrated part of the Cedar Keys Formation, its thickness is at least 1,840 ft (Miller 1986).

3.2.2 Eocene Series

3.2.2.1 Early Eocene Oldsmar Formation. Rocks of early Eocene age comprise the Oldsmar Formation, a unit that is composed of interbedded limestone and dolomite. The lower part of the unit contains gypsum and thin beds of anhydrite, and it is usually more extensively dolomitized than the upper part. The dolomite beds within the unit vary greatly in thickness and contain many cavities. The designation of the Oldsmar Formation as a "Formation" rather than "Limestone" is due to the presence of significant amounts of dolomite, anhydrite, and other rocks along with the limestone (Miller 1986). The elevation of the Oldsmar Formation ranges from -900 ft, NGVD, in the western part of the study area to -1,400 ft, NGVD in the eastern part of the study area, and its thickness ranges from 300 to 500 ft (Miller 1986).

3.2.2.2 Middle Eocene Avon Park Formation. The rocks of middle Eocene age beneath the study area formerly were separated into two limestone units that consisted of the "Lake City Limestone" and the upper "Avon Park Limestone". It is now recognized that the rocks of these units are indistinguishable lithologically and faunally, except locally (Miller 1986). Because of this, the two units of the middle Eocene age are designated as the "Avon Park Formation". The Avon Park Formation is composed of limestone of highly variable hardness that is interbedded with dolomite. The dolomite beds vary greatly in thickness and occasionally contain cavities and fractures. In many places, the Avon Park Formation is composed almost entirely of dolomite, and because of this, the Avon Park Formation is referred to as a "Formation" rather than a "Limestone" (Miller 1986).

The Avon Park Formation is less than 500 ft thick in the northern part of Bradford and northwestern Clay counties. In a southeasterly direction across the study area, the thickness of the Avon Park Formation increases to about 1,000 ft along the area's southern and eastern boundaries. The top of the Avon Park Formation slopes downward from an elevation of -100 ft, NGVD, in western Alachua County and central Marion County to -600 ft, NGVD, in northeastern Clay County (Miller 1986).

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

The top of the Ocala Limestone is a very irregular surface. These irregularities are due primarily to the dissolution of carbonate rocks by contact with ground water. As a result, cavities and even large caverns have been observed within the carbonate units (Schultz and Cleaver 1955). The dissolution of the limestone has greatly enhanced the primary porosity of the unit, making it among the most permeable rock units in the Floridan aquifer system (Miller 1986).

The Ocala Limestone is on the order of 200 to 300 ft thick in most of the study area. In central Marion County, its thickness is approximately 100 ft. The surface of the Ocala Limestone is at an elevation of about +0 ft, NGVD, or higher, in western Alachua County, and its elevation decreases from west to east through the study area. In the northeastern part of Clay County, the elevation of the top of the Ocala Limestone is approximately -400 ft, NGVD (Miller 1986).

3.2.3 Oligocene Series

The Suwannee Limestone of Olicogene age consists of carbonate and clastic rocks in parts of Florida that are south, northwest, and north of the study area (Miller 1986). Subsurface outliers that are the remnants of Oligocene age rocks removed by erosion occur in the study area in parts of Alachua and Clay counties.

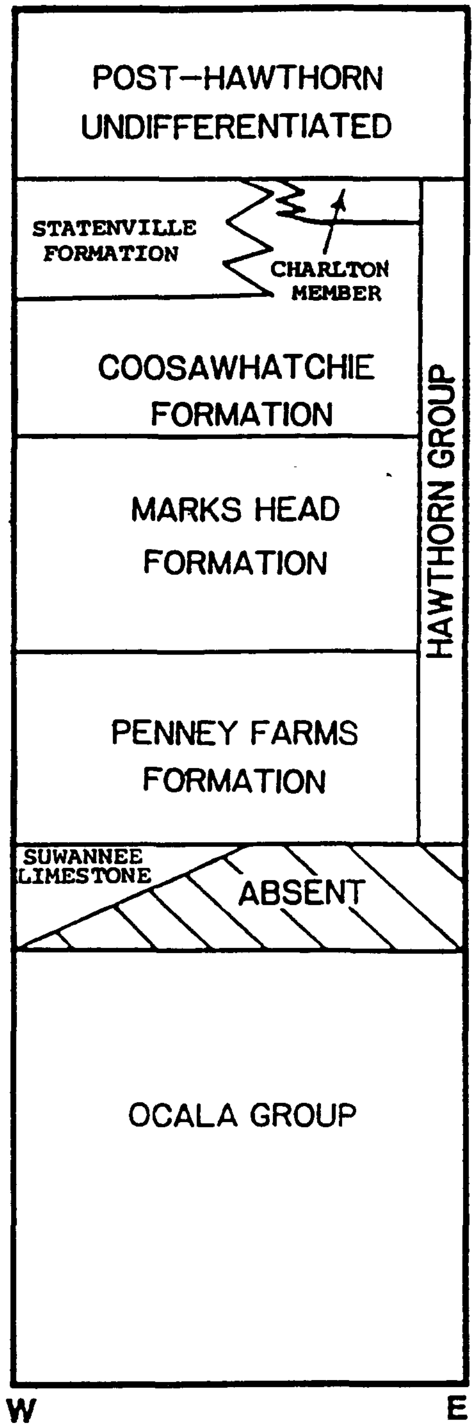
3.3 HAWTHORN GROUP

The Hawthorn Group of Miocene age consists of widely varying mixtures of clay, quartz, sand, carbonate, and phosphate (Scott 1983 and 1988). It is a very heterogenous group that consists of many discontinuous lenses of its components. In north Florida, the Hawthorn Group can be subdivided into four separate units, or, from oldest to youngest, the Penney Farms Formation, Marks Head Formation, Coosawhatchie Formation, and Statenville Formation (see Figure 3-1). The separate units of the Hawthorn Group in north Florida are recognizable in cores but are very hard to identify due to their highly variable nature.

The approximate limits of the Hawthorn Group pass through the southwest part of the study area, and it generally is not present as a laterally extensive or continuous formation in parts of southwestern Alachua and western Marion counties. In the study area, the surface elevation of the Hawthorn Group ranges from more than 150 ft, NGVD, in Alachua, Bradford, and Union counties to -50 ft, NGVD, in the eastern part of the study area and to more than -100 ft, NGVD, in the northeast part of the study area along the St. Johns River (Miller 1986). The thickness of Hawthorn Group generally increases from south to north. It is approximately 50 to 100 ft thick in Marion County and 100 to 200 ft thick in Alachua and Putnam counties. To the northeast in Clay and Duval counties, its thickness is 350 ft or more. Where it is present, the Hawthorn Group comprises most of the upper confining unit of the Floridan aquifer system (Miller 1986).

3.4 POST-HAWTHORN DEPOSITS

The post-Hawthorn deposits range in age from Pliocene (or late Miocene) to Pleistocene and Holocene (Bermes et al. 1963a, Hoenstine and Lane 1991, Leve 1966, Miller 1986, and Scott 1988). A thesis by Kane (1984) on the origin of the



Source: Scott 1988.

Figure 3-1. Lithostratigraphic Units of the Hawthorn Group in North Florida

Grandin Sands in western Putnam County includes an in-depth description of the post-Hawthorn deposits. The thickness of the post-Hawthorn deposits ranges from less than 20 ft to more than 110 ft in the UECB (personal communication, Michael Huff and Douglas A. Munch, SJRWMD, May 1992). In two boreholes drilled along Trail Ridge, north of Keystone Heights, the thickness of the post-Hawthorn deposits was 49 and 84 ft (Pirkle et al. 1970).

3.4.1 Pliocene Deposits

The Pliocene deposits are differentiated from the Hawthorn Group by the absence or near absence of phosphate within them (Leve 1966). The deposits are composed of interbedded clay and clayey sand, fine to medium grained, well sorted sand, shell, and soft limestone.

The transition between the underlying Hawthorn Group into the overlying Pliocene deposits is evident in gamma-ray logs, because the gamma-ray activity in the Hawthorn Group is generally significantly higher than the activity in the underlying and overlying formations (Scott 1988). The transition usually is marked by an unconformity consisting of coarse sands and phosphates. No distinct line of transition exists between the Pliocene and the overlying Pleistocene and Holocene deposits (Leve 1966).

3.4.2 Pleistocene and Holocene Deposits

Pleistocene and Holocene deposits cover 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 Holocene deposits vary in lithology and texture over short distances, both horizontally and vertically (Bermes et al. 1963a; and Fairchild 1972).

4.0 GROUND-WATER HYDROLOGY

4.1 INTRODUCTION

The ground-water system in the north-central Florida area generally consists of a surficial aquifer system that overlies a low permeability confining unit, which in turn overlies the Floridan aquifer system, a regionally extensive aquifer system (Miller 1986)(see Table 4-1). The surficial aquifer system is under water-table conditions. The confining unit is called the upper confining unit for the Floridan aquifer system, and it consists mostly of clastic rocks of the Hawthorn Group. Locally, low-permeability beds of Pliocene deposits are considered part of the upper confining unit. In some parts of the UECB, a discontinuous artesian aquifer system called the intermediate aquifer system occurs within the upper confining unit in the Hawthorn Group bounded by two (upper and lower) confining units (Clark et al. 1964 and Southeastern Geological Society 1986). The Floridan aquifer system occurs under both artesian and non-artesian conditions within the study area. In the areas where it is confined, it is overlain by the upper confining unit. In the eastern part of the study area, the Floridan aquifer system is comprised of two zones called the upper and lower Floridan aquifers that are separated by a relatively low permeability unit called the middle semiconfining unit. In the northeastern part of the study area, the lower Floridan aquifer is separated into two layers by a relatively low permeability zone called the lower semiconfining unit. The bottom of the Floridan aquifer system is

Table 4-1 Hydrogeologic Units in North-Central Florida

<table>
<tr><th>Geologic Age</th><th>Geologic Unit</th><th colspan="3">Hydrologic Unit</th><th>Description</th></tr>
<tr><td>Pleistocene and Holocene</td><td>Pleistocene and Holocene deposits</td><td colspan="3" rowspan="2">Surficial Aquifer System</td><td rowspan="2">Consists of sands, clayey sand, and shell. Thickness ranges from 0 to more than 110 ft.</td></tr>
<tr><td>Pliocene</td><td>Pliocene deposits</td></tr>
<tr><td rowspan="3">Miocene</td><td rowspan="3">Hawthorn Group</td><td colspan="2" rowspan="3">Upper Confining Unit for Floridan Aquifer System</td><td>Upper Confining Unit</td><td rowspan="3">Consists of clay, marl, and discontinuous beds of sand, shell, dolomite, and limestone. Thickness ranges from 0 to 450 ft.</td></tr>
<tr><td>Intermediate Aquifer System</td></tr>
<tr><td>Lower Confining Unit</td></tr>
<tr><td>Oligocene and Late Eocene</td><td>Suwannee Limestone (where present) and Ocala Limestone</td><td rowspan="3">Floridan Aquifer System</td><td colspan="2">Upper Floridan Aquifer</td><td>Consists mainly of limestone of high primary and secondary porosity. Thickness ranges from 300 to 1,500 ft.</td></tr>
<tr><td>Middle Eocene</td><td>Avon Park Formation</td><td colspan="2">Middle Semiconfining Unit</td><td>Consists of leaky, low permeability limestone and dolomite. Thickness ranges from 0 to 200 ft.</td></tr>
<tr><td>Early Eocene</td><td>Oldsmar Formation</td><td colspan="2">Lower Floridan Aquifer</td><td>Consists primarily of interbedded limestone and dolomite. Thickness ranges from 1,100 to 1,400 ft. The Fernandina permeable zone, overlain by the lower semiconfining unit, occurs at the base of this unit in the northeast part of the study area.</td></tr>
<tr><td>Paleocene</td><td>Cedar Keys Formation</td><td colspan="3">Lower Confining Unit</td><td>Consists of low permeability anhydrite beds.</td></tr>
</table>

Sources: Clark et al. 1964; Hoenstine and Lane 1991; Krause and Randolph 1989; Miller 1986; Scott 1988; and Southeastern Geological Society 1986.

bounded by beds of low permeability anhydrite in the Cedar Keys Formation, which serves as the lower confining unit of the Floridan aquifer system (Miller 1986).

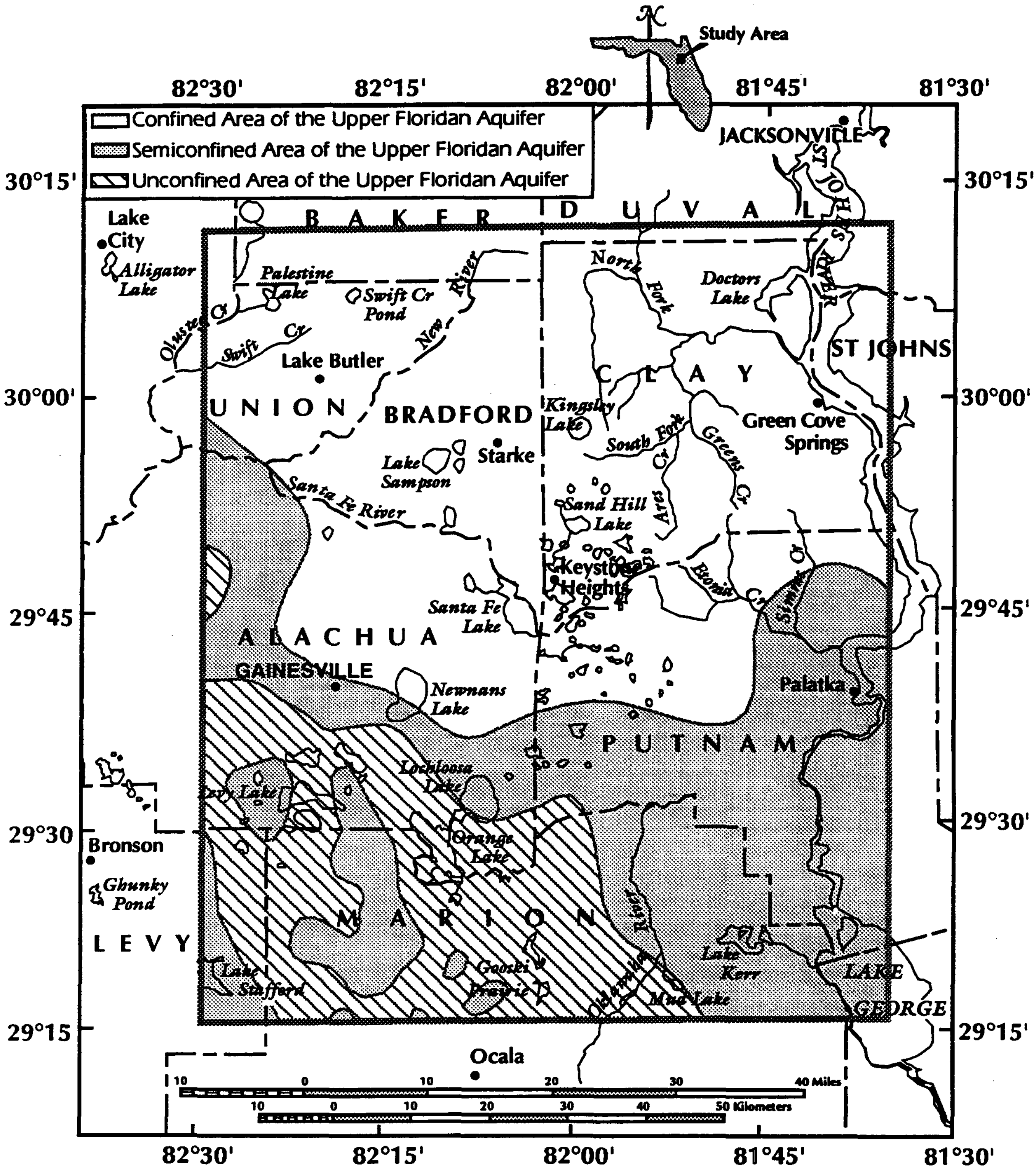
4.2 SURFICIAL AQUIFER SYSTEM

The surficial aquifer system is contained in the sand, clayey sand, and shell of the Pliocene, Pleistocene, and Holocene deposits (Kane 1984; and Clark et al. 1964) (see Table 4-1). This aquifer locally is a water-table aquifer, and its piezometric surface generally follows the local topography (Miller 1986). In the eastern part of the study area, the thickness of the surficial aquifer system ranges from 50 to 100 ft or more (Miller 1986). In parts of Alachua, Bradford, and Union counties, the surficial deposits are very thin or not present, and the water table occurs in the underlying Hawthorn Group (Hunn and Slack 1973). In parts of southwestern Alachua County and Marion County, the Hawthorn Group is not present, and the water table occurs in the surficial deposits that directly overlie the upper Floridan aquifer in these areas or in the upper Floridan aquifer (Clark et al. 1964 and Faulkner 1973).

4.3 UPPER CONFINING UNIT

The upper confining unit for the Floridan aquifer system consists of deposits of clay, sandy clay, clayey sand, marl, limestone, and dolomite of the Hawthorn Group, and, locally, low permeability beds of post-Miocene age. The effectiveness of the confining unit depends largely on its thickness, its local lithology, and the presence or absence of breaches due to karst features in the underlying limestone units of the upper Floridan aquifer. The areas that are thick and have high clay contents have much less leakage than areas that are thin with low clay content (Miller 1986). The thickness of the upper confining unit generally is the same as the thickness of the Hawthorn Group (see section 3.3, Hawthorn Group), except that the thickness of the low-permeability beds of post-Miocene age is included in the thickness of the upper confining unit in some local areas. In the northern part of the study area, the upper confining unit is generally greater than 100 ft thick and unbreached, and the upper Floridan aquifer is confined (Bush and Johnston 1988)(see Figure 4-1). In other parts of the study area, the upper confining unit is generally less than 100 ft thick or breached, or both, and the aquifer is semiconfined. The confining unit is absent or very thin in parts of the southwestern part of the study area, where the upper Floridan aquifer is unconfined.

The intermediate aquifer system is contained in the discontinuous limestone, dolomite, shell, and sand beds in the Hawthorn Group in parts of the study area, including parts of Alachua and Clay counties (Clark et al. 1964)(see Table 4-1). The separation between the surficial aquifer and intermediate aquifer is due to an upper confining unit that exists at the top of the Hawthorn Group. The degree of hydraulic connection between the surficial aquifer and the intermediate aquifer varies (Clark et al. 1964). In some locations, the confining unit is as much as 25 ft thick, and in other parts it is nearly absent. The base of the intermediate aquifer system is connected hydraulically with the upper Floridan aquifer by means of vertical leakage



Source: Bush and Johnston 1988.

Figure 4-1. Confined and Unconfined Conditions for the Upper Floridan Aquifer through the lower confining unit and due to breaches in the lower confining unit (Clark et al. 1964).

4.4 FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system in north-central Florida consists of the Oligocene Suwannee Limestone (where it is present), the late Eocene Ocala Limestone, the middle Eocene Avon Park Formation, the early Eocene Oldsmar Formation, and the Paleocene Cedar Keys Formation (Miller 1986)(see Table 4-1). The top of the Floridan aquifer system occurs at an elevation greater than 0 ft, NGVD, in western Alachua and Marion counties and on the order of -400 ft, NGVD, in Clay and Duval counties. In the study area, its thickness ranges from approximately 1,500 to 1,900 ft, and the base of the Floridan aquifer system occurs at -1,400 to -2,400 ft, NGVD. The Floridan aquifer system generally can be divided into an upper zone of high permeability, a middle semiconfining unit of low permeability and a lower zone of low-to-high permeability, which overlie a lower confining unit. The boundaries of these hydrologic 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).

4.4.1 Upper Floridan Aquifer

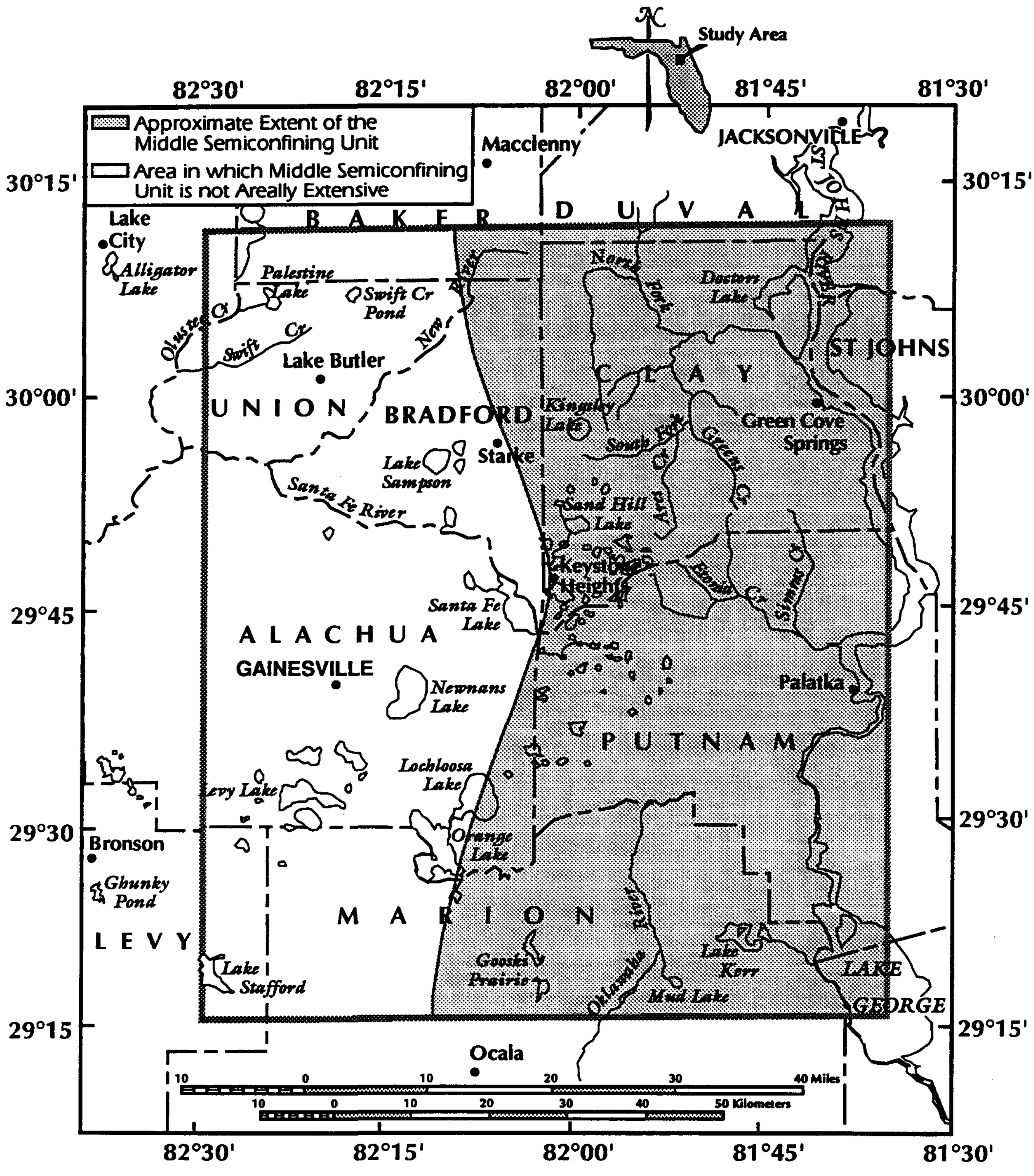
The upper Floridan aquifer is a zone of high permeability principally contained within the Ocala Limestone and the upper third of the Avon Park Formation. The high permeability is attributed to the combination of high primary and secondary porosity of the limestone that comprises this unit (Miller 1986). The high secondary porosity has resulted from the formation of dissolution cavities within the limestone of the upper Floridan aquifer. In the western part of the study area, the middle semiconfining unit is not presesnt, and the upper Floridan aquifer is considered by Miller (1986) to extend to the base of the Floridan aquifer system and to include the permeable rocks of early middle Eocene to late Paleocene ages. Based on this convention, the thickness of the upper Floridan aquifer is on the order of 1,500 ft in the western part of the study area and 300 to 500 ft in the eastern part of the study area, where the middle semiconfining unit separates the Floridan aquifer system into upper and lower units.

4.4.2 Middle Semiconfining Unit

The middle semiconfining unit occurs in the eastern part of the study area (see Figure 4-2), and it is comprised mainly of beds of limestone and dolomite that are of lower permeability than those beds above and below it. The middle semiconfining unit extends approximately from the middle to the upper third of the Avon Park Formation, although at some locations it extends upward to the base of the Ocala Limestone (Durden 1990). The thickness of the middle semiconfining unit is on the order of 100 ft in the study area (Miller 1986).

4.4.3 Lower Floridan Aquifer

The lower Floridan aquifer occurs in the eastern part of the study area and generally is contained within the lower half of the Avon Park Formation and upper



Source: Miller 1986.

Figure 4-2. Occurrence of the Middle Semiconfining Unit in the Study Area third of the Cedar Keys Formation (see Table 4-1). The permeability of rocks in the lower Floridan aquifer generally is much less than that of rocks in the upper Floridan aquifer (Miller 1986). A locally cavernous zone of relatively high permeability known as the Fernandina permeable zone occurs at the base of the lower Floridan aquifer in the northeastern part of the study area in northeast Florida and also in southeastern Georgia. This zone is usually found in the Cedar Keys Formation, and it is separated from the rest of the lower Floridan aquifer by a local confining unit called the lower semiconfining unit.

The thickness of the lower Floridan aquifer ranges from about 1,100 ft in western Clay and Putnam counties to greater than 1,400 ft in Duval County. The elevation of the top of the lower Floridan aquifer is on the order of -600 ft, NGVD, in western Clay and Putnam counties and -900 ft, NGVD, in Duval County. The elevation of the top of the Fernandina permeable zone ranges approximately from -1,400 to -1,800 ft, NGVD (Miller 1986).

4.4.4 Lower Confining Unit

The lower confining unit of the Floridan aquifer system is composed of thick anhydrite beds at the base of the upper third of the Cedar Keys Formation. The hydraulic conductivity of these beds is very low compared to the hydraulic conductivity of the carbonate rocks that are above them (Miller 1986). This unit is considered to be the bottom of the Floridan aquifer system.

4.5 RECHARGE AND DISCHARGE

4.5.1 Surficial Aquifer System

Recharge to the surficial aquifer system occurs by means of rainfall and discharge from lakes in the study area. Rainfall is the primary source of recharge, but some of the lakes also contribute recharge to the surficial aquifer in times of little or no precipitation. The average rainfall in the study area is approximately 55 inches per year (Bush and Johnston 1988).

Discharge from the surficial aquifer takes place in the form of evapotranspiration, vertically downward leakage into the intermediate aquifer, and by means of lateral discharge into area lakes. The average evapotranspiraion in the study area is approximately 36 to 38 inches per year (Bush and Johnston 1988). Other discharge occurs via pumping from domestic wells.

4.5.2 Intermediate Aquifer System

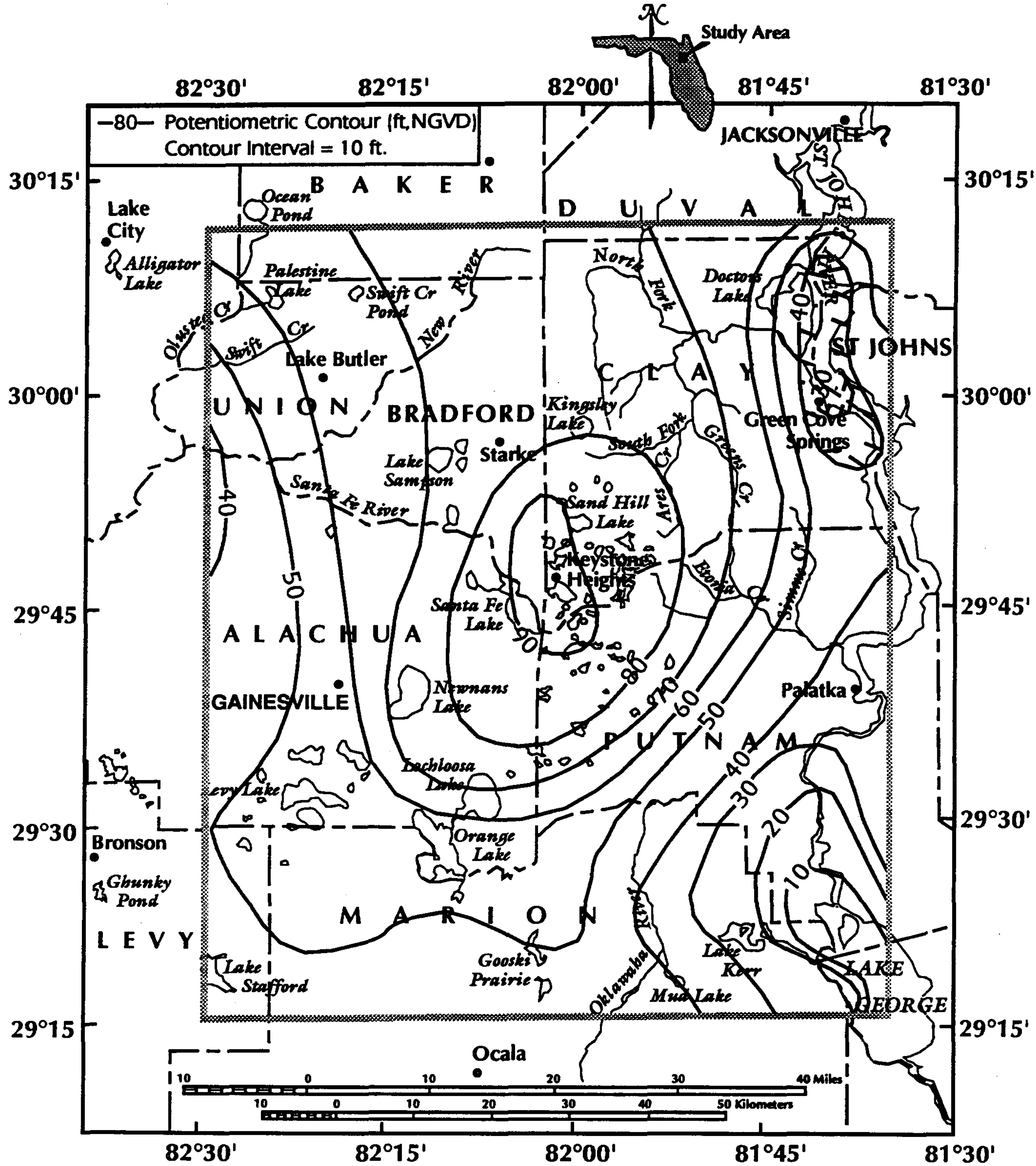
Recharge to the intermediate aquifer system occurs mainly from the overlying surficial aquifer. This occurs by means of leakage through the upper confining unit of the Hawthorn Group and where the confining unit is breached or absent. Recharge also occurs from lakes that are perched directly on the upper confining unit of the Hawthorn Group. This recharge occurs through the confining unit and also where breaches in the Hawthorn Group have formed direct hydraulic connections between the lakes and the intermediate aquifer.

Ground-water discharges from the intermediate aquifer in the form of vertically downward leakage into the Floridan aquifer system. This occurs through the lower confining unit in the Hawthorn Group and also where the confining unit has been breached or where cavities in the upper Floridan aquifer have formed hydraulic connections between the intermediate and upper Floridan aquifers (Clark et al. 1964). Discharge also occurs via pumping from wells.

4.5.3 Upper Floridan Aquifer

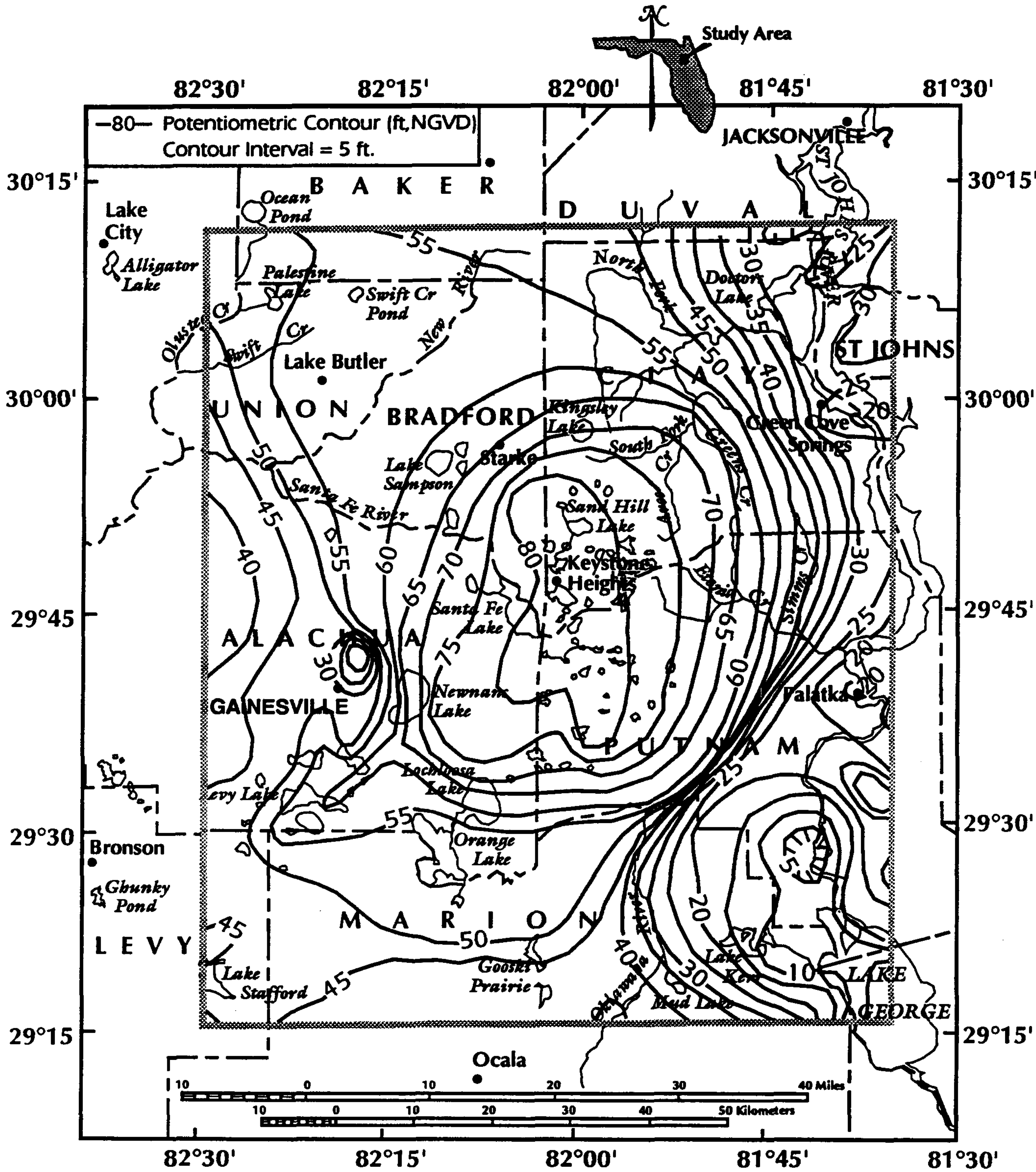
In areas where it is unconfined, recharge to the upper Floridan aquifer is derived from rainfall. In other areas, recharge is obtained from the intermediate aquifer system and from lakes and the surficial aquifer system where direct hydraulic connections exist. The recharge from the intermediate aquifer occurs through the lower confining unit of the Hawthorn Group. Also, dissolution cavities in the upper Floridan aquifer that have collapsed form hydraulic connections to the overlying intermediate aquifer, and they also can form connections completely through the Hawthorn Group into the surficial aquifer system.

Maps of the potentiometric surface of the upper Floridan aquifer have consistently delineated a major ground-water mound in the upper Floridan aquifer in the central part of the study area (e.g., see Figures 4-3 and 4-4). This mound, or potentiometric high, is centered on the Keystone Heights area. Its presence, along with higher water levels in the surficial and intermediate aquifers (Yobbi and Chappel 1979), indicates that the lakes and surficial aquifer system in this area are a major source of recharge to the underlying Floridan aquifer system. The elevation of the potentiometric surface in the Keystone Heights area was greater than an estimated 90 ft, NGVD, prior to development, and it is on the order of 80 ft, NGVD, at the pre-



Source: Johnston et al. 1980.

Figure 4-3. Estimated Potentiometric Surface in the Upper Floridan Aquifer in North-Central Florida Prior to Development



Source: Schiner and Hayes 1985.

Figure 4-4. Observed Potentiometric Surface in the Upper Floridan Aquifer in North-Central Florida in May 1985 sent. From predevelopment time to 1985, the potentiometric surface of the upper Florida aquifer declined on the order of 10 ft in a large part of the study area (see Figure 4-5). Drawdowns were more than 30 ft in the northeastern part of the study area, reflecting the effects of significant ground-water pumping in the Jacksonville area, and more than 40 ft in the vicinity of the GRU Murphree Well Field in Gainesville. Increases in the potentiometric surface on the order of 10 ft apparently occurred in the southeastern part of the study area. These increases may be due to the influence of higher water levels in the present day Rodman Reservoir, compared to pre-impoundment levels in the Oklawaha River, or, in part, due to inaccuracies in the estimated predevelopment potentiometric surface in that part of the study area.

Discharge from the upper Floridan aquifer occurs by means of diffuse discharge and spring discharge into the St. Johns River and its tributaries in the eastern and southeastern parts of the study area and in areas outside the study area to the south. Discharge also occurs by means of springs along the Santa Fe and Suwannee rivers west of the study area. Under present, developed conditions, significant amounts of discharge also occur by means of municipal, commercial, industrial, and agricultural pumpage in the study area.

4.6 HYDRAULIC CHARACTERISTICS

Hydraulic characteristics of the surficial, intermediate, and upper Floridan aquifers vary widely throughout northeast Florida. Reliable estimates of the hydraulic parameters of the lower Floridan aquifer and of the middle confining unit of the Flor-

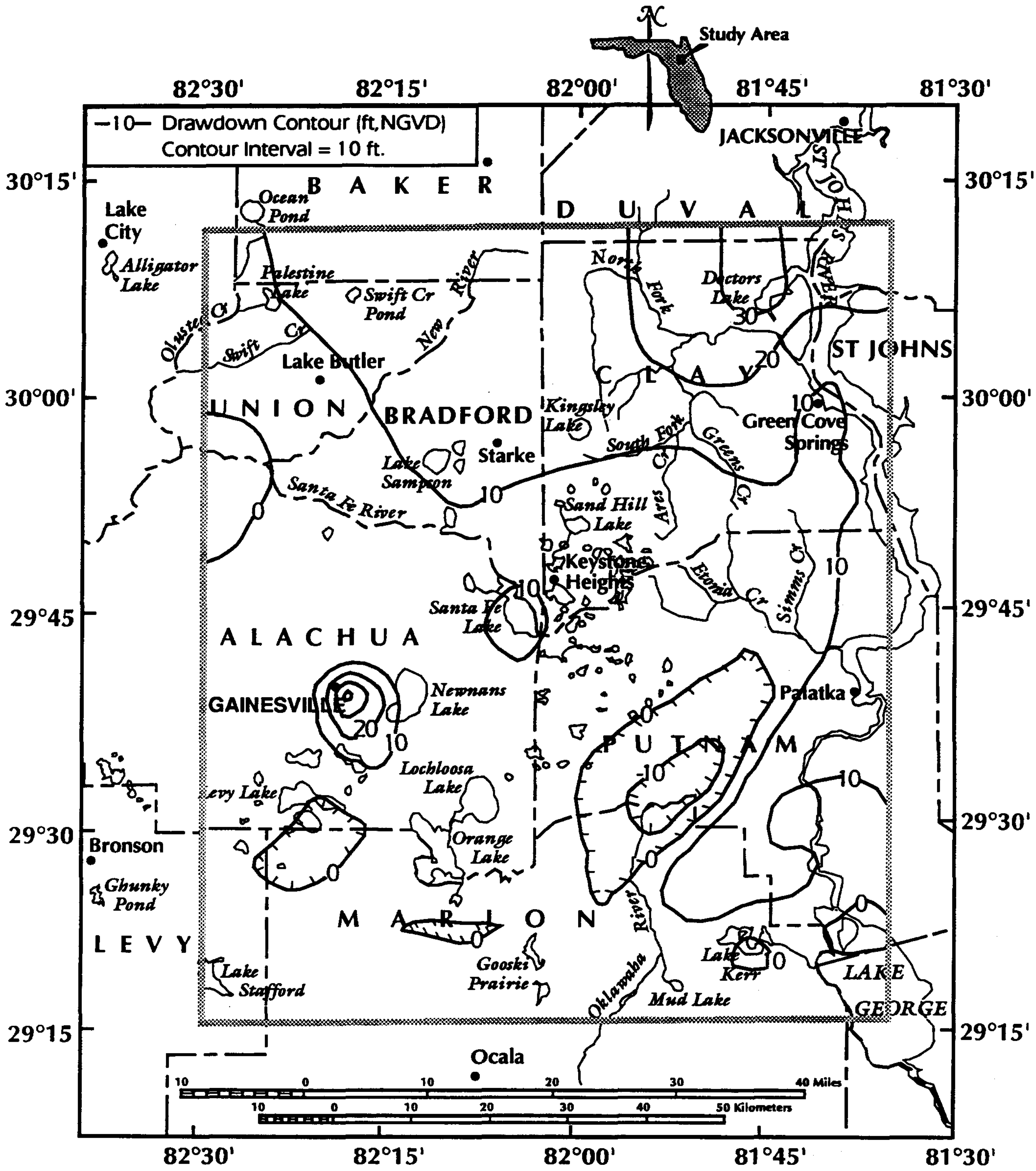


Figure 4-5. Observed Drawdown in the Potentiometric Surface in the Upper Floridan Aquifer From Predevelopment Time to May 1985

idan aquifer system generally are not available because the lower Floridan aquifer has not been tapped by wells to any significant extent (Durden and Motz 1991).

4.6.1 Surficial Aquifer

Transmissivity estimates for the surficial aquifer system range from 60 to 1,000 square feet per day (ft^2/day) in eastern Nausau County (Brown 1984). Other estimates are 950 ft^2/day along the Crescent City Ridge in Putnam County (Ross and Munch 1980), 2,400 ft^2/day near Mayport in Duval County (Franks 1980), 6,500 to 7,000 ft^2/day in the Tillman Ridge area of east-central St. Johns County (Hayes 1981), and 625 ft^2/day in the Keystone Heights area in the UECB (Motz et al. 1993). Estimates for the storativity, or specific yield, of the surficial aquifer range from 0.1 at Mayport (Franks 1980) to 0.2 in eastern Nassau County (Brown 1984).

4.6.2 Intermediate Aquifer

The transmissivity of the intermediate aquifer in the Keystone Heights area is approximatley 11,000 ft^2/day (Motz et al. 1993). The storativity of the intermediate aquifer ranges from 0.00001 to 0.001 (Brown 1984).

4.6.3 Upper Floridan Aquifer

Transmissivity values for the upper Floridan aquifer in north-central Florida are more widely reported than values for the surficial and intermediate aquifers. Values obtained for western Putnam and western Clay counties range from 100,000 to 250,000 ft^2/day (Andrews 1990). Approximate ranges of 80,500 to 132,000 ft^2/day for transmissivity and 3.14×10^{-4} to 1.34×10^{-3} day^{-1} for leakance of the upper confining unit were determined from a pumping test conducted in a well on the south shore of Lake Swan in the UECB (Yobbi and Chappell 1979). Two pumping tests at the Florida Rock Industries Gold Head sand mine near Keystone Heights have yielded transmissivities of 497,000 ft^2/day (Motz 1989) and 468,000 ft^2/day (Missimer & Associates 1991). The leakance values determined from these two tests for the upper confining unit were 6.59×10^{-5} day^{-1} (Motz 1989) and 1.74×10^{-3} day^{-1} (Missimer & Associates 1991). Estimates for the storativity of the upper Floridan aquifer typically range from 0.0001 to 0.001 (Johnston and Bush 1988; Missimer & Associates 1991; and Motz 1989).

Based on a regional-scale numerical ground-water flow model of the upper Floridan aquifer, transmissivity values in the study area range from 50,000 to 100,000 ft^2/day in the eastern part of the study area where the upper Floridan aquifer is confined and at its greatest depth to greater than 1,000,000 ft^2/day in the southwestern part of the study area where the upper Floridan aquifer is unconfined (Bush and Johnston 1988). Values for leakance of the upper confining unit range from 2.28×10^{-6} day^{-1} to 2.28×10^{-4} day^{-1} in most of the parts of the study area where the upper confining unit is present, and they are greater than 2.28×10^{-4} day^{-1} in south-central and southeastern Alachua County, where the upper Floridan aquifer is considered to be semi-confined. Based on a sub-regional numerical model in the UECB, the transmissivity of the upper Floridan aquifer is 413,000 ft^2/day, and the leakance of the upper confining unit ranges from 1.0×10^{-5} to 1.0×10^{-3} day^{-1} (Motz et al. 1993).

5.0 GROUND-WATER USE IN STUDY AREA

5.1 COMPILATION OF WATER-USE DATA

Ground-water use was compiled for the study area, which falls within three water management districts (see Figure 5-1). Fifty-five percent of the area is in SJRWMD, forty percent is in the Suwannee River Water Management District (SRWMD), and five percent is in the Southwest Florida Water Management District (SWFWMD). The year 1985 was selected as a base year to represent "present-day" conditions, and the year 2010 was selected for projections of future use. Historically, May is the month when water use in Florida is at a maximum (see Figure 5-2). Accordingly, water use was compiled and projected for May 1985 and May 2010, respectively, to represent monthly periods when ground-water withdrawals would be greatest and the impact on ground-water levels at a maximum (Sheaffer 1993).

5.2 MAY 1985 GROUND-WATER USE

Similar to USGS methodology (Marella 1988b), ground-water withdrawals were grouped into five major categories: public supply; self-supplied domestic; commercial and industrial; agricultural; and thermoelectric power generation. Direct recharge of surface water was considered also.

5.2.1 Public Supply

Public supply includes water withdrawn from the ground-water system for public water-supply use. The quantity of water withdrawn by these public and/or pri-

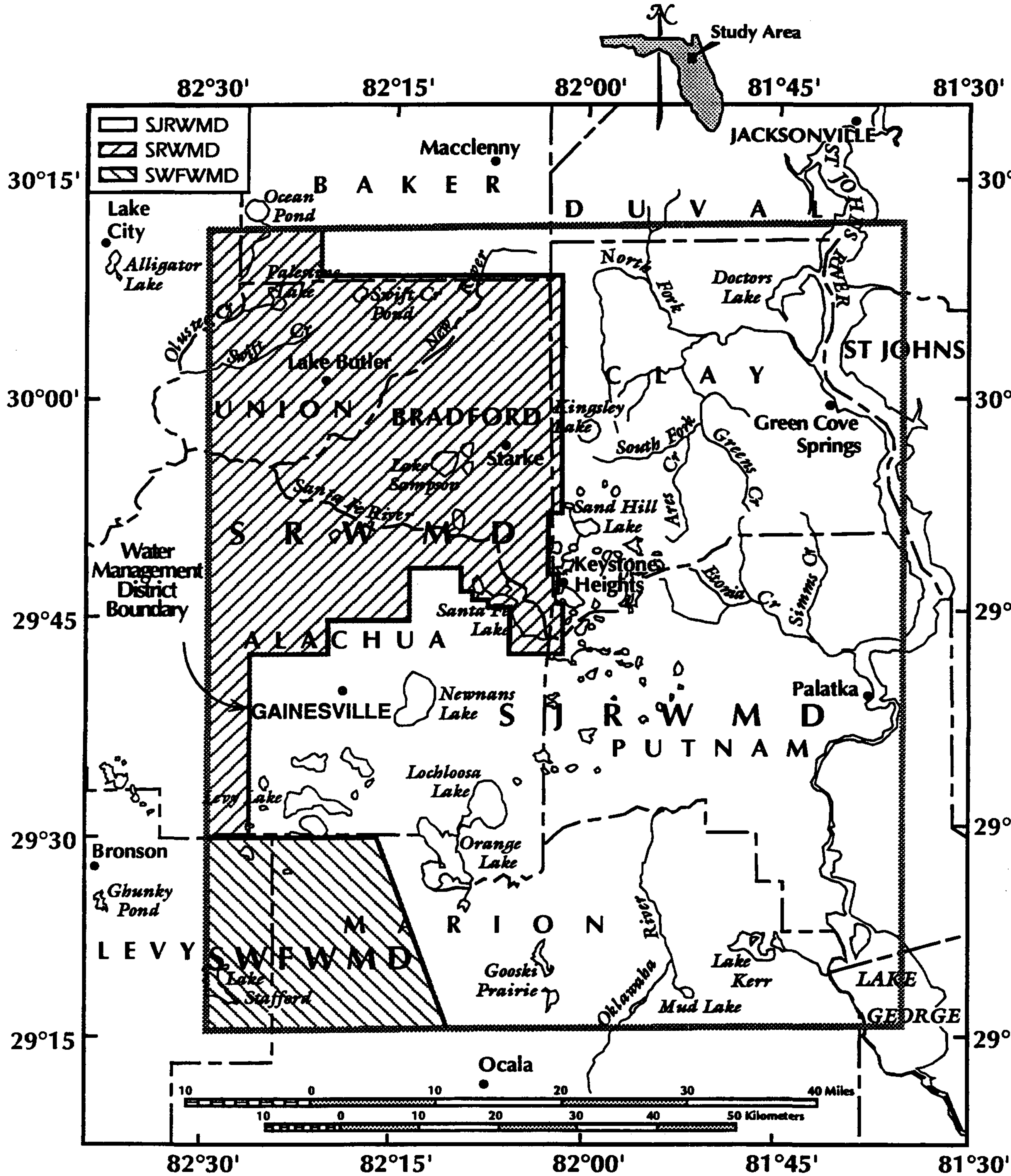
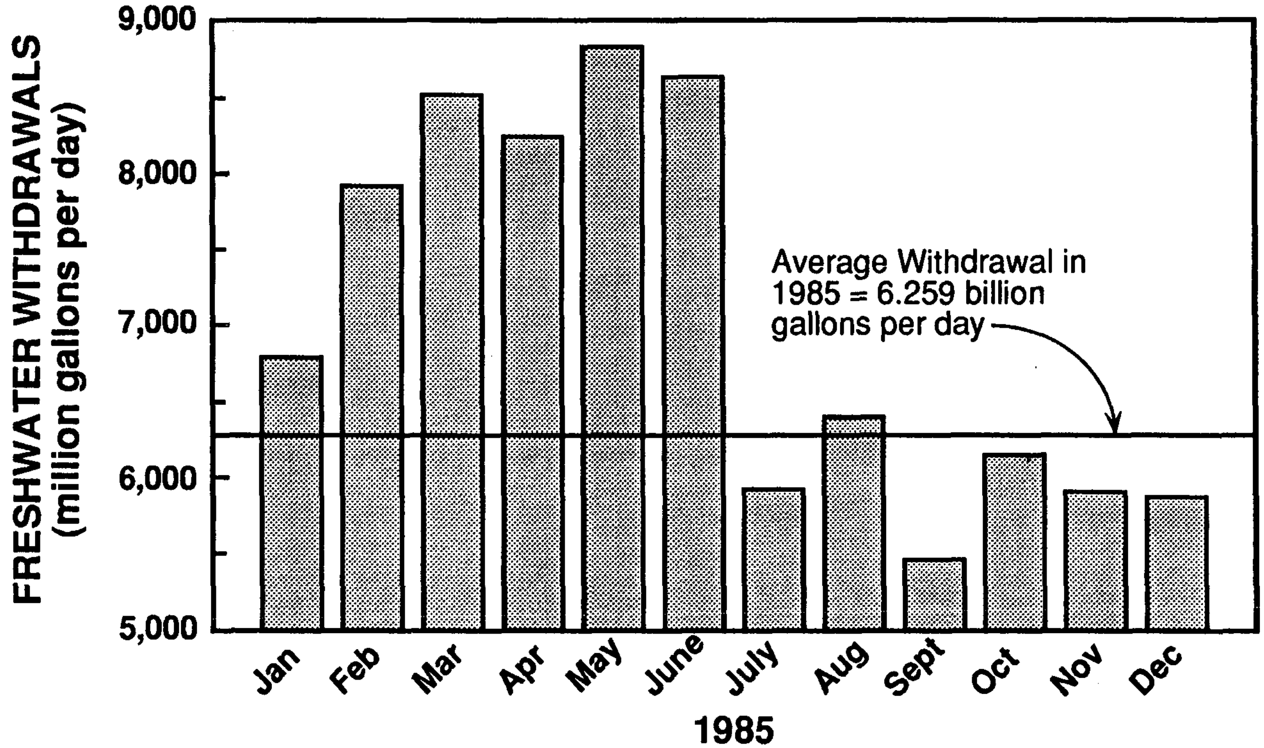


Figure 5-1. Water Management Districts in the Study Area



Source: Marella 1988b.

Figure 5-2. Monthly Fresh-Water Withdrawals in Florida for 1985 vate water suppliers varies considerably within the three districts (see Figure 5-3). The total quantity of water withdrawn for public supply in the study area was 54.82 million gallons per day (mgd) [7,330,000 cubic feet per day (ft^3/day)]. The comparatively low value for the SWFWMD public supply, 0.42 mgd (56,000 ft^3/day), can be attributed to the small part of that district enclosed in the study area and its rural nature. In addition to the ground-water use in SWFWMD, SRWMD users withdrew 6.2 mgd (823,000 ft^3/day), and SJRWMD users withdrew 48.3 mgd (6,450,000 ft^3/day). These account for 0.8 percent (SWFWMD), 11.2 percent (SRWMD), and 88.0 percent (SJRWMD) of the total ground-water pumpage for public supply in the study area.

5.2.2 Domestic

Most self-supplied domestic users pump less than 10,000 gpd and are not required to obtain permits from the districts, making it difficult to determine the exact amounts and effects of this pumping in the region. USGS values (Marella 1985b) were used as a basis for estimating this pumpage. These values were estimated by the USGS using population figures for each county derived from total users within each county minus residents served by public supply. The percentage of land area for each county included within the study area was computed and used as a factor of the total domestic pumpage for each county delineated in this study (see Table 5-1). The total domestic pumpage for all of the counties in the study area was estimated to be 28.2 mgd.

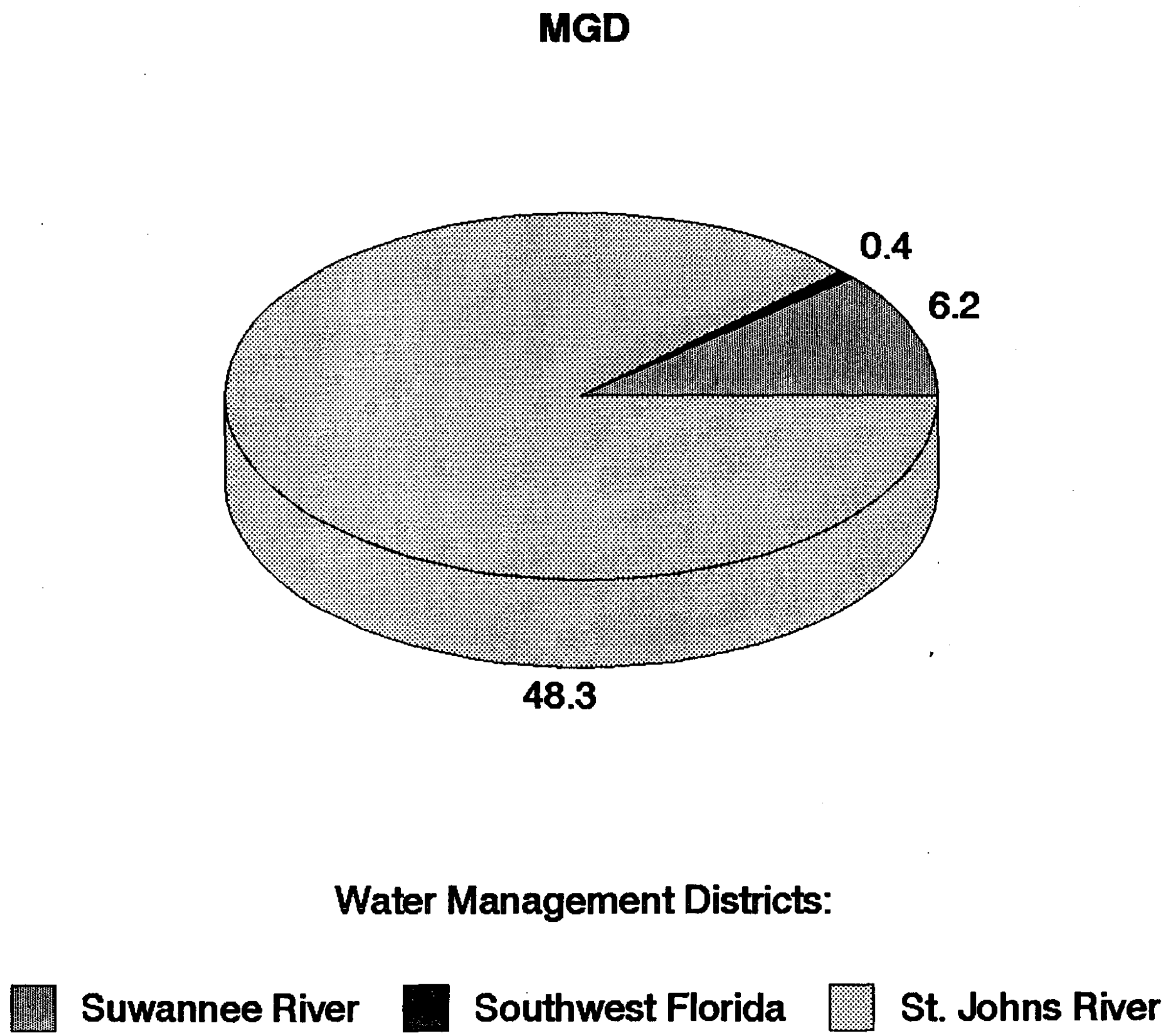


Figure 5-3. May 1985 Public-Supply Ground-Water Withdrawals

Table 5-1 1985 Domestic Self-Supplied Ground-Water Withdrawals

	Estimated Percent of County in Study Area	Domestic Pumpage for Entire County (mgd)	Estimated Domestic Pumpage in Study Area (mgd)	Percent of Total Domestic Pumpage
Alachua	71	7.8	5.5	19.5
Baker	22	1.9	0.4	1.4
Bradford	100	2.6	2.6	9.2
Clay	98	2.7	2.6	9.3
Duval	5	15.5	0.8	2.7
Levy	8	2.2	0.2	0.6
Marion	65	15.3	9.9	35.0
Putnam	85	6.4	5.4	19.0
Union	87	0.9	0.7	2.6
St. Johns	7	2.1	0.1	0.5
TOTAL			28.2	100.0

Note: Quantities for Columbia and Volusia counties in study area are insignificant and were not computed.

Compared to the total pumpage in the study area, the 28.2 mgd accounts for 13.7 percent of the total withdrawals. However, problems arose in trying to determine the spatial distribution of the domestic pumpage for the ground-water model as well as in determining how much of the domestic pumpage was withdrawn from the Floridan aquifer system. As a result, self-supplied domestic usage, although a significant part of the total pumpage, was not included in the MODFLOW well files subsequently created for the ground-water model.

5.2.3 Commercial and Industrial

Commercial and industrial usage is a broad category that includes self-supplied institutional, governmental, recreational, mining, and manufacturing facility pumpage. The total water withdrawn in the study area by commercial and industrial facilities in May 1985 was 63.1 mgd (8,430,000 ft^3/day), accounting for 35.5 percent of the total pumpage in the region. The low rate of withdrawal within SWFWMD is attributed to the small population and small area of the part of this water management district included within the study area. Pumpage within SWFWMD totaled 0.1 mgd (18,000 ft^3/day), along with 3.0 mgd (405,000 ft^3/day) in SRWMD and 59.9 mgd (8,012,000 ft^3/day) in SJRWMD (see Figure 5-4). These values comprise 0.2 percent (SWFWMD), 4.7 percent (SRWMD), and 95.1 percent (SJRWMD) of the total pumpage for commercial and industrial facilities. Georgia Pacific in Palatka pumped 44.9 mgd (6,005,970 ft^3/day) in May 1985, which accounts for 75.0 percent of the industrial usage in SJRWMD and 25.3 percent of the total pumpage in the study area.

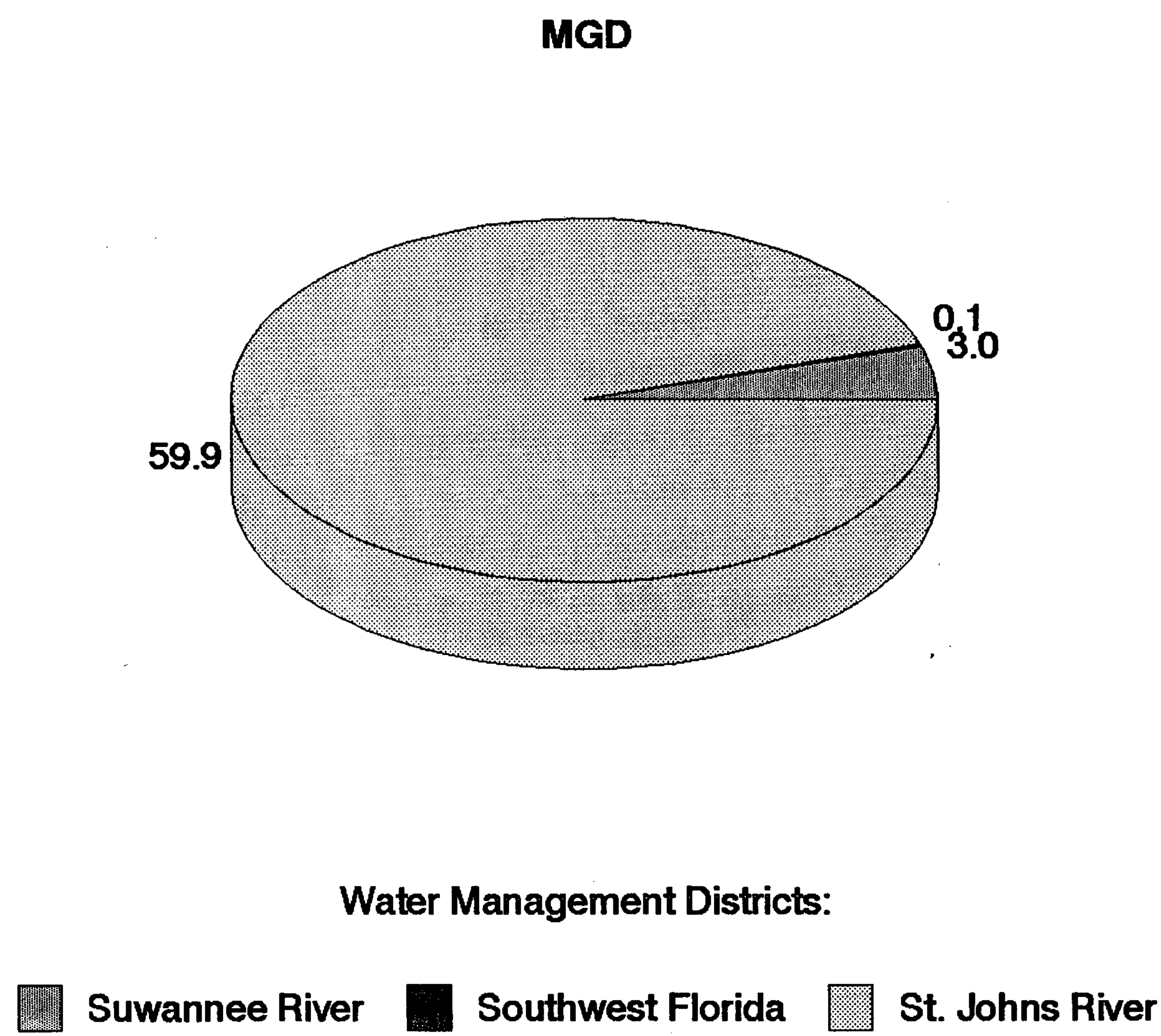


Figure 5-4. May 1985 Commercial and Industrial Ground-Water Withdrawals

5.2.4 Agricultural

Agricultural water use in the study area includes irrigation for commercial crops and water for livestock purposes. Water-use values for SJRWMD were based on permitted agricultural irrigation, estimated water use for 1985, and also on water-use projections made for 1990 (Marella 1986b and Lynne and Kiker 1991). Within SWFWMD, the permitted amount of ground-water withdrawals for irrigational use is related to crop type and land acreage. This value is based on future expectations rather than current usage, however, and it was thought to be unrealistically high. To better estimate actual agricultural usage, SWFWMD and USGS water-use values (Stieglitz 1986 and Marella 1988b) were used to estimate the average daily pumping rate per permitted user. Monthly fluctuations were standardized by using a multiplying ratio that converted the data into comparable May withdrawals. This ratio was computed from total May withdrawals compared to total yearly withdrawals. For SRWMD, limited information was available pertaining to crop types within the area. The monthly distributions for agricultural pumpage in SWFWMD and agricultural land-use and water-use projections for SJRWMD (Stieglitz 1986 and Marella 1988b) were applied to existing data obtained from SRWMD. Applications were based on the assumption of similar crop type withdrawals suggested by similar location within the water management districts by latitude. Although not entirely realistic, these methods are felt to be the most rational processes available to evaluate the agricultural withdrawals within each district given the limited amount of available data.

Estimated agricultural ground-water withdrawals totaled 55.35 mgd (7,400,000 ft^3/day) for May 1985. SJRWMD users withdrew 33.87 mgd (4,527,000 ft^3/day), SRWMD users withdrew 15.09 mgd (2,017,000 ft^3/day), and SWFWMD users withdrew 6.39 mgd (855,000 ft^3/day) (see Figure 5-5). This pumpage represents 31.1 percent of the total ground-water pumpage from the study area for May 1985.

5.2.5 Thermoelectric

Ground-water withdrawals for May 1985 thermoelectric power totaled 4.5 mgd (594,000 ft^3/day). This accounts for approximately 2.6 percent of the total pumpage in the region. SJRWMD users withdrew 1.3 mgd (171,000 ft^3/day), and SRWMD users withdrew 3.2 mgd (423,000 ft^3/day)(see Figure 5-6). There were no withdrawals from SWFWMD users in the study area for thermoelectric power generation. The 1985 withdrawals for thermoelectric power generations in the state of Florida decreased more than 1,700 mgd from 1975 to 1985 although production in the state of Florida increased. The lower pumpage rate for 1985 is attributed to the process of recycling cooling water within the power plants (Marella 1985b).

5.2.6 Recharge

Direct recharge plays a significant role in the ground-water system of the study area and the computer model of the area. There are at least four site-specific areas where large quantities of surface water directly recharge the ground-water system: Haile Sink; Alachua Sink; Lake Alice; and Kanapaha Wastewater Treatment Plant (see Figure 5-7). Alachua Sink and Lake Alice recharge the aquifer by means of surface-water runoff and treated wastewater, and Haile Sink recharges the aquifer by

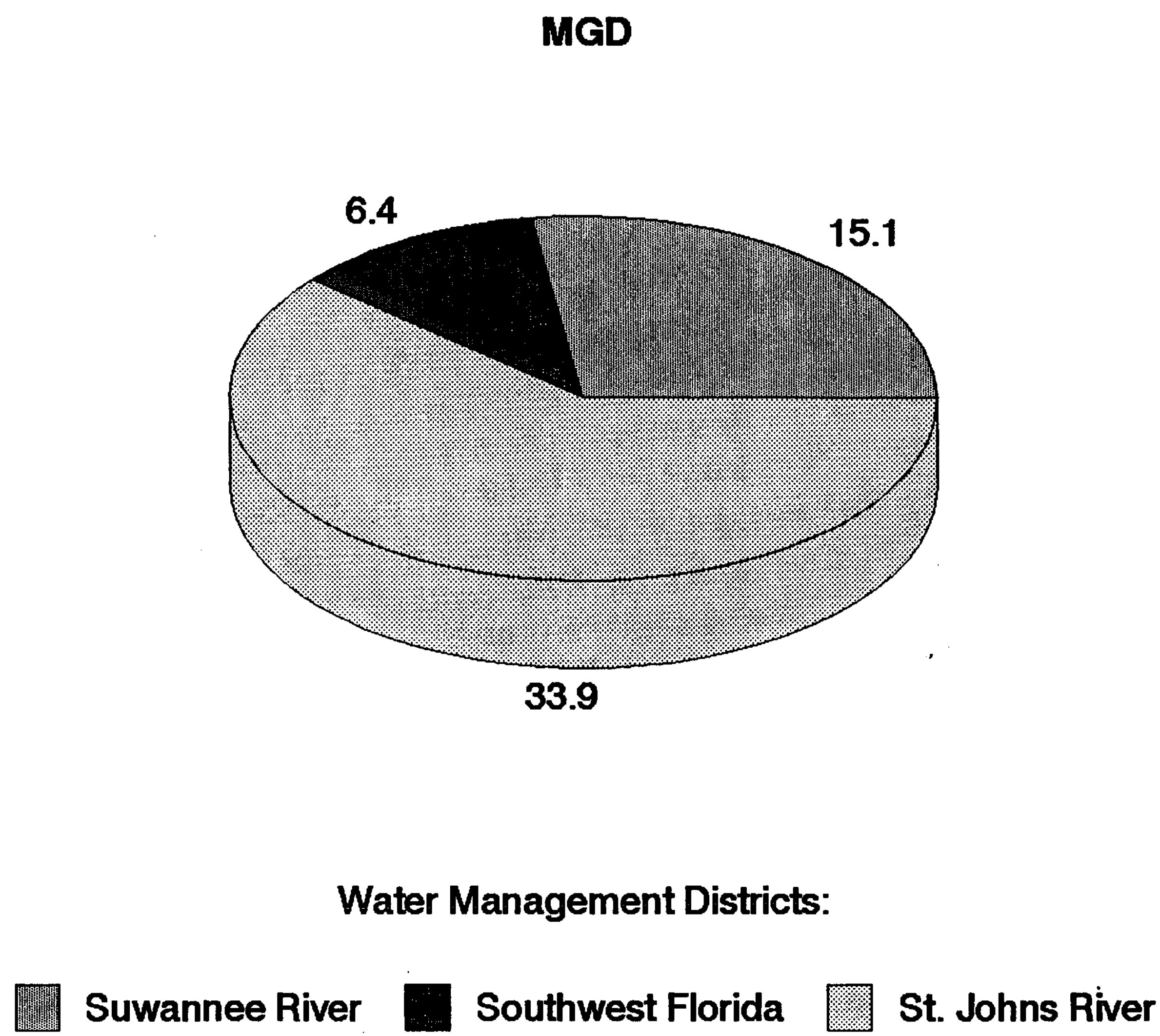


Figure 5-5. May 1985 Agricultural Ground-Water Withdrawals

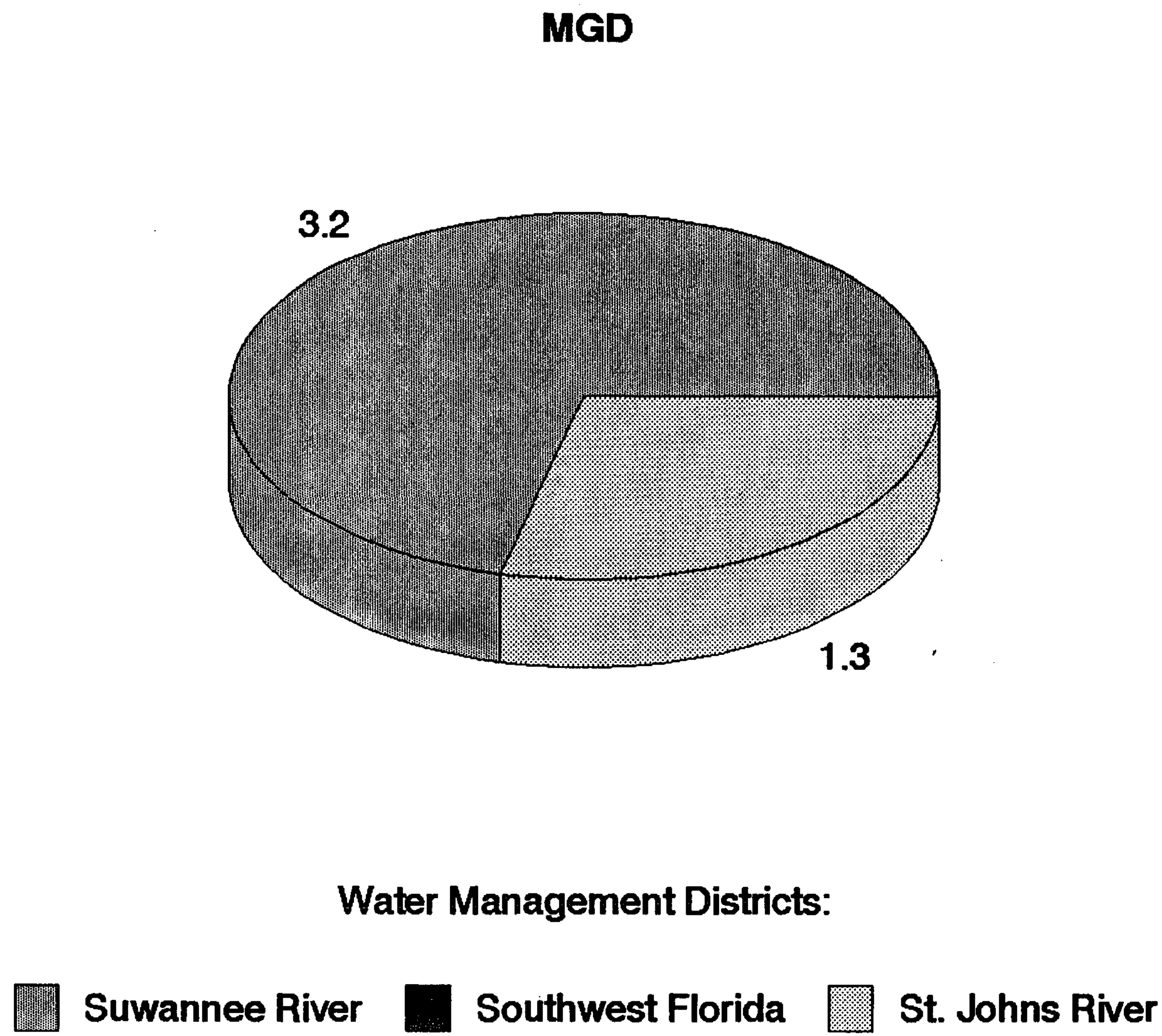


Figure 5-6. May 1985 Thermoelectric Power Generation Ground-Water Withdrawals

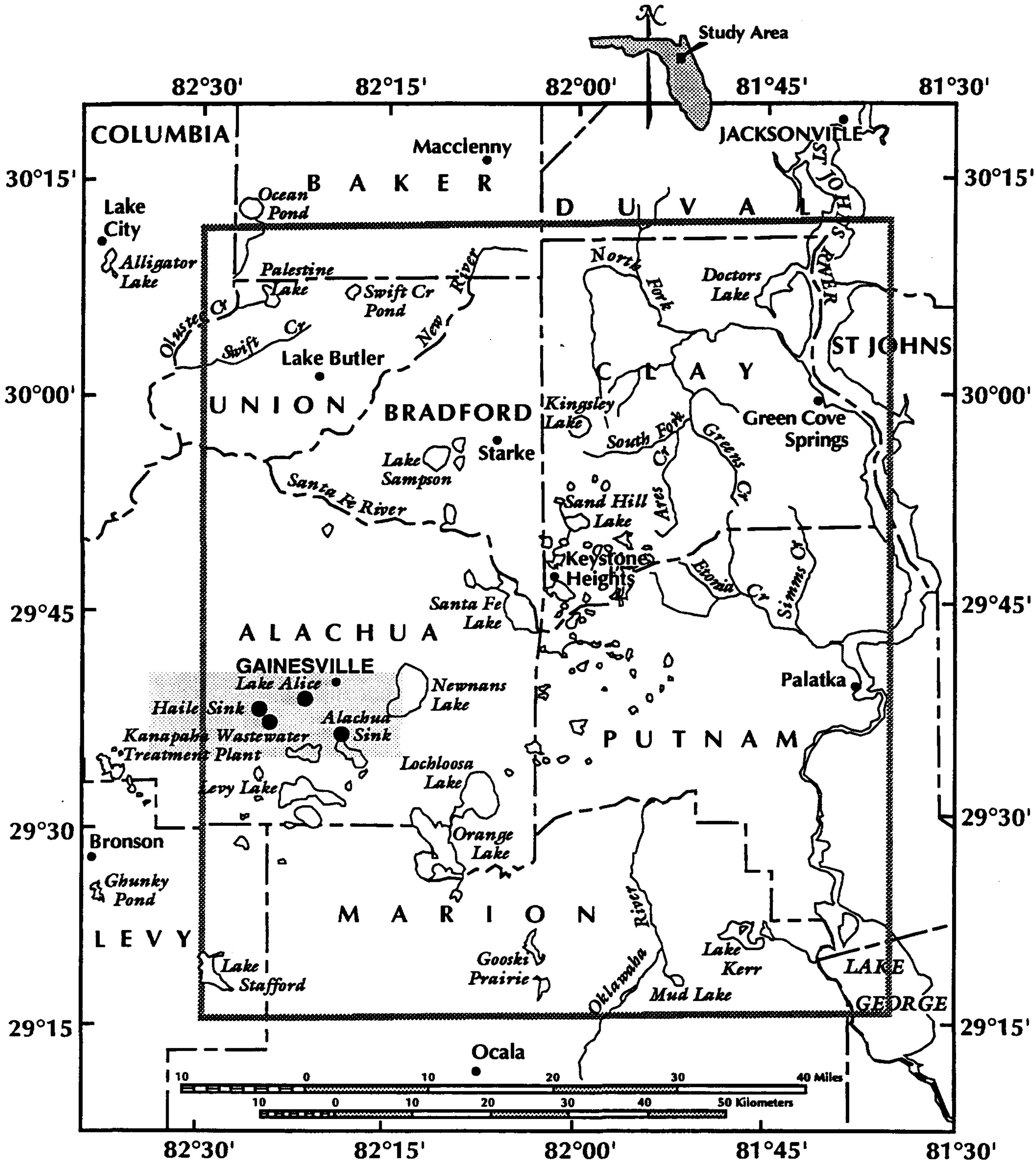


Figure 5-7. Locations of Haile Sink, Alachua Sink, Lake Alice, and Kanapaha Wastewater Treatment Plant

means of surface-water runoff. The Kanapaha Wastewater Treatment Plant discharges its effluent into a recharge well in the lower part of the Floridan aquifer system.

Flow rates for Haile Sink and Alachua Sink were very difficult to quantify. Conservatively high values were estimated based on flow measurements reported by Phelps (1987). The estimated values were 4.30 mgd (574,000 ft^3/day) and 9.87 mgd (1,320,000 ft^3/day) for Haile Sink and Alachua Sink, respectively. Lake Alice values were based on information obtained from reports compiled by UF for the Florida Department of Environmental Regulation. The total recharge was estimated as 2.08 mgd (278,080 ft^3/day). The Kanapaha recharge value was obtained from effluent discharge data from the wastewater treatment plant and estimated to be 6.10 mgd (815,310 ft^3/day).

5.3 MAY 2010 GROUND-WATER USE

5.3.1 Public Supply

Projections for May 2010 public-supply withdrawals were based on available withdrawal and projected population information. Public-supply per capita values were derived from historical data. May 2010 public-supply ground-water withdrawals were estimated by multiplying these values by the estimated 2010 population (Marella 1992a). In some cases, estimates for future values were obtained directly from the users. Projected public-supply withdrawals increased significantly from the May 1985 withdrawal rates. SJRWMD users are projected to use 76.8 mgd (10,270,000 ft^3/day), whereas 6.3 mgd (836,000 ft^3/day) is the projected usage within SRWMD, and 0.5 mgd (71,000 ft^3/day) is the projected usage within SWFWMD (see Figure 5-8). These withdrawals are projected to increase from 54.8 mgd in 1985 to 83.6 mgd in 2010, a 34-percent increase. The substantial increase in public-supply use is attributed to increases in residential and touristic populations.

The projected public-supply 2010 ground-water withdrawals do not account for conservation measures or decreases in ground-water withdrawals due to development of alternative sources of water supply such as reclaimed wastewater and desalinated brackish and salt water. Thus, the estimated 2010 public supply values are conservatively high and represent likely maximum public-supply withdrawal rates that will result in the greatest impacts on the Floridan aquifer system.

5.3.2 Domestic

May 1985 domestic self-supplied withdrawals were contingent on public-supply users within each county. A percentage based on public supply increases for the state of Florida compared to domestic-supply increases for the state of Florida (Marella 1992a; see Figure 5-9) was applied to the public-supply increase in the study area to obtain an estimate for May 2010 domestic self-supplied withdrawals of 30.5 mgd, an 8 percent increase in withdrawal rates. Similar to the 1985 case, the self-supplied domestic pumpage for 2010 was not included in the MODFLOW well files created for the ground-water model.

5.3.3 Commercial and Industrial

In general, commercial and industrial ground-water withdrawals are anticipated by the water management districts to remain constant or to decrease due to industrial

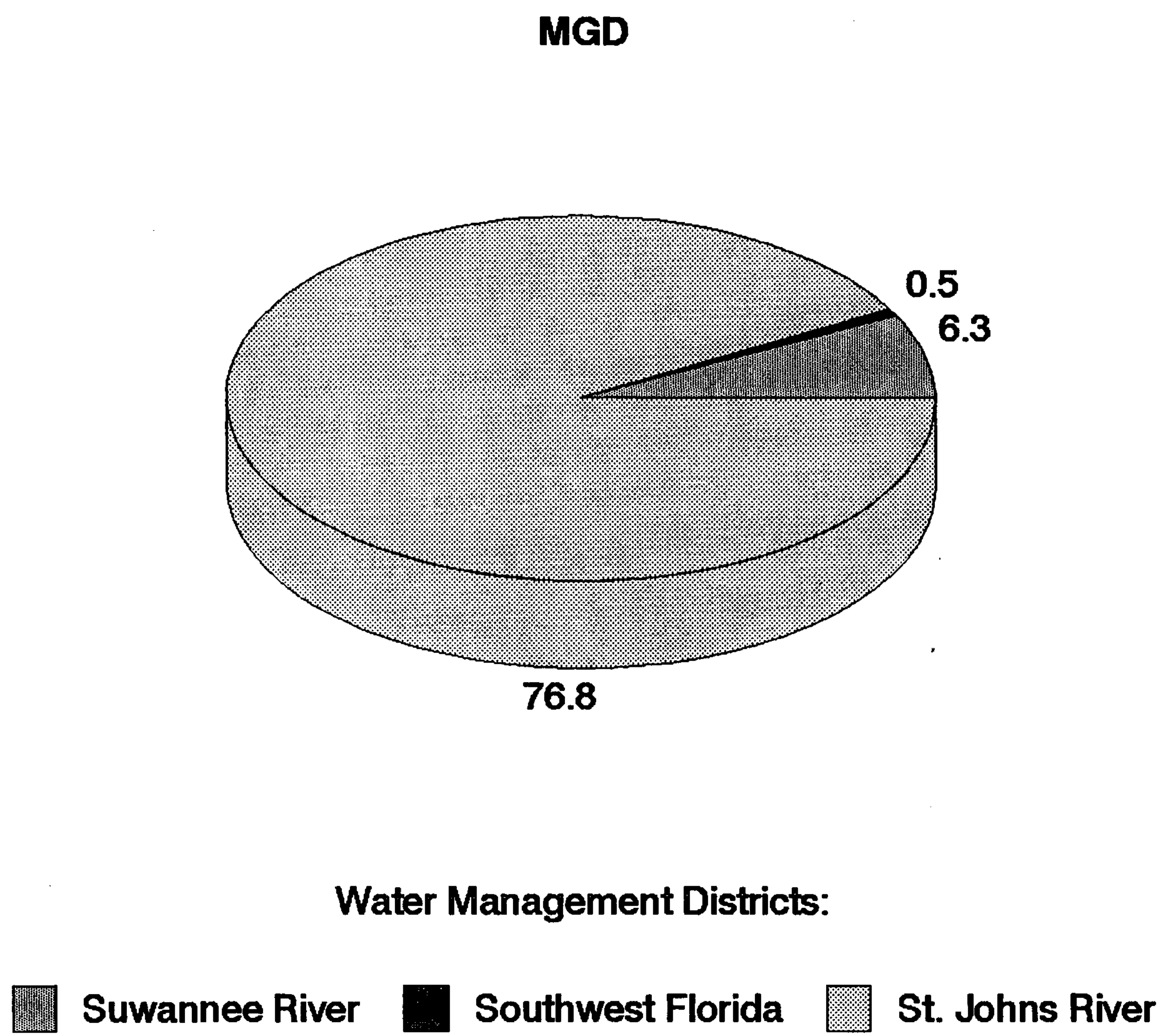
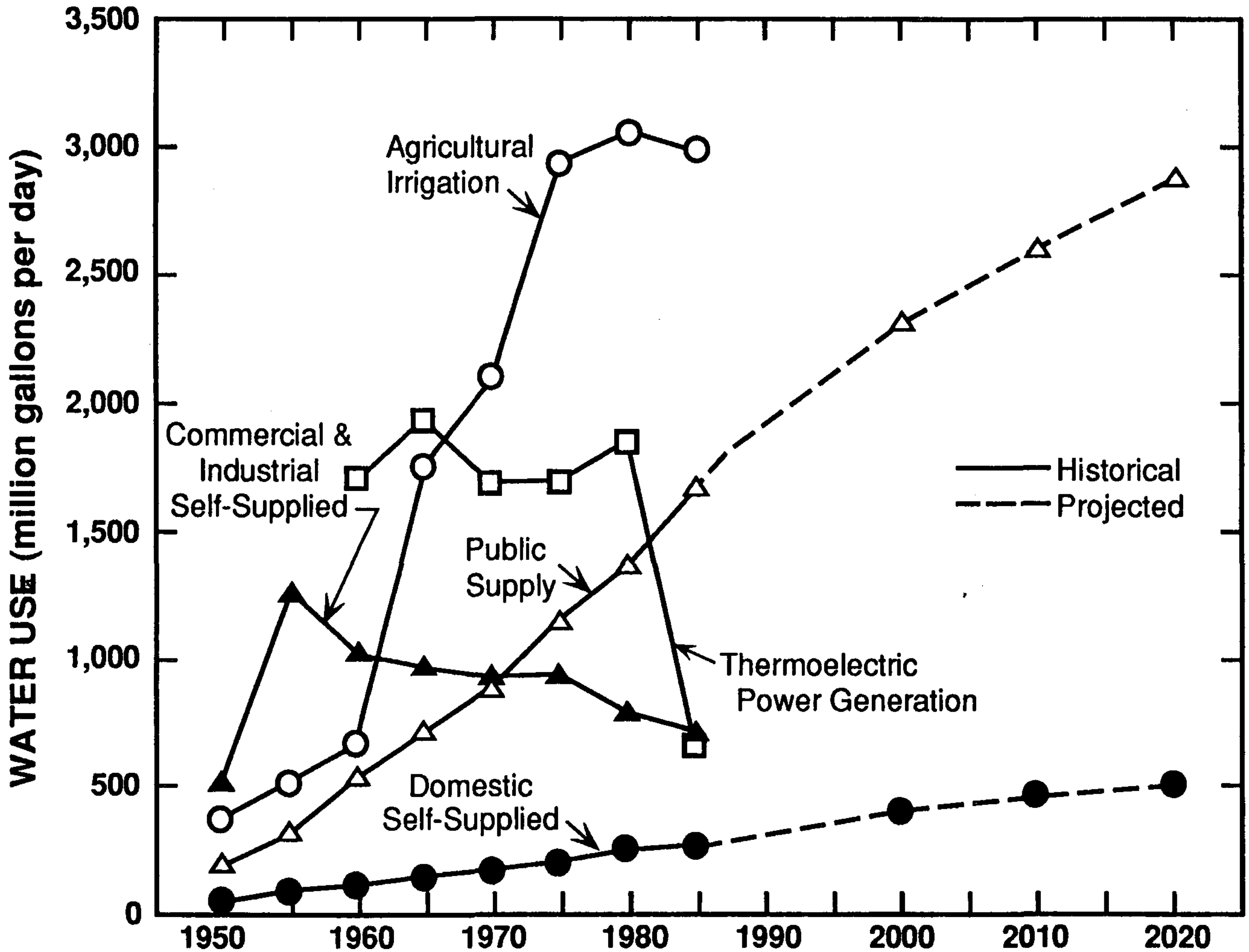


Figure 5-8. May 2010 Public-Supply Ground-Water Withdrawals



Source: Marella 1992b.

Figure 5-9. Historical Fresh-Water Use by Category and Projected Public-Supply and Domestic Self-Supplied Water Use in Florida for 1950-2020 efforts to conserve water in recent years. In some cases, information was obtained directly from individual users for projections of May 2010 ground-water withdrawals. For example, Georgia Pacific in Palatka projects that it will pump 25.0 mgd in May 2010, a significant reduction from the 44.9 mgd that was pumped in May 1985. SJRWMD users are projected to pump 46.5 mgd (6,222,000 ft^3/day), SRWMD users 2.9 mgd (381,000 ft^3/day), and SWFWMD users 0.1 mgd (17,700 ft^3/day)(see Figure 5-10). Pumpage within the SWFWMD is projected to remain the same from 1985 to the year 2010.

5.3.4 Agricultural

May 2010 agricultural usage was estimated using the same process as for the May 1985 agricultural values. It was assumed that crops and land usage would remain constant, supporting consistent agricultural monthly multiplication factors within the three districts. Agricultural water-use coefficients for 2010 were developed based on USGS estimated agricultural water use for 1990. The 1990 data were termed recent and more reliable than 1985 data and were the basis for the 2010 projections. Projected estimates for total withdrawal rates for the water management districts are 41.9 mgd (5,596,000 ft^3/day) for SJRWMD, 13.2 mgd (1,768,000 ft^3/day) for SRWMD, and 9.9 mgd (1,327,000 ft^3/day) for SWFWMD (see Figure 5-11).

5.3.5 Thermoelectric

Withdrawal rates for thermoelectric power users were estimated for May 2010 by averaging historical information. In May 1985, thermoelectric power users

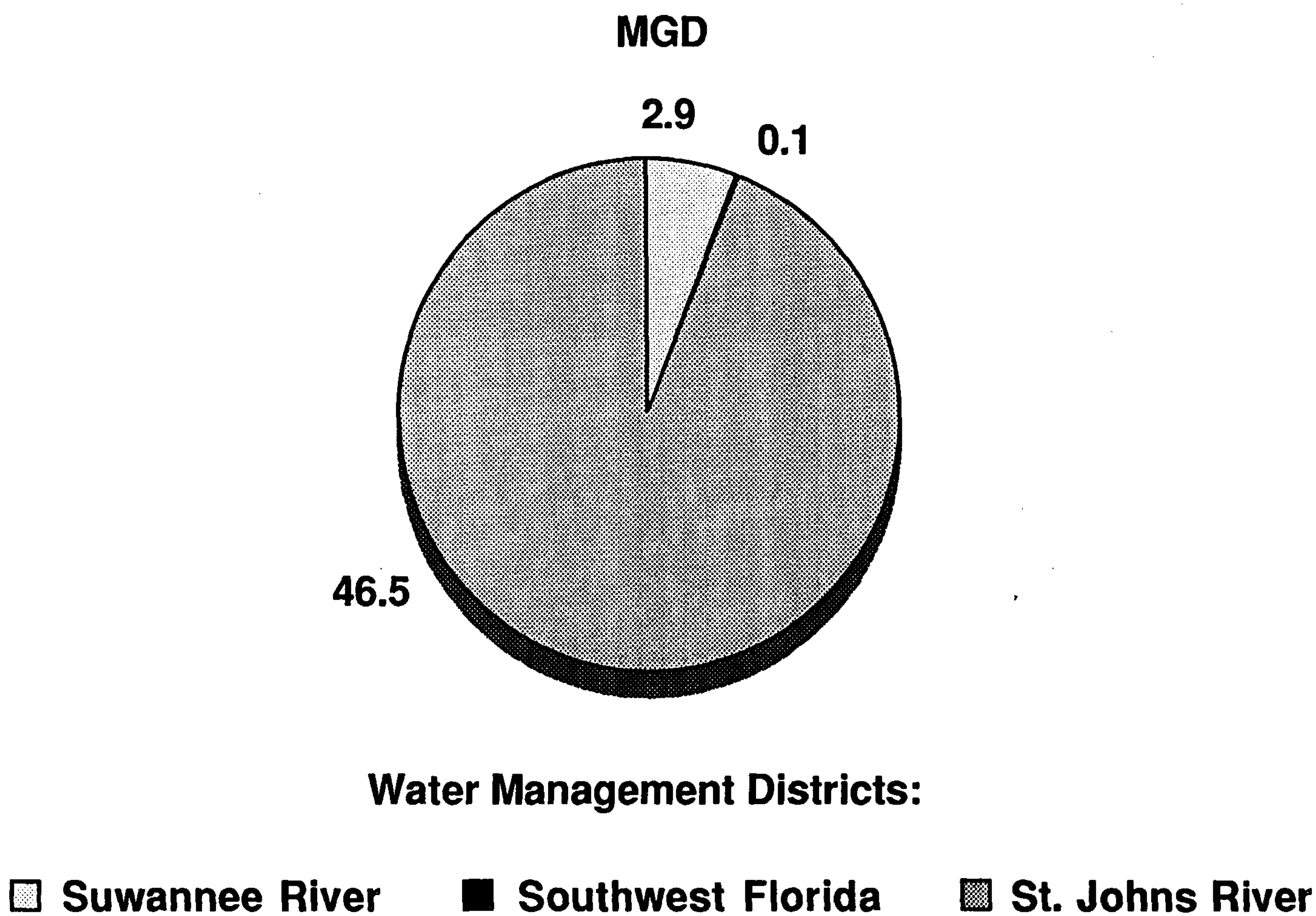


Figure 5-10. May 2010 Commercial and Industrial Ground-Water Withdrawals

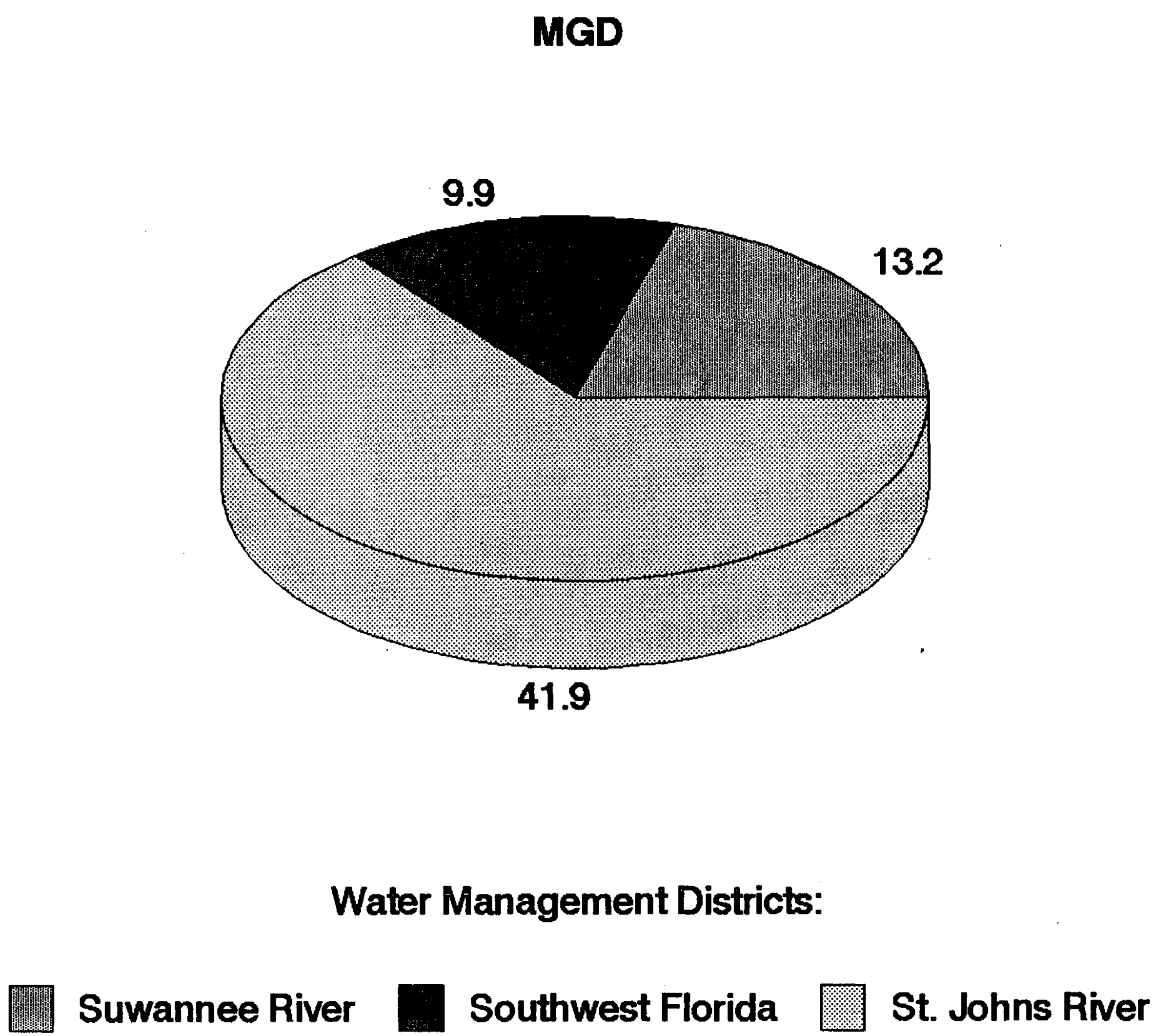


Figure 5-11. May 2010 Agricultural Ground-Water Withdrawals

pumped 4.44 mgd, whereas in 2010, it is projected that users will pump 4.06 mgd, a 0.38 mgd decrease in ground-water withdrawals. Users within SJRWMD and SRWMD are projected to pump 0.9 mgd (120,000 ft^3/day) and 3.2 mgd (423,000 ft^3/day), respectively (see Figure 5-12). There are no actual projections for future withdrawals for thermoelectric power generation within the study area, and the difference in withdrawal rates between 1985 and 2010 is attributed to the data being averaged over a broader range of years for the 2010 withdrawal rates.

5.3.6 Recharge

Site-specific recharge was estimated to increase from 22.3 mgd to 31.0 mgd within the study area from May 1985 to May 2010. The Kanapaha Wastewater Treatment Plant represents the most significant increase in recharge, which is projected to increase from 6.1 mgd in 1985 to 14.3 mgd in 2010, a 134 percent increase. The estimate is based on a historical average of available data with a 3.5 percent average increase per year. Lake Alice recharge was approximated from historical data, and it is estimated that it will contribute 2.6 mgd to the Floridan aquifer system. Alachua Sink and Haile Sink are estimated to have the same recharge rates as in 1985, because of difficulties and uncertainties in compiling data for these sources.

5.4 TOTAL GROUND-WATER USE

For May 1985, pumpage from the ground-water system in the study area was 54.8 mgd for public supply, 28.2 mgd for domestic self-supply, 63.1 mgd for commercial and industrial use, 55.4 mgd for agriculture, and 4.4 mgd for thermoelectric

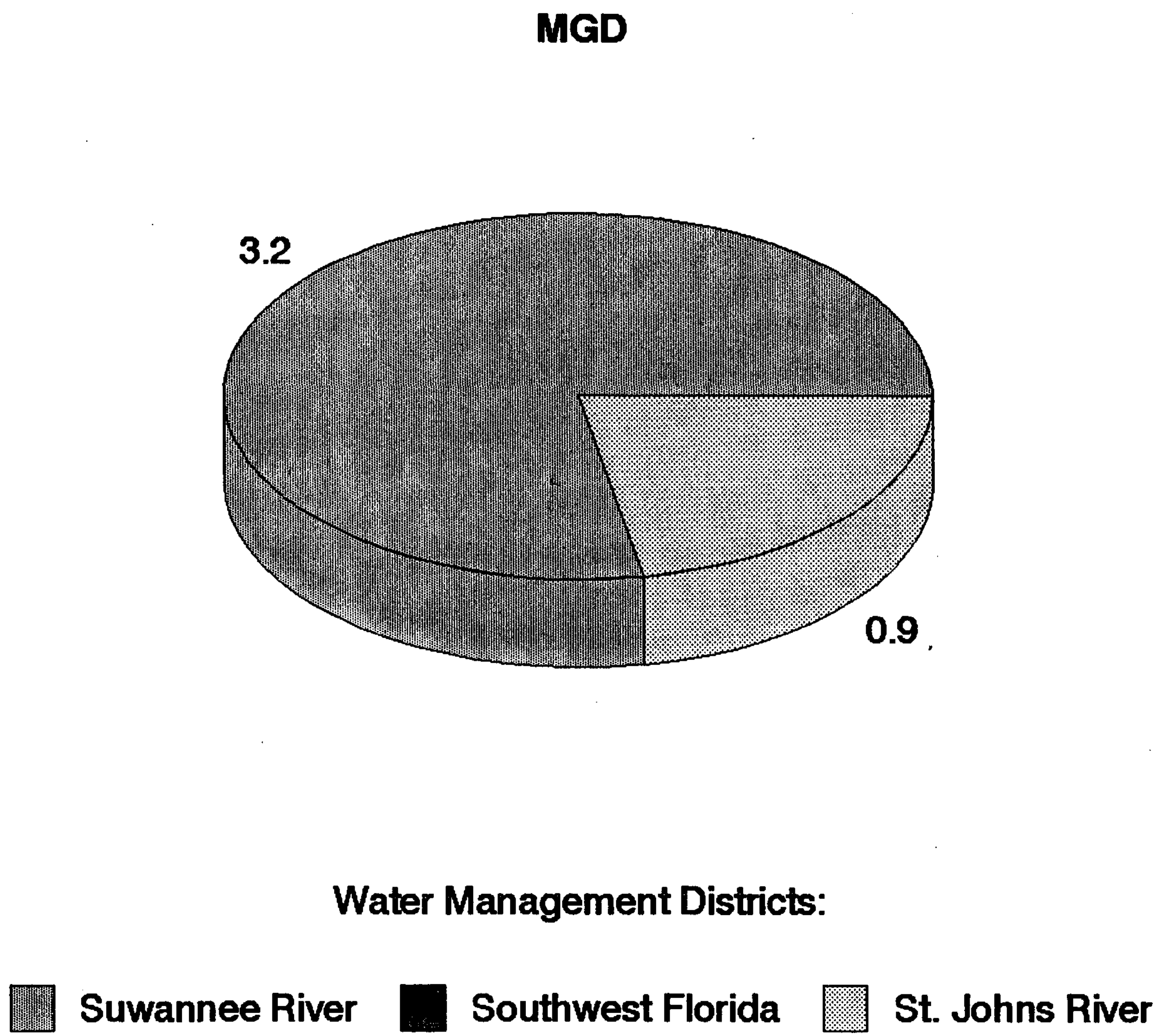
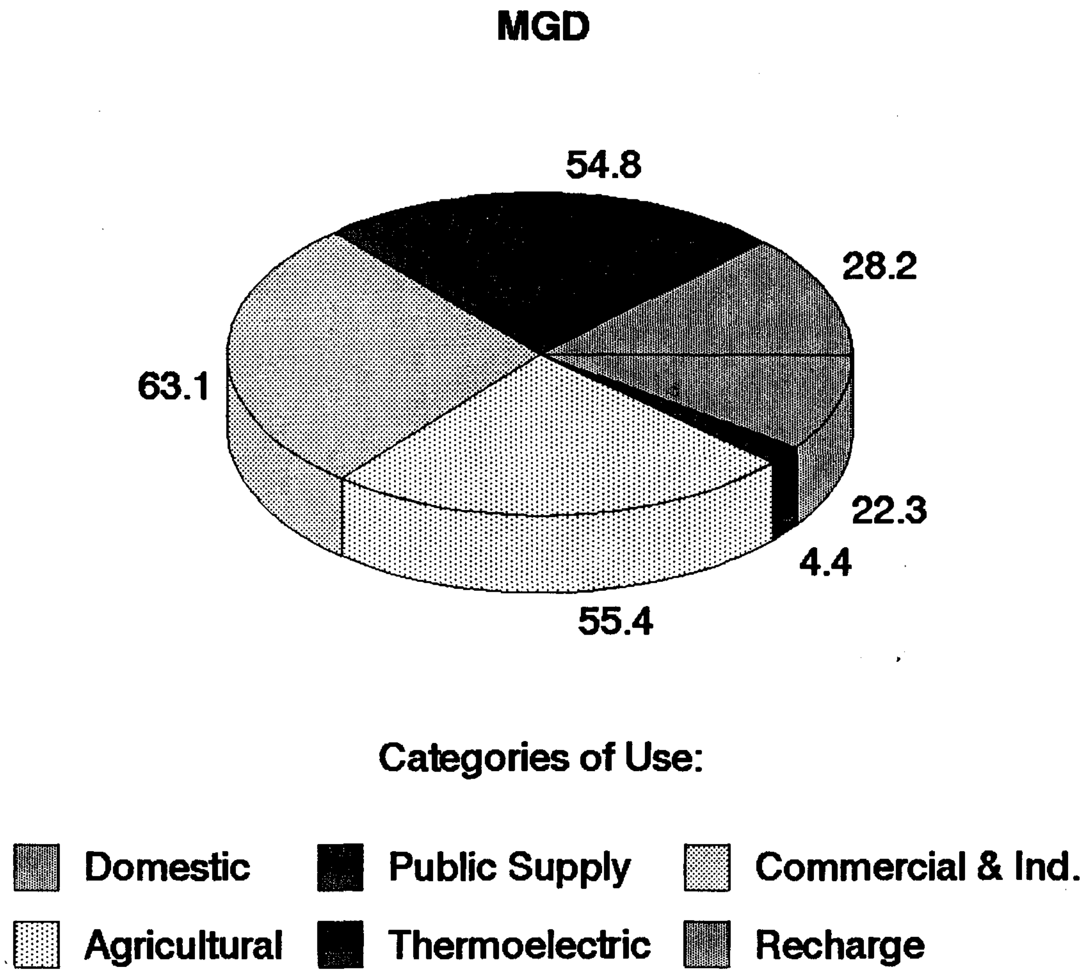


Figure 5-12. May 2010 Thermoelectric Power Generation Ground-Water Withdrawals

power generation (see Figure 5-13). Excluding the pumpage for domestic self-supply, the total estimated pumpage from the ground-water system was 177.7 mgd, and recharge to the ground-water system at the four site-specific locations was estimated to be 22.3 mgd (see Table 5-2). The net pumpage from the ground-water system is the difference between these numbers, or 155.4 mgd.

For May 2010, pumpage from the ground-water system in the study area is projected to be 83.6 mgd for public supply, 30.5 mgd for domestic self-supply, 49.5 mgd for commercial and industrial use, 65.0 mgd for agriculture, and 4.1 mgd for thermoelectric power generation (see Figure 5-14). Excluding pumpage for domestic self-supply, the total pumpage from the ground-water system is projected to be 202.2 mgd, and recharge to the ground-water system at the four site-specific locations is projected to be 31.0 mgd (see Table 5-3). The projected net pumpage from the ground-water system is the difference between these numbers, or 171.2 mgd.



Note: Domestic self-supply not included in MODFLOW well file, and recharge adds water to ground-water aquifer system.

Figure 5-13. May 1985 Ground-Water Use (Withdrawals and Recharge)

Table 5-2 May 1985 Ground-Water Usage in Study Area

Use / Water Management District	Domestic Self-Supply (mgd)	Public Supply (mgd)	Commercial and Industrial (mgd)	Agri-cultural (mgd)	Thermoelectric Power Generation (mgd)	Total Pumpage (Without Recharge) (mgd)	Recharge (mgd)	Net Pumpage (With Recharge) (mgd)
SJRWMD	--	48.25	59.94	33.87	1.28	143.34	8.18	135.16
SRWMD	--	6.16	3.03	15.09	3.16	27.44	14.17	13.27
SWFWMD	--	0.42	0.13	6.39	0.0	6.94	0.0	6.94
Totals	28.2[a]	54.83	63.1	55.35	4.44	177.72	22.35	155.37

[a]Total for domestic self-supply not included in MODFLOW well file.

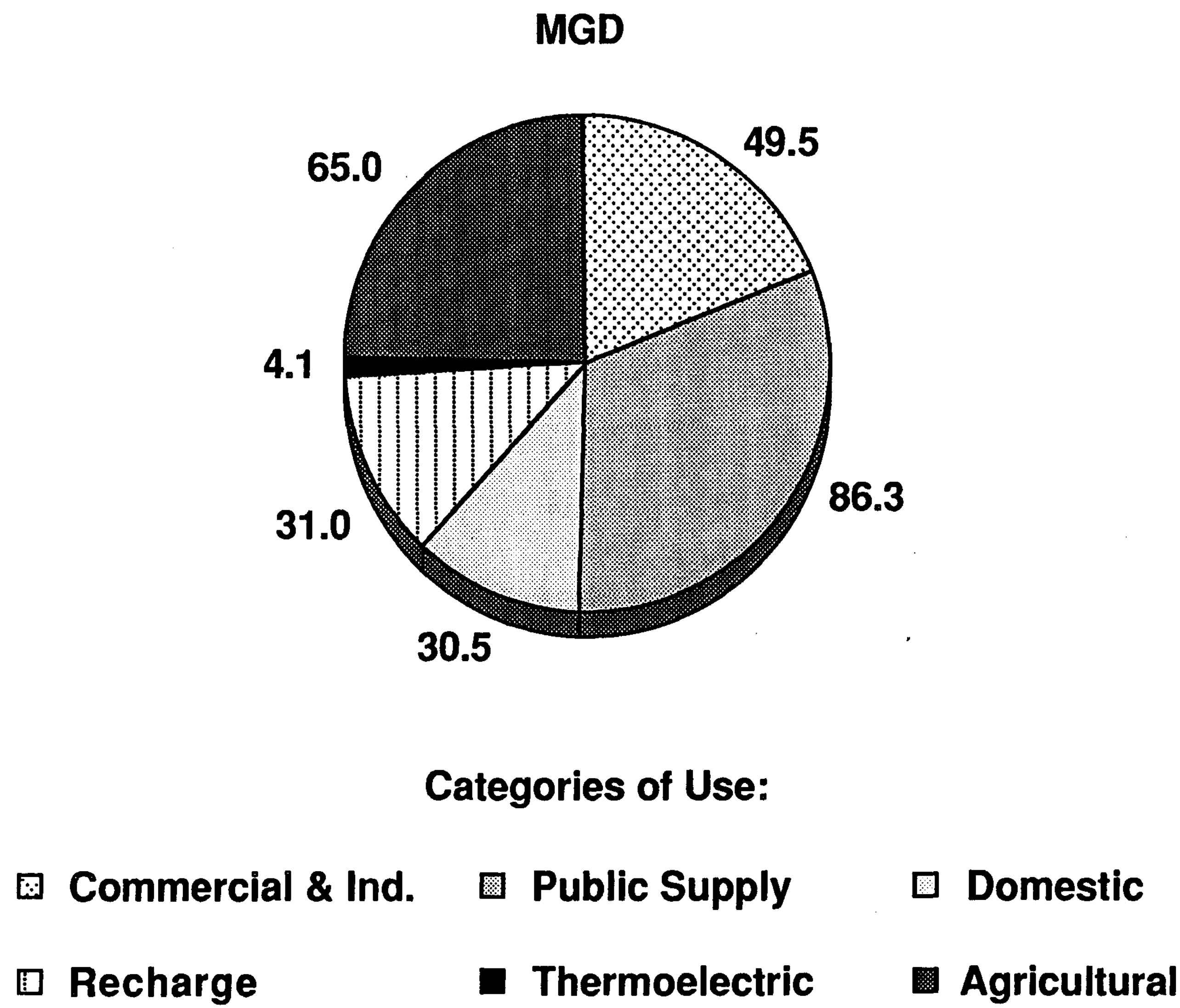


Figure 5-14. May 2010 Ground-Water Use (Withdrawals and Recharge)

Table 5-3 May 2010 Ground-Water Usage in Study Area

Use Water Management District	Domestic Self-Supply (mgd)	Public Supply (mgd)	Commercial and Industrial (mgd)	Agri-cultural (mgd)	Thermoelectric Power Generation (mgd)	Total Pumpage (Without Recharge) (mgd)	Recharge (mgd)	Net Pumpage (With Recharge) (mgd)
SJRWMD	--	76.83	46.54	41.86	0.9	166.13	16.82	149.31
SRWMD	--	6.26	2.85	13.23	3.16	25.5	14.17	11.33
SWFWMD	--	0.53	0.13	9.92	0.0	10.58	0.0	10.58
Totals	30.5[a]	83.62	49.52	65.01	4.06	202.21	30.99	171.22

[a]Total for domestic self-supply not included in MODFLOW well file.

6.0 TEMPORAL AND SPATIAL CHANGES IN GROUND-WATER LEVELS

6.1 LONG-TERM GROUND-WATER LEVEL CHANGES

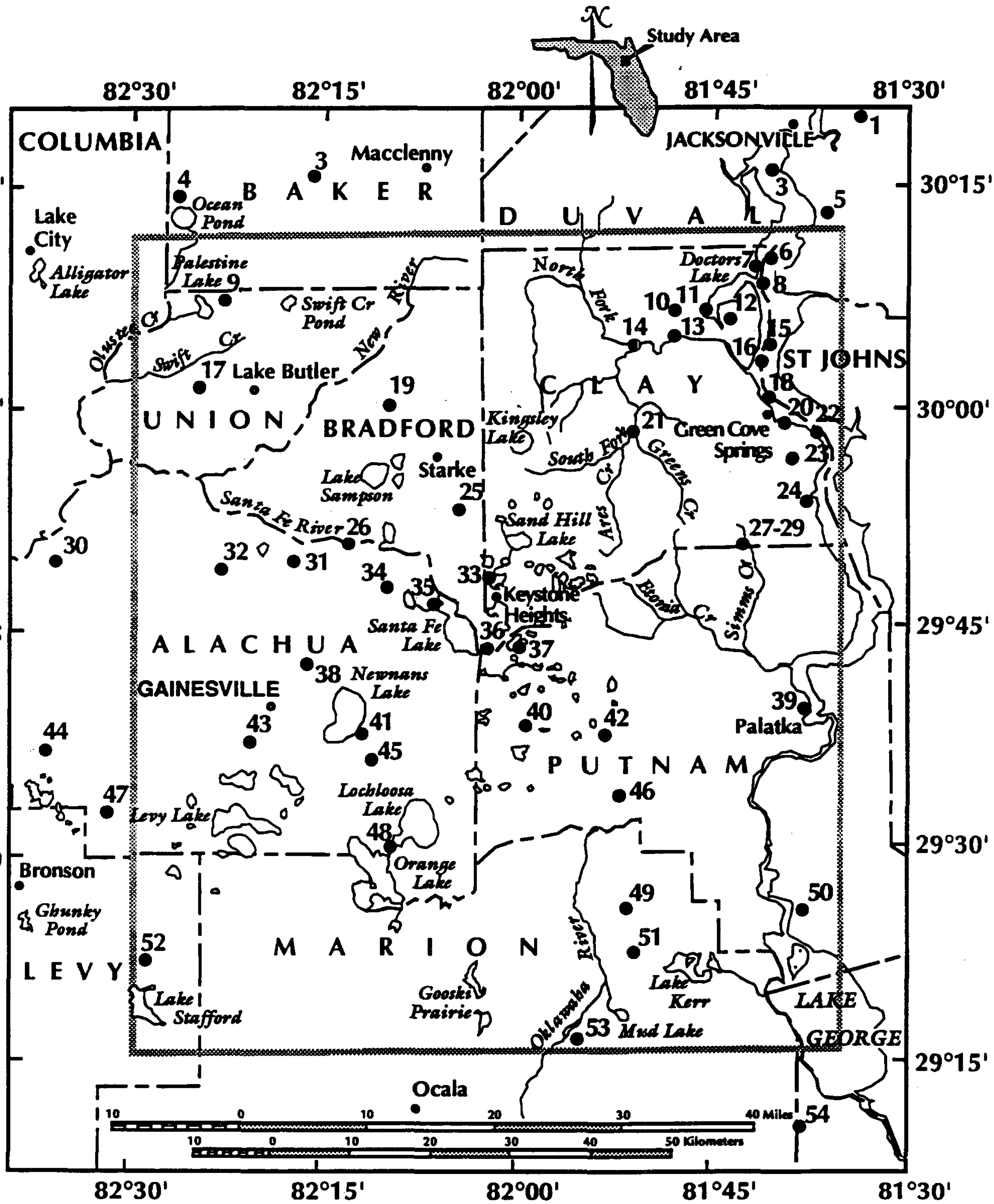
Hydrogeologic, rainfall, and water-use data for the study area were evaluated to investigate the causes of the declines in the water levels in the upper Floridan aquifer in parts of the study area over the past twenty to thirty years (Gay 1993). Most of the ground-water data, obtained from SJRWMD and SRWMD, was derived from three sources: SJRWMD, SRWMD, and the USGS. Unfortunately, much of the data did not include information prior to the late 1970's. Other sources of ground-water data included the historical reports on water levels in artesian and non-artesian aquifers in Florida from 1961 through 1978 [Healy (1966-1980) and Clark et.al. (1964)], and Stringfield's (1936) report on artesian water in Florida. Rainfall data were evaluated for the six rain gages in and adjacent to the study area: Gainesville, Starke, Palatka, Jacksonville, Lake City, and Ocala. The Starke records are very sporadic and were not very useful to the investigation, however. Water-use information was obtained from the USGS water-use reports published approximately every five years (Pride 1973; Leach 1978 and 1983; Leach and Healy 1980; and Marella 1985 and 1990) and the SJRWMD annual water-use surveys (Marella 1981-1986b and 1988a-1992a; and Florence 1990-1992).

6.2 GROUND-WATER LEVEL CHANGES IN THE UPPER FLORIDAN AQUIFER

Using the historical water-level data for the upper Floridan aquifer, water-level changes in the study area were determined for the time period from 1960 to 1992. This time period was chosen because it is the longest time period for which reliable data could be obtained for most of the study area. Since the northeast section of the study area has experienced the greatest levels of decline and longer-term data are available for this area, drawdowns in the upper Floridan aquifer also were determined from 1934 to 1992 for Clay County. Two techniques were used to determine the changes in the hydraulic heads in the upper Floridan aquifer: actual measurements from 1934, 1960, and 1992, and linear regression conducted on data from individual wells to determine the rate of change in ground-water levels in a given area. After reviewing data from more than 460 wells located in the study area, data from 54 wells were used for this analysis (see Figure 6-1). Descriptive information including location and physical characteristics for these wells is provided in Appendix 1 (Gay 1993).

6.2.1 Determining Drawdowns.

Actual ground-water level measurements in May or June 1934, May or June 1960, and May 1992 were used to determine drawdowns at a given well (see Appendix 2, Gay 1993). If data points were unavailable or highly erratic relative to data points in the same general time period, ground-water levels were used from an adja-



Note: Numbers correspond to well identification numbers in Appendix.

Figure 6-1. Wells Used in Determining Drawdowns in the Upper Floridan Aquifer in North-Central Florida cent time period. In many cases, data records for individual wells did not extend back to 1960 or 1934, but it was possible to trace them back through older reports containing ground-water level information (i.e., Clark et al. 1964; Healy 1966-1980; and Stringfield 1936).

Drawdowns at individual wells also were determined by using linear regression to determine the rate of change in water levels over time (see Appendix 3, Gay 1993). For example, the water level in well 10 (USGS 300649081485901), located in the northeast part of the study area, had a slope of -0.0011 ft/day (see Appendix 3, Gay 1993). This resulted in a calculated drawdown of 12.6 ft from 1960 to 1992. This value compares favorably with the net drawdown of 11.89 ft based on the measurements taken in June 1962 and May 1992 at this well (see Figure 6-2). In most cases, drawdowns that were determined using the two different techniques matched very closely (see Appendices 2 and 3, Gay 1993). The rates of change of water levels over time based on the linear regression were remarkably similar for a given region in the study area. For example, three wells (9, 17, and 19) located in the northwest region of the study area had similar rates of change: -0.0008 ft/day; -0.0007 ft/day; and -0.0008 ft/day (see Appendix 3, Gay 1993).

6.2.2 Drawdowns in the Upper Floridan Aquifer 1960-1992

Water levels in the upper Floridan aquifer declined from 1960 to 1992 throughout most of the study area (see Figure 6-3). The northwest part of the study area experienced an approximate net decline of 8.5 ft, or 0.27 ft/year. In the center

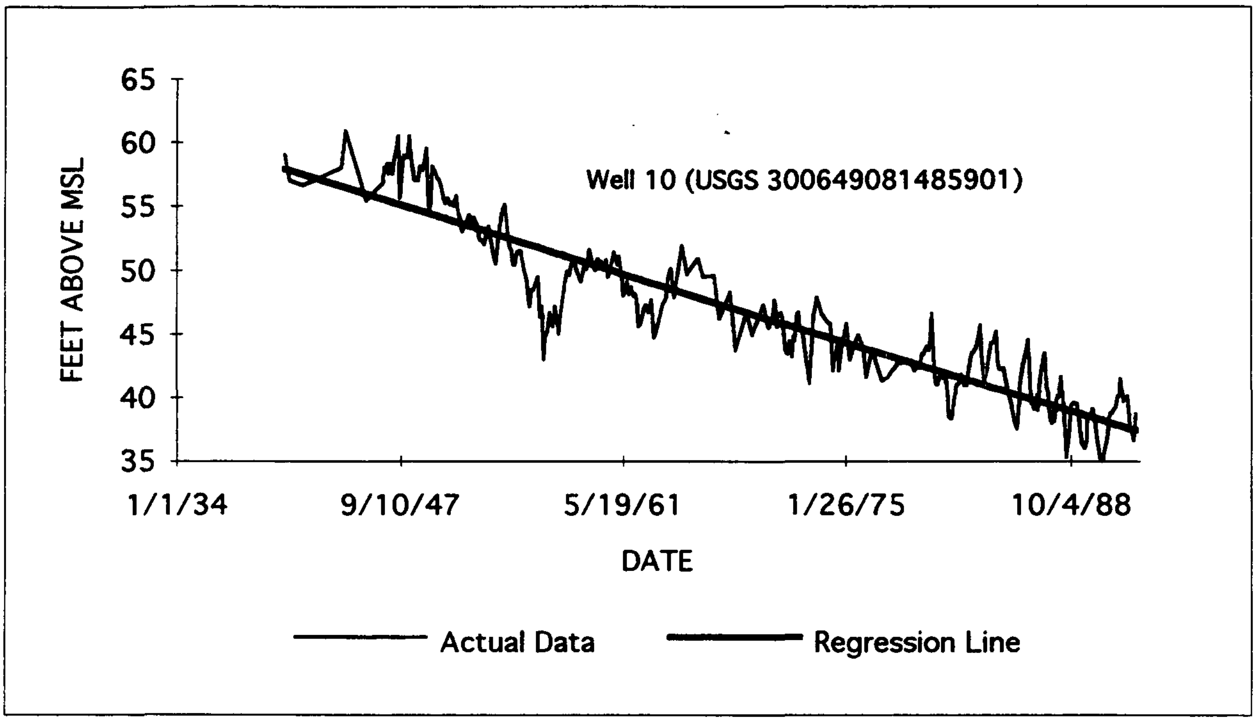
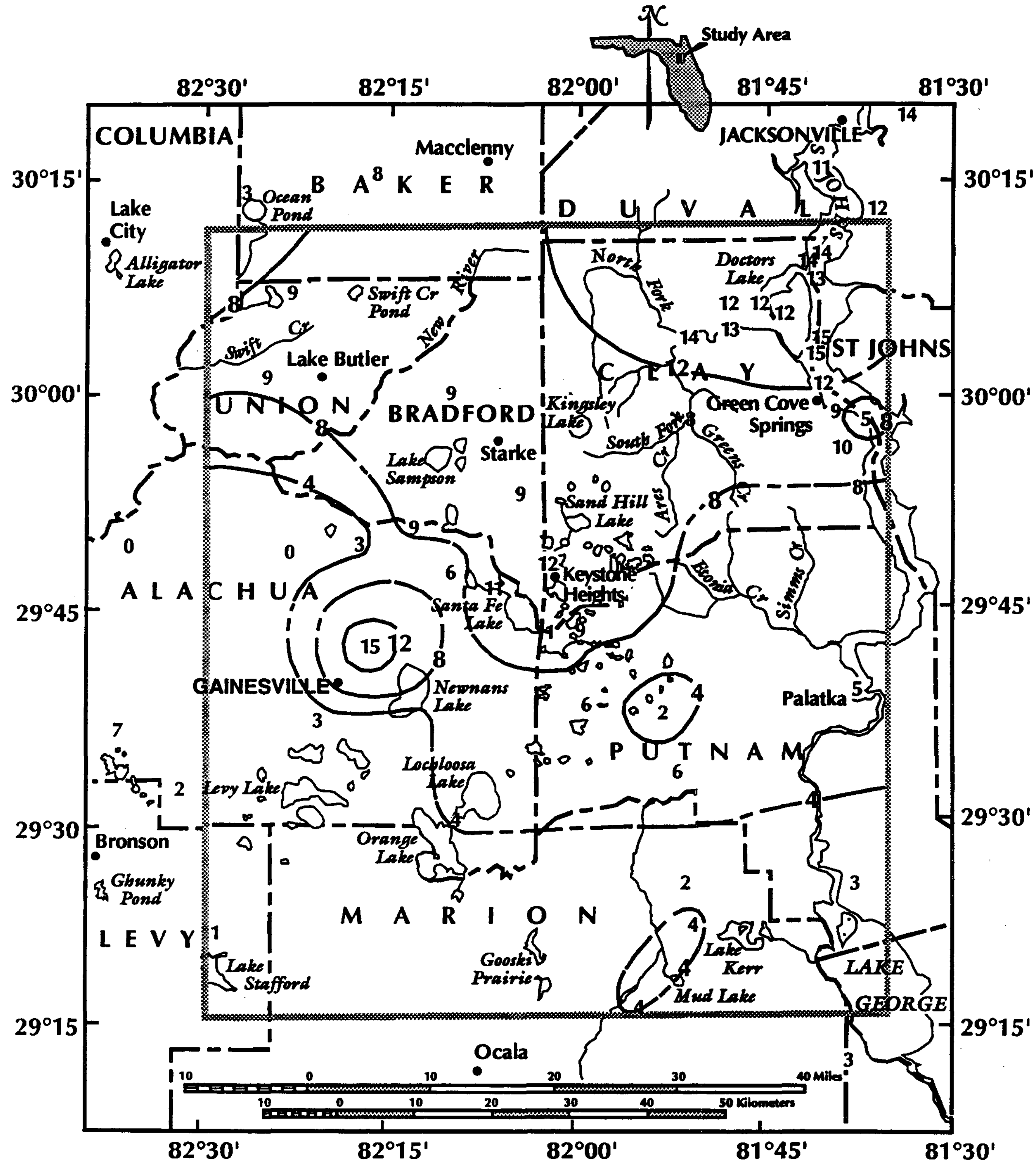


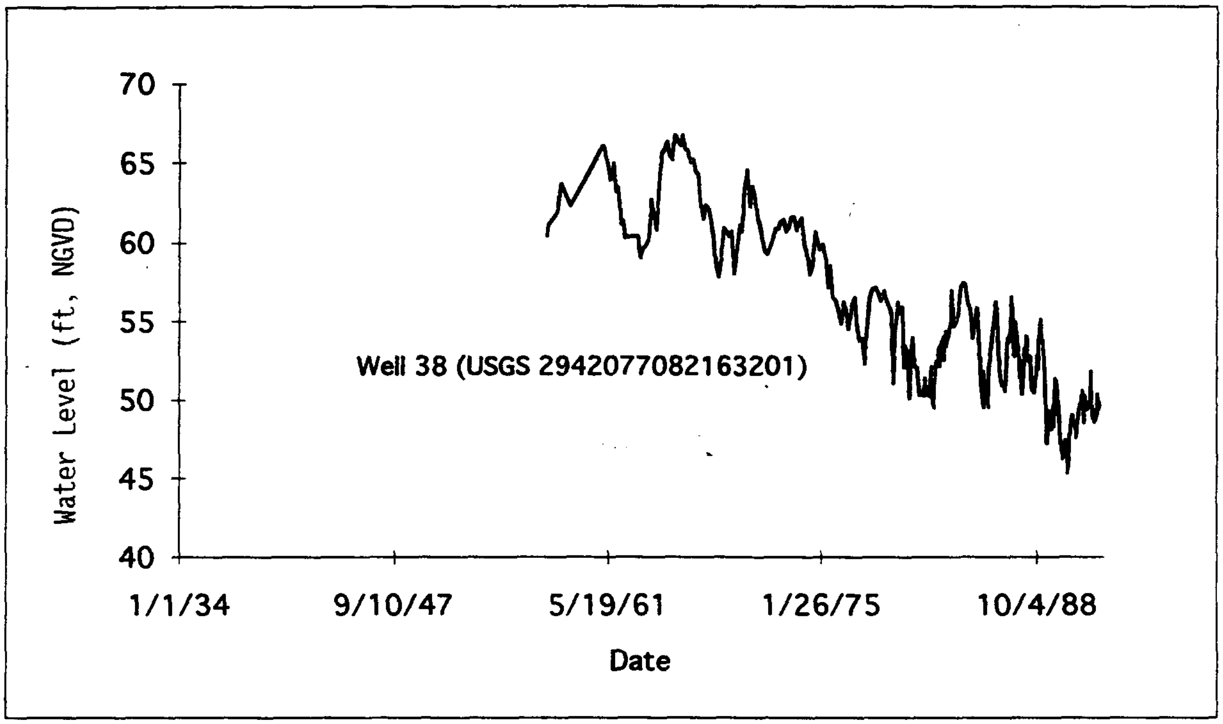
Figure 6-2. Linear Regression for Well 10 in Clay County to Determine the Rate of Change in Ground-Water Levels in the Upper Floridan Aquifer



Note: Contour interval is 4 ft, and dashed lines represent inferred position of contours.

Figure 6-3. Drawdowns in the Potentiometric Surface in the Upper Floridan Aquifer in North-Central Florida from 1960 to 1992 of the region, the net declines ranged from 6 to 12 ft, which is an approximate decline of 0.19 to 0.37 ft/year. The northeast area showed the greatest drawdowns, and the drawdowns increased toward the City of Jacksonville. Near Orange Park, net drawdowns ranged from 12 to 15 ft, which is a decline of approximately 0.4 ft/year. In the southeast and southwest areas, the drawdowns showed more variation. In the southwest, net ground-water level declines ranged from 0 to 15 ft from 1960 to 1992. In the southeast, net declines ranged from 2 and 6 ft, or approximately 0.1 to 0.2 ft/year. The hydrographs of several wells with long periods of record located in different parts of north-central Florida further demonstrate the drawdowns in the region (see Figures 6-2 and 6-4).

Since two different techniques were used to estimate drawdowns in the study area and given the inherent variability in water-level measurements reported over an extended time period, the ground-water level declines may vary by 3 to 5 ft in either the positive or negative direction. Based on this limit to the accuracy of the results, it can be concluded that the northwest, northeast, and central parts of the study area have experienced significant drawdowns. The limited accuracy may invalidate the drawdowns estimated in the southwest and southeast sections. However, upon reviewing the actual water-level data and the results of the linear regression, it can be observed that over 90 percent of the wells exhibited water-level declines and/or negative slopes (see Appendices 2 and 3, Gay 1993). Thus, it appears that much of the study area has experienced a regional decline in water levels in the upper Floridan aquifer.



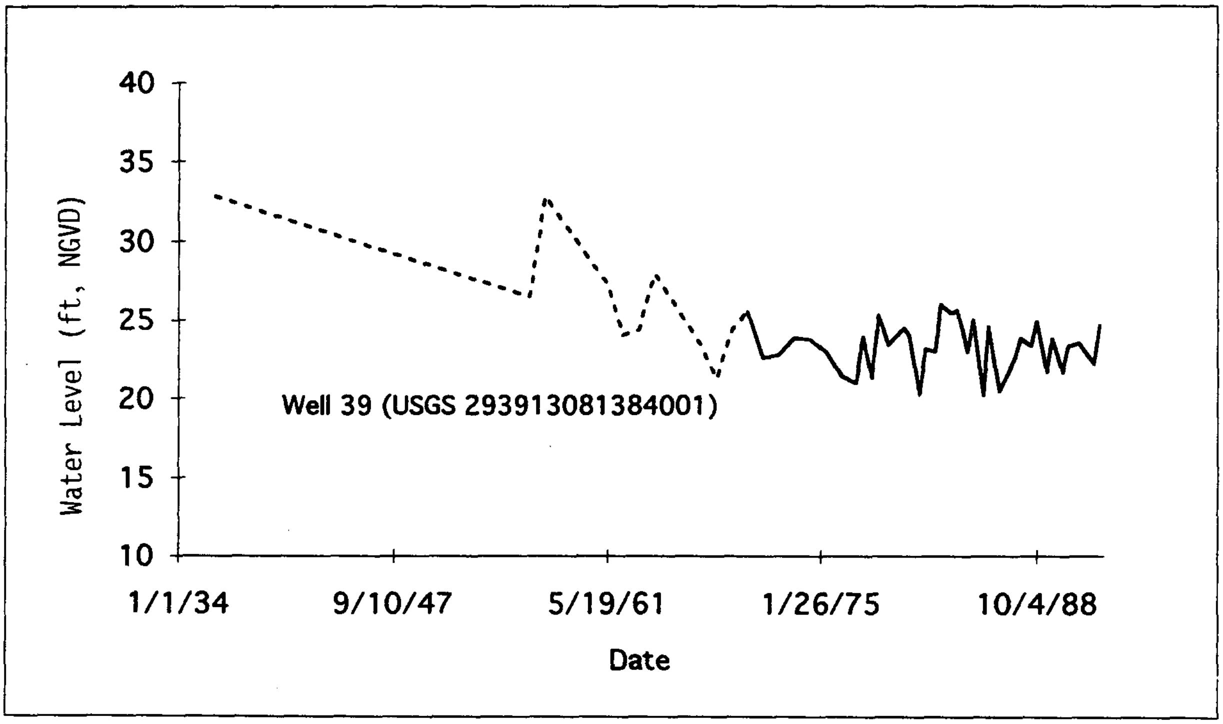


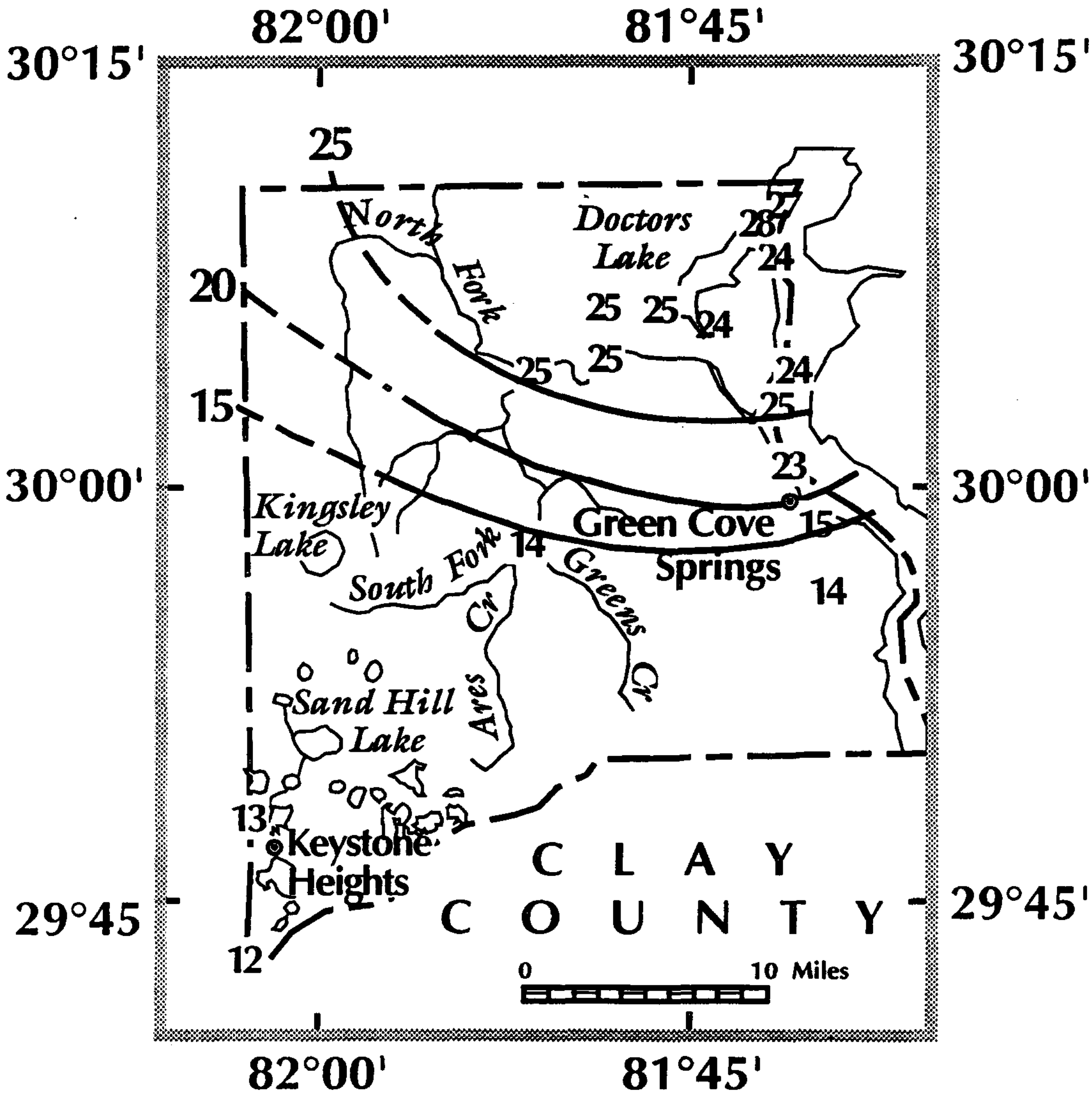
Figure 6-4. Hydrographs for Wells 38 and 39 in the Upper Floridan Aquifer in North-Central Florida for 1934-1988

6.2.3 Drawdowns in the Upper Floridan Aquifer in Clay County for 1934-1992.

The upper Floridan aquifer has experienced significant drawdowns in Clay County over the past sixty years (see Figure 6-5). The greatest declines occurred in the northeast corner of the study area where net drawdowns ranged from 24 to 28 ft, which is an approximate drawdown rate of 0.45 ft/year. Water levels in the two wells located near Keystone Heights both declined a total of 12 ft and had an estimated drawdown rate of 0.21 ft/year (Appendices 2 and 3, Gay 1993). From northeast Clay County toward the southeast, net drawdowns ranged from 12 to 28 ft. Overall, the hydraulic heads in Clay County declined approximately 2.1 to 4.8 ft every 10 years from 1934 to 1992.

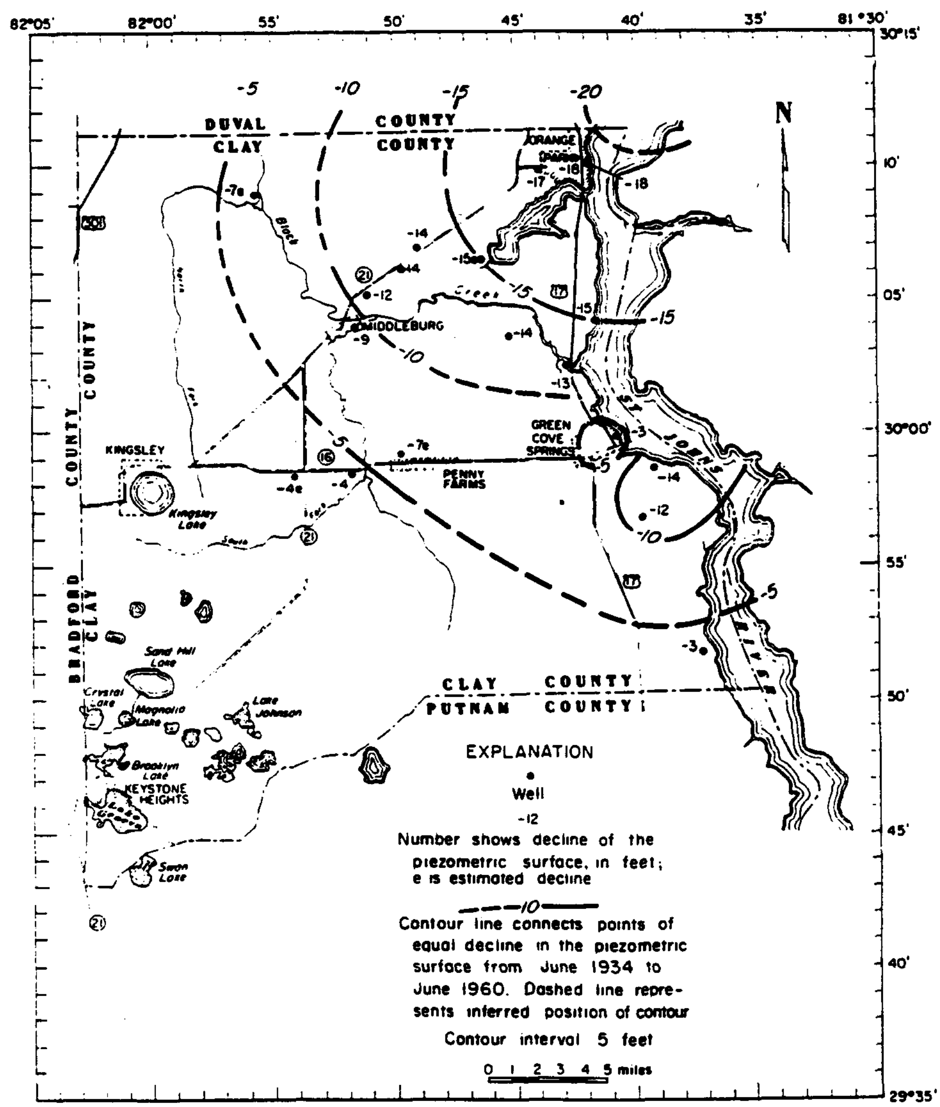
Water-level measurements for wells in the southwest corner of Clay County are not available prior to the late 1950's. Drawdowns from 1934 to 1992 in this area are, most likely, significantly greater than 12 ft, or 0.21 ft/year. Based on actual drawdowns from 1960 to 1990 and estimated drawdowns using linear regression, the ground-water levels may have declined approximately 20 ft, or 0.35 ft/year, from 1934 to 1992 near Keystone Heights (see Appendices 2 and 3, Gay 1993).

Drawdowns in the upper Floridan aquifer in Clay County also were determined from 1934 to 1960 by Clark et al. (1964) and from 1934 to 1976 by Bentley (1977) (see Figures 6-6 and 6-7). A cone of depression extended outward from Orange Park and Duval County from 1934 to 1960, and the drawdown ranged from more than 15 ft in the northeast to 5 ft in the center of the county. From 1934 to 1976, the cone of depression extended throughout most of the county, and the drawdown ranged from 30 ft in the northeast to 5 ft in the southwest. Current ground-



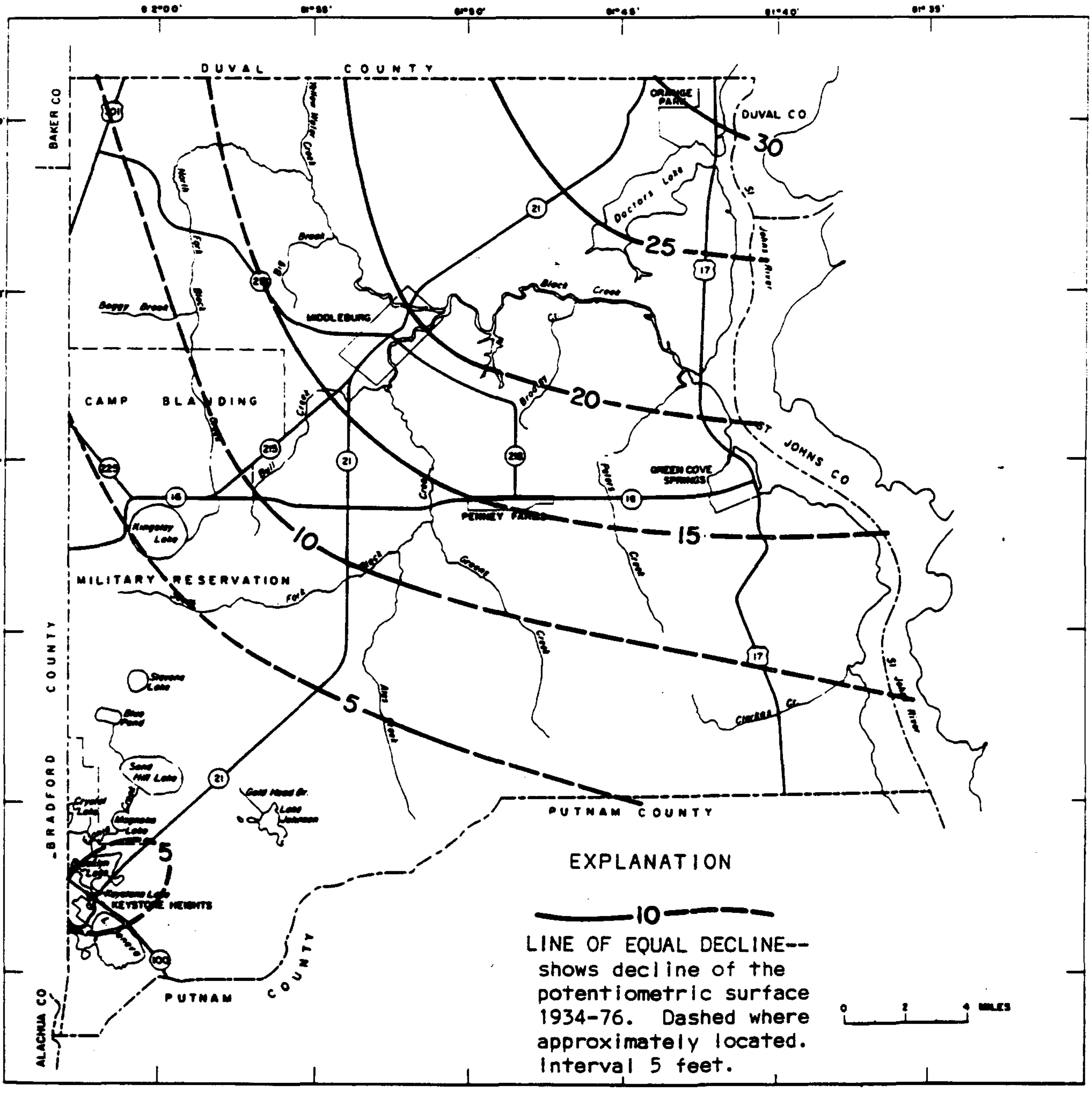
Note: Contour interval is 5 ft, and dashed lines represent inferred position of contours.

Figure 6-5. Drawdowns in the Potentiometric Surface in the Upper Floridan Aquifer in Clay County, Florida from 1934 to 1992



Source: Clark et al. 1964.

Figure 6-6. Drawdowns in the Potentiometric Surface in the Upper Floridan Aquifer in Clay County, Florida from 1934 to 1960



Source: Bentley 1977.

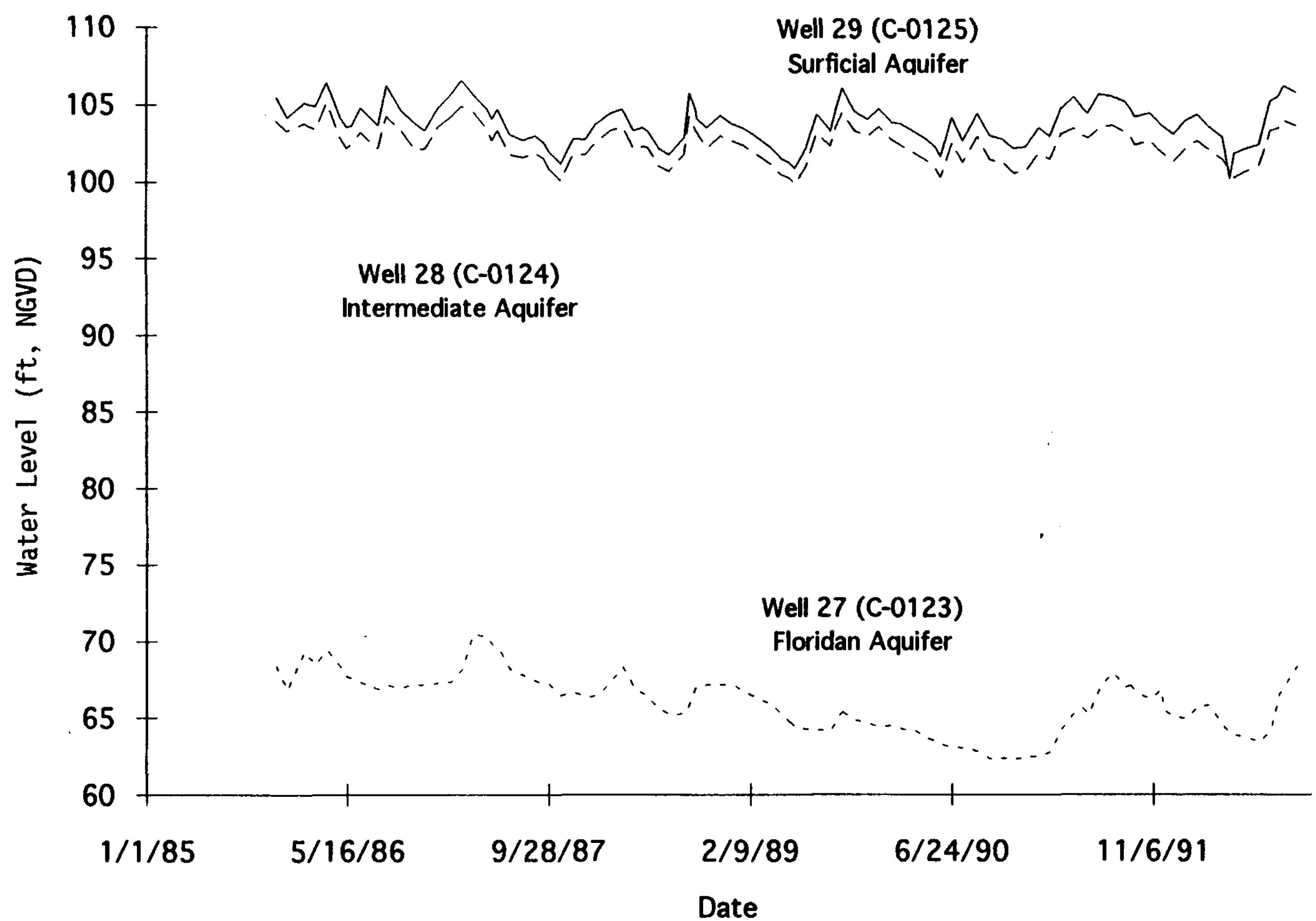
Figure 6-7. Drawdowns in the Potentiometric Surface in the Upper Floridan Aquifer in Clay County, Florida from 1934 to 1976

water levels indicate that drawdowns have not increased in the northeast corner of Clay County since 1976 (see Figure 6-5). However, drawdowns have increased in the central and southern parts of the county.

6.3 RELATED GROUND-WATER LEVEL CHANGES IN THE SURFICIAL AND INTERMEDIATE AQUIFERS

Long-term data for ground-water levels in the surficial and intermediate aquifers were not found in the available information. However, the relationship between the aquifers was examined by reviewing recent data for three wells at the same location in southeast Clay County, each drilled into a separate aquifer, with water-levels measurements made on the same day (see Figure 6-1 for location of wells 27-29 and Figure 6-8). The ground-water levels in the three aquifers show the same general responses; however, the amplitude of ground-water level responses is dampened as the depth below land surface increases. The upper two aquifers are more likely to respond to rainfall faster than the lower aquifer, while the upper Floridan aquifer is influenced by both the rainfall through downward percolation and any adjacent pumping.

All three wells experienced a decline in hydraulic head elevations from May 1986 to May 1992. Drawdowns increased with the depth of the aquifer. Actual ground-water level measurements showed a total drawdown of 1.8 ft in the surficial aquifer, 2.1 ft in the intermediate aquifer, and 3.7 ft in the upper Floridan aquifer from 1986 to 1992 (Appendix 2, Gay 1993). These drawdowns were confirmed by



Note: See Figure 6-1 for location of wells 27-29.

Figure 6-8. Hydrographs for Selected Wells at the Same Location Showing Water-Level Changes in Three Aquifers the negative rates of decline determined using linear regression: -0.0002 ft/day in the surficial aquifer; -0.0003 ft/day in the intermediate aquifer; and -0.0013 ft/day in the upper Floridan aquifer (Appendix 3, Gay 1993).

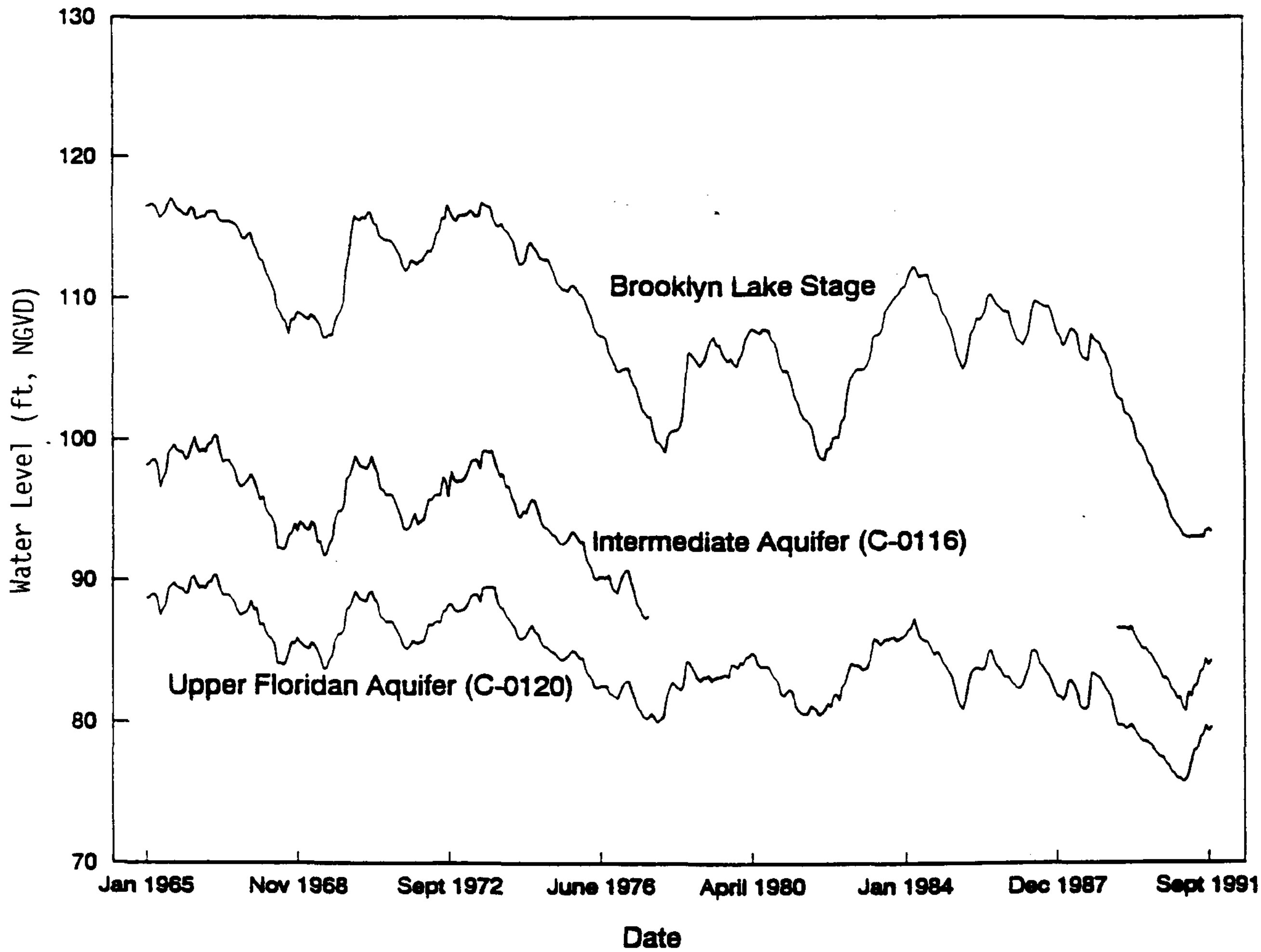
Another example of the hydraulic relationship between the upper aquifers and the upper Floridan aquifer is demonstrated by Motz et al. (1993). In the center of the study area in the UECB, water levels in the upper Floridan aquifer, the intermediate aquifer, and Brooklyn Lake showed similar responses (see Figure 6-9). As might be expected, the stage changes in the lake were more significant than the ground-water level changes in the intermediate aquifer and the upper Floridan aquifer. Unlike the aquifers, the lake receives precipitation directly as recharge, and evaporation plays a significant role as discharge.

6.4 MAJOR FACTORS THAT CONTRIBUTE TO CHANGES IN GROUND-WATER LEVELS

Two major factors, rainfall and ground-water pumpage, were evaluated as potential causes of the changes in ground-water levels in the upper Floridan aquifer.

6.4.1 Rainfall

The long-term annual rainfall at the six stations in and adjacent to the study area is similar for each of the different locations (see Figure 6-10). Most of the stations experienced above average and below average rainfalls during the same time periods. Nevertheless, rainfall for a given day, month or year can vary significantly from one location to the next. An example is the variability in annual rainfall at three



Source: Motz et al. 1993.

Figure 6-9. Hydrographs for Two Wells and Brooklyn Lake Stage Near Keystone Heights, Florida

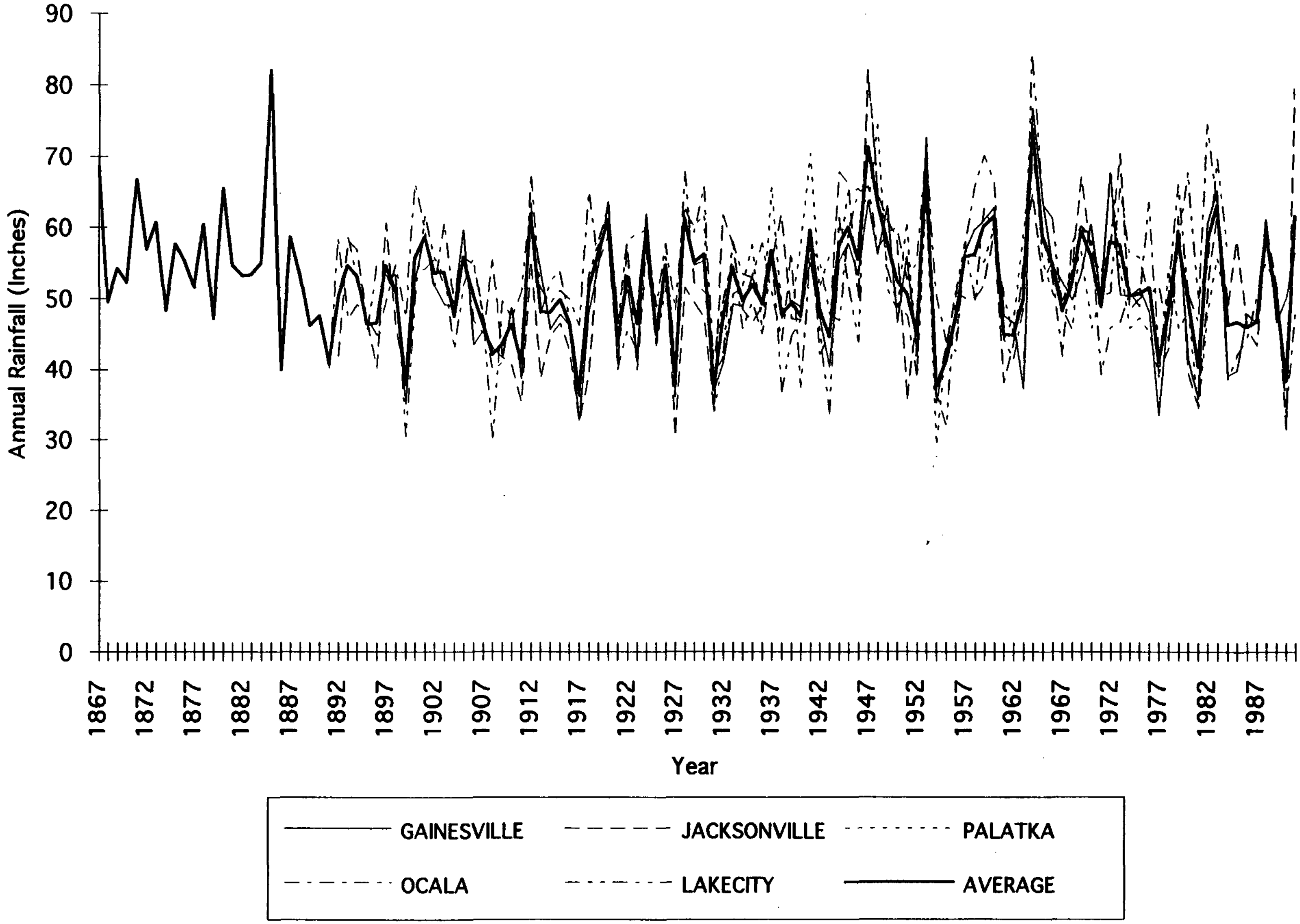


Figure 6-10. Annual Rainfall for Stations in North-Central Florida

different locations in 1992: 51.65 inches in Gainesville; 63.14 inches in Jacksonville; and 40.46 inches in Ocala. This is further demonstrated by the varying statistics for each station: the years of maximum rainfall; the years of minimum rainfall; and the cumulative departures from 1960 to 1992 (see Table 2-1 and Figure 6-11). The spatial variability of the rainfall can be attributed to the variability of the local showers and thunderstorms during the summer months that are the major sources of precipitation in the region.

From 1934-1992 and 1960-1992, the mean annual rainfall values at Gainesville, Jacksonville, and Lake City have been higher than the long-term average rainfalls at each location (see Table 6-1). For example, the mean long-term annual rainfall from 1897 to 1992 at Gainesville is 50.91 inches, while the mean annual rainfall from 1934 to 1992 is 52.12 inches. The exception is at Ocala, where the mean annual rainfall from 1960 to 1992 was approximately 1.4 inches less than the long-term mean annual rainfall from 1891 to 1992. The higher mean annual rainfall values from 1934 and 1960 to 1992 at most locations do not correspond with the decreases in ground-water levels that have occurred in the area over the same periods of time (see Figures 6-3 and 6-5).

The cumulative rainfall departures for Jacksonville and Gainesville show two distinct trends in precipitation during the period from 1960 to 1992 (see Figure 6-11). For Gainesville, there was a period of consistently above average rainfall from 1960 to 1972 (4.28 inches/year) and a period of below average rainfall from 1973 to 1992 (2.71 inches/year). The rainfall at Jacksonville shows a similar pattern. There was a

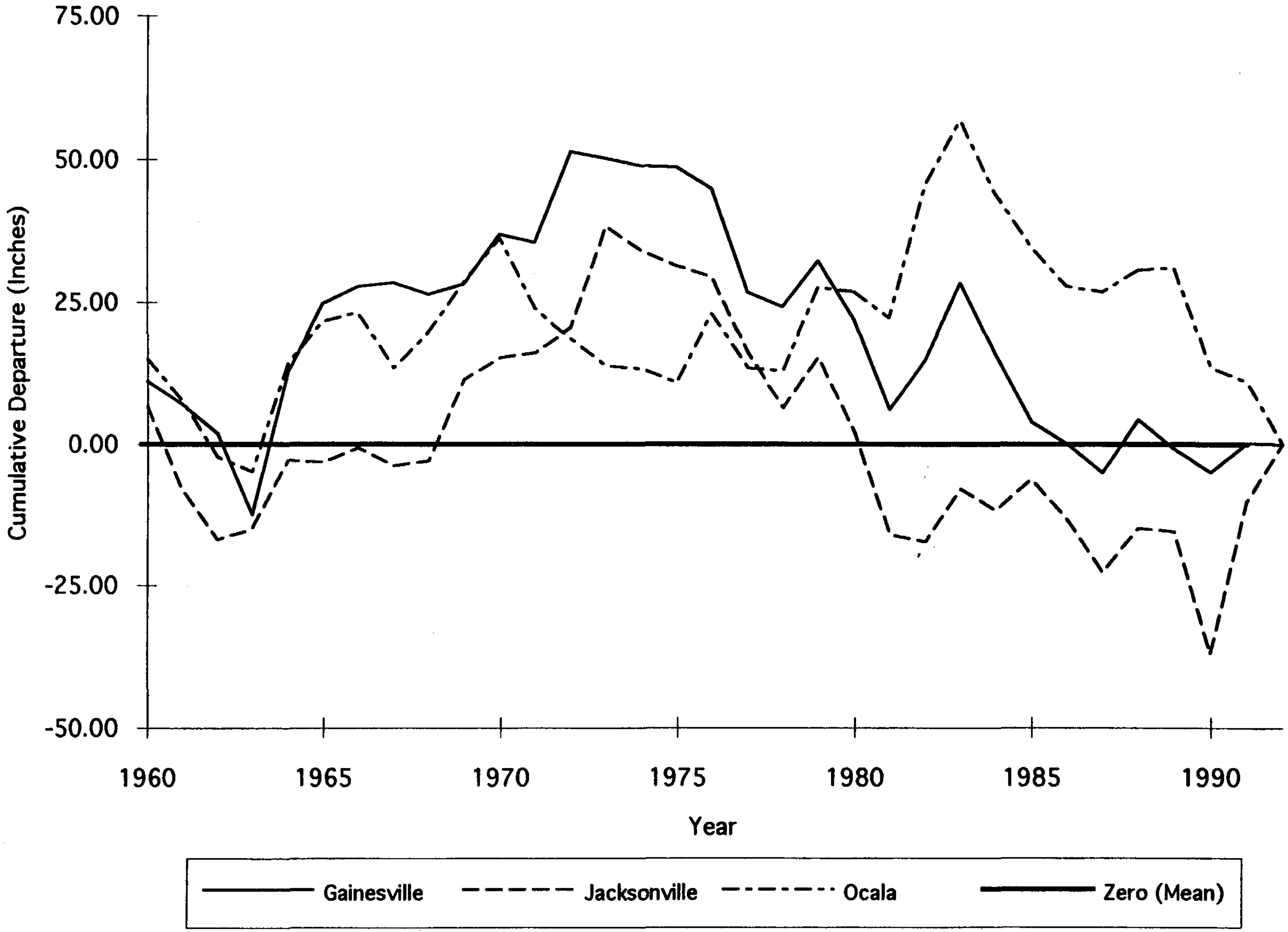


Figure 6-11. Cumulative Departures from Mean Annual Rainfall from 1960 to 1992 for Stations in and Adjacent to the Study Area

Table 6-1 Annual Rainfall for Various Periods for Stations in North-Central Florida

Location	Long-Term Average (inches)	Period of Record	1960-1992 Average (inches)	1934-1992 Average (inches)
Gainesville	50.91	1/1897 - 12/1992	51.81	52.12
Jacksonville	51.78	1/1867 - 12/1992	52.82	53.01
Lake City	52.22	1/1893 - 12/1992	55.69	53.49
Palatka	52.60	1/1923 - 12/1984	NA	NA
Ocala	52.84	1/1891 - 12/1992	51.47	53.16
Starke	52.57	2/1958 - 4/1985	NA	NA
MEAN	52.15			

period of above average rainfall from 1960 to 1973 (2.94 inches/year) and a period of below average rainfall from 1974 to 1992 (2.13 inches/year). Although the decline in rainfall is moderate compared to the period of above average rainfall, the below rain fall average experienced over the past 19 years likely has impacted ground-water levels in the upper Floridan aquifer.

Assuming that the rainfall amounts at Gainesville and Jacksonville are representative of the study area, rainfall has declined 0.2 ft/year since 1974. Based on ground-water level data in the upper Floridan aquifer since the mid 1970's, the hydraulic head has declined an estimated 0.1 ft/year near Gainesville to 0.4 ft/year near Orange Park (Appendices 1-3, Gay 1993). Prior to 1974, rainfall increased 0.3 ft/year from 1960 to 1973, but ground-water levels did not increase correspondingly during this same time period. This is confirmed by the long-term hydrographs for wells in the area, which show relatively continuous declines in ground-water levels starting back in the 1930's (see Figures 6-2 and 6-4).

6.4.2 Ground-Water Use

Ground-water pumpage from the upper Floridan aquifer has increased over the past 20 to 30 years in the vicinity of the study area (see Figure 6-12). From 1970 to 1990, ground-water use in the study area and adjacent areas increased from 242.41 mgd to 434.91 mgd; this is a 79.4 percent increase over a 20-year period (see Table 6-2). Ground-water use in north-central Florida increased at a greater rate than the entire state, in which ground-water use increased 71.6 percent from 1970 to 1990. The population in the region increased 63.2 percent from 1970 to 1990, increasing

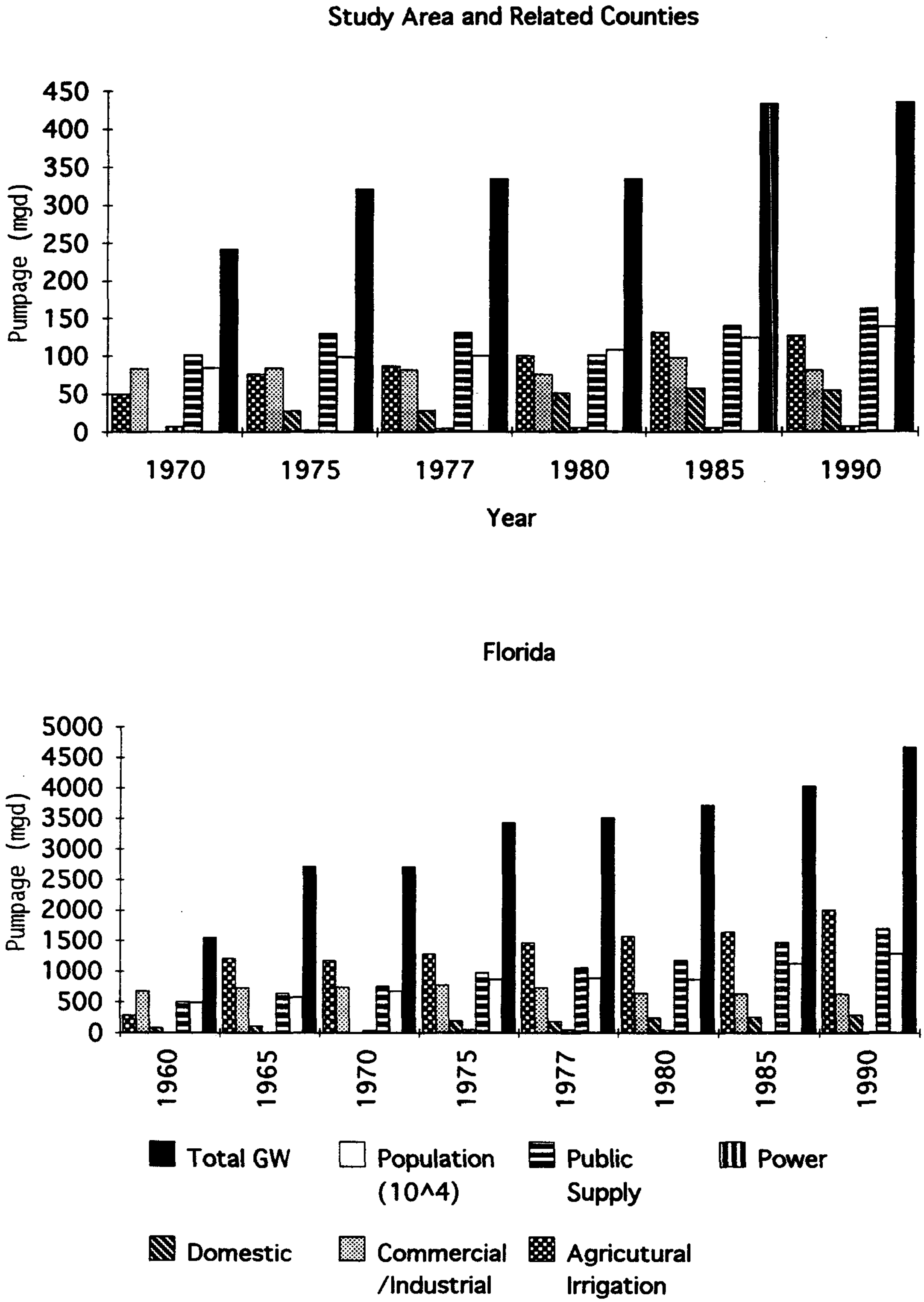


Figure 6-12. Ground-Water Pumpage for Florida and Counties in and Adjacent to the Study Area

Table 6-2 Ground-Water Pumpage for Selected Counties in Florida

Ground-Water Withdrawal (million gallons per day)							Percent Change
County	1970	1975	1977	1980	1985	1990	1970-1990
Alachua	26.40	30.81	36.75	43.543	51.42	52.12	97.42
Baker	0.50	2.56	2.70	3.364	6.07	7.87	1474.00
Bradford	8.87	5.84	6.74	7.95	9.25	8.96	1.01
Clay	7.20	13.92	13.44	13.491	21.26	25.20	250.00
Duval	132.70	155.77	154.02	129.631	159.30	152.98	15.28
Levy	4.90	3.63	4.21	4.319	14.14	21.52	339.18
Marion	11.70	31.18	33.24	34.18	49.14	49.20	320.51
Putnam	25.85	40.61	40.62	59.519	70.27	61.43	137.64
St. Johns	23.50	35.84	41.14	37.188	50.22	51.26	118.13
Union	0.79	1.21	1.22	1.111	2.11	4.37	453.16
Study area & related areas	242.41	321.37	334.08	334.30	433.18	434.91	79.41
Florida	2718.3	3430.2	3506.4	3715.3	4030.4	4664.7	71.60

Note: Pumpage in Columbia and Volusia counties is insignificant in study area.

Source: USGS Water Use Trends Reports.

from 846,470 persons to 1,381,431 persons (see Table 6-3). Since population growth in the area was smaller than the growth in ground-water withdrawals rates, the average ground-water use per capita has increased in north Florida. By contrast, the state population growth from 1970 to 1990 is greater than the state growth in ground-water pumpage, which indicates that the average ground-water use per capita in the state has decreased from 1970 to 1990.

Alachua, Clay, Marion, and Putnam counties have all shown large increases in water use and populations. In Clay County, ground-water use increased 250 percent from 1970 to 1990, and the population increased 230.5 percent during the same 20-year period (see Tables 6-2 and 6-3). The largest water uses in north Florida are for public supply (37.5 percent), industrial and commercial supply (18.7 percent), and agricultural irrigation (29.3 percent) (Marella 1990). The largest ground-water withdrawals in the study area are by Gainesville Regional Utilities (GRU), which pumped 19.13 mgd in 1991, and Georgia Pacific in Palatka, which pumped 15.54 mgd in 1991. The large water users in the study area pumped nearly 153 mgd in 1991 (see Table 6-4 and Figure 6-13). The areas of greatest drawdown generally coincide with the areas of large water uses (see Figure 6-3). For example, a well (USGS 2942070 82163201) located near the GRU Murphree Well Field showed a net decline of 15 ft from 1958 to 1992 (SW 6, see Appendix 2, Gay 1993). The most obvious impact of pumping is the cone of depression extending out from the City of Jacksonville, and which has expanded farther outward in distance over time (see Figures 6-5, 6-6, and 6-7). Ground-water use in Duval County was 152.9 mgd in 1990.

Table 6-3 Population for Selected Counties in Florida

	Population						Percent Change
County	1970	1975	1977	1980	1985	1990	1970-1990
Alachua	104764	130800	133800	151300	172900	181596	73.34
Baker	9242	12300	12700	15300	17310	18486	100.02
Bradford	14625	16300	16900	20000	23400	22515	53.95
Clay	32059	47700	50300	67000	85358	105956	230.50
Duval	528865	578300	573200	571000	624084	672971	27.25
Levy	12756	15600	159--	19900	22460	25923	103.22
Marion	69030	93500	101100	122500	157853	194833	182.24
Putnam	36290	43500	44700	50500	56823	65070	79.31
St. Johns	30727	40200	42800	51300	68822	83829	172.82
Union	8112	10400	10200	10200	10686	10252	26.38
Study area & related areas	846470	988600	1001600	1079000	1239696	1381431	63.20
Florida	6789443	8685100	8917100	8749200	11327734	12937926	90.56

Note: Pumpage in Columbia and Volusia counties is insignificant in study area.

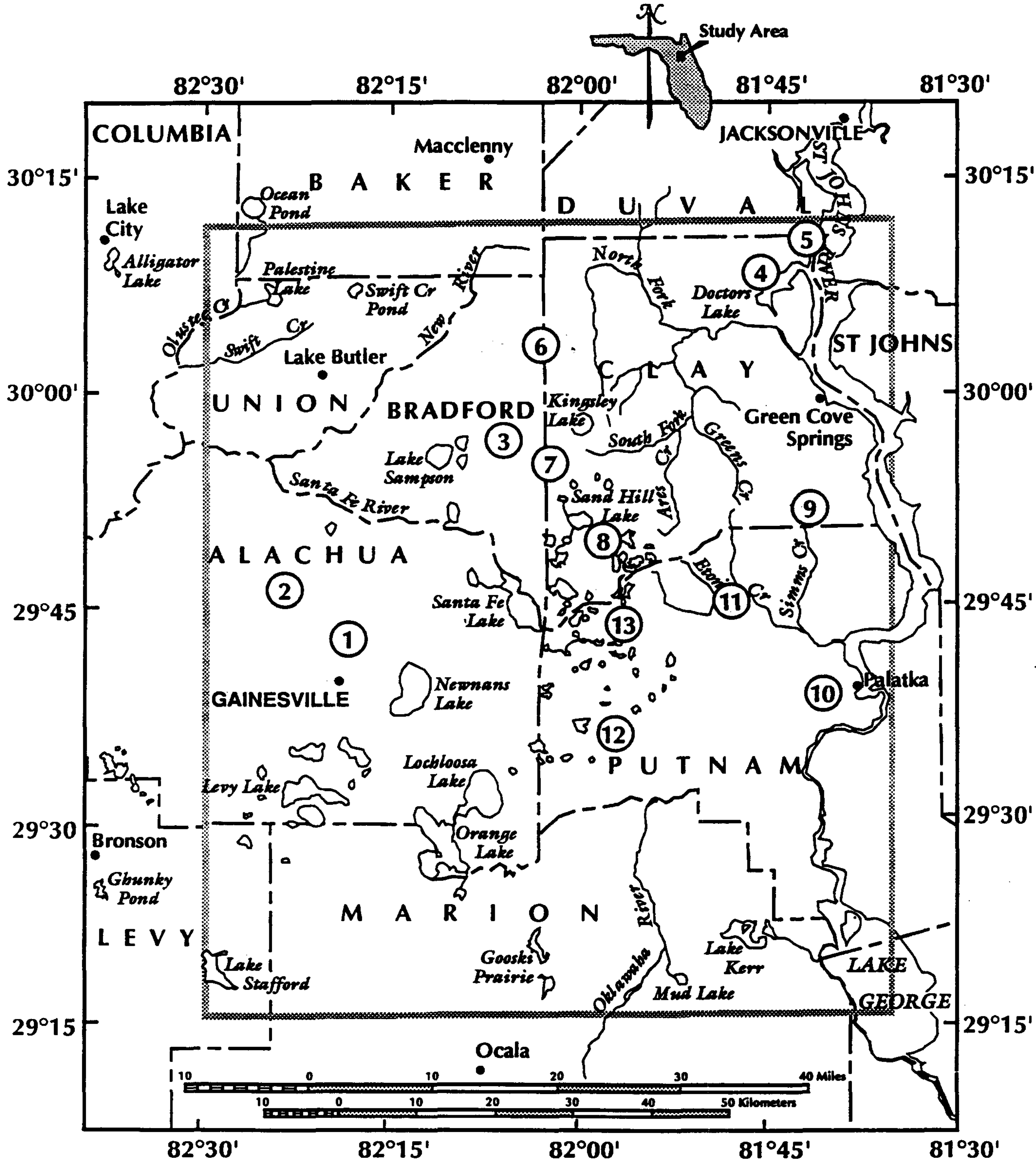
Source: USGS Water Use Trends Reports.

Table 6-4 Ground-Water Withdrawals for Selected Users in North-Central Florida in 1991

User ID	User	Type	County	Average Daily Pumpage (mgd)
1	Gainesville Regional Utilities	Public Supply	Alachua	19.13
2	Deerhaven (1990)	Power	Alachua	2.07
3	City of Starke	Public Supply	Bradford	1.16
4	Kingsley Service Company	Public Supply	Clay	6.16
5	Orange Park	Public Supply	Clay	1.32
6	E. I. Dupont - Highlands Plant	Industrial	Clay	1.18
7	E. I. Dupont - Trail Ridge Plant	Industrial	Clay	1.92
8	Florida Rock - Keystone Mine	Industrial	Clay	1.45
9	RGC Mineral Sands	Industrial	Clay	1.09
10	Palatka	Public Supply	Putnam	2.9
11	Georgia Pacific - Palatka	Industrial	Putnam	15.54
12	Feldspar Corp. - Edgar Mine	Industrial	Putnam	5.23
13	Florida Rock - Grandin Mine	Industrial	Putnam	2.02
	Duval County	All	Duval	152.9

Notes: User identification numbers refer to locations shown on Figure 6-13. Includes most users over 1.0 mgd.

Sources: SJRWMD and SRWMD.



Note: Numbers correspond to user ID numbers in Table 6-4.

Figure 6-13. Major Users of Ground Water in North-Central Florida

7.0 EVALUATION OF SHORT-TERM GROUND-WATER LEVEL CHANGES IN THE UPPER FLORIDAN AQUIFER USING MULTIPLE REGRESSION ANALYSIS

7.1 DEVELOPMENT OF REGRESSION RELATIONS USED TO ESTIMATE CHANGES IN GROUND-WATER LEVELS IN THE UPPER FLORIDAN AQUIFER

Multiple regression analysis was used to determine how changes in rainfall, evaporation, and ground-water pumpage from the upper Floridan aquifer may have caused short-term changes in water levels in the upper Floridan aquifer. The multiple regression approach gives a first approximation of the relation between the response of ground-water levels to changes in rainfall, potential evaporation, and ground-water pumpage (Lopez and Fretwell 1992). The analysis was based on the monthly changes in hydraulic heads, end of the month rainfall totals, estimated monthly potential evaporation rates, and monthly withdrawals from 1985 to 1990. This time frame was chosen because suitable monthly values for water use and ground-water levels were available during this period.

The monthly change in ground-water level was considered the dependent variable, and monthly rainfall totals, potential evaporation rates, and ground-water withdrawals were considered the independent variables. Since ground water is pumped from over 540 locations in the study area, the ground water withdrawal points were grouped into pumping centers based on pumping rates and geographic distribution (see

Figure 7-1). Ten pumping centers were used to represent the wells in the study area, including a small part of the pumpage in Duval County. An eleventh pumping center outside the study area represented most of the pumping in Duval County.

Linear regression analysis assumes that a straight-line relationship exists between each independent variable and the dependent variable (Haan 1977). The multiple regression equation used for this analysis was:

$$Y = m_r * X_r + m_e * X_e + \sum b_n * m_n * X_{pn} \tag{7-1}$$

where: b_n = weighted distance factor (1/ft^2);

m_e = coefficient for potential evaporation;

m_n = coefficient for pumping centers;

m_r = coefficient for rainfall;

n = 1,2, . . ., 11

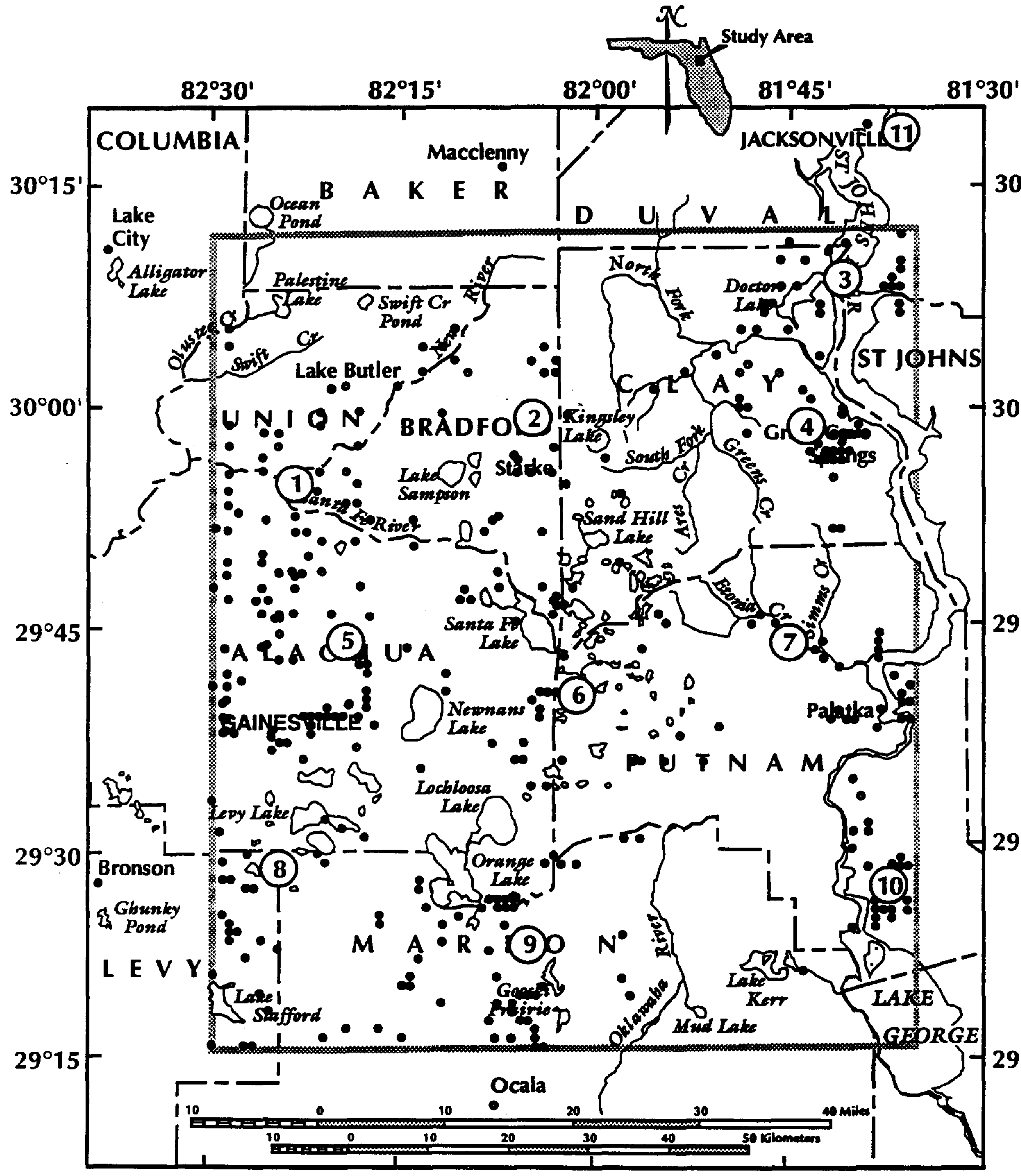
X_e = monthly potential evaporation totals (-ft);

X_{pn} = monthly withdrawals from each pumping center (-ft^3);

X_r = monthly rainfall totals (ft); and

Y = monthly change in ground-water levels (ft).

The coefficients for rainfall and pumping centers were determined by means of the regression analysis. The weighted distance factor was the inverse of the square of the distance between each pumping center and a well location. Ground-water level changes were based on the differences between the measurements taken at the end of each month. Rainfall for a given location was assumed to be the rainfall at the



Note: Small circles are individual withdrawal points, and large circles represent pumping centers.

Figure 7-1. Ground-Water Withdrawal Points in May 1990 and Pumping Centers Used in Regression Analysis nearest rain gage. This assumption is based on the Thiessen method for determining rainfall at a given point in a watershed (Chow et al. 1988). The rainfall from Gainesville was used for all well locations, except one location in the northeast section of the study area. For this location, the rainfall from Jacksonville was used, since it was the rain gage closest to the well. The potential evaporation was estimated by using the pan evaporation measured in Gainesville multiplied by the monthly pan coefficients derived from a study conducted on Lake Okeechobee (Kohler 1954). The monthly pan coefficients for January to December are 0.77, 0.69, 0.73, 0.84, 0.82, 0.85, 0.91, 0.91, 0.85, 0.76, 0.71, and 0.83, respectively (Kohler 1954). Monthly pumpage amounts were determined from water-use amounts for each user using data obtained from SJRWMD, SRWMD, and SWFWMD. The locations of the pumping centers were determined by calculating weighted distances based on the well locations and pumping rates.

7.2 APPLICATION OF MULTIPLE REGRESSION ANALYSIS TO ESTIMATE GROUND-WATER LEVEL CHANGES IN THE UPPER FLORIDAN AQUIFER

Water levels at five wells (37, 33, 45, 19, and 8; see Figure 6-1 on p. 74 for locations) in the study area were examined using multiple regression analysis to estimate changes in hydraulic heads in the upper Floridan aquifer due to ground-water pumpage and climatic factors. The well name, time period of the regression analysis, intercept of the regression line, regression coefficient of each independent variable, correlation coefficient r^2, and t statistic for each coefficient were summarized for the various regression relations (see Table 7-1). Many different regression relations were used to estimate the changes in ground-water levels at each well by varying the combinations of the independent variables: current and previous monthly rainfalls; current and previous monthly potential evaporation rates; and current and previous monthly water pumpage from the different pumping centers. Four regression relations were retained for each well: the relation with the best results; the relation with the worst results; and two other relations (see Table 7-1).

The correlation coefficient, or r^2, can be used to evaluate how well the regression relation estimates the monthly changes in hydraulic heads in the upper Floridan aquifer. A higher r^2 statistic indicates a stronger relationship between the dependent variable and independent variables. The r^2 statistic ranges between 0 and 1. In the regression relations developed in this study, the r^2 statistics ranged from 0.36 to 0.87 (see Table 7-1). Well 8 (USGS 300834081421301) located in the northeast section of the study area had the lowest r^2 statistics, ranging from 0.37 to 0.54, and well 19 (USGS 300020082103001) located in the northwest section of the study area had the highest r^2 statistics, ranging from 0.76 to 0.87. Well 45 (A-0005) also had very low r^2 statistics, ranging from 0.36 to 0.60. Well 37 (P- 0001) and well 33 (C-0120) had r^2 statistics ranging from 0.56 to 0.79 and from 0.64 to 0.75, respectively. Wells 19, 33, and 37 with continuous or daily records of ground-water levels, had relations with higher r^2 statistics than wells 8 and 45, in which periodic ground-water level measurements normally are made near the end of each month (see

Table 7-1 Results of the Regression Relations Used to Determine Changes in Monthly Ground-Water Levels in the Upper Floridan Aquifer

Well	Period	Intercept	Coefficient* Variable		r^2	t
P-0001 37	1/1985 - 12/1990	0.33	-38.95	*PC11	0.56	-0.54
			-1461.3	*PC10		-0.56
			522.38	*PC9		0.26
			173.43	*PC8		0.43
			8.00	*PC7		0.56
			0.73	*PC6		0.26
			214.15	*PC5		1.58
			-441.72	*PC4		-0.47
			416.29	*PC3		1.45
			-502.47	*PC2		-1.71
			316.86	*PC1		0.31
			0.33	*EVAP		0.35
			1.23	*RAIN		3.78
P-0001 37	1/1985 - 12/1990	-0.59	-37.1	*PC11	0.66	-0.58
			-1822.8	*PC10		-0.79
			1196.20	*PC9		0.65
			-253.05	*PC8		-0.67
			-3.80	*PC7		-0.29
			1.30	*PC6		0.52
			160.32	*PC5		1.32
			-296.90	*PC4		-0.35
			408.93	*PC3		1.60
			-527.83	*PC2		-2.01
			17.12	*PC1		0.02
			0.84	*EVAP		0.99
			0.91	*LAGRAIN		3.95
			1.19	*RAIN		4.10
P-0001 37	1/1986 - 12/1990	0.63	15.17	*PC11	0.73	0.22
			-437.19	*PC8		-1.04
			1.18	*PC7		0.08
			1.35	*LAGPC6		0.64
			0.16	*PC6		0.07
			239.96	*PC5		2.02
			-355.66	*PC4		-0.60
			-53.26	*PC3		-0.14
			-190.81	*PC2		-0.71
			189.97	*PC1		0.25
			0.01	*LAG2EVAP		0.01
			-0.69	*LAGEVAP		-0.55
			1.57	*EVAP		1.53
			0.16	*LAG2RAIN		0.72
			0.73	*LAGRAIN		3.15
			1.12	*RAIN		3.82

Table 7-1 Continued

Well	Period	Intercept	Coefficient* Variable		r^2	t
P-0001 37	1/1987-12/1990	0.64	28.956	*PC11	0.79	0.33
			-621.38	*PC8		-1.29
			10.29	*PC7		0.56
			2.19	*LAGPC6		0.96
			-1.20	*PC6		-0.46
			290.09	*PC5		2.20
			62.66	*PC4		0.09
			-179.18	*PC3		-0.42
			-480.64	*PC2		-1.28
			64.73	*PC1		0.08
			0.03	*LAG2EVAP		0.02
			-1.00	*LAGEVAP		-0.65
			1.96	*EVAP		1.56
			0.28	*LAG2RAIN		1.16
			0.81	*LAGRAIN		3.14
			1.14	*RAIN		3.63
C-0120 33	1/1986-12/1990	1.52	-12.22	*PC11	0.64	-0.18
			1140.12	*PC10		0.33
			-1301.4	*PC9		-0.50
			-78.03	*PC8		-0.18
			10.87	*PC7		0.49
			10.12	*PC6		0.38
			127.60	*PC5		1.04
			-423.56	*PC4		-0.58
			439.16	*PC3		1.41
			-73.10	*PC2		-0.50
			620.41	*PC1		1.06
			1.09	*RAIN		4.47
C-0120 33	1/1986-12/1990	0.28	-37.62	*PC11	0.73	-0.61
			-1535.2	*PC10		-0.47
			775.25	*PC9		0.31
			-482.08	*PC8		-1.12
			-2.97	*PC7		-0.14
			35.44	*PC6		1.42
			92.44	*PC5		0.84
			-572.27	*PC4		-0.83
			248.89	*PC3		0.82
			-86.94	*PC2		-0.66
			393.22	*PC1		0.74
			-0.92	*LAGEVAP		-1.09
			2.60	*VAP		2.67
			0.69	*LAGRAIN		3.22
			1.29	*RAIN		4.67

Table 7-1 Continued

Well	Period	Intercept	Coefficient*	Variable	r^2	t
C-0120 33	1/1986-12/1990	-0.93	-38.87	*PC11	0.74	-0.65
			-413.45	*PC8		-0.94
			14.21	*LAGPC7		0.59
			-10.28	*PC7		-0.43
			1.60	*LAGPC6		0.09
			32.12	*PC6		1.49
			-109.67	*LAGPC5		-1.20
			58.79	*PC5		0.54
			-549.92	*PC4		-1.10
			351.94	*PC3		1.11
			-95.84	*PC2		-0.71
			277.30	*PC1		0.58
			0.22	*LAGEVAP		0.19
			2.33	*EVAP		2.40
			0.93	*LAGRAIN		3.37
			1.38	*RAIN		4.89
C-0120 33	1/1986-12/1990	-1.07	-55.201	*PC11	0.75	-0.95
			13.03	*LAGPC7		0.54
			-9.94	*PC7		-0.42
			-2.36	*LAGPC6		-0.13
			30.40	*PC6		1.41
			-137.33	*LAGPC5		-1.44
			90.62	*PC5		0.83
			-561.88	*PC4		-2.04
			384.44	*PC3		1.26
			-110.56	*PC2		-0.82
			0.85	*LAG2EVAP		0.85
			0.22	*LAGEVAP		0.16
			2.09	*EVAP		2.08
			0.21	*LAG2RAIN		1.00
			0.96	*LAGRAIN		3.43
			1.38	*RAIN		4.89
A-0005 45	1/1986-12/1990	2.58	257.76	*PC11	0.36	1.00
			458.00	*PC10		0.07
			-70.40	*PC9		-0.04
			-31.95	*PC8		-0.11
			131.85	*PC7		1.18
			-81.67	*PC6		-0.84
			107.22	*PC5		1.45
			68.25	*PC4		0.01
			65.38	*PC3		0.04
			-506.35	*PC2		-0.44
			545.91	*PC1		0.30
			-0.43	*EVAP		-0.25
			0.18	*RAIN		0.30

Table 7-1 Continued

Well	Period	Intercept	Coefficient* Variable	r^2	t
A-0005 45	1/1986-12/1990	1.35	156.834 *PC11	0.57	0.74
			-1919.8 *PC10		-0.35
			594.92 *PC9		0.38
			-434.98 *PC8		-1.74
			0.49 *PC7		0.01
			57.82 *PC6		0.68
			29.53 *PC5		0.47
			-48.21 *PC4		-0.01
			376.31 *PC3		0.29
			-123.25 *PC2		-0.13
			564.71 *PC1		0.38
			0.88 *EVAP		0.61
			1.88 *LAGRAIN		4.79
			0.48 *RAIN		0.96
A-0005 45	1/1986-12/1990	1.37	177.77 *PC11	0.58	0.83
			-2273.4 *PC10		-0.41
			722.90 *PC9		0.45
			-396.37 *PC8		-1.56
			-12.25 *PC7		-0.13
			52.36 *PC6		0.61
			31.15 *PC5		0.49
			33.82 *PC4		0.01
			-8.13 *PC3		-0.01
			36.00 *PC2		0.04
			398.39 *PC1		0.27
			1.34 *LAGEVAP		0.90
			-0.03 *EVAP		-0.02
			1.91 *LAGRAIN		4.83
			0.58 *RAIN		1.14
A-0005 45	1/1986-12/1990	1.37	162.14 *PC11	0.60	1.10
			423.68 *PC9		0.57
			-432.89 *PC8		-1.53
			-50.29 *PC7		-0.51
			17.05 *LAGPC6		0.38
			38.12 *PC6		0.53
			-21.39 *LAGPC5		-0.40
			44.49 *PC5		0.81
			295.23 *PC2		0.31
			592.48 *PC1		0.39
			1.98 *LAG2EVAP		1.04
			0.15 *LAGEVAP		0.06
			-0.77 *EVAP		-0.43
			0.43 *LAG2RAIN		1.01
			2.02 *LAGRAIN		3.74
			0.43 *RAIN		0.81

Table 7-1 Continued

Well	Period	Intercept	Coefficient* Variable	r^2	t
300020082103001	1/1985-12/1990	3.07	7.43172 *PC11	0.76	0.18
19			5754.09 *PC10		0.96
			-5980.2 *PC9		-1.21
			344.91 *PC8		0.58
			66.35 *PC7		1.17
			-143.11 *PC6		-1.08
			82.92 *PC5		0.64
			407.08 *PC4		0.41
			790.57 *PC3		4.52
			5.98 *PC2		0.93
			69.76 *PC1		0.45
			1.15 *RAIN		5.68
300020082103001	1/1985-12/1990	2.24	-11.19 *PC11	0.82	-0.27
19			-1314.3 *PC10		-0.22
			-622.76 *PC9		-0.13
			-133.75 *PC8		-0.21
			8.42 *PC7		0.15
			32.53 *PC6		0.24
			51.42 *PC5		0.42
			398.72 *PC4		0.41
			623.52 *PC3		3.56
			-1.34 *LAGPC2		-0.13
			6.63 *PC2		0.72
			-14.10 *PC1		-0.10
			0.77 *LAGEVAP		0.98
			0.62 *EVAP		0.69
			0.78 *LAGRAIN		3.82
			1.33 *RAIN		5.53
300020082103001	1/1985-12/1990	2.01	-6.14 *LAGPC11	0.82	-0.10
19			-0.12 *PC11		0.00
			-447.63 *PC8		-0.77
			-3.30 *PC7		-0.06
			34.00 *PC6		0.32
			57.99 *PC5		0.46
			109.51 *PC4		0.20
			632.31 *PC3		3.89
			-0.84 *LAGPC2		-0.08
			6.42 *PC2		0.66
			-14.11 *PC1		-0.10
			0.86 *LAGEVAP		-0.97
			0.41 *EVAP		0.46
			0.23 *LAG2RAIN		1.16
			0.74 *LAGRAIN		3.72
			1.32 *RAIN		5.73

Table 7-1 Continued

Well	Period	Intercept	Coefficient*	Variable	r^2	t
30002008210300119	1/1986-12/1990	1.08	-60.45	*LAGPC11	0.87	-1.01
			7.12	*PC11		0.12
			73.82	*PC7		1.36
			64.42	*PC6		0.66
			-80.93	*PC5		-0.63
			674.00	*PC4		2.86
			-4.66	*PC3		-0.46
			0.62	*LAGPC2		0.05
			0.74	*PC2		0.07
			-43.43	*PC1		-0.43
			0.03	*LAG2EVAP		0.04
			1.71	*LAGEVAP		1.51
			0.87	*EVAP		1.04
			0.08	*LAG2RAIN		0.48
			0.63	*LAGRAIN		3.49
			1.35	*RAIN		5.97
3008340814213018	1/1985-12/1990	1.82	-4.49	*PC11	0.37	-0.16
			-953.20	*PC10		-0.04
			-3359.6	*PC9		-0.09
			-278.78	*PC8		-0.05
			-182.16	*PC7		-0.91
			-101.37	*PC6		-0.09
			-1925.2	*PC5		-0.84
			299.32	*PC4		0.35
			0.16	*PC3		0.62
			2353.21	*PC2		1.60
			4294.92	*PC1		0.46
			0.25	*EVAP		0.09
			2.07	*RAIN		2.54
3008340814213018	1/1986-12/1990	1.83	-2.37	*PC11	0.41	-0.08
			-23285	*PC10		-1.01
			42026.6	*PC9		1.10
			-4539.2	*PC8		-0.69
			-195.56	*PC7		-0.81
			1831.56	*PC6		1.24
			-1360.7	*PC5		-0.54
			-232.91	*PC4		-0.26
			0.50	*PC3		1.64
			442.08	*PC2		0.28
			4627.28	*PC1		0.49
			-0.19	*EVAP		-0.07
			0.08	*LAGRAIN		0.09
			0.89	*RAIN		0.91

Table 7-1 Continued

Well	Period	Intercept	Coefficient* Variable		r²	t
3008340814213018	1/1986-12/1990	3.55	-5.4015	*PC11	0.54	-0.20
			-20759	*PC10		-1.01
			15601	*PC9		0.45
			-8118.4	*PC8		-1.35
			-77.39	*PC7		-0.35
			1026.12	*PC6		0.77
			909.14	*PC5		0.39
			429.94	*PC4		0.53
			0.36	*PC3		1.29
			250.92	*PC2		0.17
			5928.67	*PC1		0.70
			-11.95	*LAGEVAP		-3.49
			8.54	*EVAP		2.35
			0.53	*LAGRAIN		0.67
			-0.40	*RAIN		-0.42
3008340814213018	1/1986-12/1990	2.42	-31.31	*PC11	0.54	-0.96
			30.86	*LAGPC11		0.97
			-6171.6	*PC8		-1.06
			-27.69	*PC7		-0.13
			524.96	*PC6		0.43
			607.61	*PC5		0.26
			42.04	*PC4		0.09
			0.10	*LAGPC3		0.35
			0.33	*PC3		1.18
			129.55	*PC2		0.10
			4529.26	*PC1		0.59
			-11.46	*LAGEVAP		-2.87
			8.54	*EVAP		2.20
			-0.89	*LAG2RAIN		-0.99
			0.76	*LAGRAIN		0.86
			-0.67	*RAIN		-0.67

Variable Description:

EVAP = monthly potential evaporation;
LAGEVAP = previous month's potential evaporation;
LAGPCN = previous month's ground-water withdrawal from pumping center N;
LAGRAIN = previous month's rainfall;
LAG2EVAP = previous potential evaporation from two months ago;
LAG2RAIN = previous rainfall from two months ago;
PCN = monthly ground-water withdrawal from pumping center N (N=1, . . . , 11); and
RAIN = monthly rainfall of nearest rain gage.

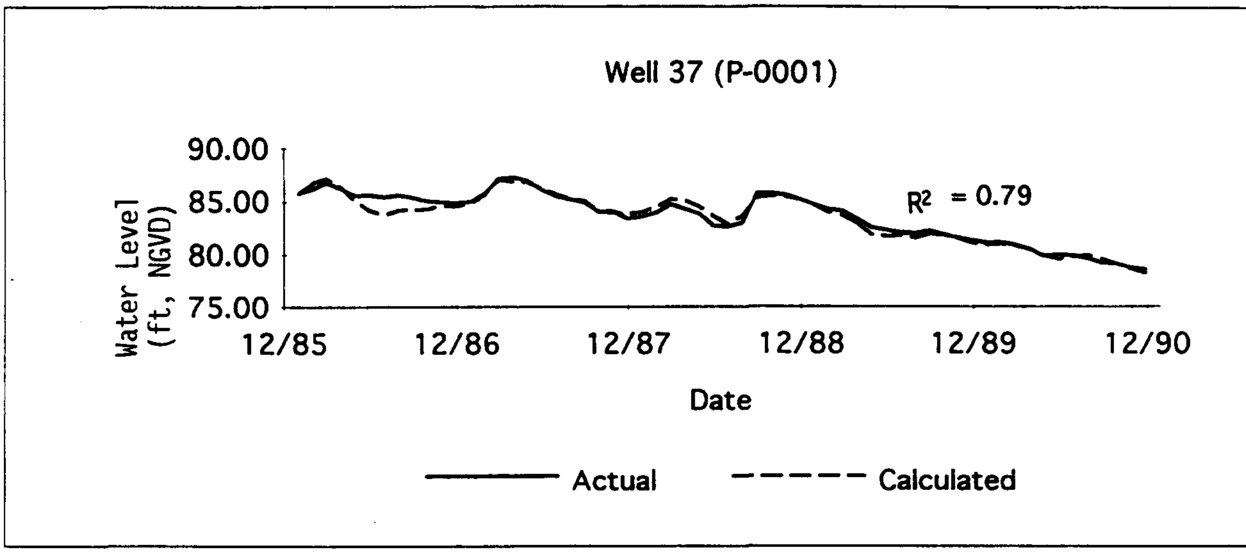
Table 7-1). The r^2 statistics tended to increase with the addition of the previous month's climatic factors. For example, the r^2 statistic for well 37 (P-0001) increased from 0.56 to 0.66 when the independent variable LAGRAIN (previous month's rainfall) was added to the regression relation. The regression relations for the period from 1986 to 1990 had higher r^2 statistics than regression relations for the period from 1985 to 1990.

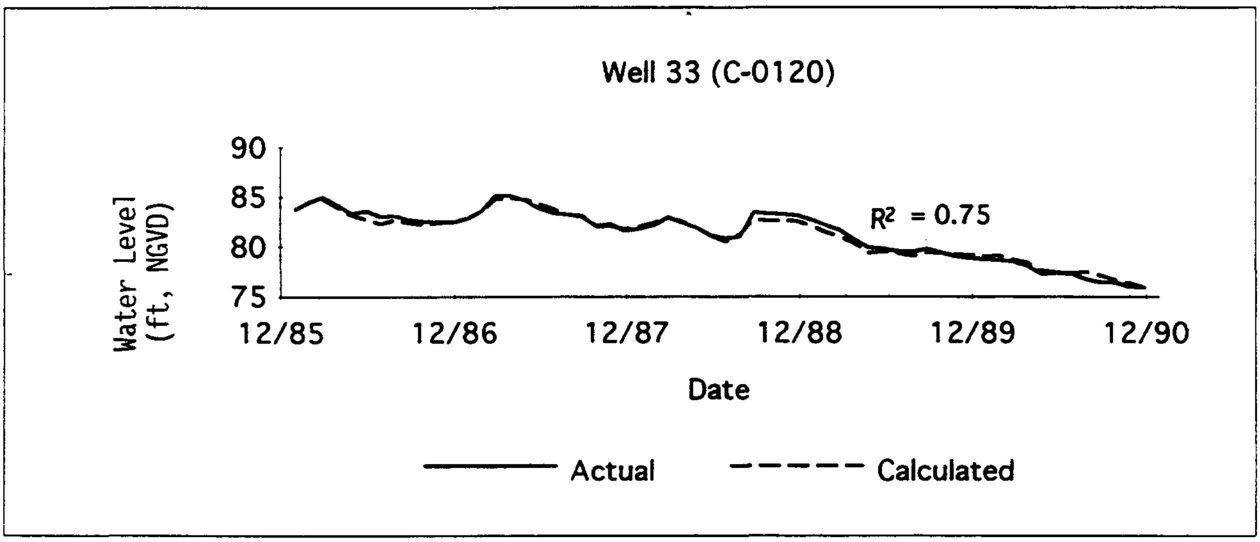
The absolute value of the t statistic indicates the relative influence of each independent variable in the regression relation. The higher the absolute value of the t statistic, the more useful the variable is in estimating ground-water level changes.

The current and previous monthly rainfalls usually had the highest t statistics in the regression relations and had positive coefficients (see Table 7-1). In many relations, at least one pumping center had a fairly high t value and had a positive coefficient. In regression relations with the higher r^2 statistics, the monthly potential evaporation had a significant t statistic and had a positive coefficient. In some cases, the previous month's potential evaporation had a significant t value and a positive coefficient. Positive coefficients would be expected for significant independent variables, since rainfall was entered as a positive number, and potential evaporation and ground-water pumping were entered as negative numbers. The pumping centers had high coefficients, because input pumping amounts were extremely low when multiplied by the weighted distance factor, which is the reciprocal of the square of distance between the well and pumping center. For example, at pumping center 4, 48,900,000 ft^3 of water were withdrawn in May 1990, and the distance from this pumping center to well 19 (P-0001) is 138,000 ft. The input pumping amount equals -48,900,000 ft^3 $(138{,}000\ ft)^2$ = -0.00257 ft.

7.3 COMPARISONS OF ESTIMATED AND MEASURED HYDRAULIC HEADS IN THE UPPER FLORIDAN AQUIFER

For each well, the regression relation with the highest r^2 statistic was used to estimate ground-water level changes, and these values were used to calculate hydraulic heads in the upper Floridan aquifer. To calculate the hydraulic heads using the regression relation at each well, the actual ground-water level at the well in December 1985 was used as the starting value, and the estimated sequential monthly changes in ground-water levels were added to this value to obtain estimated monthly hydraulic heads in the upper Floridan aquifer from 1986 to 1990. The calculated values were plotted with the actual ground-water level measurements taken at each well (see Figures 7-2 and 7-3). As would be expected, for the wells at which the regression relations had the highest r^2 statistics, i.e., wells 37, 33, and 19, the calculated ground-water levels closely matched the actual ground-water levels from 1986 to 1990. The calculated ground-water levels for wells 45 and 8 showed more variations from the actual ground-water levels from 1986 to 1990. This would be expected, since these two wells had much lower r^2 statistics than the other three wells. All of the wells showed declining ground-water levels from 1986 to 1990 for both observed and estimated values.





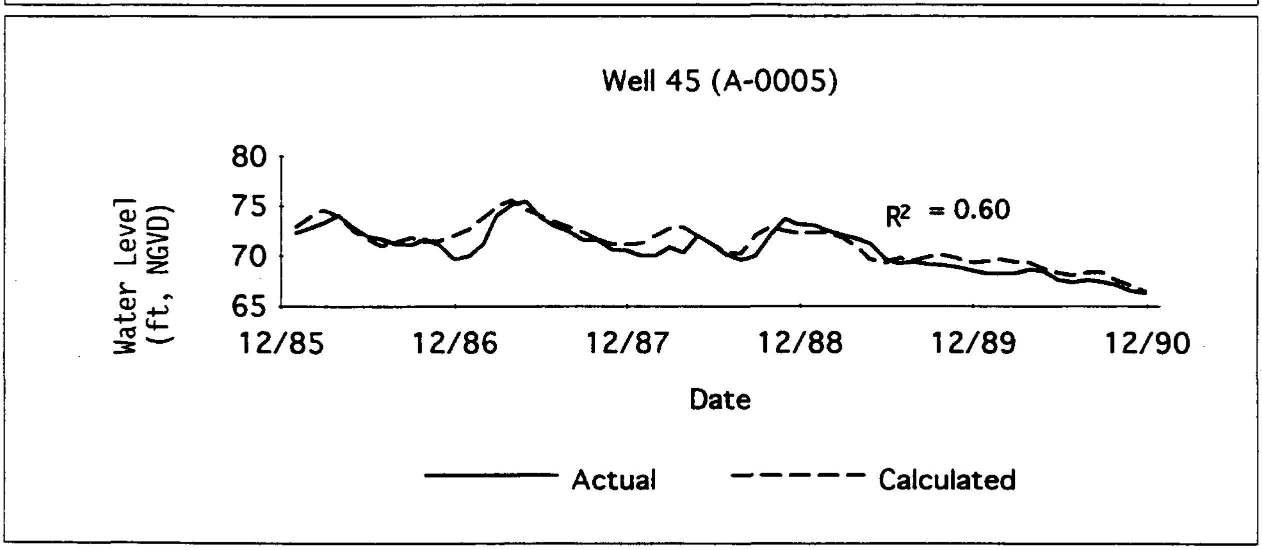


Figure 7-2. Hydrographs of Actual and Calculated Hydraulic Heads in the Upper Floridan Aquifer from 1986 to 1990 for Wells 37, 33, and 45

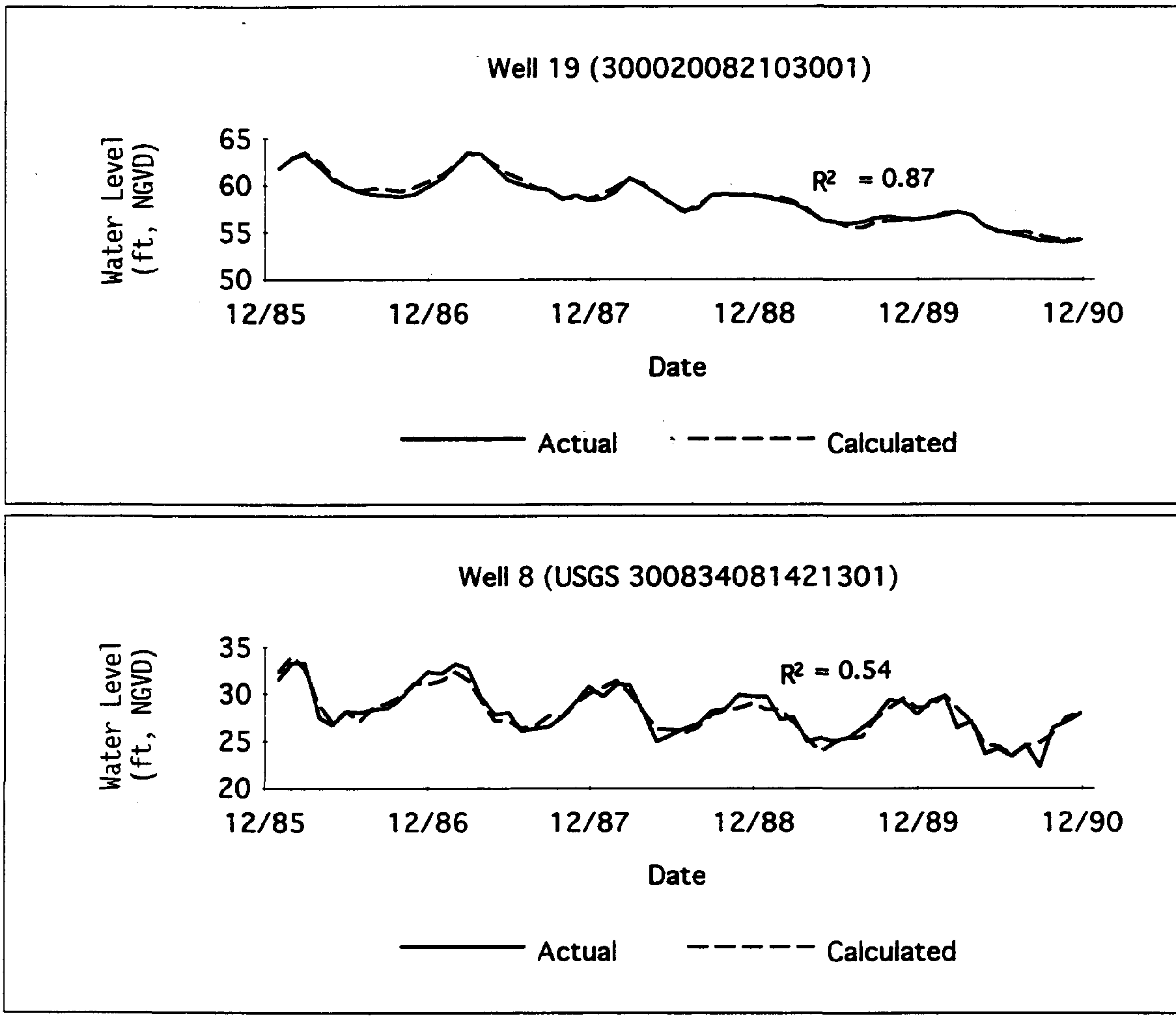


Figure 7-3. Hydrographs of Actual and Calculated Hydraulic Heads in the Upper Floridan Aquifer from 1986 to 1990 for Wells 19 and 8

Greater confidence is developed in the regression relation, when the regression relation demonstrates the ability to predict the critical periods of low and high ground-water levels. Most of the plotted regression relations showed the important high and low heads at the appropriate times (see Figures 7-2 and 7-3). For example, at well 37, the observed ground-water levels ranged from 78.61 to 87.32 ft, NGVD, and estimated ground-water levels ranged from 78.22 to 87.14 ft, NGVD. At well 45, the observed ground-water levels ranged from 66.24 to 75.41 ft, NGVD, and estimated ground-water levels ranged from 66.45 to 75.55 ft, NGVD. After comparing the calculated hydraulic heads versus the actual head measurements, it appears that the regression relations developed for the wells adequately predicted the changes in ground-water levels from 1986 to 1990. However, the regression relations developed for wells 8 and 45 showed more discrepancies between actual and predicted ground-water level changes from 1986 to 1990 than the other three wells (see Figures 7-2 and 7-3).

7.4 APPLICATION OF REGRESSION RELATIONS TO ESTIMATE CHANGES IN GROUND-WATER LEVELS IN THE UPPER FLORIDAN AQUIFER IN RESPONSE TO CHANGES IN RAINFALL AND GROUND-WATER PUMPAGE

The regression relations with the highest r^2 statistics were used to examine the ground-water level changes at wells 37 and 19 in response to varying the rainfall and pumpage. The usual procedure is to vary the value of one of the independent variables while holding the others constant and computing the corresponding change in the dependent variable. Because the effects of changing rainfall or pumpage on water levels in the aquifer are cumulative, a different procedure was used in this investigation. To evaluate the effect of changing rainfall, varying percentages of average monthly rainfall and actual ground-water pumpage were used in the regression relations to estimate the changes in ground-water levels at each well. To determine the effect of changing ground-water pumpage, varying percentages of average monthly ground-water pumpage and actual rainfall amounts were used in the regression relations to estimate changes in ground-water levels at each well. This method was used by Lopez and Fretwell (1992) to evaluate the relation between changes in water levels in the surficial and upper Floridan aquifers and lake stage and changes in climatic conditions and well-field pumpage using multiple linear regression relations.

7.4.1 Limitation of Regression Relations

The multiple linear regression relations that were developed in this study are only "best fit" models that represent the complex natural processes that determine the changes in water levels in the upper Floridan aquifer. The input data determine the results of the regression relation: the independent variable coefficients; and the regression constants. The application of the regression equations to other data, such as varying percentages of rainfall and ground-water pumpage, may produce erroneous results (Lopez and Fretwell 1992). Caution must be used when examining the outcomes in the changes in ground-water levels due to varying rainfall and ground-water withdrawals.

7.4.2 Effects of Varying Rainfall on Ground-Water Levels

The regression relations for wells 37 and 19 with the highest r^2 statistics were used to examine changes in ground-water levels in response to varying average rainfall amounts. Sequential estimates of monthly water levels at each well were computed using the regression relation by inputting 75, 90, 100, 110, and 125 percent of average monthly rainfall, while keeping all other independent variables unchanged. The average monthly rainfall from 1986 to 1990 was used, since both regression relations were determined over this same time frame (see Table 7-2). The average annual rainfall in Gainesville from 1986 to 1990 was 49.94 inches, which is less than one inch below the annual average rainfall from 1897 to 1992 of 50.91 inches. The observed and estimated hydraulic heads in 1990 were calculated for each well (see Tables 7-3 and 7-4 and Figures 7-4 and 7-5).

In the regression relations, increasing the percent of average rainfall amounts causes ground-water levels to increase in the upper Floridan aquifer (Tables 7-3 and 7-4 and Figures 7-4 and 7-5). For example, when inputting 75, 100, and 125 percent of average monthly rainfall in the regression relation for well 37, the hydraulic heads in December 1990 were calculated to be 66.63, 78.21, and 89.79 ft, NGVD, respectively (Table 7-3). The hydraulic heads at well 19 in December 1990 were calculated to be 43.43, 54.17, and 64.91 ft, NGVD, respectively, when inputting 75, 100, and 125 percent of average monthly rainfall in the regression relation for well 19 (Table 7-4). For both wells, the observed water levels are very close to the estimates com-

Table 7-2 Observed Monthly Rainfall for 1990 and Mean Monthly Rainfall Values at Gainesville, Florida

Month	1990 Actual Rainfall (inches)	Average 1897-1992 (inches)	Average 1986-1990 (inches)	Average 1986-1990 (feet)
Jan	1.88	3.06	3.44	0.287
Feb	2.86	3.50	3.84	0.320
Mar	3.62	3.68	5.36	0.447
Apr	3.67	2.99	1.49	0.124
May	3.18	3.49	2.73	0.228
Jun	5.71	6.55	5.13	0.427
Jul	10.43	7.12	5.78	0.482
Aug	8.1	7.28	8.95	0.746
Sep	2.14	5.36	5.63	0.469
Oct	3.51	2.94	2.41	0.201
Nov	1.07	1.92	2.87	0.239
Dec	1.39	3.02	2.31	0.193
SUM	47.56	50.91	49.94	4.16
0.75*SUM	35.67	38.18	37.45	3.12
0.90*SUM	42.80	45.82	44.94	3.75
1.10*SUM	52.32	56.00	54.93	4.58
1.25*SUM	59.45	63.64	62.42	5.20

Table 7-4 Observed and Estimated Monthly Hydraulic Heads in the Upper Floridan Aquifer at Well 19 (3000200812103001) in 1990 When Varying Average Rainfall Amounts

Month	Actual Head (feet)	Estimated monthly hydraulic heads in the upper Floridan aquifer with varying amounts of rainfall where number equals percentage of average rainfall (feet)					
		75	90	100	110	125	Actual[a]
01/90	56.48	47.67	52.91	56.40	59.89	65.13	56.54
02/90	56.76	48.17	53.50	57.05	60.61	65.94	57.01
03/90	57.14	48.25	53.70	57.34	60.97	66.43	57.04
04/90	56.76	47.73	53.26	56.94	60.62	66.15	56.79
05/90	55.59	46.34	51.93	55.65	59.38	64.97	55.66
06/90	55.05	45.37	51.06	54.86	58.66	64.36	54.97
07/90	54.77	44.50	50.34	54.23	58.13	63.97	54.90
08/90	54.5	44.12	50.16	54.19	58.22	64.26	55.01
09/90	54.05	43.82	50.03	54.17	58.31	64.53	54.59
10/90	54.02	43.46	49.76	53.97	58.17	64.48	54.32
11/90	53.93	43.35	49.73	53.98	58.23	64.62	54.16
12/90	54.16	43.43	49.87	54.17	58.47	64.91	54.16

[a]Actual rainfall data from 1986 to 1990 used to estimate heads.

Note: Datum is NGVD.

Table 7-3 Observed and Estimated Monthly Hydraulic Heads in the Upper Floridan Aquifer at Well 37 (P-0001) in 1990 When Varying Average Rainfall Amounts

Month	Actual Head (feet)	Estimated monthly hydraulic heads in the upper Floridan aquifer with varying amounts of rainfall where number equals percentage of average rainfall (feet)					
		75	90	100	110	125	Actual[a]
01/90	81.07	71.38	77.02	80.78	84.54	90.18	80.92
02/90	81.15	71.49	77.23	81.05	84.88	90.62	81.04
03/90	80.89	71.35	77.22	81.13	85.04	90.90	80.84
04/90	80.56	70.78	76.74	80.71	84.68	90.63	80.49
05/90	79.91	69.98	76.00	80.02	84.04	90.07	79.95
06/90	80.03	69.32	75.45	79.54	83.63	89.76	79.60
07/90	79.96	68.80	75.08	79.26	83.45	89.72	79.82
08/90	79.65	68.33	74.81	79.13	83.45	89.93	79.93
09/90	79.19	67.94	74.61	79.06	83.50	90.17	79.58
10/90	79.16	67.44	74.23	78.76	83.29	90.08	79.13
11/90	78.78	67.02	73.90	78.49	83.07	89.95	78.68
12/90	78.61	66.63	73.58	78.21	82.84	89.79	78.22

[a]Actual rainfall data from 1986 to 1990 used to estimate heads.

Note: Datum is NGVD.

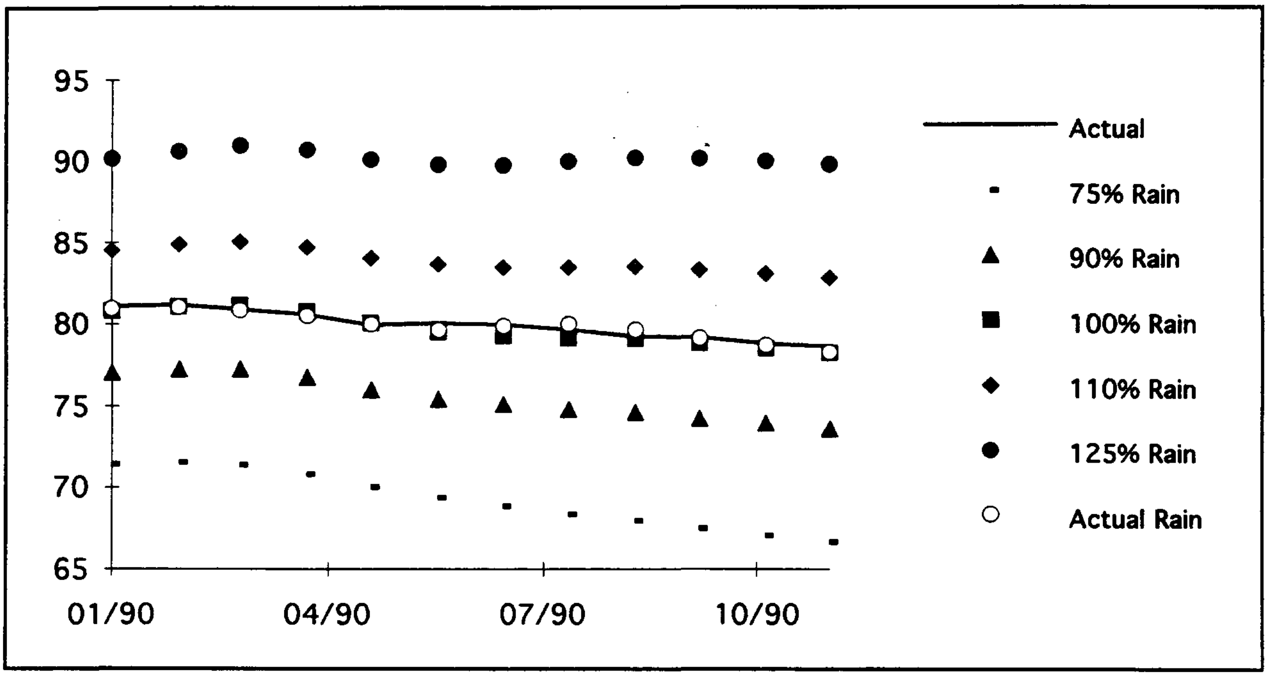


Figure 7-4. Observed and Estimated Monthly Ground-Water Levels in the Upper Floridan Aquifer at Well 37 (P-0001) in 1990 When Varying Average Rainfall Amounts

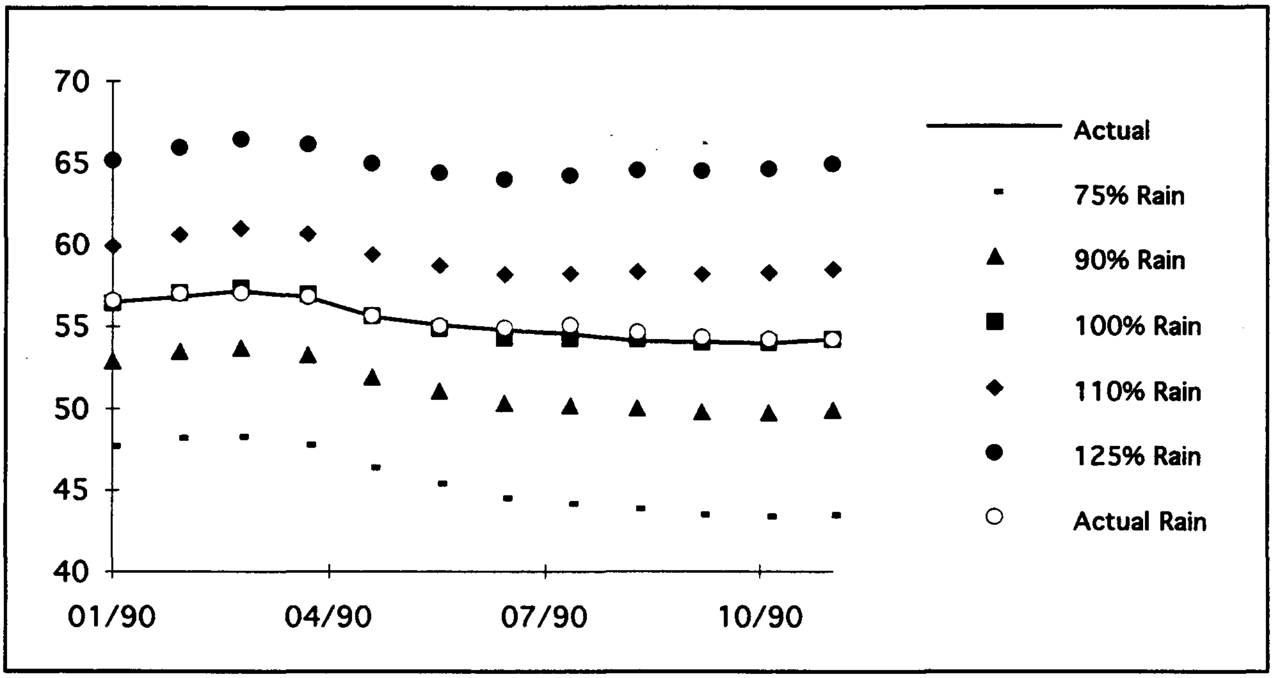


Figure 7-5. Observed and Estimated Monthly Ground-Water Levels in the Upper Floridan Aquifer at Well 19 (3000200812103001) in 1990 When Varying Average Rainfall Amounts

puted using 100 percent of the average monthly rainfall. The actual rainfall at Gainesville in 1990 was closest to 100 percent of average rainfall from 1986 to 1990.

After reviewing the actual ground-water levels from 1986 to 1990 at wells 37 and 19 (see Figures 7-2 and 7-3), it appears that rainfall from 1986 to 1990 would have to have been above normal to maintain the ground-water levels at the same levels from 1986 to 1990. For well 37, the actual and estimated ground-water levels ranged between 86.80 and 84.16 ft, NGVD, for 1986 (see Figure 7-2). Based on the regression relation for well 37 (Table 7-1), the monthly rainfall from 1986 to 1990 would have to have been approximately 110 percent above average to maintain ground-water levels in 1990 at well 37 near the 1986 values (Table 7-3). For well 19, the actual and estimated ground-water levels ranged between 63.48 and 58.70 ft, NGVD, for 1986 (Figure 7-3). Based on the regression relation for well 19 (Table 7-1), the monthly rainfall from 1986 to 1990 also would have to have been approximately 110 percent above average to maintain ground-water levels in 1990 at well 19 near the 1986 values (Table 7-4).

7.4.3 Effects of Varying Ground-Water Pumpage on Ground-Water Levels

Sequential estimates of monthly ground-water levels at each well were computed using the regression relation by inputting 75, 90, 100, 110, and 125 percent of the average regional monthly pumpage and actual monthly rainfall and potential evaporation. The average monthly withdrawals from 1986 to 1990 were used, since the regression relations with the highest r^2 statistics for wells 37 and 19 were determined over this time period. The average monthly withdrawals for two selected pumping centers and for all pumping centers combined is presented in Table 7-5. The average pumpage from 1986 to 1990 was 12.12×10^9 ft^3/year (248.6 mgd), which is less than the actual annual pumpage in 1990 of 13.7×10^9 ft^3/year (280.8 mgd). The observed and estimated hydraulic heads in 1990 for each well are presented in Tables 7-6 and 7-7 and plotted against time in Figures 7-6 and 7-7.

In the regression relations, increasing pumpage causes ground-water levels to decrease in the upper Floridan aquifer (see Tables 7-6 and 7-7) and Figures 7-6 and 7-7). For example, when inputting 75, 100, and 125 percent of average monthly regional pumpage in the regression relation for well 37, the hydraulic heads in May 1990 were calculated to be 94.46, 79.26, and 64.07 ft, NGVD, respectively (Table 7-6). The hydraulic heads at well 19 in May 1990 were calculated to be 68.33, 55.76, and 43.20 ft, NGVD, respectively, when inputting 75, 100, and 125 percent of average monthly pumpage in the regression relation for well 19 (Table 7-7). For both wells, the observed water levels are very close to the estimates computed using 100 percent of the average monthly withdrawals (Tables 7-6 and 7-7 and Figures 7-6 and 7-7).

After reviewing the observed ground-water levels from 1986 to 1990 at wells 37 and 19 (Figures 7-2 and 7-3), it appears that withdrawal amounts from 1986 to 1990 would have to have been below average to maintain the ground-water levels at the same levels from 1986 to 1990. Based on the regression relation for well 37 (Table 7-1), the monthly regional pumpage from 1986 to 1990 would have to have been approximately 10 percent below average to maintain ground-water levels in 1990

Table 7-5 Observed Pumpage in 1990 and 1986-1990 Mean Pumpage for Pumping Centers 2 and 6 and Total for All Pumping Centers

Month	1990 Actual Pumpage for Pumping Center 2 (ft^3)	Average Pumpage 1986-1990 for Pumping Center 2 (ft^3)	1990 Actual Pumpage for Pumping Center 6 (ft^3)	Average Pumpage 1986-1990 for Pumping Center 6 (ft^3)	1990 Actual Pumpage for All Pumping Centers (ft^3)	Average Pumpage 1986-1990 for All Pumping Centers (ft^3)
Jan	29,586,336.2	32,267,556.0	59,757,406.5	52,084,961.1	1,037,439,351.5	907,170,791.4
Feb	28,221,930.1	31,318,787.7	61,218,865.4	53,174,225.8	979,296,639.2	843,218,878.6
Mar	30,121,819.9	33,865,982.8	88,360,523.7	68,661,421.3	1,197,259,437.2	996,887,114.0
Apr	30,289,324.4	34,496,955.9	100,401,444.4	80,579,328.3	1,206,173,910.8	1,108,434,155.1
May	32,129,777.7	36,336,981.4	115,959,612.7	89,847,511.9	1,442,236,914.5	1,274,418,389.8
Jun	29,193,633.3	32,970,333.9	71,977,334.9	62,126,940.6	1,197,610,901.9	1,083,833,030.4
Jul	29,201,866.8	34,574,038.2	63,699,066.6	58,332,380.4	1,185,725,335.3	1,062,575,280.1
Aug	28,632,542.7	33,333,186.0	53,776,054.4	56,691,694.7	1,155,745,782.2	1,031,747,497.0
Sep	27,834,174.7	32,604,652.5	54,490,567.6	54,614,890.2	1,132,402,698.2	970,647,856.0
Oct	26,986,139.8	32,355,263.3	56,819,814.3	58,617,168.0	1,088,788,298.7	992,756,523.0
Nov	24,377,111.6	30,336,833.4	50,952,825.0	53,845,492.6	1,029,955,280.4	913,955,036.2
Dec	24,612,812.0	29,142,050.8	44,889,991.7	52,188,259.2	1,047,387,693.9	932,234,122.1
SUM	341,187,469.4	393,602,622.0	822,303,507.1	740,764,274.0	13,700,022,243.9	12,117,878,673.6
Mean (mgd)	7.0	8.1	16.9	15.2	280.8	248.3

Table 7-6 Observed and Estimated Monthly Hydraulic Heads in the Upper Floridan Aquifer at Well 37 (P-0001) in 1990 When Varying Regional Average Pumpage Amounts

Month	Actual Head (feet)	Estimated monthly hydraulic heads in the upper Floridan aquifer with varying amounts of pumpage where number equals percentage of average pumpage (feet)					
		75	90	100	110	125	Actual[a]
01/90	81.07	94.16	85.59	79.87	74.15	65.68	80.92
02/90	81.15	94.58	85.90	80.12	74.34	65.67	81.04
03/90	80.89	94.85	86.08	80.23	74.38	65.61	80.84
04/90	80.56	94.76	85.83	79.87	73.92	64.98	80.49
05/90	79.91	94.46	85.34	79.26	73.19	64.07	79.95
06/90	80.03	94.32	85.00	78.78	72.56	63.23	79.60
07/90	79.96	94.83	85.30	78.95	72.60	63.08	79.82
08/90	79.65	95.56	85.82	79.33	72.84	63.10	79.93
09/90	79.19	95.86	85.92	79.30	72.68	62.75	79.58
10/90	79.16	95.86	85.70	78.94	72.17	62.02	79.13
11/90	78.78	95.85	85.51	78.61	71.72	61.38	78.68
12/90	78.61	95.72	85.20	78.19	71.17	60.65	78.22

[a]Actual pumping data from 1986 to 1990 used to estimate heads.

Note: Datum is NGVD.

Table 7-7 Observed and Estimated Monthly Hydraulic Heads in the Upper Floridan Aquifer at Well 19 (300020082103001) in 1990 When Varying Regional Average Pumpage Amounts

Month	Actual Head (feet)	Estimated monthly hydraulic heads in the upper Floridan aquifer with varying amounts of pumpage where number equals percentage of average pumpage (feet)					
		75	90	100	110	125	Actual[a]
01/90	56.48	68.28	61.32	56.68	52.04	45.09	56.54
02/90	56.76	68.81	61.77	57.08	52.38	45.35	57.01
03/90	57.14	69.13	61.96	57.19	52.41	45.24	57.04
04/90	56.76	69.00	61.66	56.77	51.88	44.55	56.79
05/90	55.59	68.33	60.79	55.76	50.74	43.20	55.66
06/90	55.05	67.81	60.09	54.93	49.78	42.05	54.97
07/90	54.77	68.06	60.16	54.90	49.64	41.74	54.90
08/90	54.5	68.43	60.38	55.01	49.65	41.60	55.01
09/90	54.05	68.33	60.15	54.70	49.25	41.07	54.59
10/90	54.02	68.17	59.84	54.28	48.73	40.40	54.32
11/90	53.93	68.21	59.76	54.12	48.49	40.04	54.16
12/90	54.16	68.40	59.83	54.11	48.40	39.82	54.16

[a]Actual pumping from 1986 to 1990 used to estimate heads

Note: Datum is NGVD.

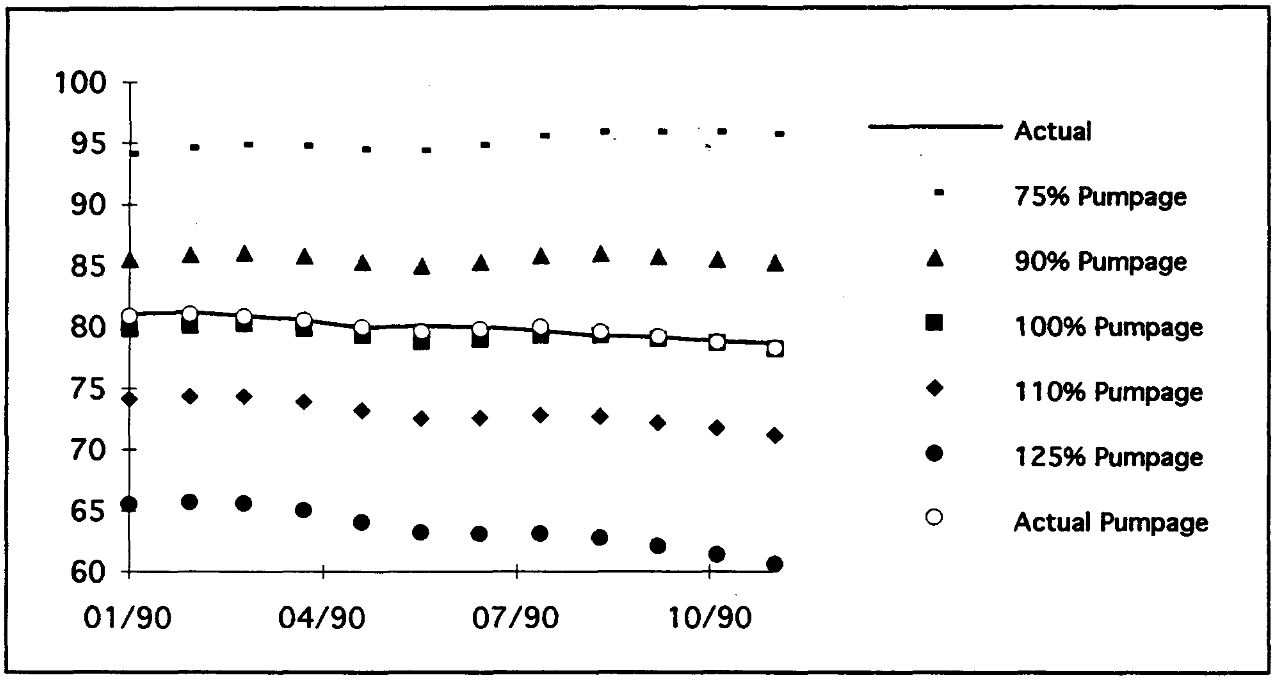


Figure 7-6. Observed and Estimated Monthly Ground-Water Levels in the Upper Floridan Aquifer at Well 37 (P-0001) in 1990 When Varying Regional Average Pumpage Amounts

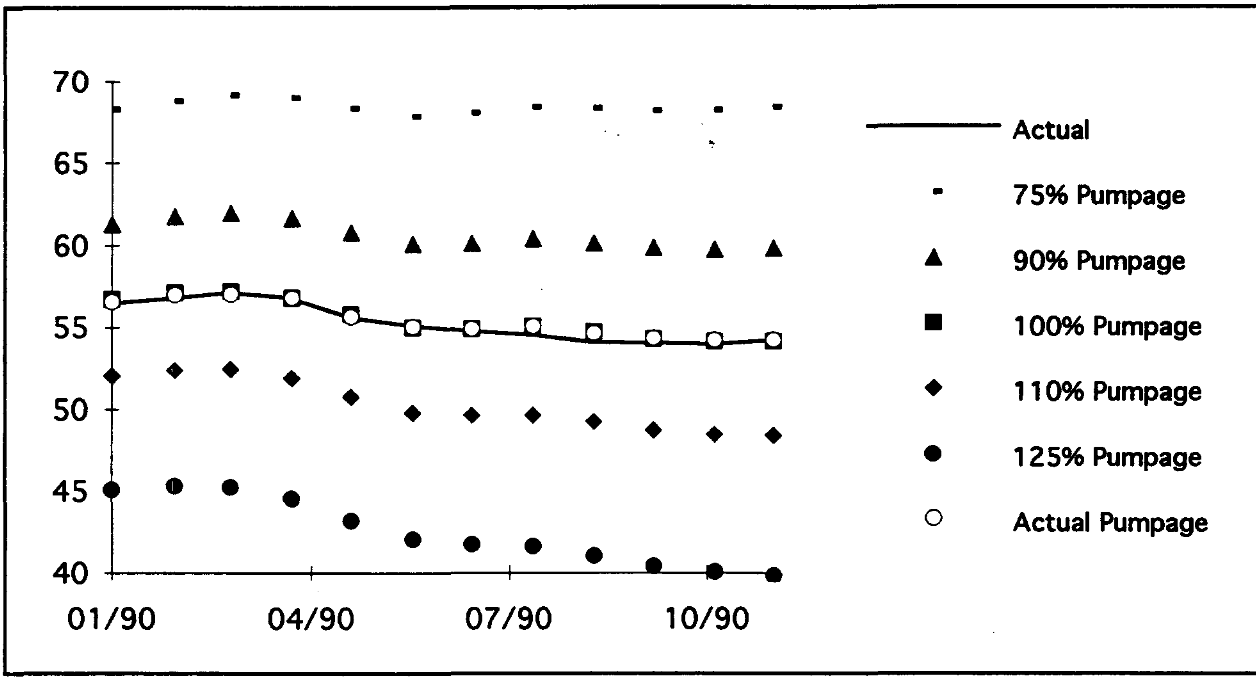


Figure 7-7. Observed and Estimated Monthly Ground-Water Levels in the Upper Floridan Aquifer at Well 19 (300020082103001) in 1990 When Varying Regional Average Pumpage Amounts

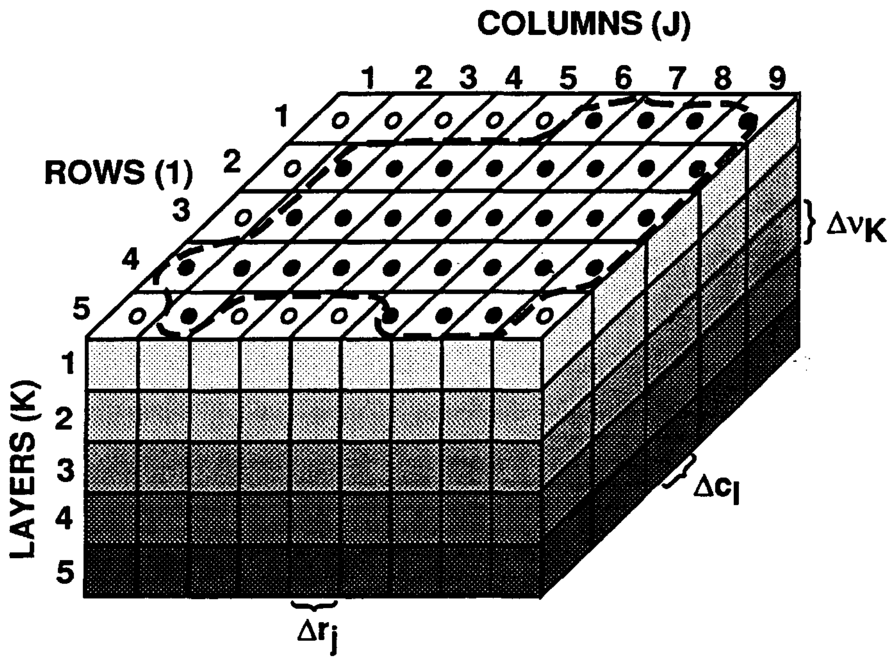
at well 37 near the 1986 values (Figure 7-2 and Table 7-6). Based upon the regression relation for well 19 (Table 7-1), the monthly regional pumpage from 1986 to 1990 also would have to have been approximately 10 percent below average to maintain ground-water levels in 1990 at well 19 near the 1986 values (Figure 7-3 and Table 7-7).

8.0 SIMULATION OF THE PREDEVELOPMENT POTENTIOMETRIC SURFACE OF THE UPPER FLORIDAN AQUIFER

8.1 MODEL SELECTION

The USGS modular three-dimensional finite-difference ground-water flow model MODFLOW (McDonald and Harbaugh 1988) was used to simulate the ground-water system in the study area. As described in this chapter, an initial, or preliminary, simulation was made of the predevelopment potentiometric surface of the upper Floridan aquifer. Subsequently, as described in Chapter 9, a simulation was made of the May 1985 potentiometric surface using water-level data for more current conditions.

In MODFLOW, an aquifer system is discretized with a mesh of blocks called cells, the locations of which are described in terms of rows, columns, and layers (see Figure 8-1). An i,j,k indexing system is used, and within each cell, the hydraulic head is calculated at a point called a node, which is at the center of each block. Version 3.95 of MODFLOW was used in the simulation; it was modified slightly in that the size of the x-array, which allocates space in the central memory of the computer for data arrays and lists, was increased from 30,000 to 900,000. Version 2.7 of the preprocessor PREMOD (Anderson 1989) was used to prepare some of the input files, along with a text editor, and version 2.1 of the postprocessor POSTMOD (Williams 1988) was used to write output files in an x-y-z format. MODVIEW (Durden 1994b), a software program that calculates statistical results for arrays such as draw-



— — Aquifer Boundary

● Active Cell

o 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.

Source: McDonald and Harbaugh 1988.

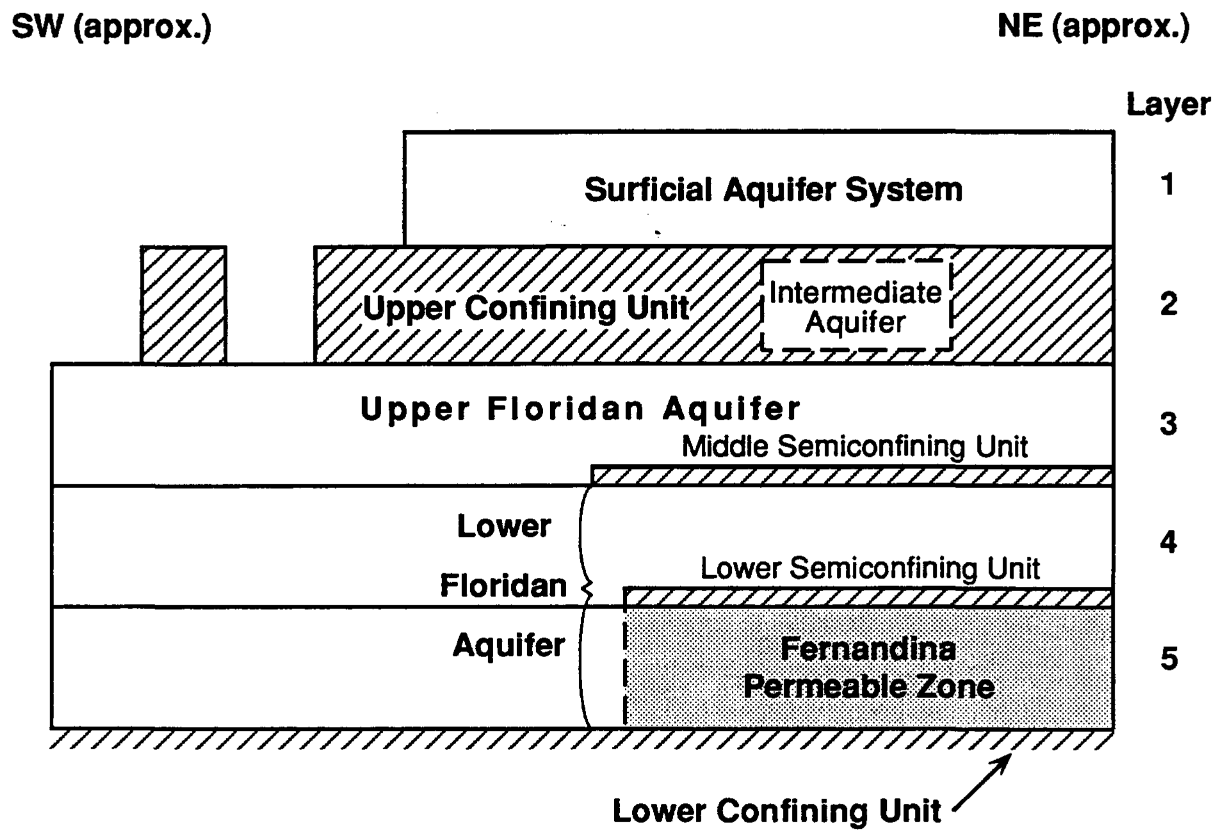
Figure 8-1. Discretized Hypothetical Aquifer System down and head and uses a visual, color-coded scheme to indicate different ranges in values in such arrays, was used to help calibrate the model.

8.2 CONCEPTUALIZATION AND AQUIFER PARAMETERS

8.2.1 Hydrologic Units and Discretization

In the western part of the study area, where the middle semiconfining unit is absent, the lower Floridan aquifer as defined by Miller (1986) does not exist. In this area, Miller combined the upper and lower Floridan aquifers into one unit called the "upper Floridan aquifer". For modeling purposes in this study, however, the lower Floridan aquifer was considered to be a separate aquifer unit throughout the study area, which is consistent with the modeling approaches used in this and/or adjacent areas by Bush and Johnston (1988), Krause and Randolph (1989), and Tibbals (1990). In the model area where the middle semiconfining unit is absent, the upper and lower Floridan aquifers are hydraulically well-connected anyway, so this modeling approach also in effect is consistent with Miller's (1986) convention.

Accordingly, the hydrogeologic system in the study area was considered to consist of five layers, or aquifer units, separated by confining units (see Figure 8-2). Layer one represents the surficial deposits and the water-table aquifer, which are present in most, but not all, of the study area. Layer two represents the Hawthorn Group, which generally acts as the upper confining unit for the Floridan aquifer system. However, in some areas where the surficial deposits are absent, the Hawthorn Group is the uppermost hydrologic unit. In these areas, the water table is in the



Note: Conceptualization extends approximately from the southwest to the northeast through the study area, and it is not drawn to scale.

Sources: Bush and Johnston 1988, Clark et al. 1964, Hunn and Slack 1983, Krause and Randolph 1989, Miller 1986, Puri and Vernon 1964, Scott 1983 and 1988, and Tibbals 1990.

Figure 8-2. Conceptualization of Hydrogeologic System in Study Area

Hawthorn Group, and it was necessary to treat the Hawthorn Group as an aquifer unit in order to include this feature of the hydrologic system. Layer three represents the upper Floridan aquifer, which is unconfined in most of the southwestern part of the study area and confined everywhere else. Layers four and five represent the lower Floridan aquifer. In the northeastern part of the study area, layer four represents the part of the lower Floridan aquifer above the lower semiconfining unit, and layer five represents the part of the lower Floridan aquifer below the lower semiconfining unit, e.g., the Fernandina permeable zone.

The study area was discretized into 53 rows that ranged in size from 5,000 ft to 20,000 ft and 54 columns that ranged in size from 5,000 ft to 15,000 ft (see Figure 8-3 and Table 8-1). This grid resulted in the study area being 287,000 ft from east to west and 344,000 ft from north to south. Layer one was assigned constant head nodes in the area where it is present, and no-flow, or inactive, cells, in the area where it is not present (see Figure 8-4). Layer two was assigned active cells in the area where it is overlain by layer one, constant head cells in the area where it is the uppermost hydrologic unit, and inactive cells in the areas where it is absent (see Figure 8-5). All of the cells in layers three, four, and five were active cells.

8.2.2 Phreatic Surface and Hydraulic Heads for Floridan Aquifer System

The water table in layer one (and layer two, where it is the uppermost hydrologic unit) was represented as a constant-head source bed using a model based on average regional conditions for the north-central Florida area (Caprara 1993). It was assumed that the water table was a subdued replica of the topography, which is con-

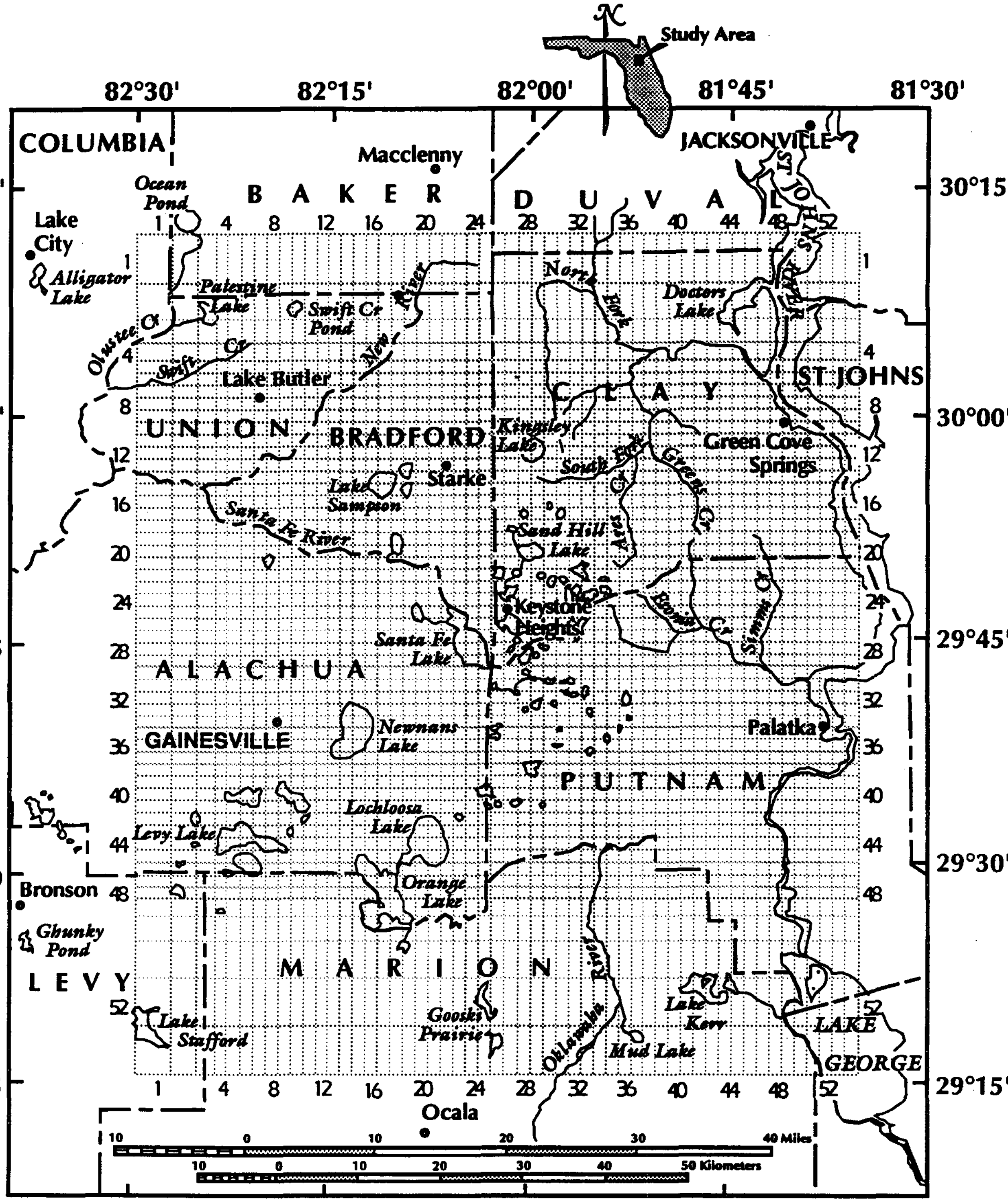


Figure 8-3. Discretization of Study Area

Table 8-1 Dimensions of Rows and Columns in MODFLOW Model

Column Number	Width of Column (ft)	Row Number	Height of Row (ft)
1	15,000	1, 52, 53	20,000
2	10,000	2, 51	15,000
3	7,000	3, 50	10,000
4-54	5,000	4, 49	7,000
-	-	5-48	5,000

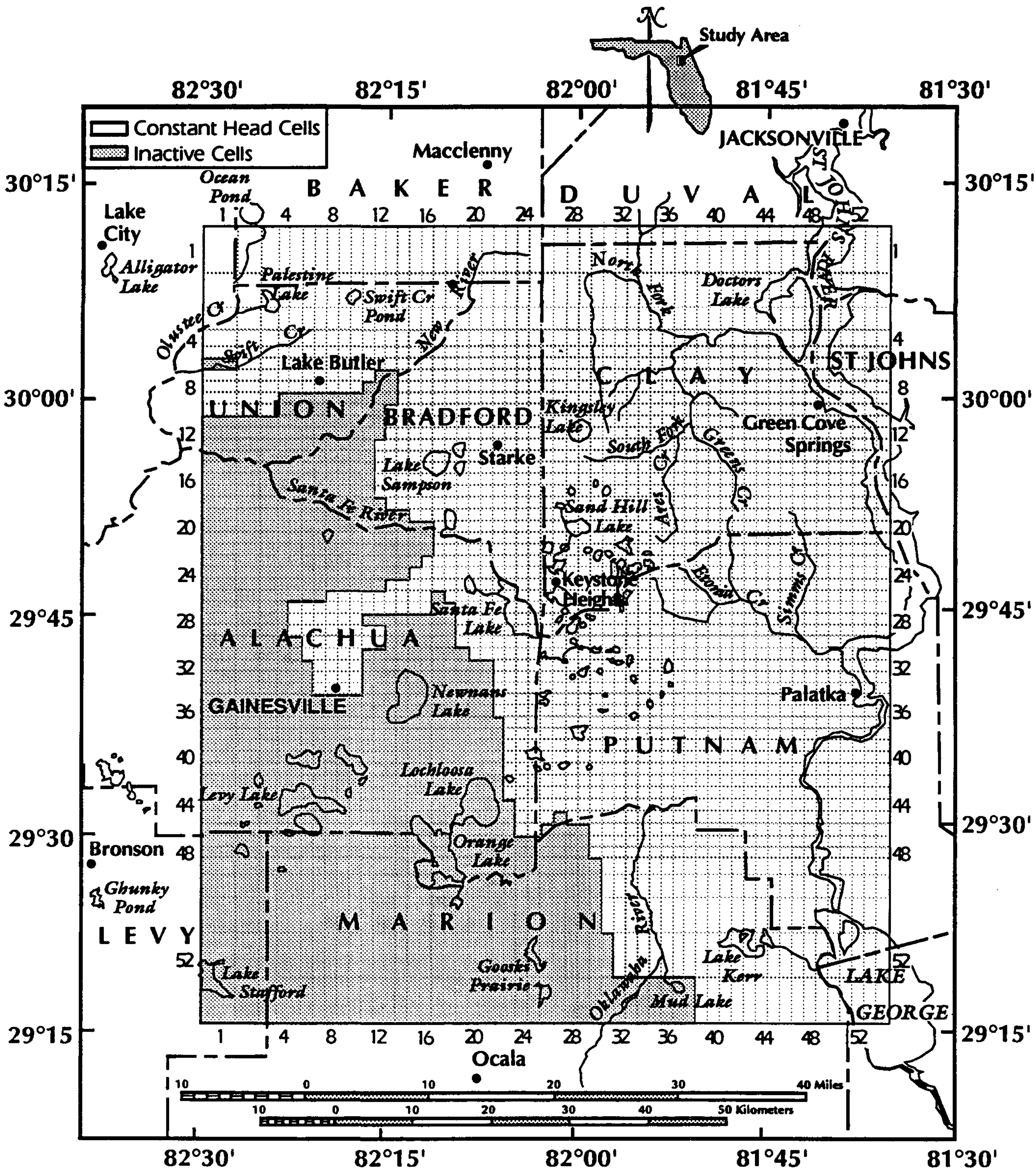


Figure 8-4. Constant Head and Inactive Cells in Layer One

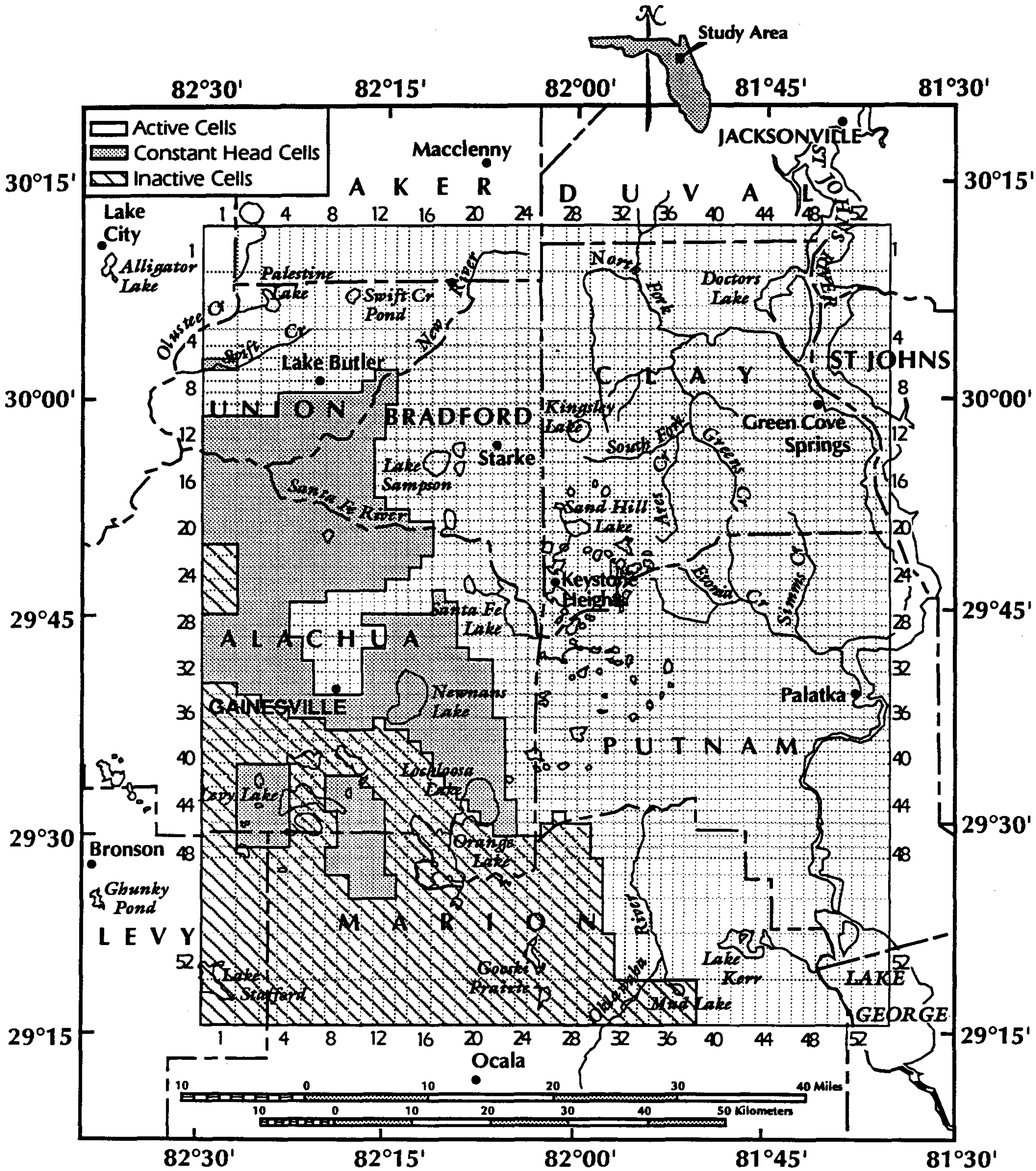
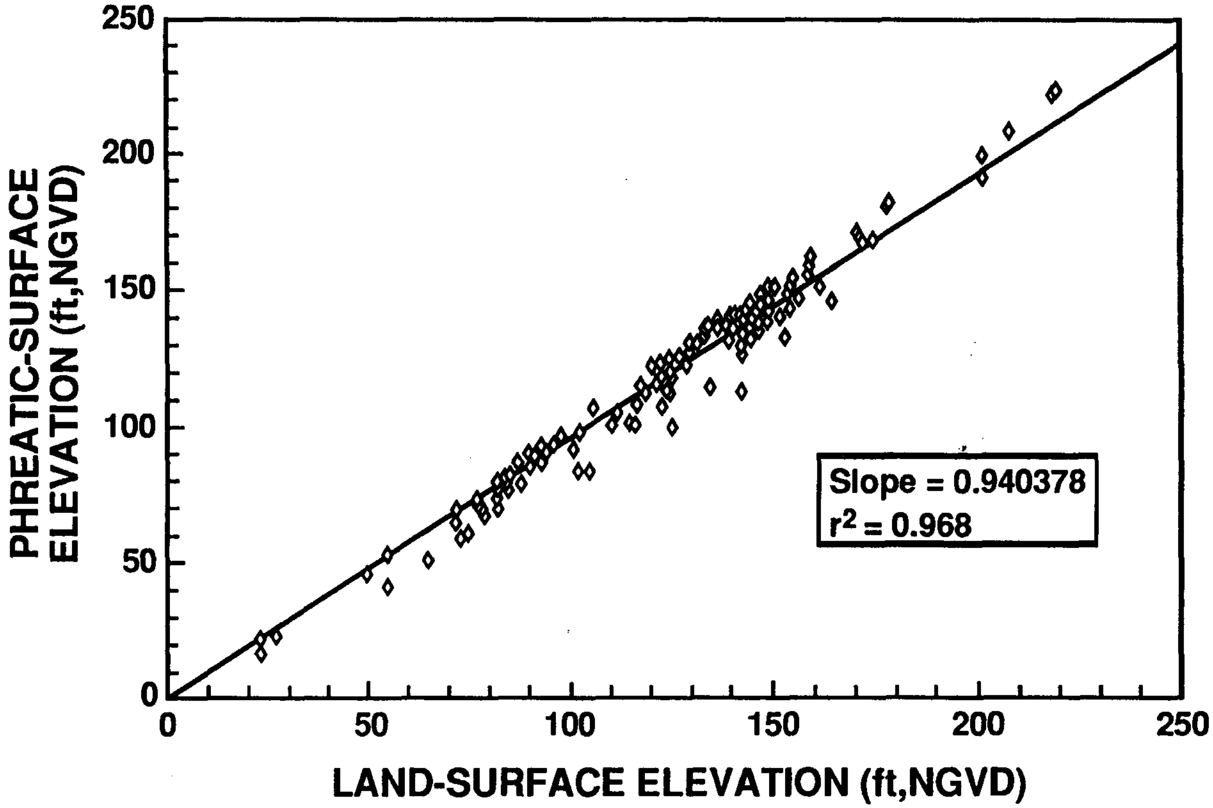


Figure 8-5. Active, Constant Head, and Inactive Cells in Layer Two

sistent with many hydrogeologic findings (e.g., King 1899, Tolmann 1937, Hubbert 1940, Freeze and Cherry 1979, Williams and Williamson 1989, Domenico and Schwartz 1990, Durden and Motz 1991, and Motz et al. 1993), and that a relation could be developed between land-surface elevation and the elevation of the phreatic surface. Water-level data for wells in the study area were obtained from reports by Clark et al. (1963) and Bermes et al. (1963b), because these reports contained wells in the study area and were the only sources of data that contained enough information to extract both land-surface elevation at the wells and elevation of the water surface in the wells. Using data selected from 146 wells that were considered to be representative of average rainfall conditions, a line of best fit was developed for the data (see Figure 8-6). This line of best fit, which was forced through the origin of the data for greater accuracy at lower elevations, has a correlation coefficient (r^2) of 0.968. From the regression, an equation relating the phreatic-surface to land-surface elevation in the study area can written:

$$\textit{Phreatic-surface elevation (ft, NGVD)} = 0.940\ \textit{(Land-surface elevation)(ft, NGVD)} \tag{8-1}$$

Land-surface elevations were obtained from the center point of each cell from USGS 7.5-minute topographic quadrangle maps for use with Equation 8-1. The phreatic-surface elevations were calculated using the regression equation and the center point elevations in areas where the topographic relief was not great and where the water table was not affected significantly by bodies of water. In cases where the topography varied excessively, an areal average of the land-surface elevation was esti-



Source: Caprara 1993.

Figure 8-6. Phreatic-Surface Versus Land-Surface Elevation in North-Central Florida mated over the entire cell. In cases where a body of water or swamp area covered more than 50 percent of the cell, the water-surface elevation, which was taken from either the USGS 7.5-minute topographic quadrangle map or averaged from historic lake-stage records, was used as the phreatic-surface elevation, and the regression equation was not applied. For cases where water covered less than 50 percent of the cell, but the phreatic aquifer enclosed by the cell was obviously influenced by surrounding bodies of water, a phreatic surface was estimated based on water levels of the surrounding water bodies. It was assumed that the results could be used to represent the predevelopment phreatic surface for layer one (and where appropriate, for layer two).

The starting heads for layer three were represented by values obtained for the center of each cell from the predevelopment potentiometric surface in the upper Floridan aquifer (see Figure 4-3). This map is a composite of many other maps and is the best estimate that can be made with available data of the configuration of the "average" potentiometric surface as it existed prior to development (Johnston et al. 1980).

Very little, if any, data exist for water levels in the lower Floridan aquifer. Accordingly, starting heads in layers four and five were assumed arbitrarily to be spatially uniform and equal to 50.0 ft, NGVD.

<u>8.2.3 Aquifer Parameters</u>

The predevelopment simulation was run as a steady-state simulation, with one stress period and one time step equal to 1.0 day. Layer one was unconfined; the value of the hydraulic conductivity in layer one, K_1, was not a factor in this simulation, because of the assumption that layer one is a constant-head source bed. The aquifer bottom elevation was an array based on Scott (1988), and the vertical leakance, or V_{cont1} in MODFLOW, for layer one was assumed spatially uniform and equal to 5.0×10^{-4} day^{-1}. Layer two was treated as a confined/unconfined layer with a variable transmissivity calculated from the saturated thickness and hydraulic conductivity. The hydraulic conductivity for layer two was assumed to be $K_2 = 5.0 \times 10^{-3}$ ft/day to represent the relatively low hydraulic conductivity of most of this unit. The aquifer top elevation was the same as the aquifer bottom elevation in layer one and used the same array based on Scott (1988). The aquifer bottom elevation was an array equal to the elevation of the upper Floridan aquifer based on Miller (1986). The spatially variable values of V_{cont2} for layer two represent the leakance of the upper confining unit, and they were a calibration parameter adjusted during the calibration process. Starting values for V_{cont2} were based on Bush and Johnston (1985).

Layer three was treated as a confined/unconfined layer with a constant transmissivity (with respect to time) at each spatial location. This layer represents the upper Floridan aquifer, and the spatially variable transmissivity values (T_3) were a calibration parameter adjusted during the calibration process. Starting values were based on Bush and Johnston (1985). The aquifer top elevation was the same array as the bottom of layer two and was based on Miller (1986). The values of V_{cont3} for layer three represent the leakance of the middle semiconfining unit. In the eastern part of the study area, where the middle semiconfining unit is present (see Figure 4-2), V_{cont3} was assigned a value of 5.0×10^{-5} day^{-1}, based on Tibbals (1990). In the western part of the study area, where the middle semiconfining unit generally is absent, the value for V_{cont3} was assumed to be 1.0×10^{-2} day^{-1}.

Layers four and five were completely confined, and transmissivities T_4 and T_5 were set equal to 100,000 ft^2/day. The value of V_{cont4} for layer four represents the leakance of the lower semiconfining unit, and it was assumed to be 1.0×10^{-2} day^{-1}.

8.2.4 Spring Discharges

Drains were used to represent spring discharges from layer three along the St. Johns River and its tributaries. Spring locations were based on Tibbals (1990) and on data obtained from SJRWMD. Thirty-three locations represent named springs along the St. Johns River, base-flow pickup along parts of the Oklawaha River, and hypothetical springs in the northeast part of the study area between Wadesboro and Green Cove Springs (see Figure 8-7 and Table 8-2). For each spring, the elevation at which the spring discharged was estimated from the USGS 7.5-minute topographic quadrangle map, and the conductance, which describes the head loss between the drain and the region of cell in which the prevailing head in the aquifer exists, was treated as a lumped parameter and adjusted during calibration of the model.

8.2.5 Recharge and Evapotranspiration

Direct recharge generally occurs to the uppermost hydrologic unit. In this simulation, recharge occurs to layer three where this unit is unconfined and the cells are active. Recharge does not affect the constant head cells in layers one and two. A recharge rate of 2.70×10^{-2} ft/day (12 inches/year), representing the net recharge to the water table and to the ground-water system, was used in the simulation to represent recharge to the active cells in layer three.

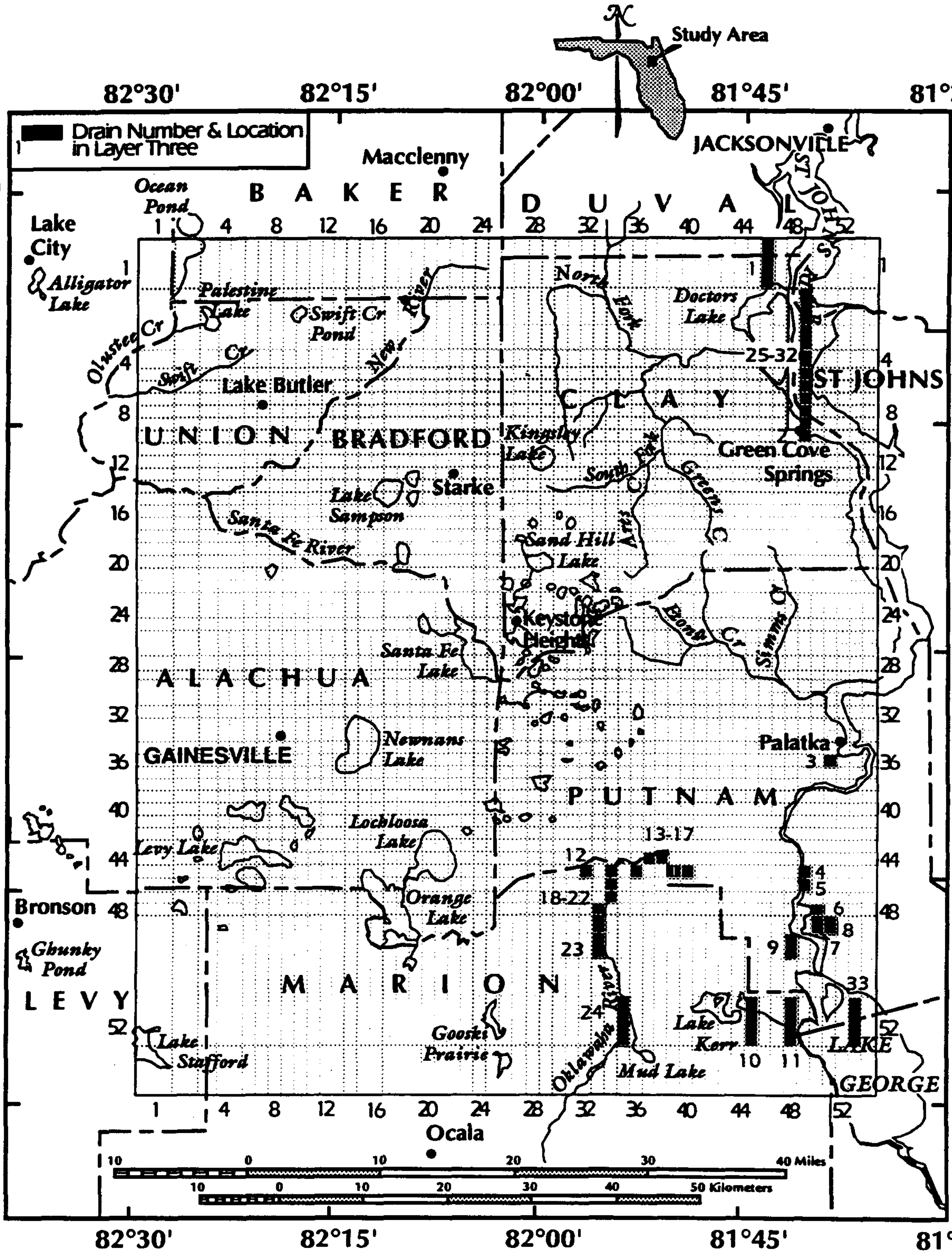


Figure 8-7. Locations of Drains in Layer Three

Table 8-2 Springs and Drains in Layer Three

Spring	Drain Number	Row	Column	Discharge Head (ft, NGVD)	Conductance (ft^2/day)
Wadesboro Spring	1	1	46	0.0	5.80×10^3
Green Cove Springs	2	10	49	0.0	1.76×10^4
Whitewater Springs	3	36	51	0.0	7.06×10^3
Satsuma and Nashua Springs	4	45	49	0.0	2.08×10^4
Welaka Springs	5	46	49	0.0	1.10×10^4
Mud Spring	6	48	50	0.0	2.00×10^4
Forest Springs	7	49	50	0.0	3.00×10^3
Beecher Springs	8	49	51	0.0	9.00×10^4
Croaker Hole Spring	9	50	48	0.0	8.00×10^5
Salt Springs	10	52	45	5.0	2.00×10^5
Salt Springs Pickup	11	52	48	0.0	7.50×10^4
Orange Springs	12	45	32	25.0	4.00×10^4
Oklawaha River Pickup	13	45	40	20.0	2.54×10^4
do.	14	45	39	20.0	2.54×10^4
do.	15	44	38	20.0	2.54×10^4
do.	16	44	37	20.0	2.54×10^4
do.	17	45	36	20.0	2.54×10^4
do.	18	45	34	20.0	2.54×10^4
do.	19	46	34	20.0	2.54×10^4

Table 8-2 Continued

Spring	Drain Number	Row	Column	Discharge Head (ft, NGVD)	Conductance (ft^2/day)
do.	20	47	34	20.0	2.54×10^4
do.	21	48	33	20.0	2.54×10^4
do.	22	49	33	20.0	2.54×10^4
do.	23	50	33	20.0	7.50×10^4
do.	24	52	35	0.0	5.00×10^4
Hypothetical Spring	25	2	49	0.0	5.00×10^3
do.	26	3	49	0.0	5.00×10^3
do.	27	4	49	0.0	5.00×10^3
do.	28	5	49	0.0	5.00×10^3
do.	29	6	49	0.0	5.00×10^3
do.	30	7	49	0.0	5.00×10^3
do.	31	8	49	0.0	5.00×10^3
do.	32	9	49	0.0	5.00×10^3
Lake George	33	52	53	0.0	1.25×10^5

Similarly, evapotranspiration generally occurs from the uppermost hydrologic unit. In this simulation, evapotranspiration occurs from layer three where this unit is unconfined and the cells are active. The maximum evapotranspiration rate from the active cells in layer three was assumed to be 0.00845 ft/day (37.0 inches/year), based on Bush and Johnston (1988). The surface in layer three at which evapotranspiration is at a maximum is an array whose values are equal to the top of the upper Floridan aquifer, based on Miller (1986). The extinction depth, or the depth below which evapotranspiration ceases, was assumed to be 10.0 ft.

8.2.6 General Head Boundary Conditions

In MODFLOW, at a general head boundary, flow into or out of an active cell from an external source is proportional to the difference between the head in the cell and the head assigned to the external source. The external cell can be considered to represent a constant head boundary located some distance away from the active cell, and flow occurs to or from the cell if the heads in the cell and at the external source are different. If the heads in the cell and at the external source are the same, then flow does not occur between the cell and the external source, and a no-flow boundary, or streamline, can be considered to exist between the active cell and the external source.

In the study area, the Floridan aquifer system is a regionally extensive aquifer that does not have physical boundaries or limits that result in constant-head or no-flow boundaries. Thus, in a simulation, it is more realistic to allow for the effects of pumping and other stresses to extend beyond the boundaries represented in the model. By using general head boundaries instead of constant head or no-flow boundaries in simulating this system, it was possible to include the effects of pumping and other stresses near the model boundaries, allowing the effects of these stresses to extend beyond the boundaries if necessary without creating unrealistically large flows near the boundaries. Also, changes in pumping or other stresses near a streamline, or no-flow boundary, can change the location of the streamline and the no-flow condition in a regionally extensive aquifer; by using general head boundaries in regions where no-flow boundaries would occur, it was possible to include this effect also.

In the simulation, 210 general head boundaries were assigned around the peripheries of each of layers three, four, and five, for a total of 630 general head boundaries for the simulation. Conductances for each general head boundary were obtained from the product of the transmissivity and width of the cell divided by the length of the flow path between the constant-head source and the adjacent active cell. The distances from the constant-head sources to the centers of the adjacent active cells are 15,000 ft on the north, south, and west boundaries of the model and 5,000 ft on the east boundary of the model. Boundary head values at each external source were obtained from the predevelopment potentiometric surface in the upper Floridan aquifer based on Johnston et al. (1980).

8.3 CALIBRATION

8.3.1 Comparison with Estimated Predevelopment Potentiometric Surface

The ground-water flow model was calibrated by calculating the potentiometric surface for layer three and comparing it to the estimated predevelopment potentiometric surface in the upper Floridan aquifer (Figure 4-3). The convergence criterion for the head in layer three was set equal to 0.1 ft, and the maximum number of iterations was chosen to be 100. Values for the transmissivity in layer three (T_3), vertical leakance in layer two (V_{cont2}), and conductances for the drains and general head boundaries in layer three were adjusted until the estimated and calculated head differences in layer three were within reasonable agreement. The model simulation that was considered to be calibrated required only 22 iterations; for this simulation, the mean of the differences between the estimated and calculated heads is 0.251 ft, and the standard deviation of the differences is 2.19 ft (see Figure 8-8 and Table 8-3). The maximum head in layer three, equal to 92.1 ft., NGVD, occurs at row 29, column 26, and the minimum head, equal to 7.75 ft, NGVD, occurs at row 50, column 48.

Values for V_{cont2} in layer two, representing the leakance of the upper confining unit, range from 1.0×10^{-6} to 1.0×10^{-2} day^{-1} (see Figure 8-9). Values for the transmissivity in layer three, representing the upper Floridan aquifer, range from 50,000 to 1,000,000 ft^2/day (see Figure 8-10). Conductances for the drains that represent the springs in layer three range from 3.00×10^3 to 8.00×10^5 ft^2/day (see Table 8-2).

8.3.2 Water Budget

In the predevelopment simulation, inflows to the ground-water system of the model are derived from constant head boundaries (3.84 inches/year), direct recharge to layer three (1.93 inches/year), and head dependent boundaries (0.83 inches/year)

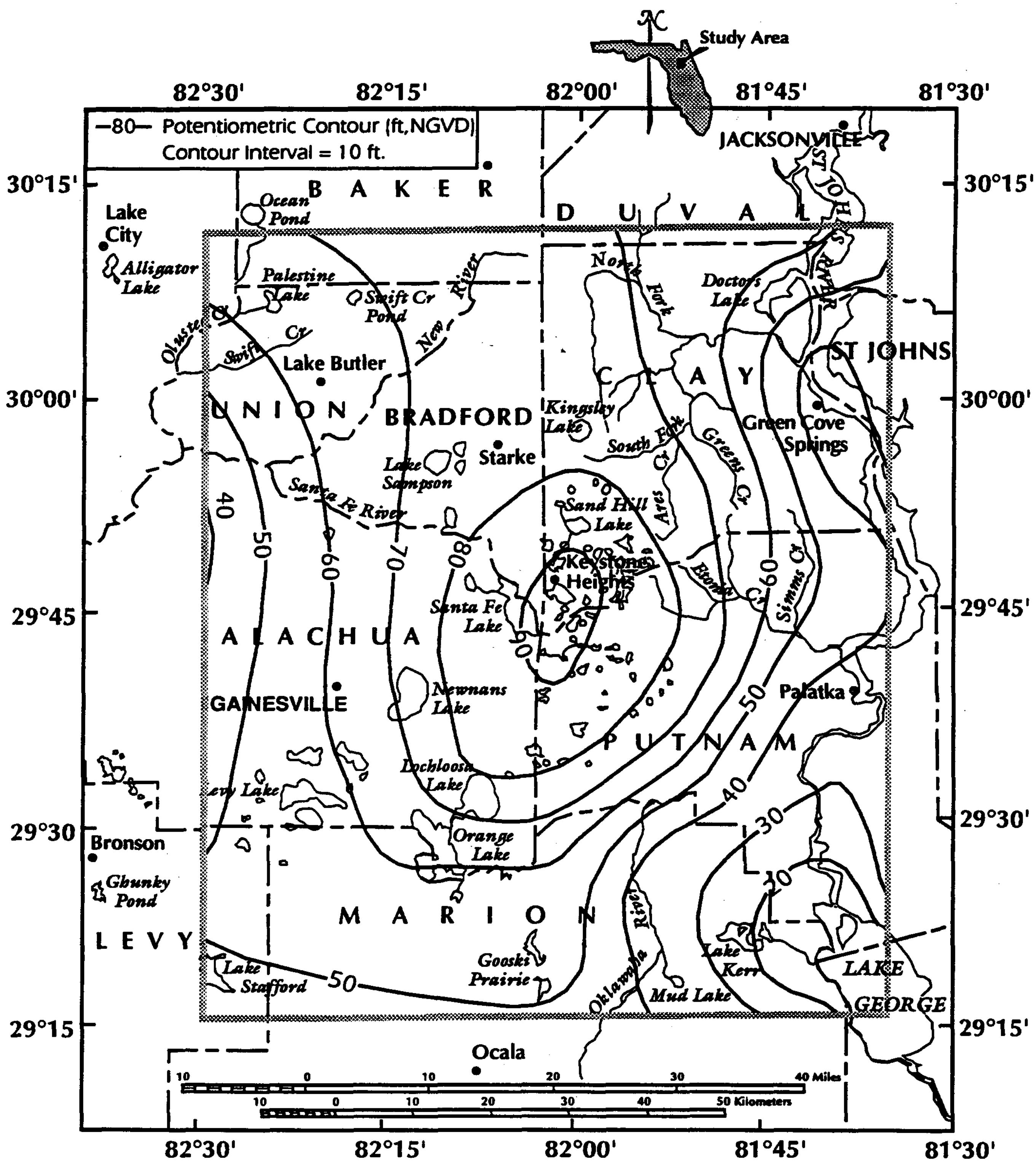


Figure 8-8. Calculated Predevelopment Potentiometric Surface in the Upper Floridan Aquifer

Table 8-3 Statistical Results for Calibration Run and Sensitivity Analysis for the Predevelopment Simulation

Statistical Parameter	Calibration Results	0.1 V_{cont1}	10.0 V_{cont1}	0.5 K_2	2.0 K_2	0.1 V_{cont2}	10.0 V_{cont2}	0.5 T_3	2.0 T_3
Maximum Head Difference (ft)	5.86 at (13,48)[a]	10.2 at (11,50)	7.96 at (21,30)	5.86 at (13,48)	5.86 at (13,48)	12.9 at (2,47)	39.4 at (17,27)	11.0 at (21,30)	9.73 at (11,49)
Minimum Head Difference (ft)	-6.60 at (46,34)	-18.5 at (19,24)	-7.14 at (5,49)	-6.60 at (46,34)	-6.60 at (46,34)	-33.8 at (29,30)	-20.5 at (4,49)	-11.9 at (5,49)	-8.89 at (30,30)
Mean of the Differences (ft)	0.251	-4.06	1.32	0.251	0.251	-10.9	12.2	1.77	-1.73
Standard Deviation of the Differences (ft)	2.19	5.44	2.67	2.19	2.19	10.4	12.6	3.32	3.32
Mean of the Absolute Values (ft)	1.75	5.12	2.44	1.75	1.75	11.7	14.6	3.10	3.01

[a]Indicates row and column location.

Table 8-3 Continued

Statistical Parameter	0.1 V_{cont3}	10.0 V_{cont3}	0.5 T_4	2.0 T_4	0.1 V_{cont4}	10.0 V_{cont4}	0.5 T_5	2.0 T_5
Maximum Head Difference (ft)	8.93 at (21,31)	10.9 at (11,49)	6.66 at (20,20)	5.77 at (51,46)	5.90 at (13,48)	5.76 at (32,5)	6.49 at (20,20)	5.77 at (51,46)
Minimum Head Difference (ft)	-8.72 at (5,49)	-7.50 at (20,37)	-6.41 at (46,34)	-8.92 at (19,24)	-6.59 at (46,34)	-6.57 at (46,34)	-6.52 at (46,34)	-8.62 at (19,24)
Mean of the Differences (ft)	0.722	0.219	1.11	-1.04	2.86	0.209	1.05	-0.991
Standard Deviation of the Differences (ft)	2.80	3.27	2.40	2.57	2.17	2.17	2.40	2.55
Mean of the Absolute Values (ft)	2.31	2.51	2.17	2.25	1.74	1.73	2.15	2.21

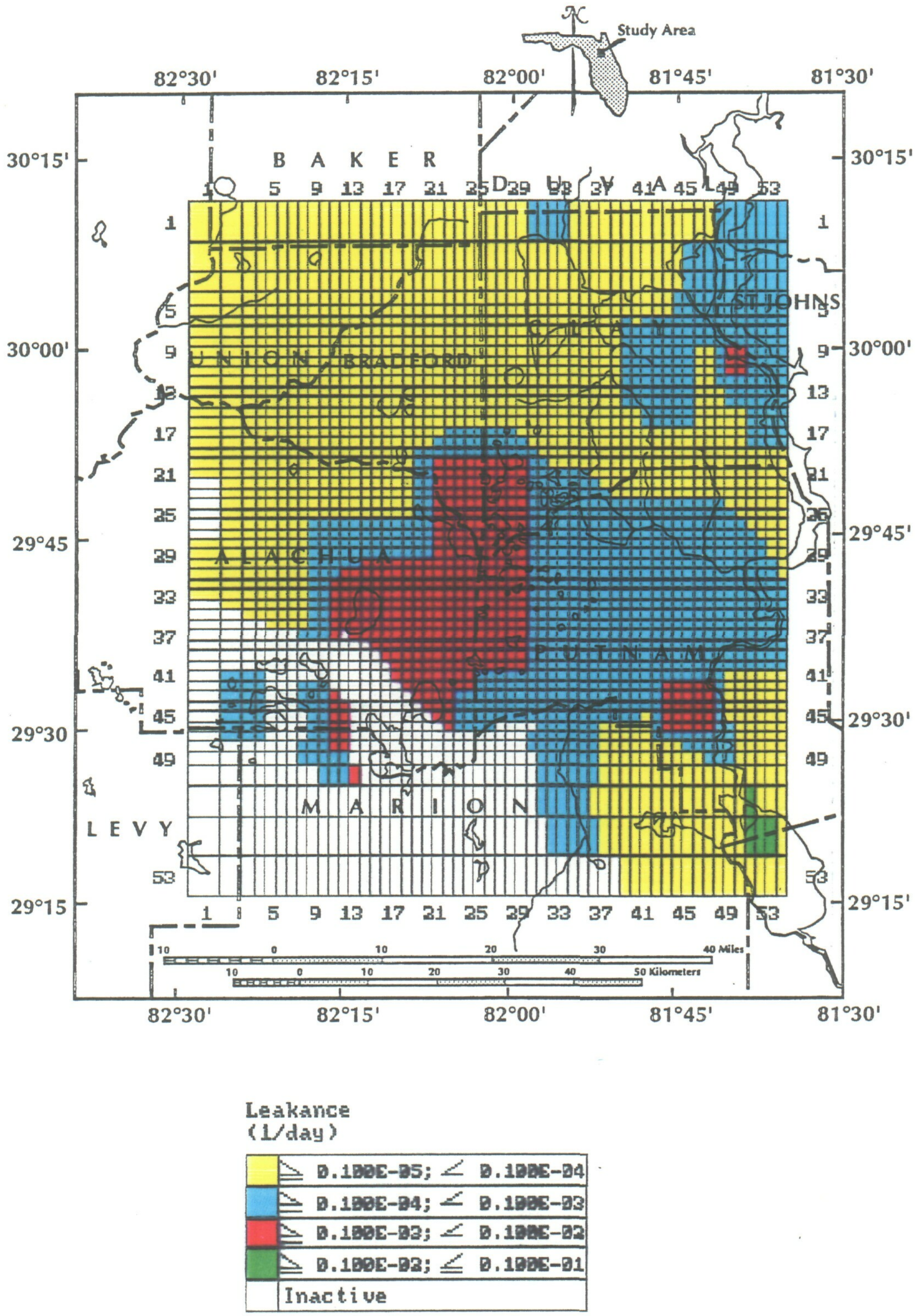


Figure 8-9. Leakance Values for the Upper Confining Unit in the Predevelopment Simulation

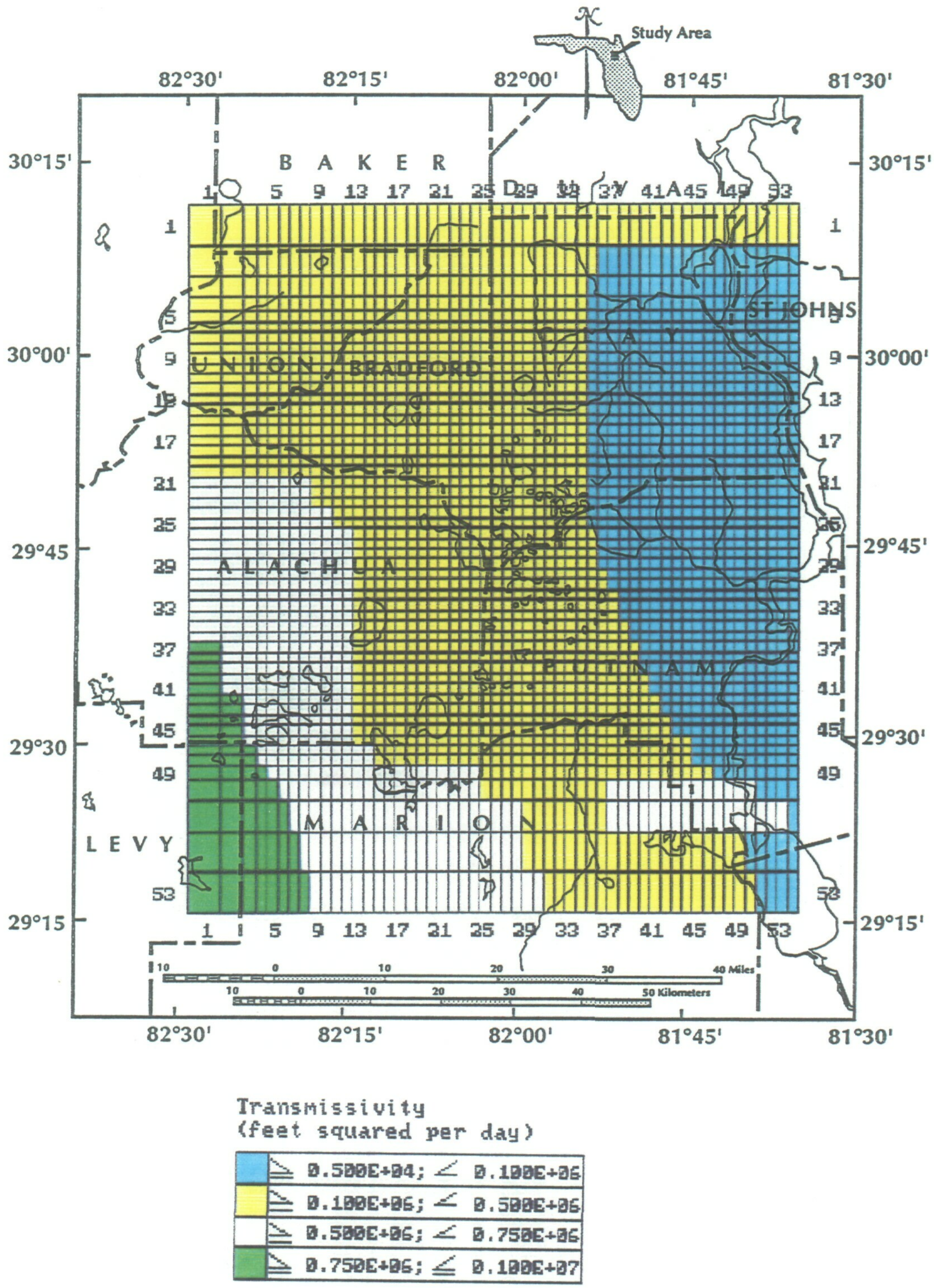


Figure 8-10. Transmissivity Values for the Upper Floridan Aquifer in the Predevelopment Simulation

(see Table 8-4). Outflows from the ground-water system occur at constant head boundaries (0.98 inches/year), drains that represent discharge at springs (0.95 inches/year), evapotranspiration from layer three (0.60 inches/year), and head dependent boundaries (4.07 inches/year). In the predevelopment simulation, the total inflows are 6.60 inches/year, which is a realistic value compared to other simulations in areas adjacent to the study area (e.g., Durden and Motz 1991), and they are balanced by the total outflows.

8.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the calculated heads in layer three by varying the leakance value for layer one, the hydraulic conductivity and leakance values for layer two, and the transmissivity and leakance values for layers three, four, and five (see Table 8-3). Based on the standard deviations calculated for the estimated heads minus calculated heads for layer three, the calculated heads in layer three are most sensitive to the changes in leakance values for layer two. The heads in layer three are also relatively sensitive to the leakance values for layers one and three and to the transmissivity values in layer three. The heads in layer three are less sensitive to changes in the transmissivities in layers four and five and relatively insensitive to changes in hydraulic conductivity values in layer two and the leakance value for layer four.

Table 8-4 Water Budget for Active Cells in Predevelopment Simulation

	Flowrate:	
Inflow:	(ft^3/day)	(inches/year)
Constant Head Boundaries	8.66×10^7	3.84
Recharge	4.36×10^7	1.93
Head Dependent Boundaries	1.87×10^7	0.83
Total Inflow	1.49×10^8	6.60
Outflow:		
Constant Head Boundaries	2.21×10^7	0.98
Drains	2.15×10^7	0.95
Evapotranspiration	1.35×10^7	0.60
Head Dependent Boundaries	9.18×10^7	4.07
Total Outflow	1.49×10^8	6.60

9.0 SIMULATION OF THE MAY 1985 POTENTIOMETRIC SURFACE IN THE UPPER FLORIDAN AQUIFER

9.1 MODEL AND AQUIFER PARAMETERS

9.1.1 Hydrologic Units and Discretization

The May 1985 potentiometric surface and water-use data were used with MODFLOW to simulate conditions that existed in May 1985 in the upper Floridan aquifer. Similar to the predevelopment simulation, the hydrogeologic system was considered to consist of five layers, or aquifer units, separated by confining units (see Figure 8-2). Layer one represents the surficial deposits and the water-table aquifer, which is present in most, but not all, of the study area. Layer two represents the Hawthorn Group and the upper confining unit for the Floridan aquifer system. In the areas where the surficial deposits are absent, the Hawthorn Group is the uppermost hydrologic unit, and the water table is in the Hawthorn Group. Layer three represents the upper Floridan aquifer, which is unconfined in the southwestern part of the study area and confined everywhere else. Layers four and five represent the lower Floridan aquifer. In the northeast part of the study area, layer four represents the part of the lower Floridan aquifer above the lower semiconfining unit, and layer five represents the part of the lower Floridan aquifer below the lower semiconfining unit, e.g., the Fernandina permeable zone.

Similar to the predevelopment simulation, the study area was discretized into 53 rows that ranged in size from 5,000 ft to 20,000 ft and 54 columns that ranged in size from 5,000 ft to 15,000 ft (see Figure 8-3 and Table 8-1). Layer one was assigned constant head nodes in the area where it is present, and no flow, or inactive cells, in the area where it is not present (see Figure 8-4). Layer two was assigned active cells in the area where it is overlain by layer one, constant head cells in the area where it is the uppermost hydrologic unit, and no flow cells in the areas where it is absent (see Figure 8-5). All of the cells in layers three, four, and five were active cells.

The water table in layer one (and layer two, where it is the uppermost hydrologic unit) was represented as a constant-head source bed using the model based on average regional conditions for the north-central Florida area (Caprara 1993). Thus, it was assumed that water-table elevations calculated using Equation 8-1 could be used to represent the May 1985 phreatic surface for layer one (and where appropriate, for layer two). The starting heads for layer three were represented by values obtained for the center of each cell from the observed May 1985 potentiometric surface of the upper Floridan aquifer (see Figure 4-4). Starting heads in layers four and five were assumed arbitrarily to be spatially uniform and equal to 50.0 ft, NGVD.

9.1.2 Aquifer Parameters

The May 1985 simulation was run as a steady-state simulation, with one stress period and one time step equal to 1.0 day. Layer one was unconfined; the value of the hydraulic conductivity in layer one, K_1, was not a factor in this simulation because of the assumption that layer one is a constant-head source bed. The aquifer bottom elevation was an array based on Scott (1988), and the vertical leakance, or V_{cont1}, for layer one was assumed spatially uniform and equal to 5.0×10^{-4} day^{-1}. Layer two was treated as a confined/unconfined layer with a variable transmissivity calculated from the saturated thickness and hydraulic conductivity. The hydraulic conductivity for layer two was assumed to be $K_2 = 5.0 \times 10^{-3}$ ft/day to represent the relatively low hydraulic conductivity of most of this unit. The aquifer top elevation was the same as the aquifer bottom elevation in layer one and used the same array based on Scott (1988). The aquifer bottom elevation was an array equal to the elevation of the upper Floridan aquifer based on Miller (1986). The spatially variable values of V_{cont2} for layer two represent the leakance of the upper confining unit, and they were a calibration parameter adjusted during the calibration process. Values from the pre-development simulation (Figure 8-9) were used as starting values for V_{cont2} for the May 1985 simulation.

Layer three was treated as confined/unconfined with a constant transmissivity (with respect to time) at each spatial location. This layer represents the upper Floridan aquifer, and the spatially variable transmissivity values (T_3) were a calibration parameter adjusted during the calibration process. Values from the predevelopment simulation (Figure 8-10) were used as starting values for transmissivity for the 1985 simulation. The aquifer top elevation was the same array as the bottom of layer two and was based on Miller (1986). The values of V_{cont3} for layer three represent the leakance of the middle semiconfining unit. In the eastern part of the study area where the middle semiconfining unit is present, V_{cont3} for layer three was assigned values of 5.0×10^{-6} and 5.0×10^{-5} day^{-1}, based on Durden (1992) and Tibbals

(1990). In the western part of the study area, where the middle semiconfining unit is absent, V_{cont3} for layer three was assigned a value of 1.0×10^{-2} day^{-1}.

Layers four and five were completely confined, and transmissivities T_4 and T_5 were set equal to 100,000 ft^2/day. The value of V_{cont4} for layer four represents the leakance of the lower semiconfining unit, and it was set equal to 1.0×10^{-2} day^{-1}, similar to the predevelopment simulation.

9.1.3 Ground-Water Pumpage

Based on the water-use information compiled from the three water management districts, well locations were plotted on USGS topographic contour maps of the study area, and the discretized cells were identified within which the wells were located. Pumping rates for May 1985, well locations, and model layer number were delineated for the public-supply, commercial and industrial, agricultural, thermoelectric power generation, and direct recharge categories (see Table 5-2 and Figures 9-1 through 9-5). In the May 1985 simulation, pumping occurs from 305 cells in layers three and four, and direct recharge via wells occurs in three cells in layer three and in one cell in layer four (see Figures 9-6 and 9-7). The total pumping rate from all of the cells in which pumping wells are located is 2.38×10^7 ft^3/day, the recharge rate is 2.99×10^6 ft^3/day, and thus the net pumping rate is 2.08×10^7 ft^3/day.

9.1.4 Spring Discharges

Similar to the predevelopment simulation, drains were used to represent the spring discharges that occur from layer three along the St. Johns River and its tributaries. Spring locations were based on Tibbals (1990) and on data obtained from

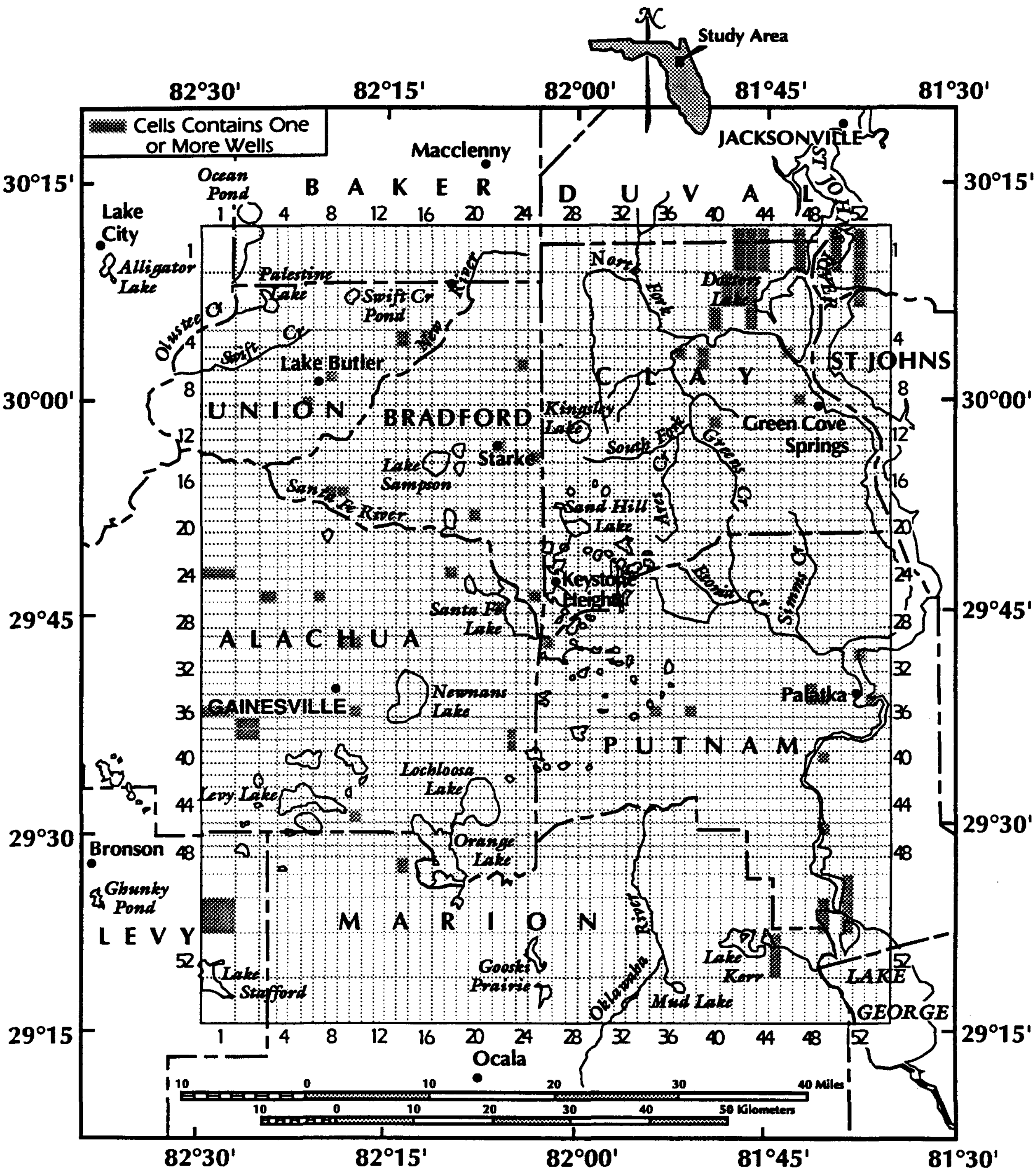


Figure 9-1. Public-Supply Wells in Layers Three and Four in the May 1985 Simulation

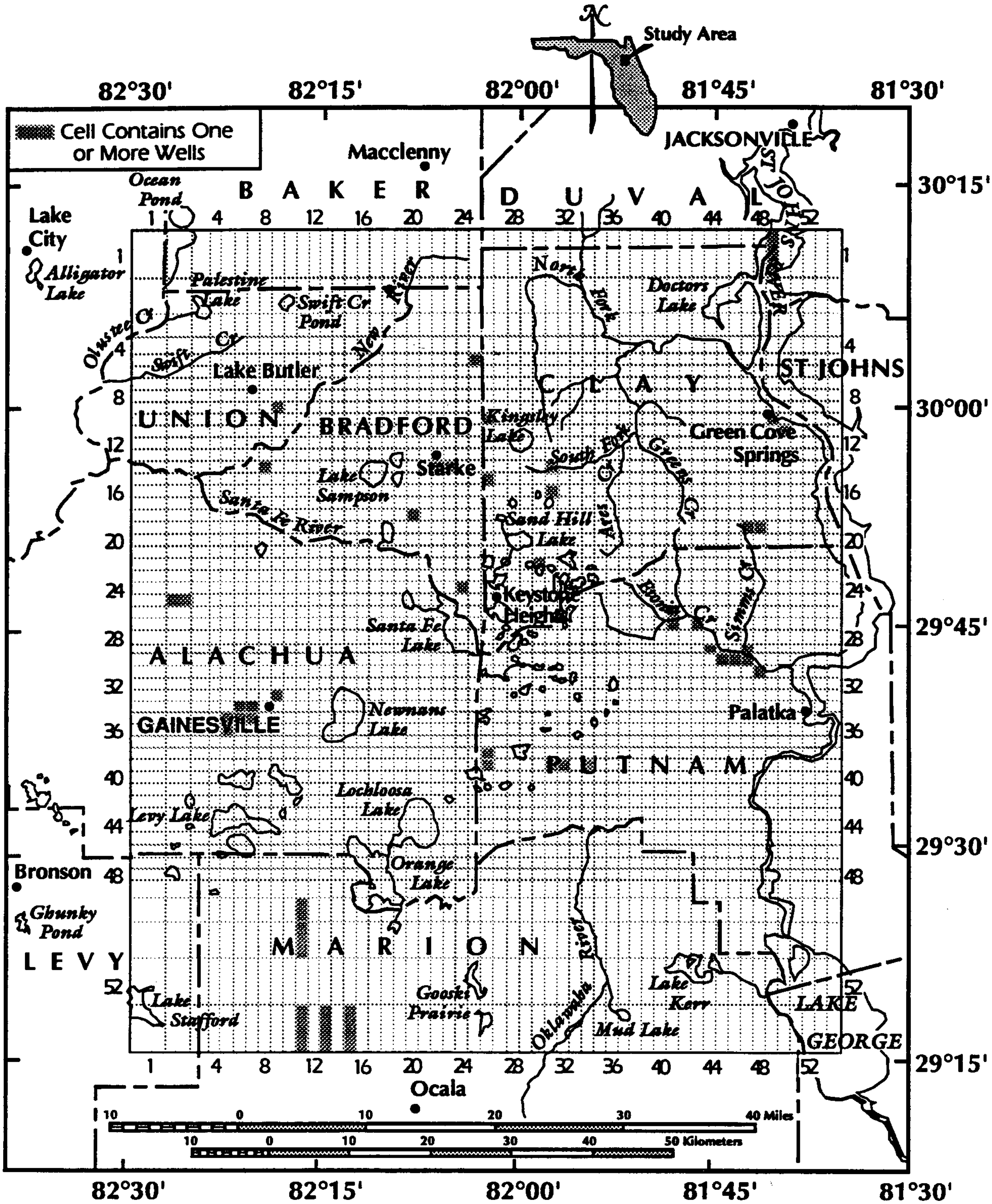


Figure 9-2. Commercial and Industrial Wells in Layers Three and Four in the May 1985 Simulation

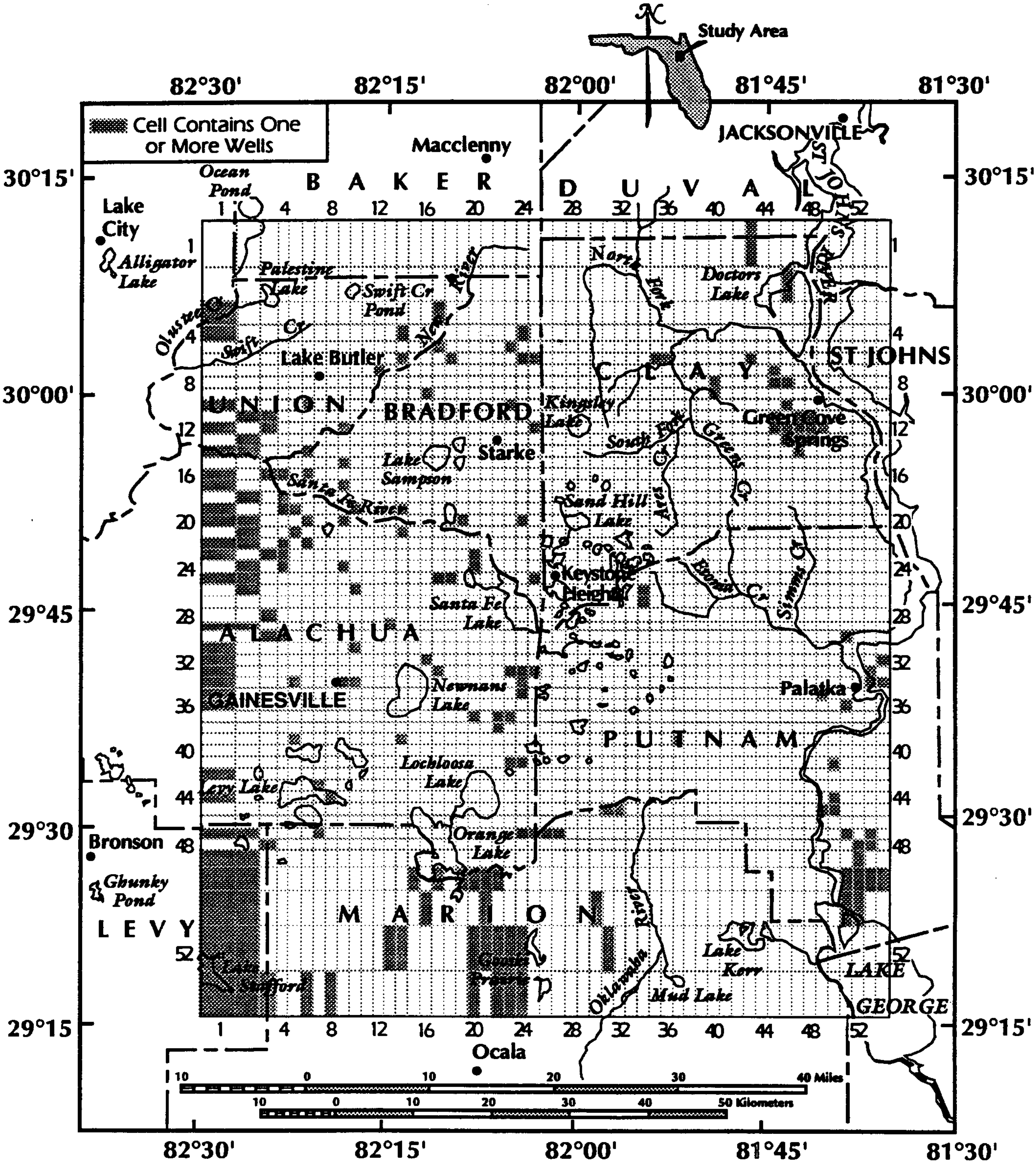


Figure 9-3. Agricultural Wells in Layers Three and Four in the May 1985 Simulation

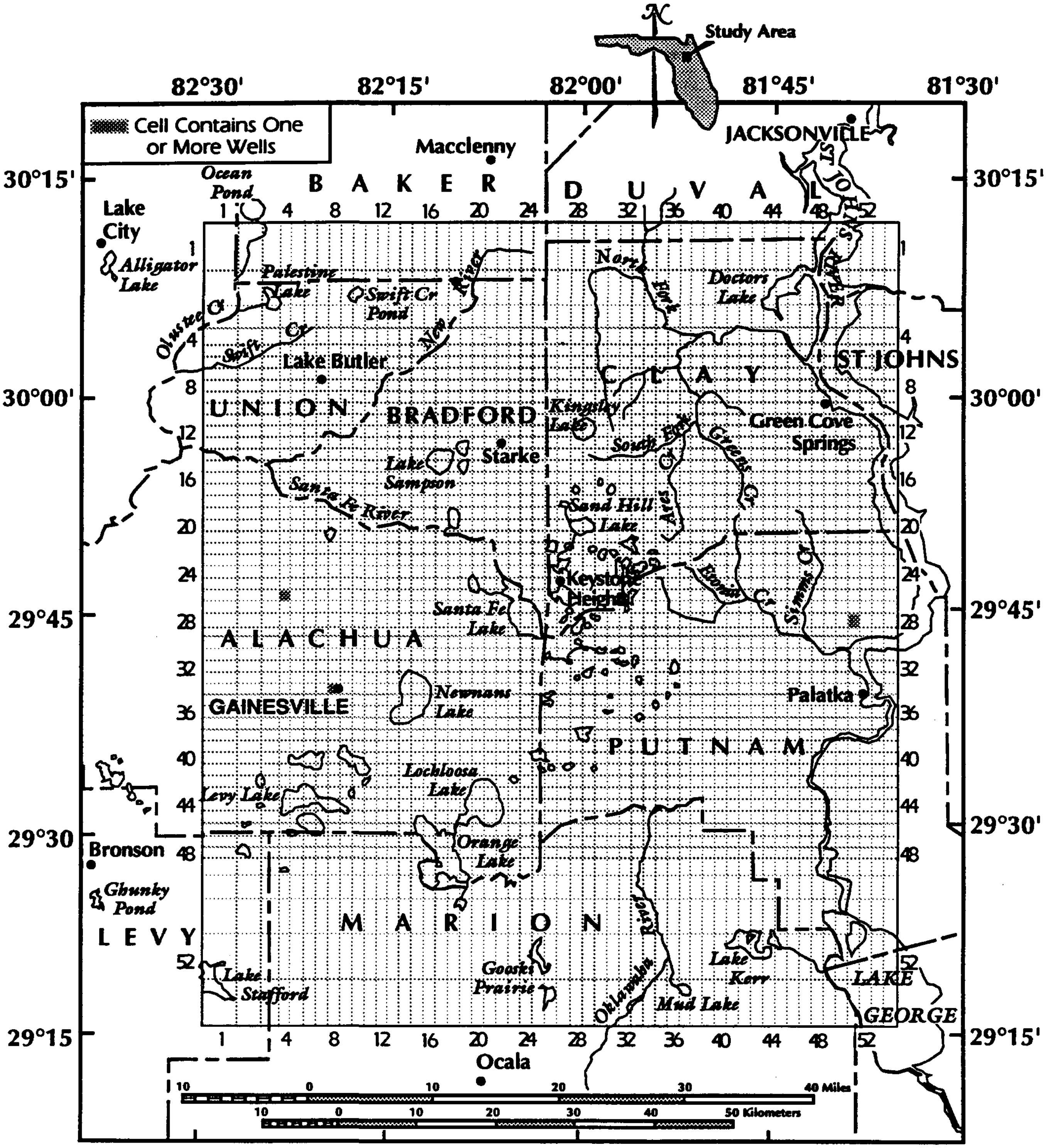


Figure 9-4. Thermoelectric Power Generation Wells in Layer Three in the May 1985 Simulation

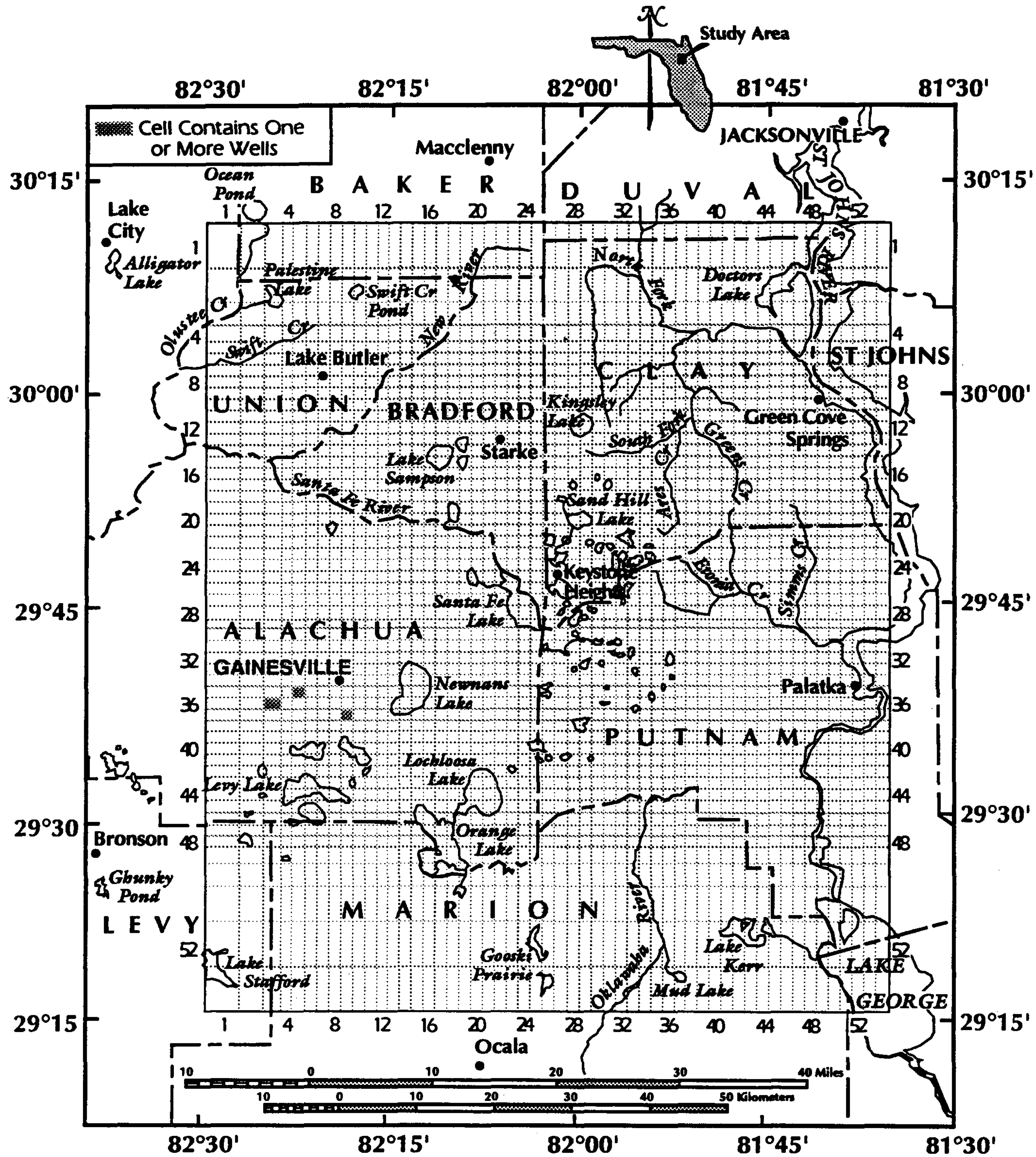


Figure 9-5. Recharge Wells in Layers Three and Four in the May 1985 Simulation

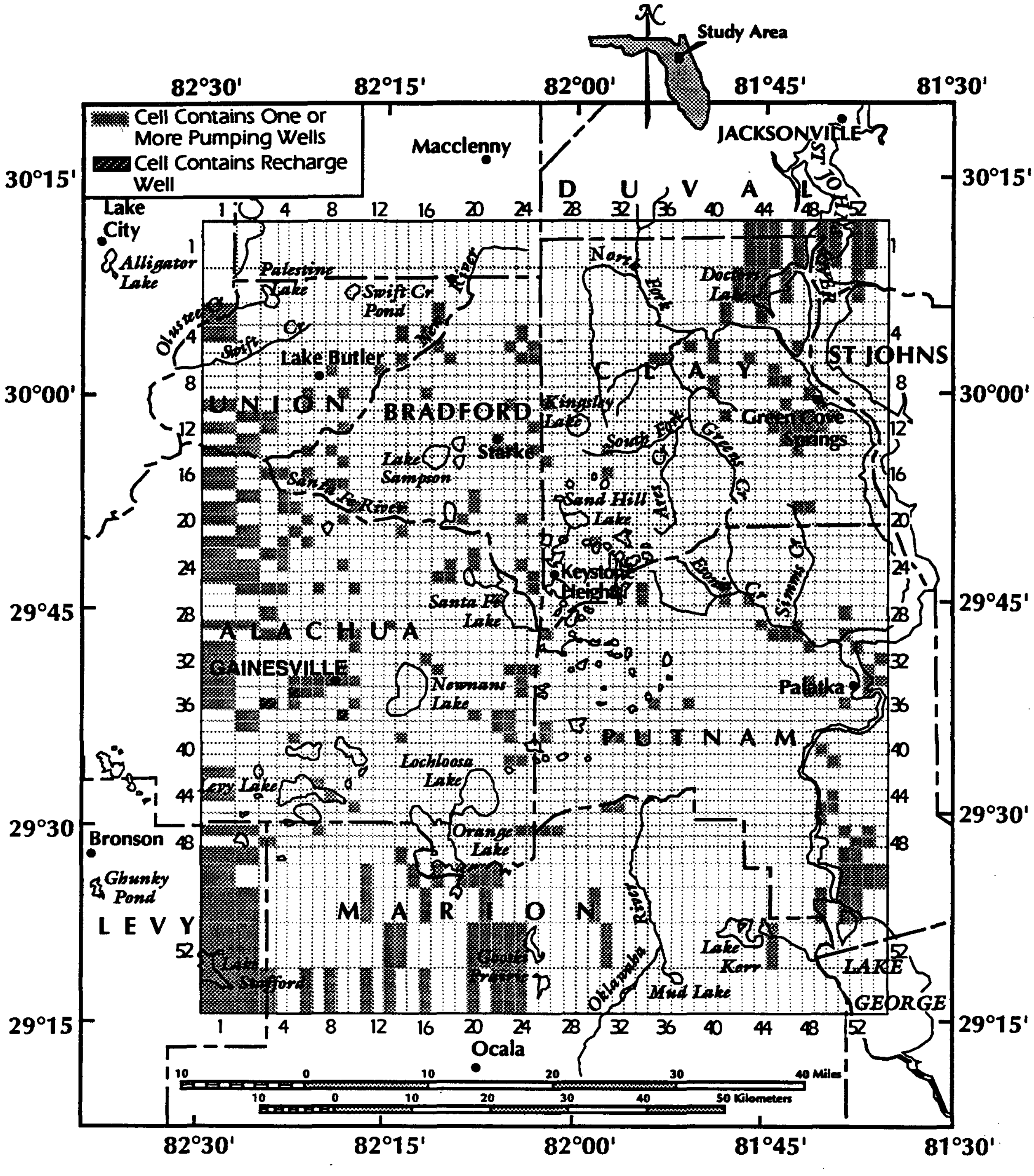


Figure 9-6. Pumping Wells (All Categories) and Recharge Wells in Layer Three in the May 1985 Simulation

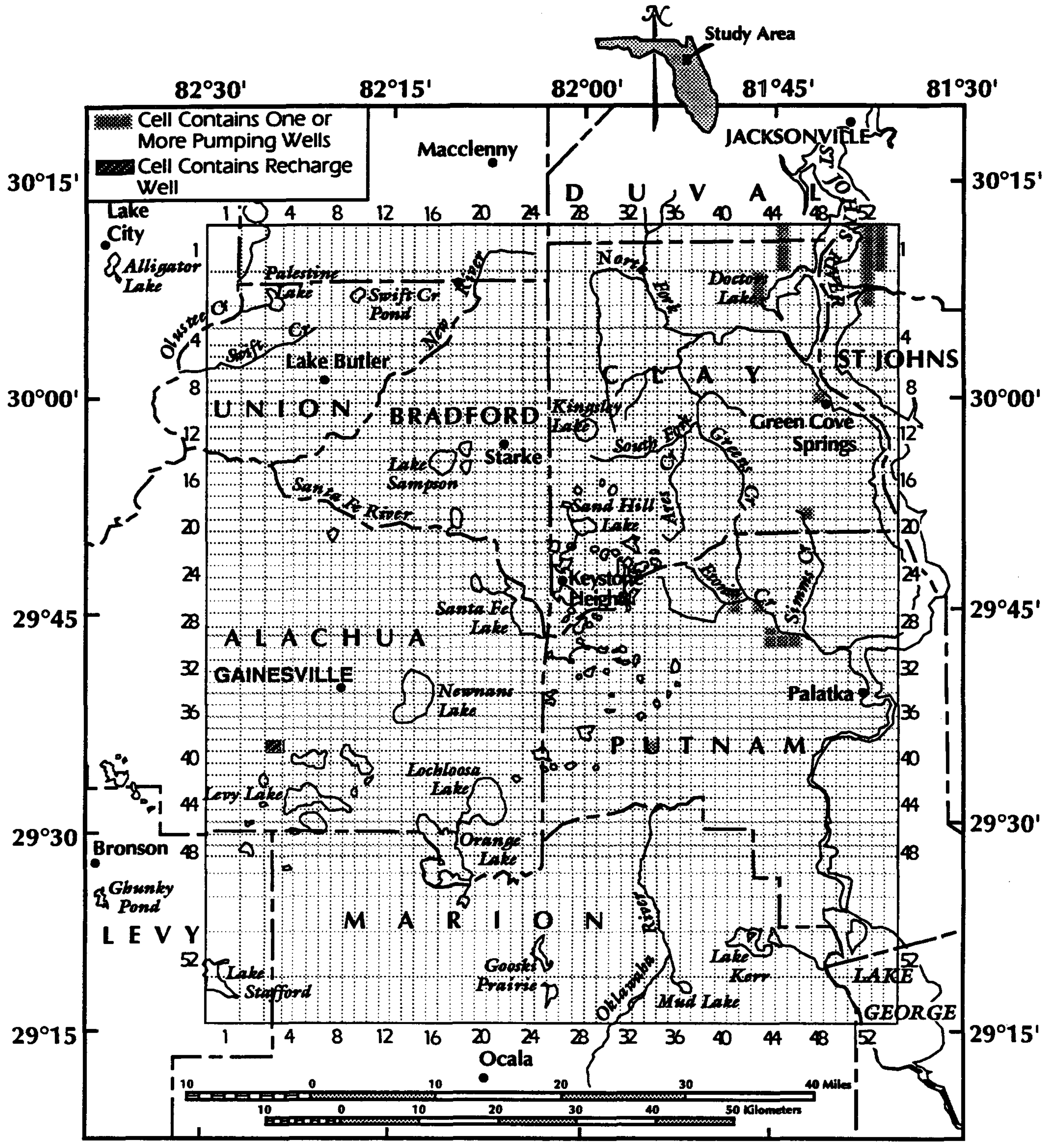


Figure 9-7. Pumping Wells (All Categories) and Recharge Well in Layer Four in the May 1985 Simulation

SJRWMD. The thirty-three locations represented named springs along the St. Johns River, base-flow pickup along parts of the Oklawaha River, and hypothetical springs in the northeast part of the study area between Wadesboro and Green Cove Springs (see Figure 8-7 and Table 9-1). For each spring, the elevation at which the spring discharged was estimated from the USGS 7.5-minute topographic quadrangle map, and the conductance was treated as a lumped parameter. Values for conductance from the predevelopment simulation (Table 8-2) were used as starting values and generally were adjusted during calibration of the May 1985 model.

9.1.5 Recharge and Evapotranspiration

Direct recharge generally occurs to the uppermost hydrologic unit. In this simulation, recharge occurs to layer three where this unit is unconfined and the cells are active. Recharge does not affect the constant head cells in layers one and two. A recharge rate of 2.70×10^{-2} ft/day (12 inches/year), representing the net recharge to the water table and to the ground-water system, was used in the simulation to represent recharge to the active cells in layer three.

Similarly, evapotranspiration generally occurs from the uppermost hydrologic unit. In this simulation, evapotranspiration occurs from layer three where this unit is unconfined and the cells are active. The maximum evapotranspiration rate from the active cells in layer three was assumed to be 0.00845 ft/day (37.0 inches/year), based on Bush and Johnston (1988). The surface in layer three at which evapotranspiration is at a maximum is an array whose values are equal to the top of the upper Floridan

Table 9-1 Springs and Drains in Layer Three in the May 1985 Simulation

Spring	Drain Number	Row	Column	Conductance (ft^2/day)	Calculated May 1985 Head (ft, NGVD)	Discharge Head (ft, NGVD)	Calculated May 1985 Discharge (ft^3/day)	Observed Discharge (ft^3/day)
Wadesboro Spring	1	1	46	5.80×10^3	25.1	0.0	1.45×10^5	1.00×10^5 [a]
Green Cove Springs	2	10	49	1.76×10^4	22.4	0.0	3.94×10^5	3.04×10^5 [a]
Whitewater Springs	3	36	51	7.06×10^3	16.0	0.0	1.13×10^5	1.22×10^5 [a]
Satsuma and Nashua Springs	4	45	49	1.00×10^4	10.4	0.0	1.04×10^5	1.79×10^5 [a]
Welaka Springs	5	46	49	1.00×10^4	8.21	0.0	8.21×10^4	9.50×10^4 [a]
Mud Spring	6	48	50	2.00×10^4	8.96	0.0	1.79×10^5	1.95×10^5 [a]
Forest Springs	7	49	50	5.00×10^3	8.31	0.0	4.15×10^4	2.59×10^4 [a]
Beecher Springs	8	49	51	1.25×10^5	11.2	5.0	7.73×10^5	9.25×10^5 [a]
Croaker Hole Spring	9	50	48	1.90×10^6	3.86	0.0	7.33×10^6	7.27×10^6 [a]
Salt Springs	10	52	45	2.00×10^6	8.51	5.0	7.02×10^6	7.02×10^6 [a]
Salt Springs Pickup	11	52	48	1.50×10^5	8.20	0.0	1.23×10^6	1.30×10^6 [b]
Orange Springs	12	45	32	2.35×10^4	49.1	25.0	5.66×10^5	6.58×10^5 [a]

Table 9-1 Continued

Spring	Drain Number	Row	Column	Conductance (ft^2/day)	Calculated May 1985 Head (ft, NGVD)	Discharge Head (ft, NGVD)	Calculated May 1985 Discharge (ft^3/day)	Observed Discharge (ft^3/day)
Oklawaha River Pickup	13	45	40	1.25×10^5	20.4	20.0	5.50×10^4	3.55×10^6 (b)
do.	14	45	39	1.25×10^5	22.3	20.0	2.91×10^5	--
do.	15	44	38	1.25×10^5	23.6	20.0	4.44×10^5	--
do.	16	44	37	1.25×10^5	30.0	20.0	1.25×10^6	--
do.	17	45	36	1.25×10^5	30.6	20.0	1.32×10^6	--
Oklawaha River Pickup	18	45	34	5.00×10^4	40.7	20.0	1.04×10^6	3.61×10^6 (b)
do.	19	46	34	5.00×10^4	37.4	20.0	8.68×10^5	--
do.	20	47	34	5.00×10^4	30.7	20.0	5.32×10^5	--
do.	21	48	33	5.00×10^4	36.1	20.0	8.03×10^5	--
do.	22	49	33	5.00×10^4	32.7	20.0	6.34×10^5	--
Oklawaha River Pickup	23	50	33	3.50×10^5	27.3	20.0	2.54×10^6	2.52×10^6 (b)
Oklawaha River Pickup	24	52	35	1.00×10^5	30.9	20.0	1.09×10^6	1.36×10^6 (b)

Table 9-1 Continued

Spring	Drain Number	Row	Column	Conductance (ft^2/day)	Calculated May 1985 Head (ft, NGVD)	Discharge Head (ft, NGVD)	Calculated May 1985 Discharge (ft^3/day)	Observed Discharge (ft^3/day)
Hypothetical Spring	25	2	49	4.00×10^3	24.9	0.0	9.98×10^4	--
do.	26	3	49	4.00×10^3	26.2	0.0	1.05×10^5	--
do.	27	4	49	4.00×10^3	26.4	0.0	1.06×10^5	--
do.	28	5	49	4.00×10^3	26.2	0.0	1.05×10^5	--
do.	29	6	49	4.00×10^3	25.9	0.0	1.04×10^5	--
do.	30	7	49	4.00×10^3	25.5	0.0	1.02×10^5	--
do.	31	8	49	4.00×10^3	24.7	0.0	9.87×10^4	--
do.	32	9	49	4.00×10^3	23.1	0.0	9.24×10^4	--
Lake George	33	52	53	1.25×10^5	8.21	0.0	1.03×10^6	6.48×10^5 (b)

Source of Data for Observed Discharge:

(a) SJRWMD
(b) Tibbals (1990)

aquifer, based on Miller (1986). The extinction depth, or the depth below which evapotranspiration ceases, was assumed to be 10.0 ft.

9.1.6 General Head Boundary Conditions

Similar to the predevelopment simulation, 210 general head boundaries were assigned around the peripheries of each of layers three, four, and five, for a total of 630 for the May 1985 simulation. Conductances for each general head boundary were obtained from the product of the transmissivity and width of the cell divided by the length of the flow path between the general head boundary and the adjacent active cell. In the May 1985 simulation, the distance from the constant-head sources to the centers of the adjacent active cells is 15,000 ft on the north, south, east, and west boundaries of the model. Boundary head values at each external source were obtained from the May 1985 potentiometric surface of the upper Floridan aquifer based on Schiner and Hayes (1985).

9.2 CALIBRATION

9.2.1 Comparison with Observed 1985 Potentiometric Surface

The ground-water flow model was calibrated by calculating the potentiometric surface for layer three and comparing it to the observed May 1985 potentiometric surface of the upper Floridan aquifer (Figure 4-4). The convergence criterion for the head in layer three was set equal to 0.1 ft, and the maximum number of iterations was chosen to be 100. Values for the transmissivity in layer three (T_3), vertical leakance in layer two (V_{cont2}), and conductances for the drains and general head boundaries in layer three were adjusted until the observed and calculated head differences in layer three were within reasonable agreement. The model simulation that was considered to be calibrated required 26 iterations; for this simulation, the mean of the differences between the observed and calculated heads is 0.592 ft, and the standard deviation of the differences is 3.36 ft (see Figure 9-8 and Table 9-2). The maximum head in layer three, equal to 85.8 ft, NGVD, occurs at row 21, column 30, and the minimum head, equal to 3.86 ft, NGVD, occurs at row 50, column 48.

At each drain location, the calculated spring discharge was obtained by multiplying the calibrated conductance value by the difference between the calculated May 1985 hydraulic head in the cell and the spring discharge elevation (see Table 9-1). Observed spring discharges were estimated from discharge data obtained from SJRWMD or, in the absence of such data, from values simulated by Tibbals (1990) for the May 1978 dry period. Overall, the calculated spring discharges totaled 3.07×10^7 ft^3/day, and there is very close agreement between the calculated and observed spring discharges in the May 1985 simulation (see Table 9-1 and Figure 9-9).

Significant differences between calculated and observed heads occur only in one area of layer three. In this area, which includes the GRU Murphree Well Field, the maximum difference between calculated and observed heads is 39.8 ft in the cell at row 32, column 10 (see Table 9-2). This difference is largely due to an apparent discrepancy in the manner in which water-level data were observed and mapped for

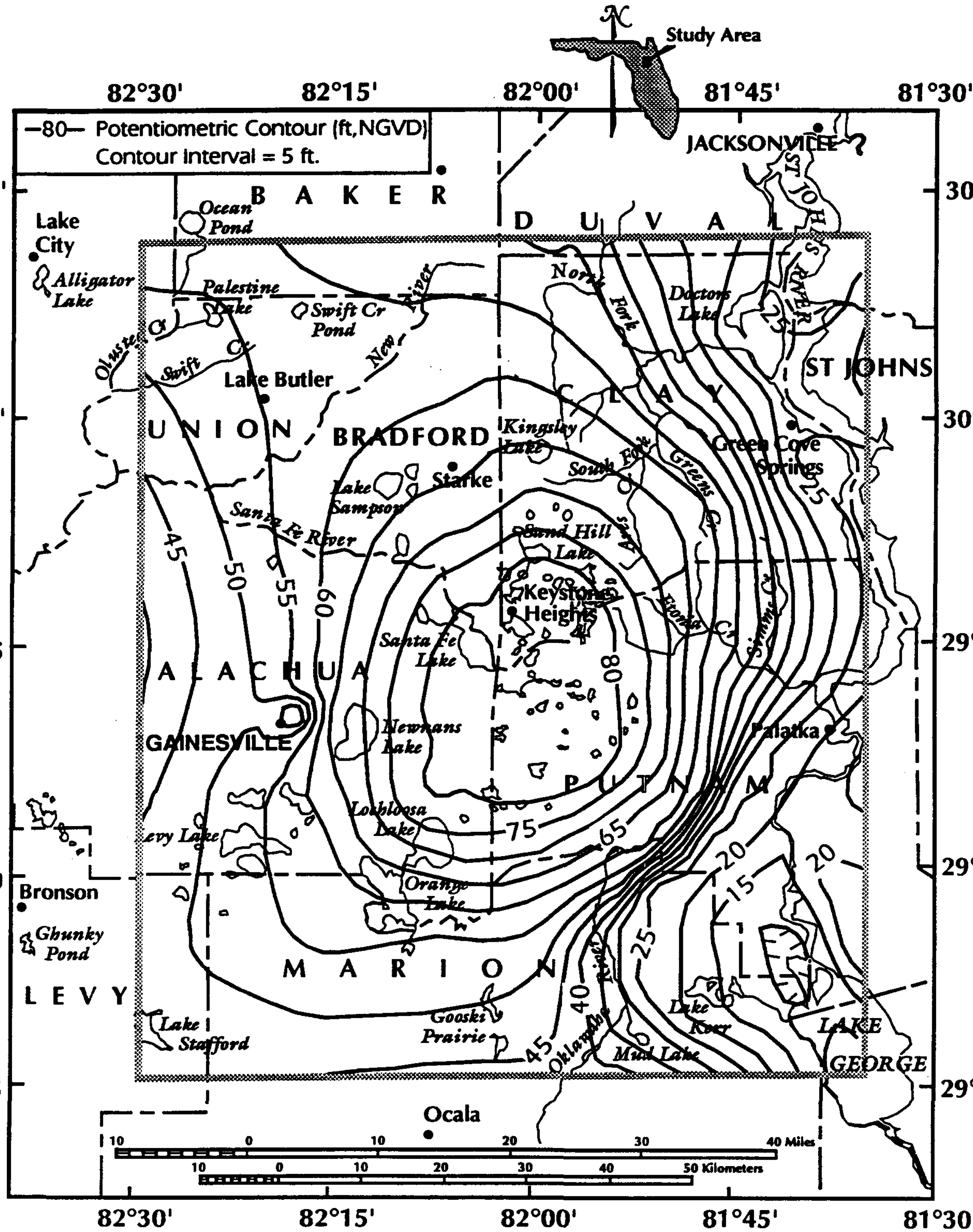


Figure 9-8. Calculated Potentiometric Surface in the Upper Floridan Aquifer in North-Central Florida for May 1985

Table 9-2 Statistical Results for Calibration Run and Sensitivity Analysis for the May 1985 Simulation

Statistical Parameter	Calibration Results	0.1 V_{cont1}	10.0 V_{cont1}	0.5 K_2	2.0 K_2	0.1 V_{cont2}	10.0 V_{cont2}	0.5 T_3	2.0 T_3
Maximum Head Difference (ft)	39.8 at (32,10)[a]	35.9 at (32,10)	41.0 at (32,10)	39.8 at (32,10)	39.8 at (32,10)	25.0 at (32,10)	60.7 at (32,10)	38.8 at (32,10)	39.8 at (32,10)
Minimum Head Difference (ft)	-14.0 at (30,9)	-23.6 at (27,41)	-12.9 at (30,9)	-14.0 at (30,9)	-14.0 at (30,9)	-41.8 at (27,41)	-14.4 at (32,46)	-48.7 at (30,9)	-11.8 at (39,31)
Mean of the Differences (ft)	0.592	-5.96	2.05	0.592	0.592	-15.3	15.5	2.20	-1.46
Standard Deviation of the Differences (ft)	3.36	6.96	3.92	3.36	3.36	12.4	13.3	4.70	4.05
Mean of the Absolute Values (ft)	2.38	6.88	3.25	2.38	2.38	15.6	16.5	3.94	3.14

[a]Indicates row and column location.

Table 9-2 Continued

Statistical Parameter	0.1 V_{cont3}	10.0 V_{cont3}	0.5 T_4	2.0 T_4	0.1 V_{cont4}	10.0 V_{cont4}	0.5 T_5	2.0 T_5	0.5 Q_T	2.0 Q_T
Maximum Head Difference (ft)	37.7 at (32,10)	43.4 at (32,10)	40.4 at (32,10)	38.6 at (32,10)	39.7 at (32,10)	39.8 at (32,10)	40.4 at (32,10)	38.6 at (32,10)	44.0 at (31,10)	31.7 at (32,10)
Minimum Head Difference (ft)	-18.4 at (30,9)	-14.1 at (27,43)	-13.8 at (30,9)	-14.2 at (30,9)	-14.3 at (30,9)	-13.9 at (30,9)	-13.8 at (30,9)	-14.5 at (30,9)	-9.98 at (45,36)	-59.2 at (30,9)
Mean of the Differences (ft)	1.15	-0.469	1.42	-0.599	0.556	0.546	1.36	-0.591	1.57	-1.38
Standard Deviation of the Differences (ft)	3.51	4.38	3.66	3.47	3.37	3.36	3.64	3.46	3.45	3.96
Mean of the Absolute Values (ft)	2.69	3.06	2.86	2.39	2.39	2.38	2.82	2.38	2.67	2.85

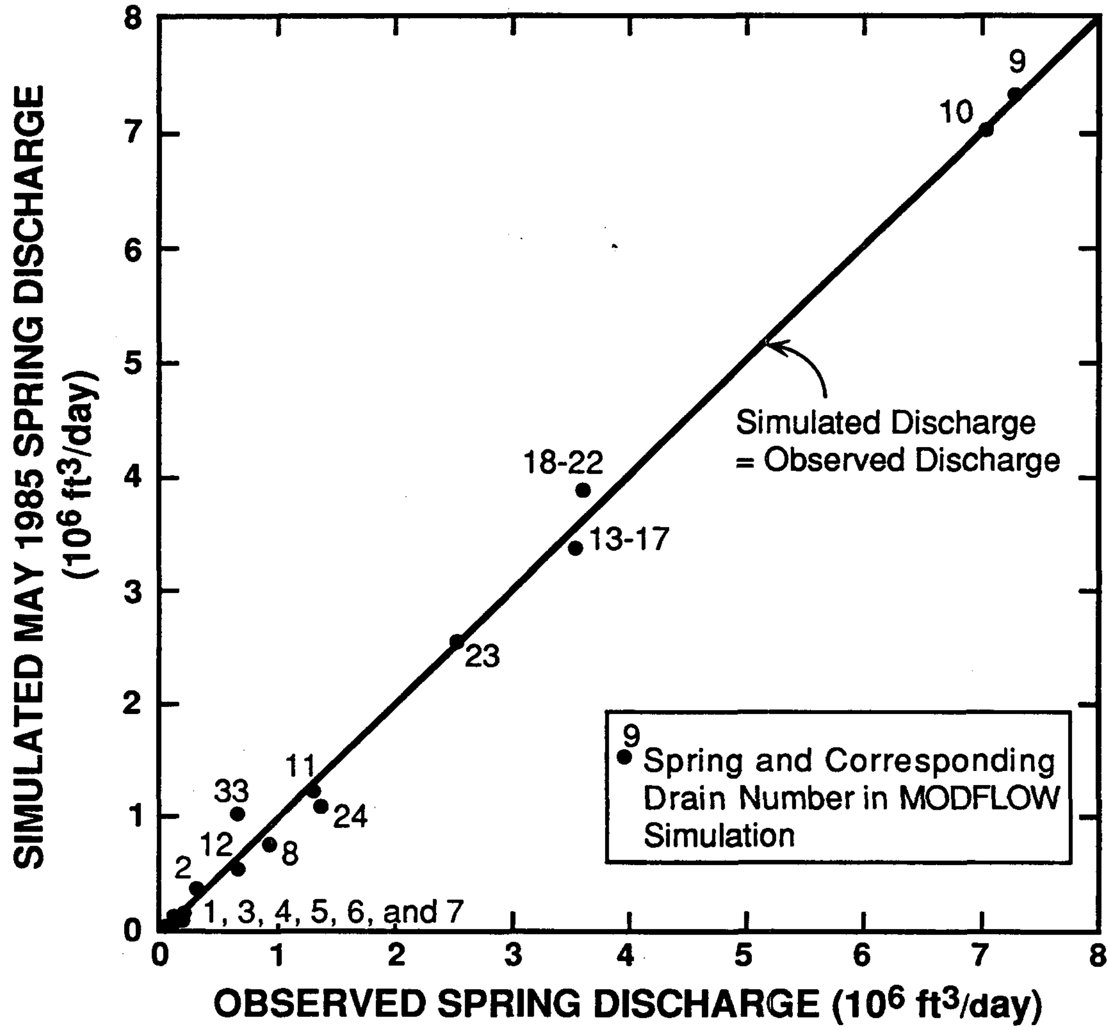


Figure 9-9. Simulated Versus Observed Spring Discharge in the May 1985 Simulation

1985. Based on data obtained from SJRWMD and GRU, the maximum pumping rate in the well field in 1985 occurred at wells that are in the cell at row 30, column 9, but the observed cone of depression that is mapped on the 1985 observed potentiometric surface is centered on the cell at row 31, column 10. This shifts the observed cone of depression diagonally to the south and east from the center of pumping. Thus, the calculated and observed heads do not agree on a cell-by-cell basis in this area. The greatest discrepancy occurs at row 32; column 10, where the calculated head is 53.32 ft, NGVD, and the observed head is reported to be 13.54 ft, NGVD, which results in the maximum difference of 39.8 ft in Table 9-2. In the May 1985 simulation, the cone of depression is centered on the cell at row 30, column 9, where the calculated head is 12.54 ft, NGVD. This value is reasonably close to the observed head of 9.63 ft, NGVD, that is mapped nearby at row 31, column 10, indicating that the pumping effects of the Murphree Well Field are modeled accurately.

Values for V_{cont2} in layer two, representing the leakance of the upper confining unit, range from 1.0×10^{-7} to 1.0×10^{-2} day^{-1} (see Figure 9-10). Values for T_3 in layer three, representing the transmissivity of the upper Floridan aquifer, generally range from 50,000 to 1,000,000 ft^2/day (see Figure 9-11). In a diagonally shaped area in the southeastern part of the study area, a value of T_3 = 5,000 ft^2/day was used to simulate the relatively steep gradient that appears on the potentiometric surface in this area (see Figures 4-4 and 9-8). In the vicinity of the GRU Murphree Well Field, the values for transmissivity and V_{cont} for layer three are different from the regional values in adjacent areas. These localized values, T_3 = 15,000 ft^2/day and V_{cont3} =

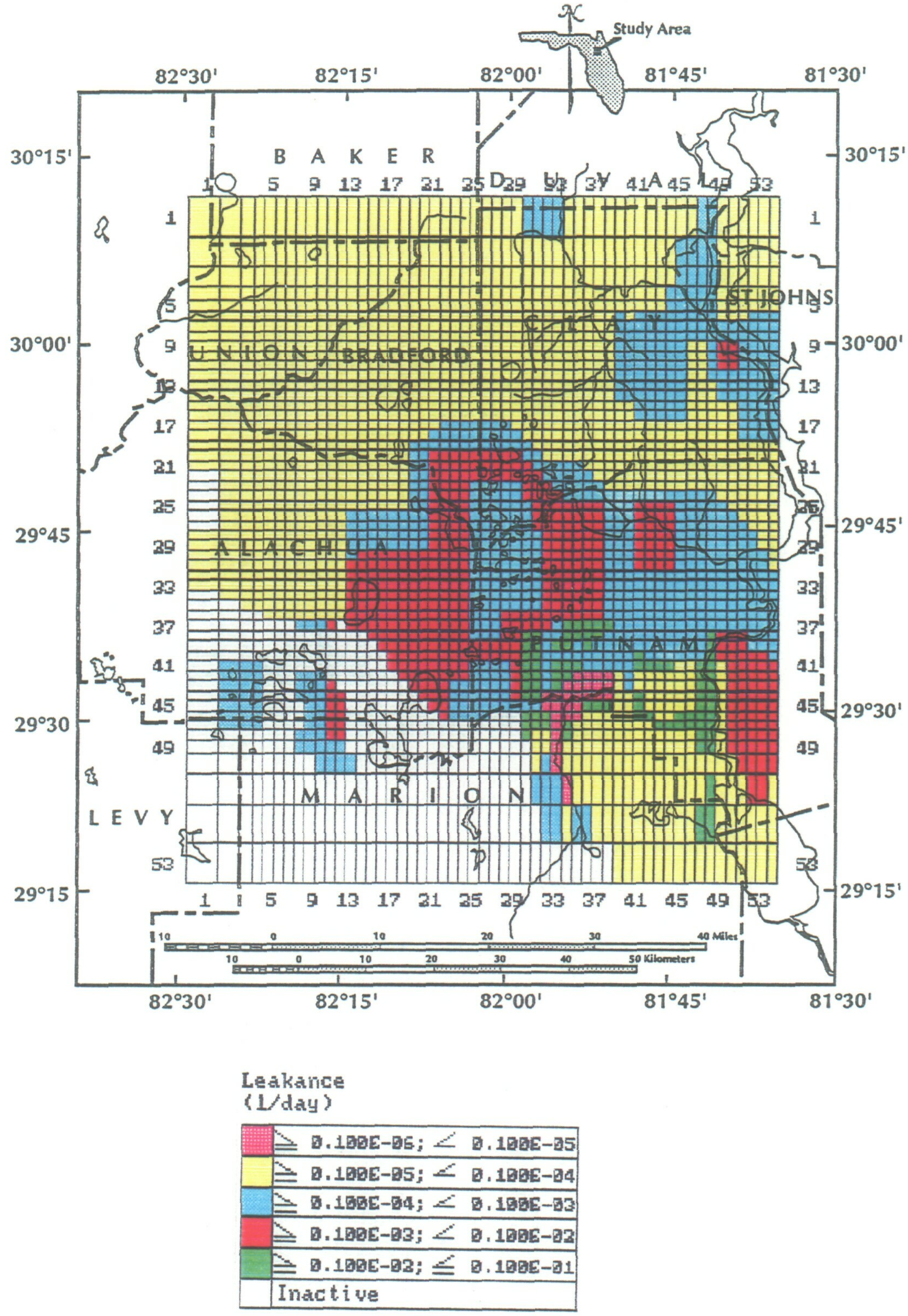


Figure 9-10. Leakance Values for the Upper Confining Unit in the May 1985 Simulation

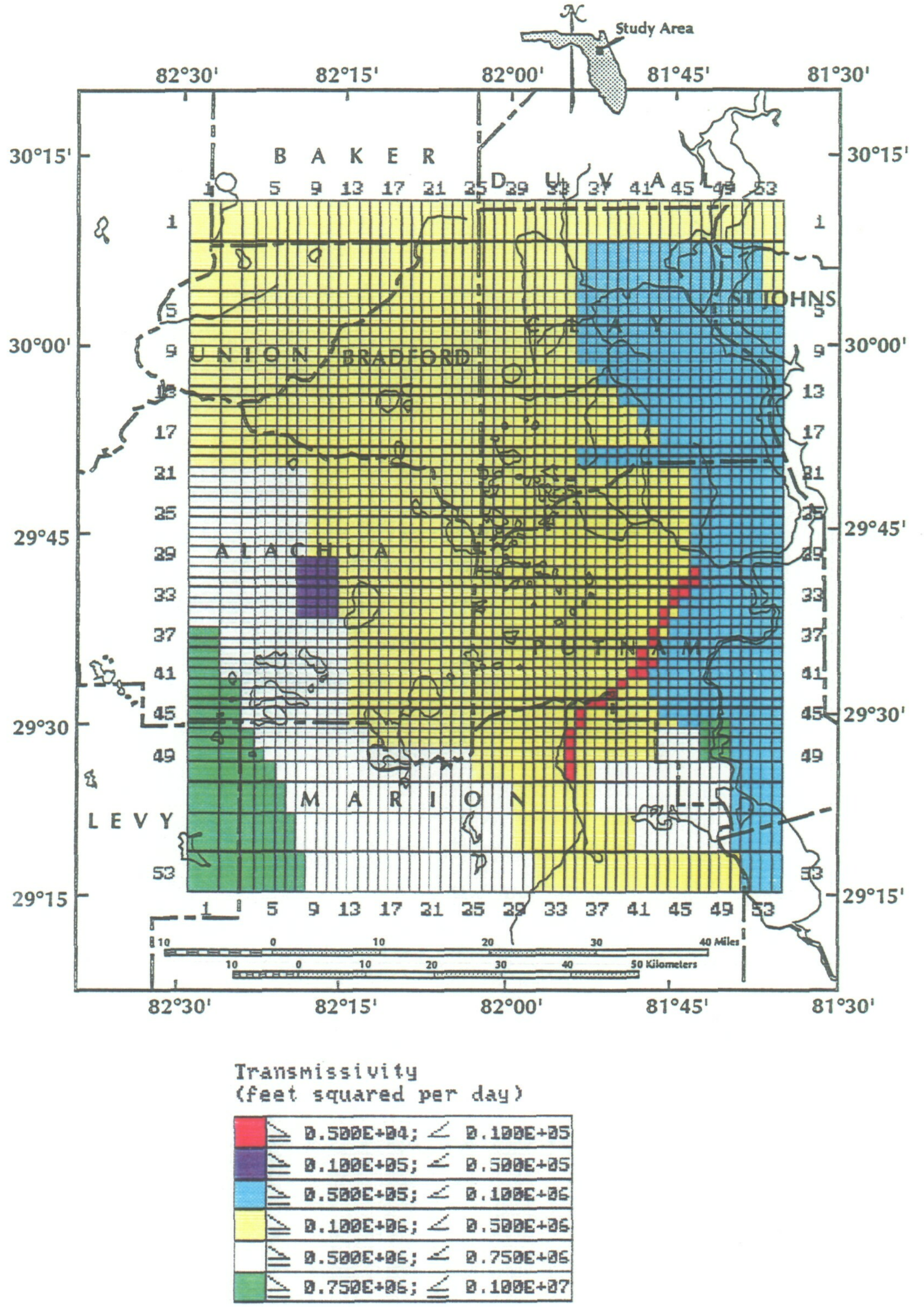


Figure 9-11. Transmissivity Values for the Upper Floridan Aquifer in the May 1985 Simulation

1.0×10^{-4} day^{-1}, simulate better the observed shape of the cone of depression and are more consistent with values used by Fischl (1994) to simulate the effects of pumping in the Murphree Well Field. Conductances for the drains that represent the springs in layer three range from 4.00×10^3 to 2.00×10^6 ft^2/day (see Table 9-1).

9.2.2 Water Budget

In the May 1985 simulation, inflows to the ground-water system of the model are derived from constant head boundaries (4.40 inches/year), drainage wells (0.13 inches/year), direct areal recharge to layer three (1.93 inches/year), and head dependent boundaries (0.83 inches/year) (see Table 9-3). Outflows from the ground-water system occur at constant head boundaries (0.47 inches/year), pumping wells (1.05 inches/year), drains that represent discharge at actual and hypothetical springs (1.36 inches/year), evapotranspiration from layer three (0.40 inches/year), and head dependent boundaries (4.01 inches/year). In the May 1985 simulation, the total inflows and outflows are the same, and they are equal to 7.29 inches/year.

9.3 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the calculated heads in layer three by varying the hydraulic conductivity and leakance values for layer two, the transmissivity and leakance values for layers three, four, and five, and the estimated pumping rates at the 309 cells in layers three and four in which pumping occurred (see Table 9-2). Based on the standard deviations calculated for the observed heads minus

Table 9-3 Water Budget for Active Cells in the May 1985 Simulation

	Flowrate:	
Inflow:	(ft^3/day)	(inches/year)
Constant Head Boundaries	9.93×10^7	4.40
Recharge Wells	2.98×10^6	0.13
Areal Recharge	4.36×10^7	1.93
Head Dependent Boundaries	1.87×10^7	0.83
Total Inflow	1.65×10^8	7.29
Outflow:		
Constant Head Boundaries	1.07×10^7	0.47
Pumping Wells	2.37×10^7	1.05
Drains	3.07×10^7	1.36
Evapotranspiration	8.94×10^6	0.40
Head Dependent Boundaries	9.04×10^7	4.01
Total Outflow	1.65×10^8	7.29

calculated heads for layer three, the calculated heads in layer three are most sensitive to the changes in leakance values for layer two (V_{cont2}). The heads in layer three are also relatively sensitive to the leakance values for layer one and three (V_{cont1} and V_{cont3}) and to the transmissivity values in layer three (T_3). The heads in layer three are less sensitive to changes in the transmissivities in layers four and five (T_4 and T_5) and the estimated pumping rates (Q_T), and they are relatively insensitive to changes in hydraulic conductivity values in layer two (K_2) and the leakance value for layer four (V_{cont4}).

9.4 MODIFIED PREDEVELOPMENT MODEL

9.4.1 Comparison With Observed Predevelopment Potentiometric Surface

To verify the calibration parameters in the May 1985 simulation, the aquifer parameters for the May 1985 simulation were used to simulate the observed predevelopment potentiometric surface (see Figure 9-12). The MODFLOW files for the predevelopment simulation in Chapter 8 representing the hydrologic units, aquifer discretization, the water table in layers one and two, the observed predevelopment potentiometric surface (Figure 4-3), recharge and evapotranspiration, and the general head boundary conditions were used in this simulation, along with the aquifer parameters and spring discharge head and conductance values (Table 9-1) that resulted from the May 1985 simulation.

In this modified predevelopment simulation, the mean of the differences between the observed and calculated heads is 0.454 ft, and the standard deviation of the differences is 4.31 (see Table 9-4). The maximum difference between the

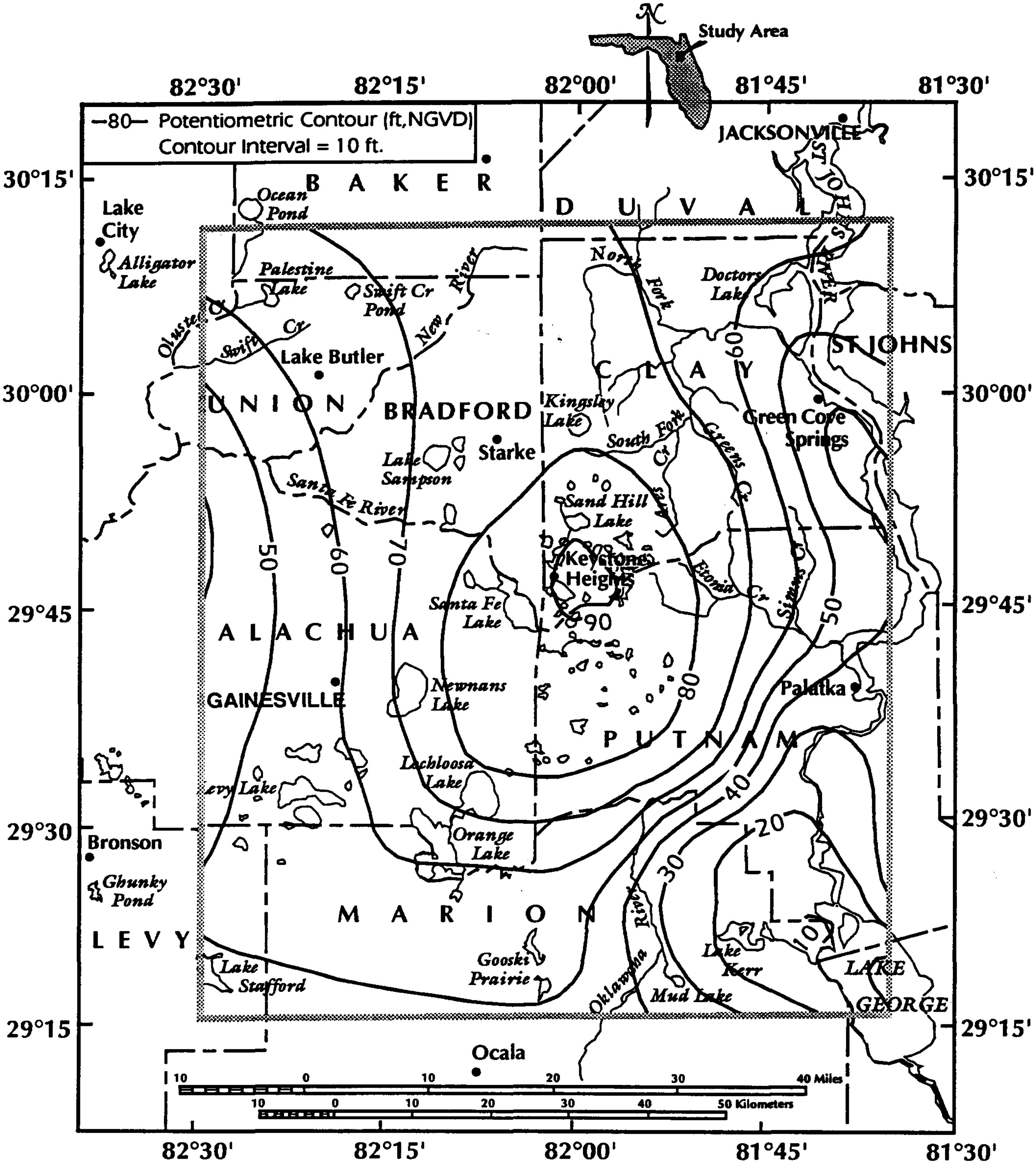


Figure 9-12. Modified Predevelopment Potentiometric Surface Calculated for the Upper Floridan Aquifer

Table 9-4 Statistical Results for the Modified Predevelopment Simulation

Statistical Parameter	Results of Comparing Calculated Versus Observed Heads
Maximum Head Difference (ft)	15.8 at (35,41)[a]
Minimum Head Difference (ft)	-17.8 at (44,38)
Mean of the Differences (ft)	0.454
Standard Deviation of the Differences (ft)	4.31
Mean of the Absolute Values (ft)	2.96

[a]Indicates row and column location.

calculated and observed heads, 15.8 ft., occurs at row 35, column 41, and the minimum difference, -17.8 ft, occurs at row 44, column 38. The maximum head in layer three, equal to 92.9 ft, NGVD, occurs at row 21, column 30, and the minimum head, equal to 4.32 ft, NGVD, occurs at row 50, column 48.

9.4.2 Water Budget

In the modified predevelopment simulation, inflows to the ground-water system are derived from constant head boundaries (3.76 inches/year), direct areal recharge to layer three (1.93 inches/year), and head dependent boundaries (0.96 inches/year) (see Table 9-5). Outflows from the ground-water system occur at constant head boundaries (0.79 inches/year), drains that represent discharge at actual and hypothetical springs (1.55 inches/year), evapotranspiration from layer three (0.55 inches/year), and head dependent boundaries (3.76 inches/year). In the modified predevelopment simulation, the total inflows and outflows are equal to 6.65 inches/year. This compares to total inflows and outflows of 6.60 inches/year calculated for the predevelopment simulation (see Table 8-4).

9.4.3 Calculated Drawdowns

The differences between the modified predevelopment potentiometric surface (Figure 9-12) and the calculated May 1985 potentiometric surface (Figure 9-8), or calculated drawdowns, are greater than 30 ft in the northeastern part of the study area near Jacksonville and in the vicinity of the GRU well field in Gainesville (see Figure 9-13). In general, the calculated drawdowns compare favorably with the observed drawdowns (Figure 4-5), except in the southeastern part of the study area. This dif-

Table 9-5 Water Budget for Active Cells in the Modified Predevelopment Simulation

	Flowrate:	
Inflow:	(ft^3/day)	(inches/year)
Constant Head Boundaries	8.49×10^7	3.76
Recharge	4.36×10^7	1.93
Head Dependent Boundaries	2.17×10^7	0.96
Total Inflow	1.50×10^8	6.65
Outflow:		
Constant Head Boundaries	1.79×10^7	0.79
Drains	3.49×10^7	1.55
Evapotranspiration	1.23×10^7	0.55
Head Dependent Boundaries	8.47×10^7	3.76
Total Outflow	1.50×10^8	6.65

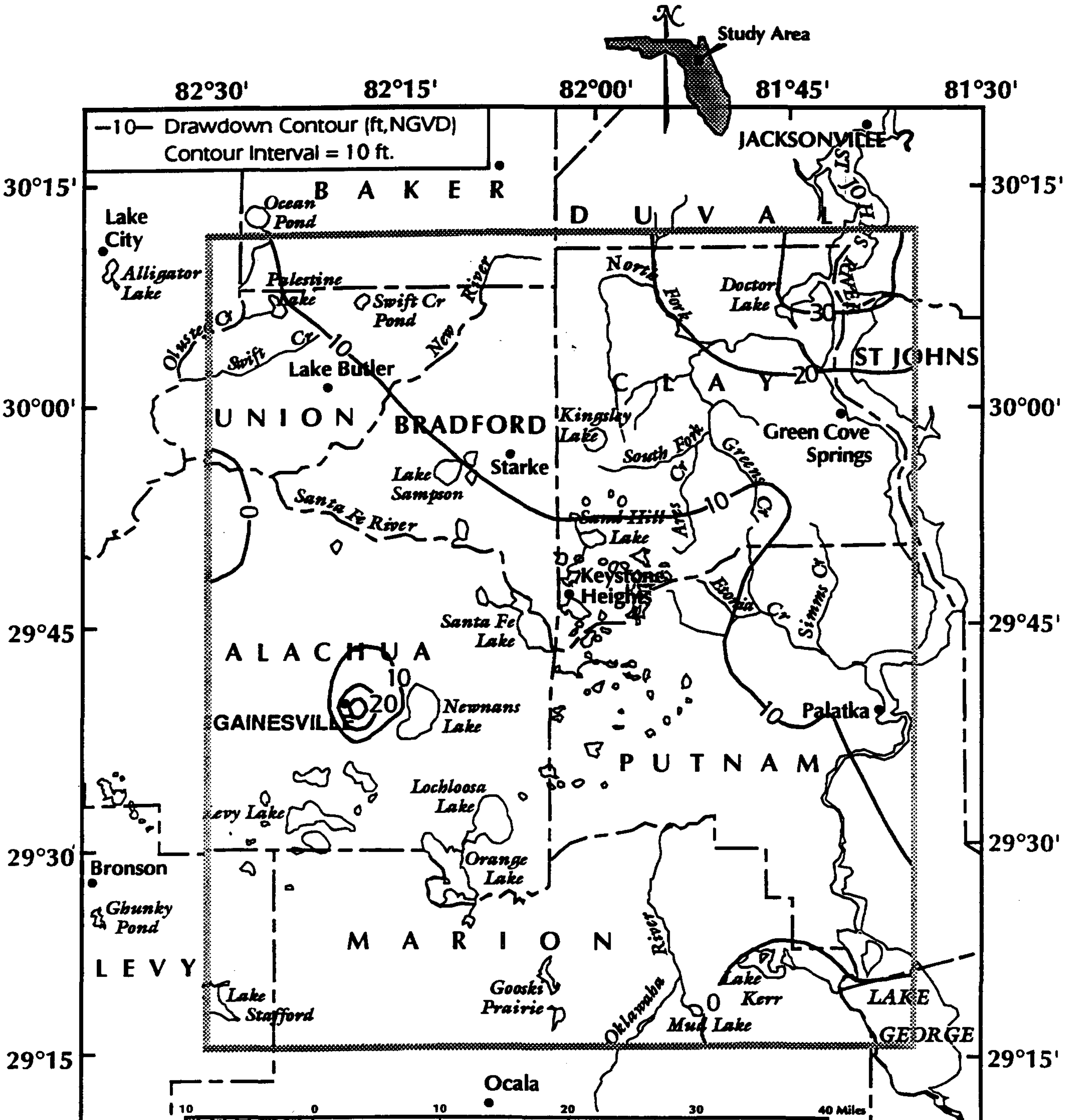


Figure 9-13. Difference Between the Modified Predevelopment and Calculated May 1985 Potentiometric Surfaces (Calculated Drawdowns)

ference between the observed and calculated drawdowns may be due to the influence of higher water levels in the present day Rodman Reservoir or, in part, due to inaccuracies in the estimated predevelopment potentiometric surface. Also, in the simulations, the predevelopment phreatic surface in layer one was assumed to be the same as the May 1985 phreatic surface. Inaccuracies in this assumption, which was made due to the lack of data for predevelopment times, also may contribute to the differences between Figures 4-5 and 9-13.

9.5 TRANSIENT SIMULATION

9.5.1 Monthly Pumpage

A transient simulation was performed by varying the May 1985 pumping rate and calculating heads as a function of time. Pumping rates were calculated for June, July, August, and September 1985 for agricultural, commercial and industrial, public supply, and thermoelectric power generation uses based on actual pumping rates for the major pumpers and on monthly pumping distributions for SJRWMD, SWFWMD, and Florida (Marella 1986a, 1986b, and 1988b and Stieglitz 1986). The injection rates for the recharge wells were assumed to be the same as May 1985 because of the relative lack of data for this category. The total net pumping rate at the 309 wells in the study area in 1985 decreased from 2.077×10^7 ft^3/day in May to 1.622×10^7 ft^3/day in June, 1.260×10^7 ft^3/day in July, 1.213×10^7 ft^3/day in August, and 1.197×10^7 ft^3/day in September (see Figure 9-14).

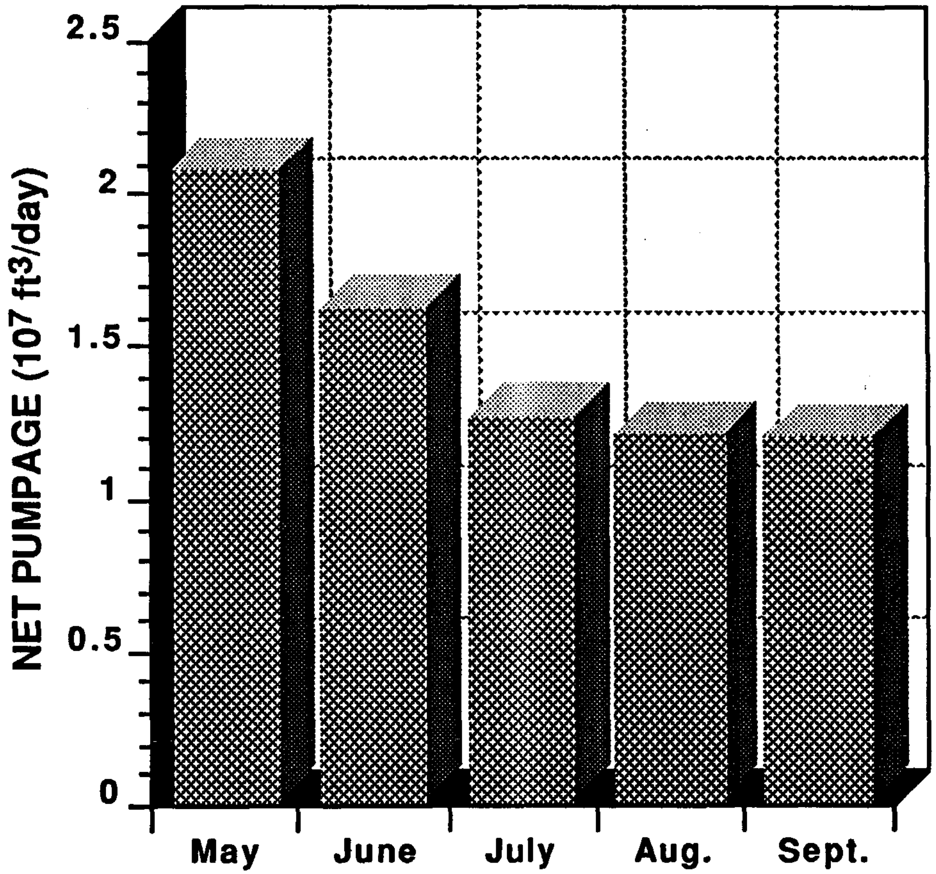


Figure 9-14. Estimated Net Pumpage for May-September 1985

9.5.2 MODFLOW Files

The MODFLOW well file for the May 1985 simulation was modified to include the pumping rates for the 309 wells for each of five simulation periods that correspond to May, June, July, August, and September 1985, respectively. Other MODFLOW files from the May 1985 simulation were modified as required to include the five simulation periods. The length of the first simulation period was made long enough for the model to run to equilibrium and match the calculated May 1985 heads in layer three. The lengths of simulation periods two through five were 30, 31, 31, and 30 days, respectively, to correspond to May, June, July, August, and September.

All of the parameters resulting from the May 1985 steady-state calibration were used in the transient simulation except for the storage coefficients, which were modified for the transient condition. A confined aquifer storage coefficient was assigned to the part of layer two that is confined and in which the cells are active, and both confined and unconfined aquifer storage coefficients were assigned to layer three. Confined aquifer storage coefficients were assigned to layers four and five. Several simulations were made in which a value of 0.1 was used for the unconfined storage coefficient in layer three, and values ranging from 0.001 to 0.005 were used for the confined aquifer storage coefficients. For each simulation, the confined aquifer storage coefficient was assumed to be spatially constant throughout layers two through five. The calculated heads in layer three changed by a few tenths of a foot over the storage coefficient range of 0.001 to 0.005, and thus they are relatively insensitive to the value chosen for the confined aquifer storage coefficient over this range.

9.5.3 Results of Simulation

Water-level data for wells in the study area were compared to transient heads calculated for layer three to evaluate the simulation. Data from four wells (see Figure 9-15 and Table 9-6) were compared to heads at locations in the model grid that correspond to the well locations. The heads at these locations were obtained by calculating an average head from the heads calculated at the four nearest cells. These four heads were weighted based on the inverse distances to the centers of the nearby cells.

The results for a confined aquifer storage coefficient of 0.001 indicate that the transient simulation was only moderately successful. At wells P-0408 and A-0005, the simulated heads increase with respect to time but at slower rates than the observed heads (see Figures 9-16 and 9-17). At the Sperry Rand well in Gainesville, the simulated heads increase in response to the decrease in pumping at the nearby GRU Murphree Well Field, while the observed heads decreased during part of the same period (see Figure 9-18), perhaps due to a localized pumping stress that is not included in the simulation. At the USGS well at Keystone Heights, the simulated heads increase at a much slower rate than the observed heads (see Figure 9-19).

The most important factor contributing to the differences between the simulated and observed responses probably is the constant head assumption that was made to describe the water table in layers one and two in the model. Based on the relative lack of temporal and spatial water-table data in the study area, compared to the water-level data available for the upper Floridan aquifer, this is a reasonable, if somewhat limiting, assumption. However, the result of this assumption is that the effect of the

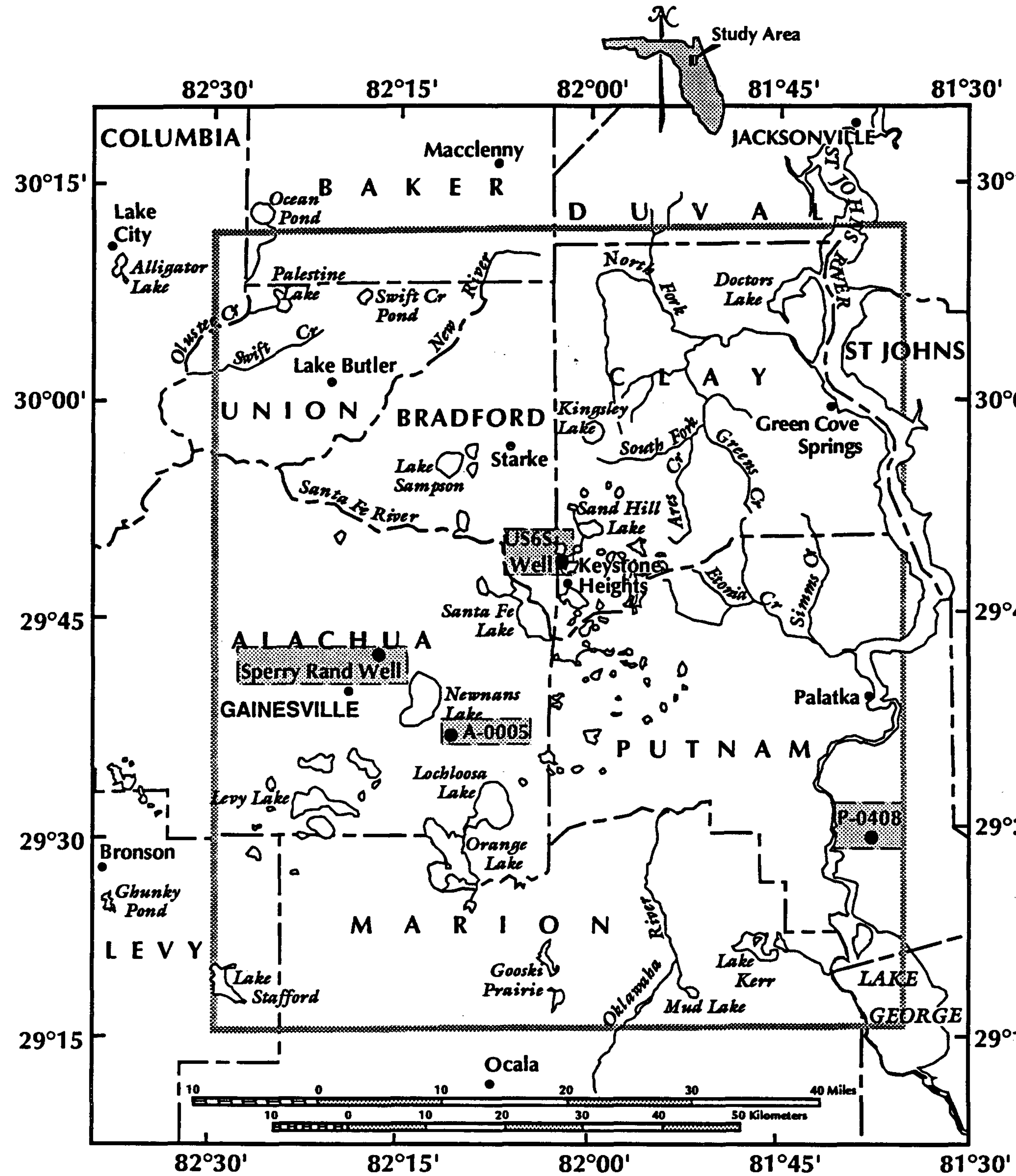


Figure 9-15. Locations of Wells Selected for Comparison to Transient Simulation

Table 9-6 Latitude-Longitude Numbers for Wells Selected for Comparison to Transient Simulation

Well	Latitude (North)	Longitude (East)
P-0408	29° 28' 59"	81° 37' 57"
A-0005	29° 35' 39"	82° 11' 26"
Sperry Rand Well at Gainesville	29° 42' 07"	82° 16' 32"
USGS Well at Keystone Heights	29° 48' 07"	82° 02' 09"

Note: See Figure 9-15 for well locations in study area.

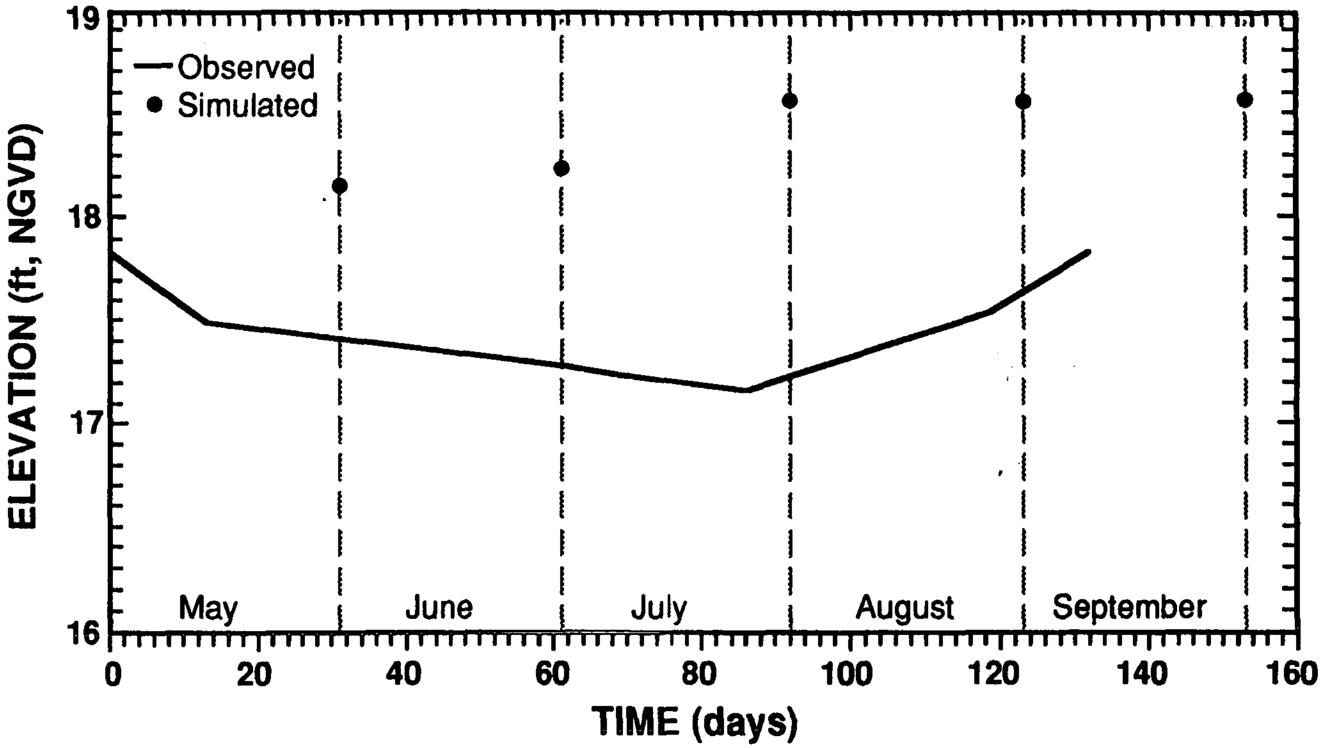


Figure 9-16. Observed and Simulated Water Levels for May-September 1985 for Well P-0408

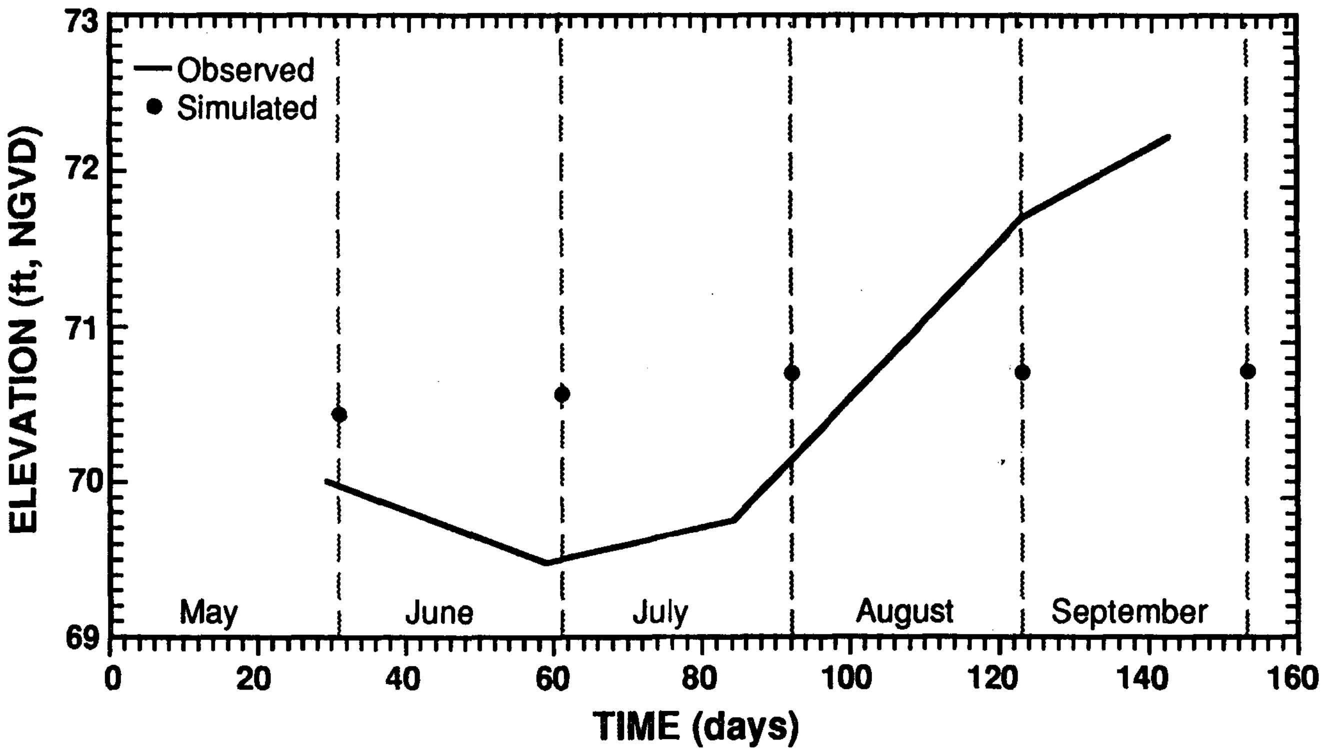


Figure 9-17. Observed and Simulated Water Levels for May-September 1985 for Well A-0005

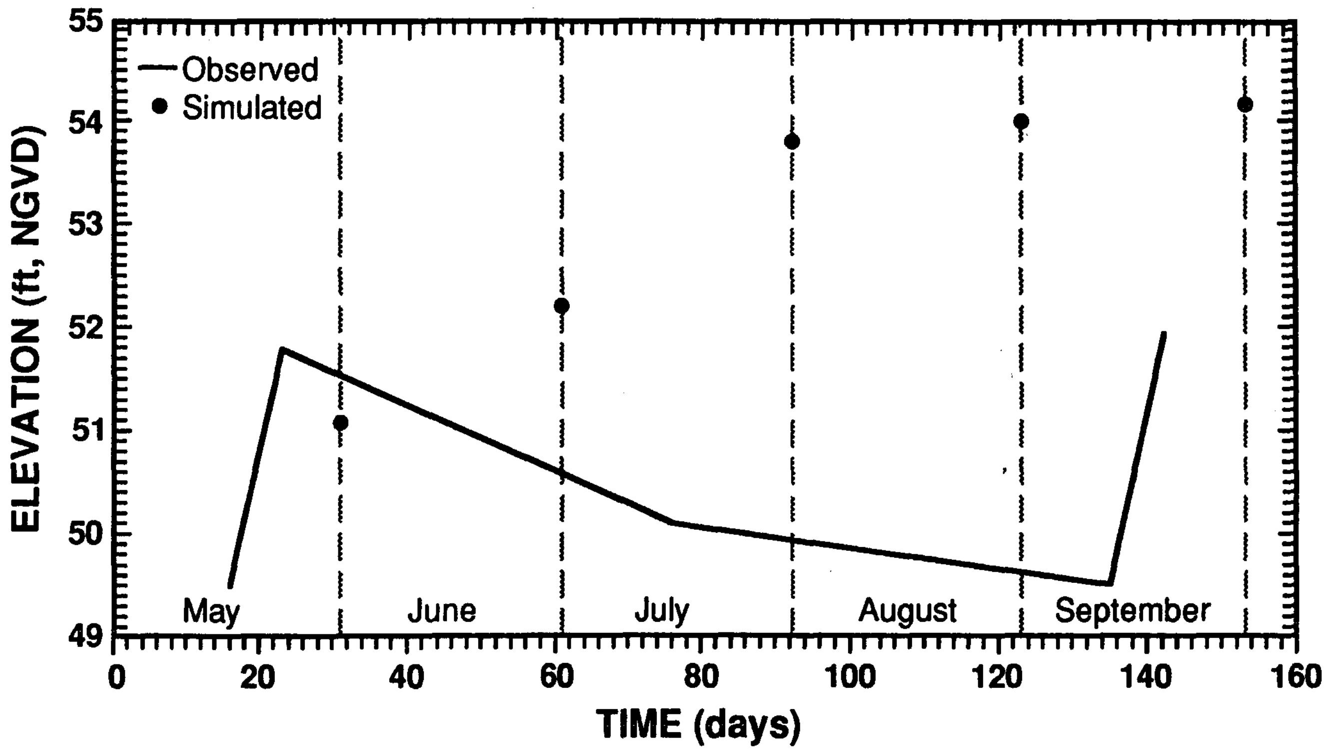


Figure 9-18. Observed and Simulated Water Levels for May-September 1985 for Sperry Rand Well at Gainesville

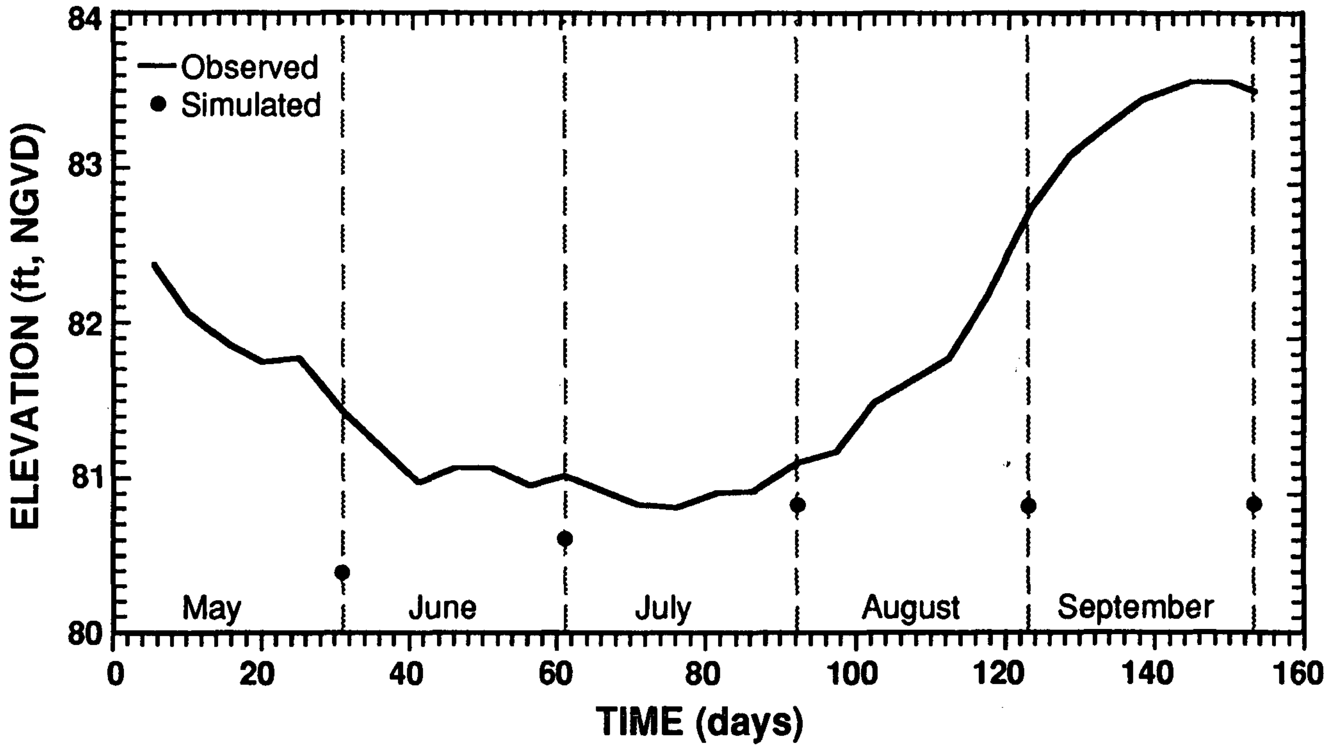


Figure 9-19. Observed and Simulated Water Levels for May-September 1985 for USGS Well at Keystone Heights

seasonal rise and fall of the water table is not included in the simulation, which instead includes the effect of the water table as an average condition. Thus, the simulated water levels in layer three do not increase or decrease as quickly as the observed water levels in the upper Floridan aquifer, which respond to a transient water table as well as to changes in pumping stresses.

10.0 PREDICTION OF FUTURE IMPACTS ON THE SURFICIAL AND UPPER FLORIDAN AQUIFERS

10.1 SIMULATION OF THE 2010 POTENTIOMETRIC SURFACE

10.1.1 MODFLOW Files and Ground-Water Pumpage

The calibrated May 1985 simulation and the projected pumping rates for May 2010 were used to predict the potentiometric surface in the upper Floridan aquifer for May 2010. The MODFLOW files for the May 1985 simulation in Chapter 9 representing the hydrologic units, aquifer discretization, the water table in layers one and two, aquifer parameters, recharge, and evapotranspiration were used in this simulation, along with the spring discharge head and conductance values (Table 9-1) that resulted from the May 1985 simulation. The general head boundary conditions used for the May 1985 simulation were adjusted for the May 2010 simulation to reflect the drawdowns predicted by Durden (1994a) for 1985 to 2010 in the adjacent areas north and east of the study area.

Based on the water-use information compiled from the three water management districts, pumpage for May 2010 was projected from the May 1985 pumping data (see Chapter 5). Pumping rates, well locations, and model layer number were delineated for the public-supply, commercial and industrial, agricultural, thermoelectric power generation, and direct recharge categories (see Figures 10-1 through 10-5). In the May 2010 simulation, pumping occurs from 319 cells in layers three and four, and direct recharge via wells occurs in three cells in layer three and in one cell in

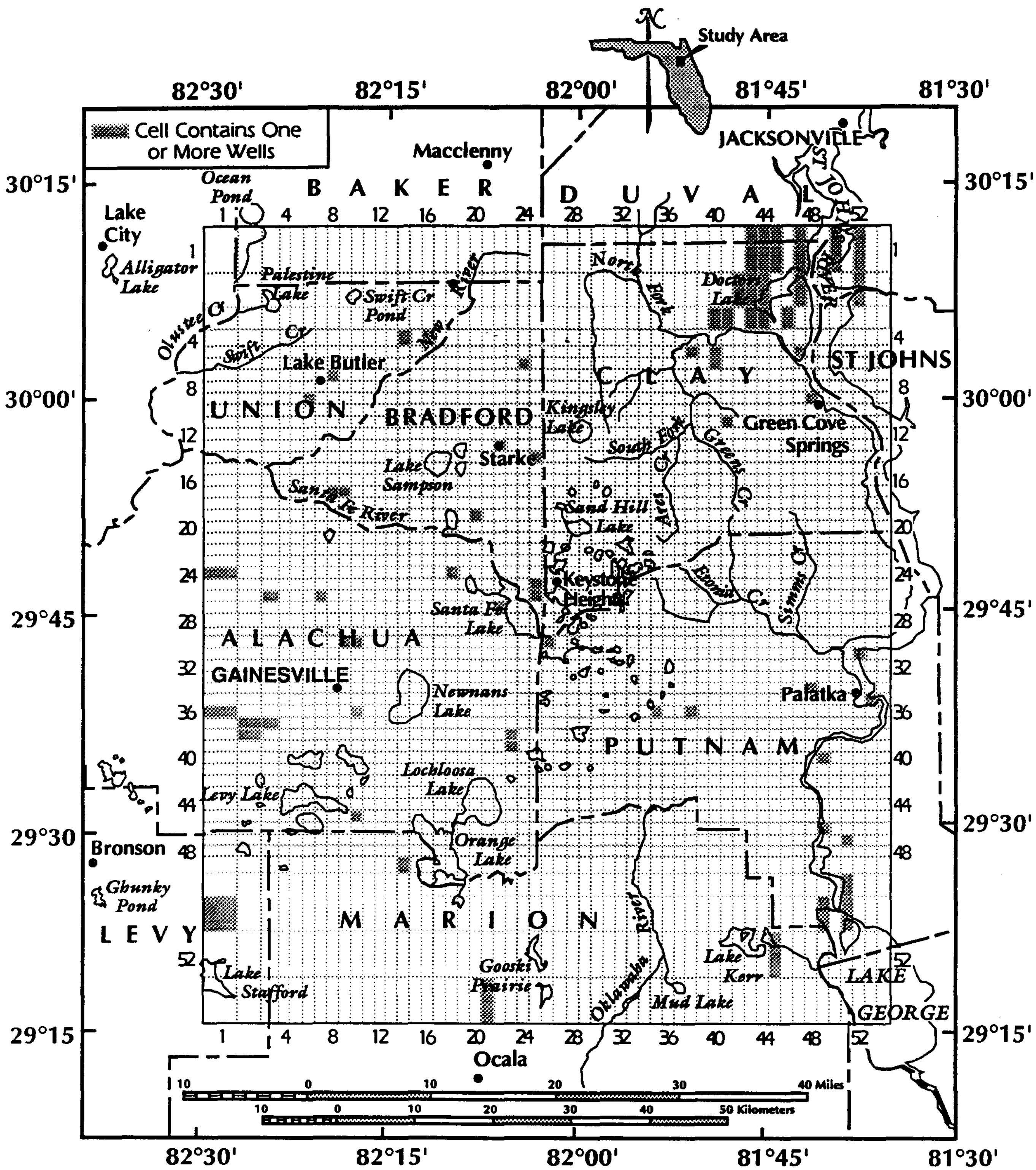


Figure 10-1. Public Supply Wells in Layers Three and Four in the May 2010 Simulation

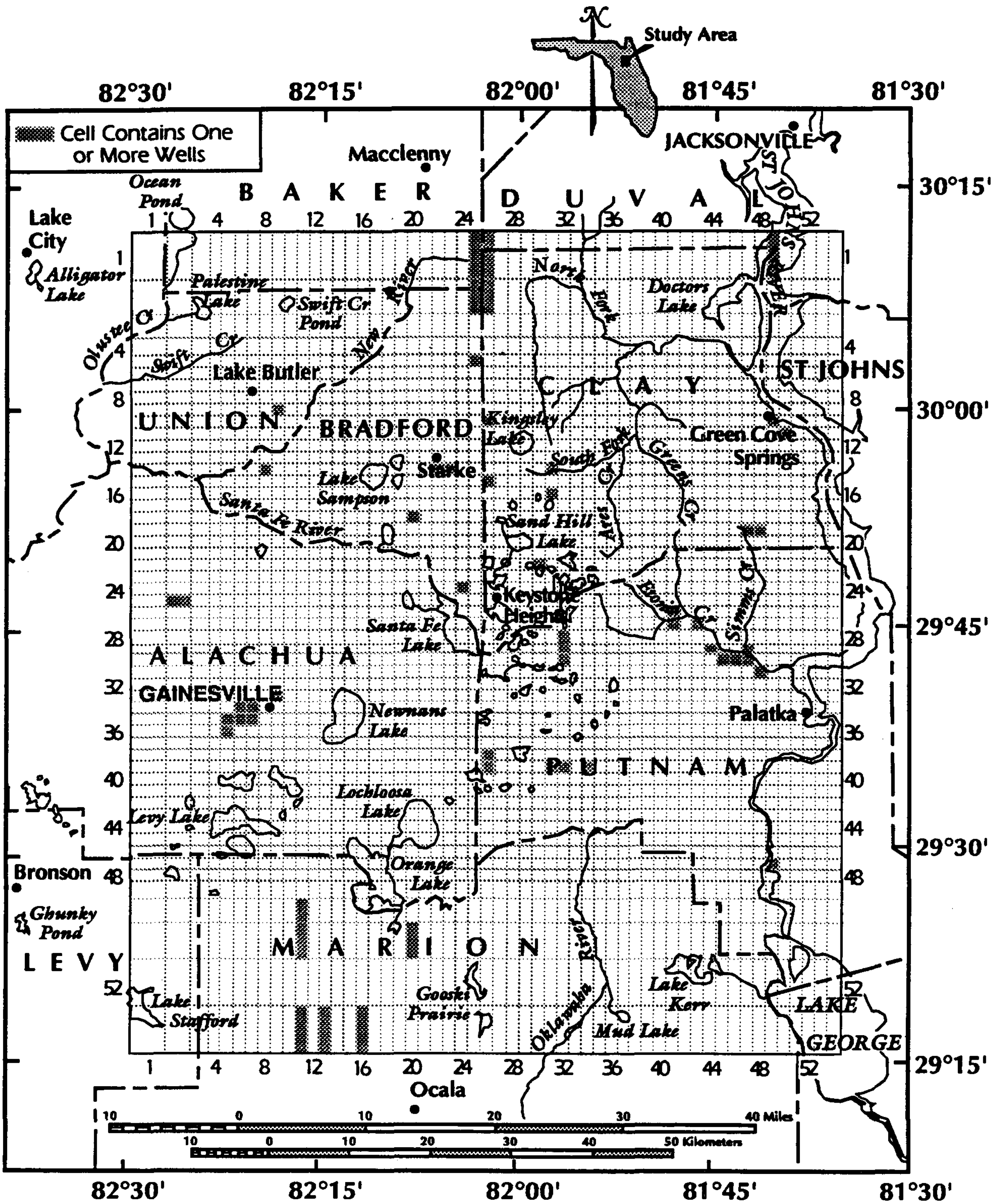


Figure 10-2. Commercial and Industrial Wells in Layers Three and Four in the May 2010 Simulation

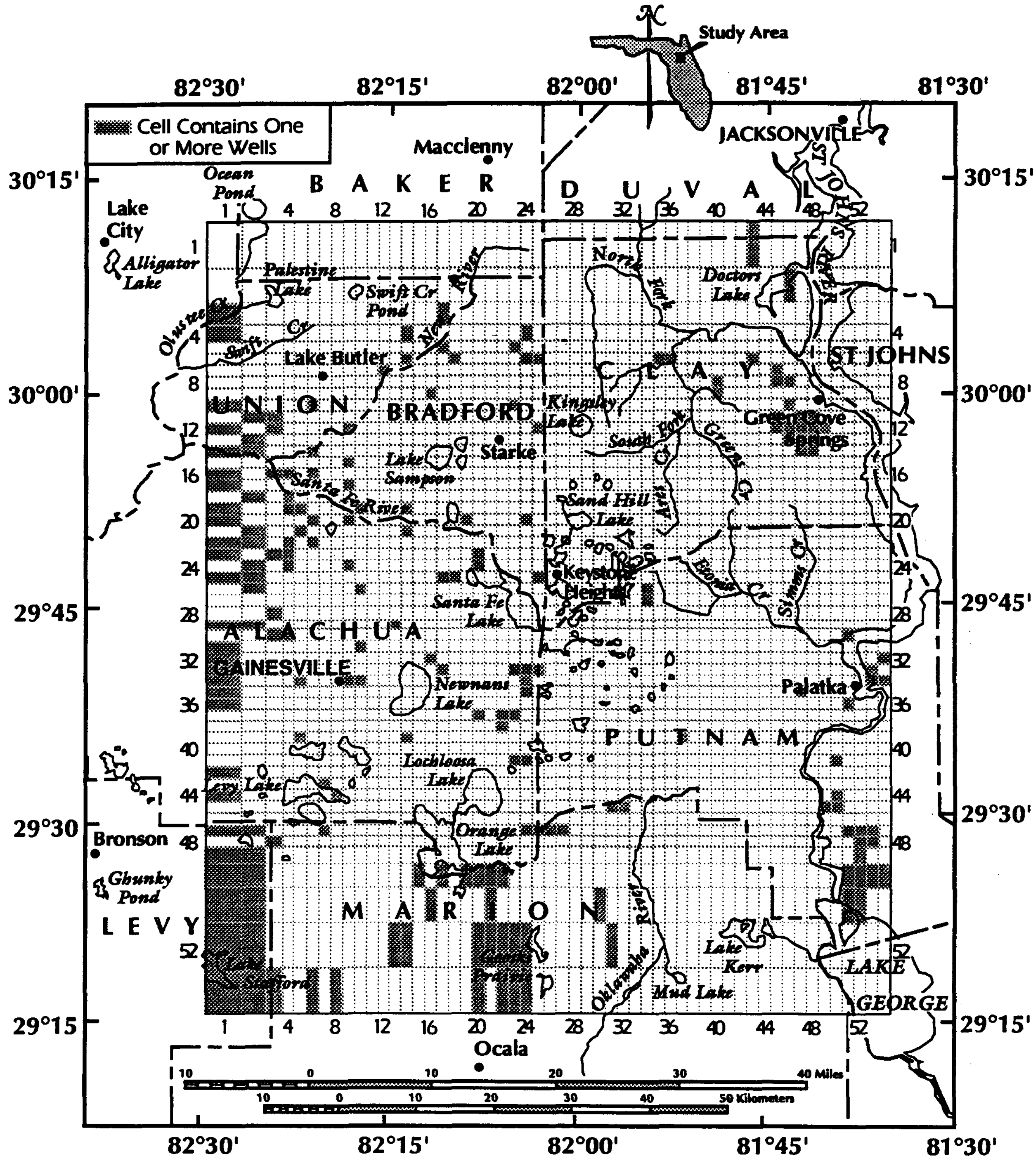


Figure 10-3. Agricultural Wells in Layers Three and Four in the May 2010 Simulation

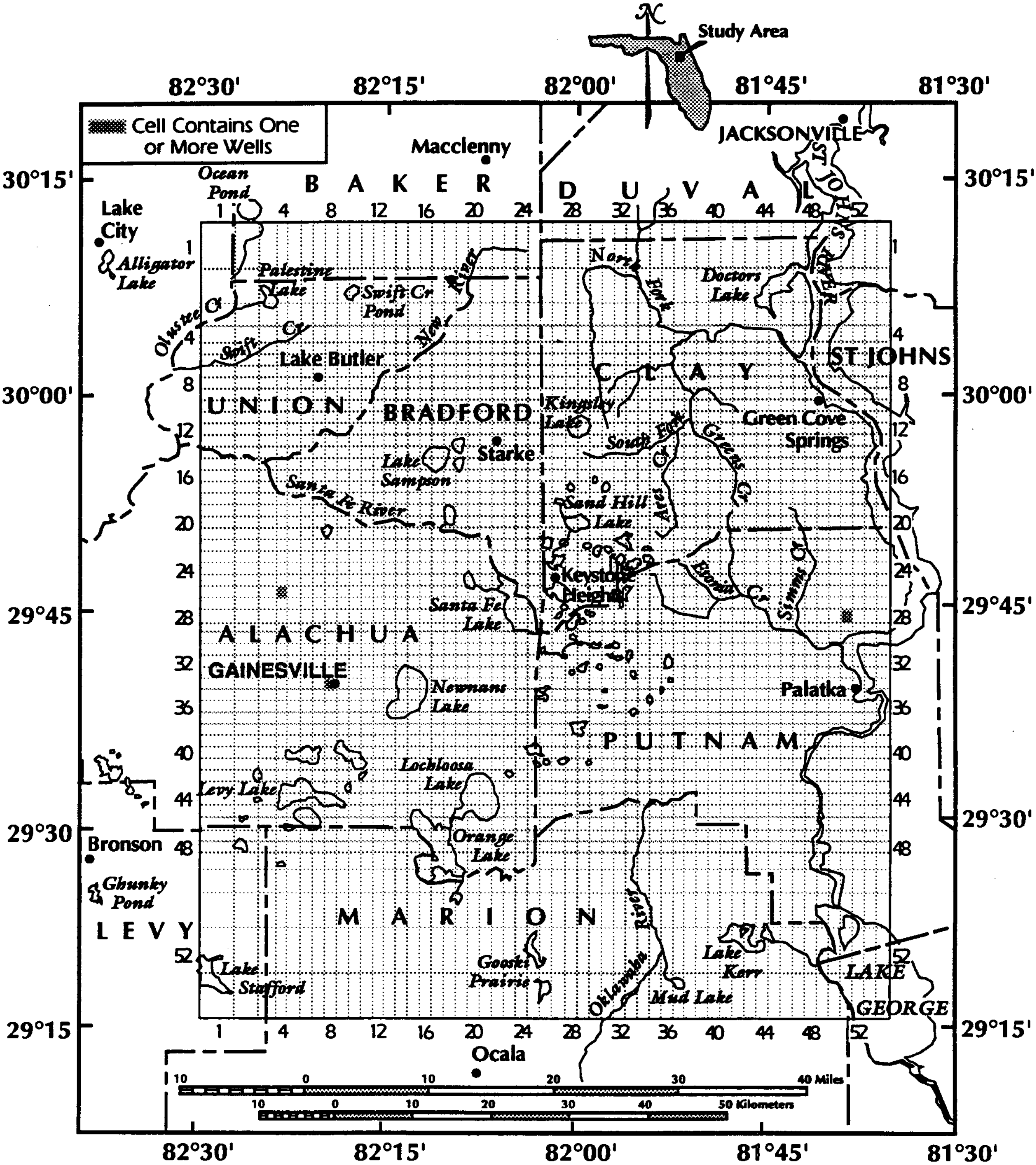


Figure 10-4. Thermoelectric Power Generation Wells in Layer Three in the May 2010 Simulation

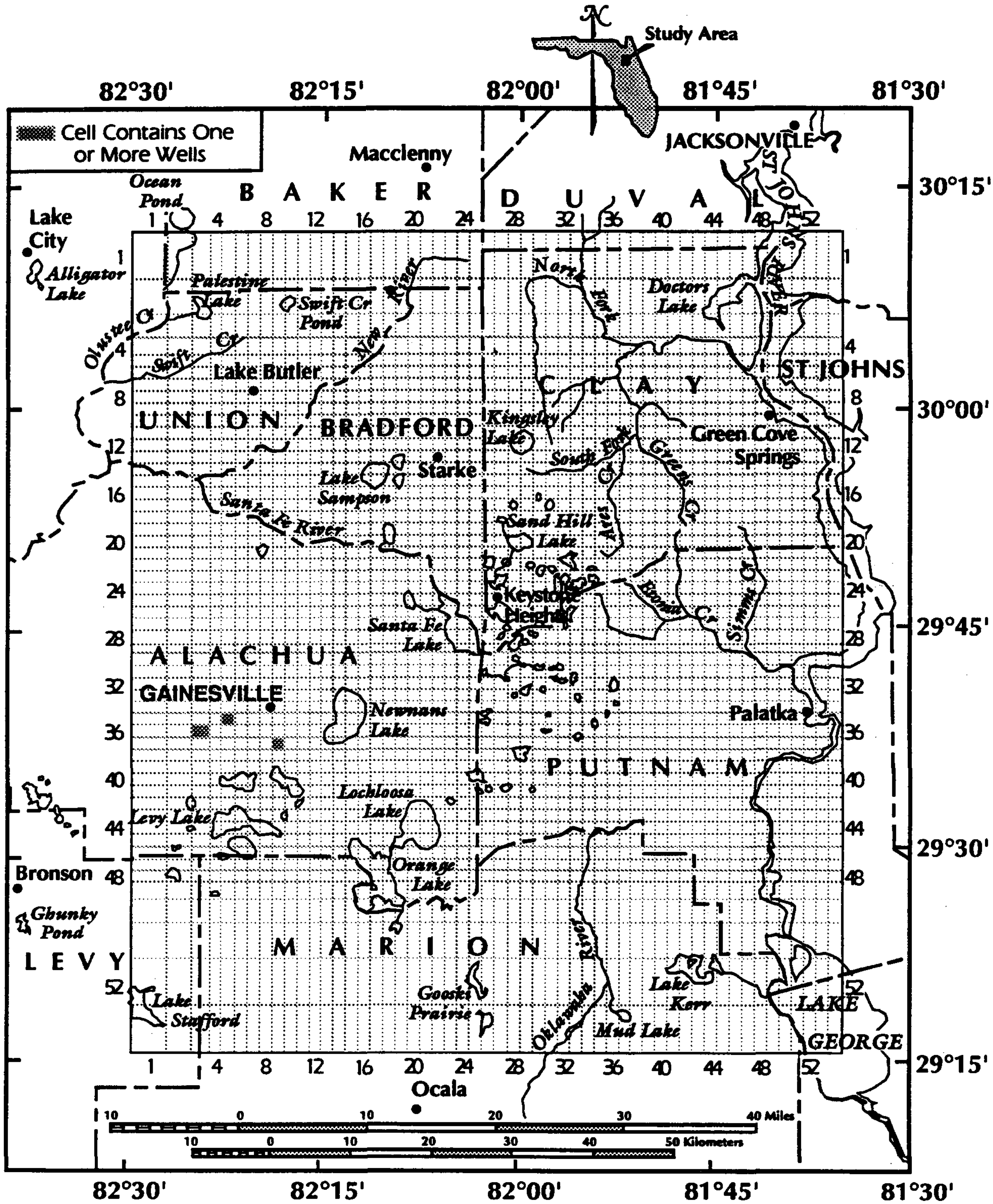


Figure 10-5. Recharge Wells in Layers Three and Four in the May 2010 Simulation

layer four (see Figures 10-6 and 10-7). The total pumping rate from all of the cells in which pumping wells are located is 2.70×10^7 ft^3/day, the recharge rate is 4.14×10^6 ft^3/day, and thus the net pumping rate is 2.29×10^7 ft^3/day. The net pumping rate for May 2010 is 10.0 percent greater than the net pumping rate for May 1985.

The May 1985 general head boundary conditions were adjusted by subtracting the drawdowns predicted by Durden (1994a) for 1985 to 2010 for the upper Floridan aquifer in the areas adjacent to the north and east parts of the study area from the boundary head values in the corresponding general head boundary cells in layer three in these areas. The maximum drawdown, 12.05 ft, was subtracted from the boundary head value in the general head boundary cell adjacent to row 1, column 52.

10.1.2 Predicted Potentiometric Surface and Water Budget for 2010

The potentiometric surface in the upper Floridan aquifer for May 2010 was predicted using the MODFLOW files from the May 1985 simulation, the modified general head boundary conditions, and the well file representing the May 2010 ground-water pumpage (see Figure 10-8). The maximum head, equal to 86.3 ft, NGVD, is predicted to occur at row 21, column 30, and the minimum head, equal to 3.83 ft, NGVD, is predicted to occur at row 50, column 48.

In the May 2010 simulation, inflows to the ground-water system of the model are derived from constant head boundaries (4.44 inches/year), drainage wells (0.18 inches/year), direct areal recharge to layer three (1.93 inches/year), and head dependent boundaries (0.90 inches/year) (see Table 10-1). Outflows from the ground-water system occur at constant head boundaries (0.48 inches/year), pumping wells (1.20

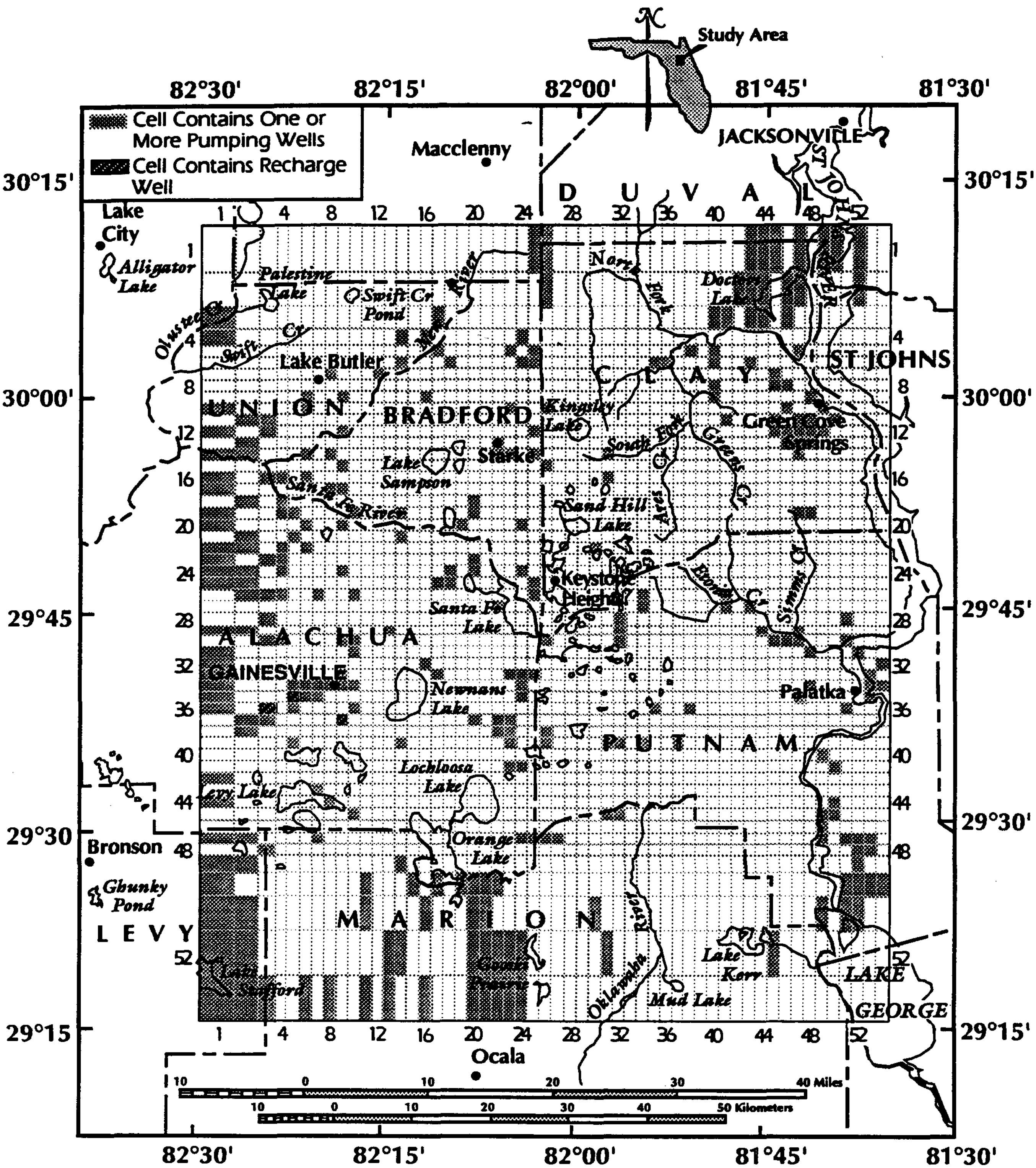


Figure 10-6. Pumping Wells (All Categories) and Recharge Wells in Layer Three in the May 2010 Simulation

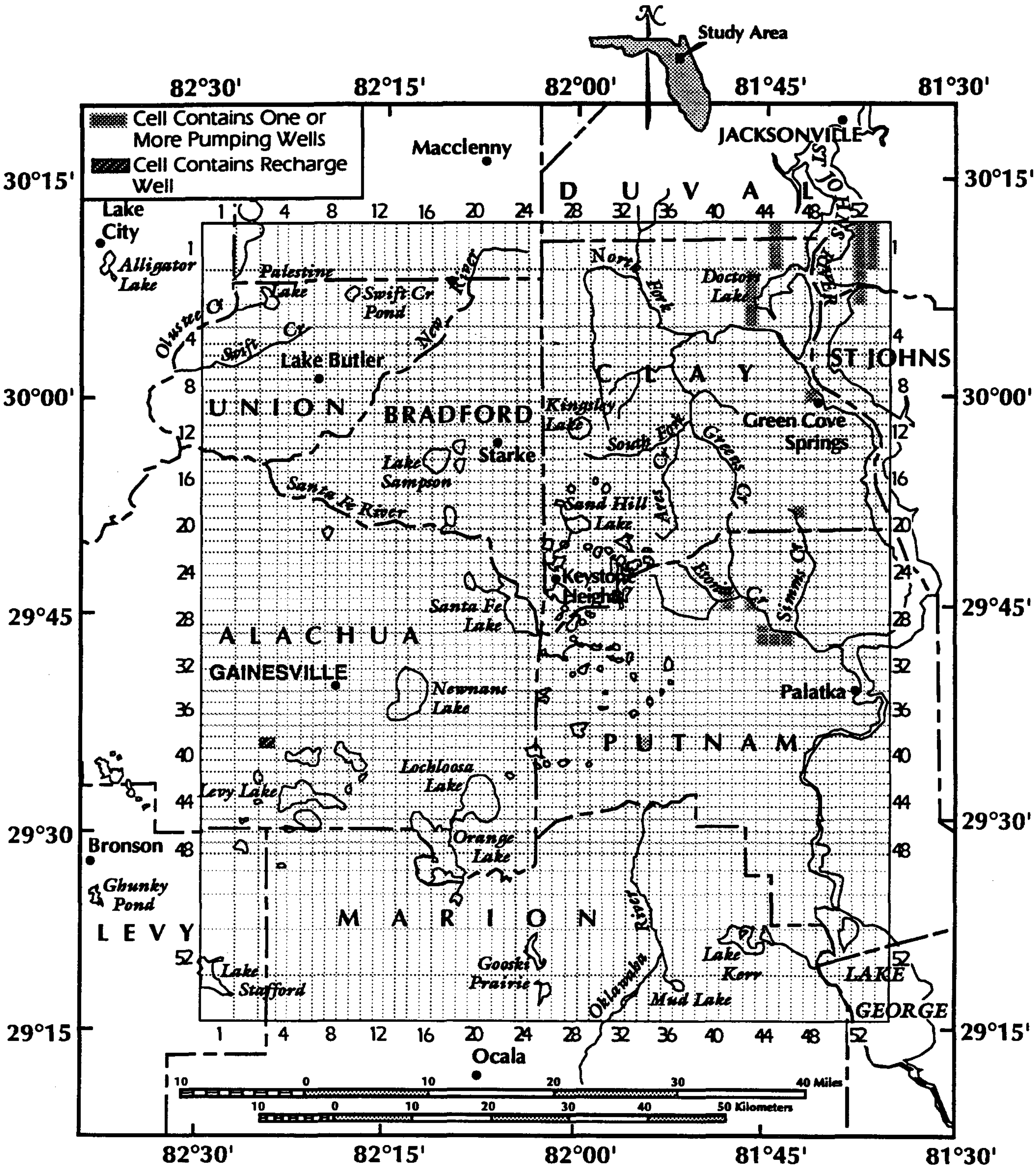


Figure 10-7. Pumping Wells (All Categories) and Recharge Wells in Layer Four in the May 2010 Simulation

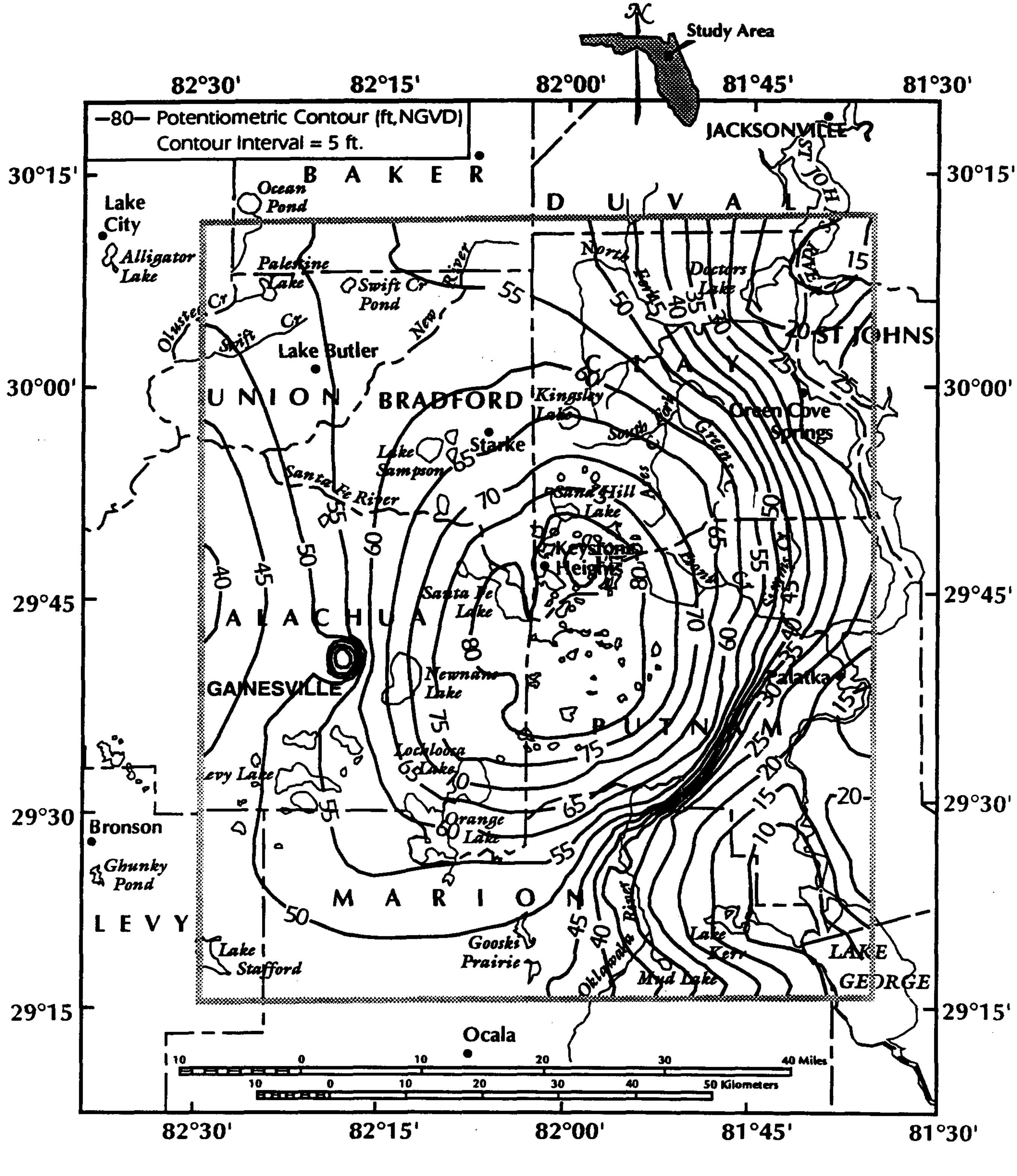


Figure 10-8. Predicted Potentiometric Surface in the Upper Floridan Aquifer in North-Central Florida in the May 2010 Simulation

Table 10-1 Water Budget for Active Cells in the May 2010 Simulation

	Flowrate:	
Inflow:	(ft^3/day)	(inches/year)
Constant Head Boundaries	1.00×10^8	4.44
Recharge Wells	4.13×10^6	0.18
Areal Recharge	4.36×10^7	1.93
Head Dependent Boundaries	2.04×10^7	0. 90
Total Inflow	1.68×10^8	7.45
Outflow:		
Constant Head Boundaries	1.07×10^7	0.48
Pumping Wells	2.70×10^7	1.20
Drains	3.04×10^7	1.35
Evapotranspiration	8.63×10^6	0.37
Head Dependent Boundaries	9.12×10^7	4.05
Total Outflow	1.68×10^8	7.45

inches/year), drains that represent discharge at springs (1.35 inches/year), evapotranspiration from layer three (0.37 inches/year), and head dependent boundaries (4.05 inches/year). In the May 2010 simulation, the total inflows and outflows are equal to 7.45 inches/year, which is only 2.19 percent greater than the total inflows and outflows of 7.29 inches/year in the May 1985 simulation (Table 9-3).

10.1.3 Predicted Changes in Water-Levels and Spring Discharges

The calculated potentiometric surfaces for May 1985 and May 2010 (Figures 9-8 and 10-8) were compared to predict the water-level changes that will occur in the upper Floridan aquifer due to the pumping changes that are projected in the study area from May 1985 to May 2010 (see Figure 10-9). Predicted water-level changes due to projected changes in pumping are negligible ($\pm$ 1 ft) in a large part of the study area. In the east-central part of the study area, water levels in the upper Floridan aquifer are predicted to increase by as much as 5 ft due to the projected decrease in pumpage at the Georgia Pacific facility in Palatka. In the GRU Murphree Well Field in Gainesville, the predicted drawdown is 19.0 ft at row 30, column 10, which compares favorably with localized 20-ft drawdowns predicted to occur from 1988 to 2010 at two individual wells in the GRU well field using an analytical model (Fischl 1994). In the northeast part of the study area, drawdowns on the order of 12.0 ft are predicted due to increased pumping in the study area in the Orange Park area and in the Jacksonville area adjacent to but outside the study area.

The total spring discharge from the upper Floridan aquifer calculated for May 2010 (3.04×10^7 ft^3/day) is only slightly less than the total spring discharge calcu-

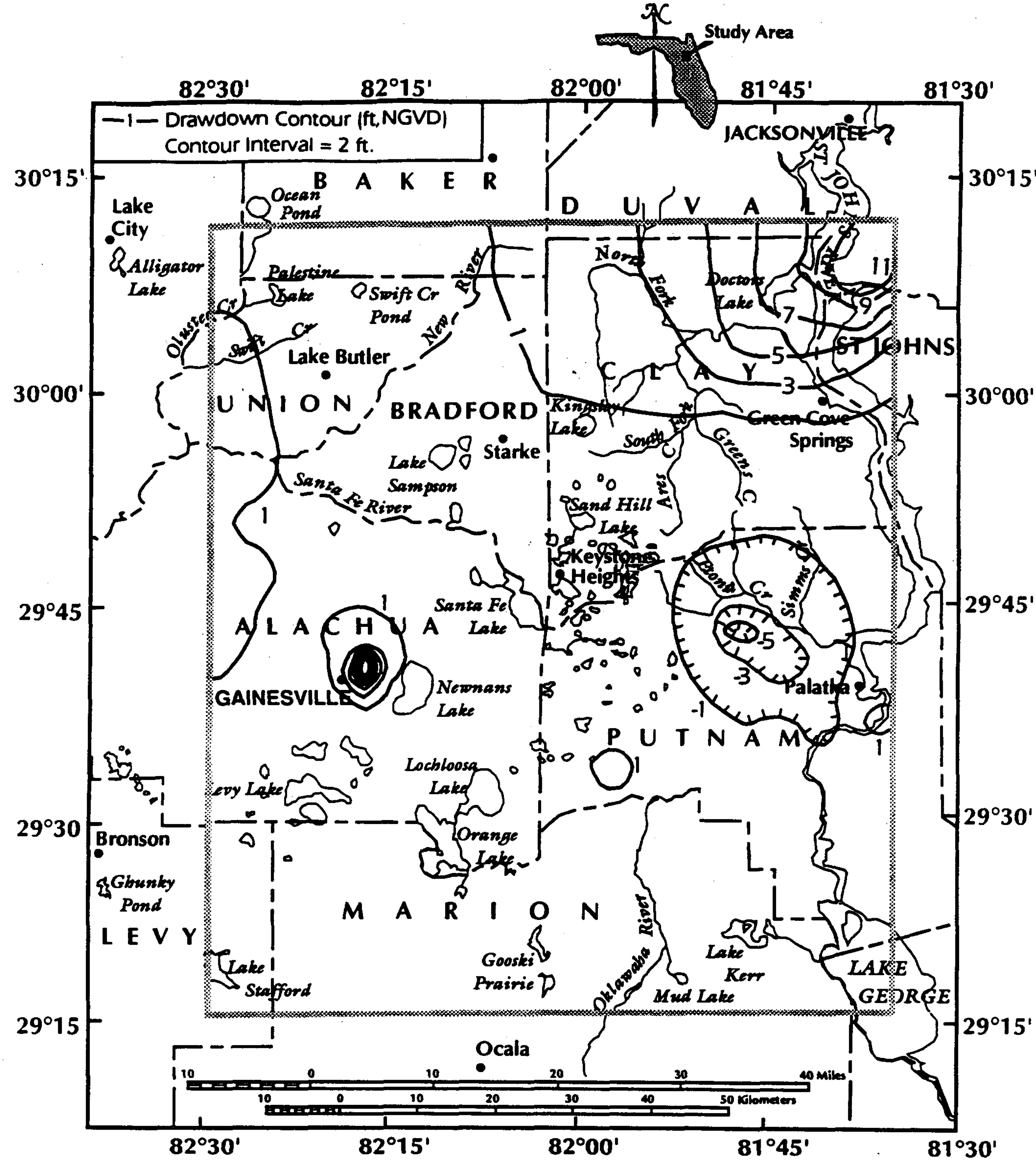


Figure 10-9. Predicted Drawdowns in the Potentiometric Surface in the Upper Floridan Aquifer Due to Changes in Pumping from May 1985 to May 2010

lated for May 1985 (3.07×10^7 ft^3/day) (see Table 10-2). Most of the individual spring discharges calculated for May 2010 are approximately the same as those calculated for May 1985, except for Wadesboro Spring and several of the hypothetical springs, which are all in the northeast part of the study area and which are affected by the predicted drawdowns in the upper Floridan aquifer in that area.

10.2 WATER-TABLE DRAWDOWNS FROM 1985 TO 2010

10.2.1 Drawdown Model

Drawdowns due to changes in pumping from May 1985 to May 2010 were calculated for layer one by modifying the calibrated MODFLOW model for the study area. In the calibrated model, layer one is a constant head source bed where it is present, and layer two is a constant head source bed where it is the uppermost hydrologic unit in the areas where layer one is absent. Activating layers one and two in the calibrated model to calculate water-table drawdowns did not produce satisfactory results, i.e., the calculated heads in layers one and two could not be compared to observed heads, because actual, observed heads in these layers are not mapped accurately enough for model calibration. Instead, the existing calibrated model was modified so that drawdowns due to the May 1985 and the May 2010 pumping rates could be calculated separately and then compared in order to estimate changes that will occur from May 1985 to May 2010 in the water-table in the surficial aquifer.

The existing calibrated model was modified so that no drawdowns occurred when the model was run unless pumping stresses were applied or changes occurred in

Table 10-2 Calculated Spring Discharges for May 1985 and May 2010

Spring	Drain Number	Calculated May 1985 Head (ft, NGVD)	Calculated May 1985 Discharge (ft^3/day)	Calculated May 2010 Head (ft, NGVD)	Calculated May 2010 Discharge (ft^3/day)
Wadesboro Spring	1	25.1	1.45×10^5	16.3	9.47×10^4
Green Cove Springs	2	22.4	3.94×10^5	22.2	3.91×10^5
Whitewater Springs	3	16.0	1.13×10^5	16.1	1.13×10^5
Satsuma and Nashua Springs	4	10.4	1.04×10^5	10.2	1.02×10^5
Welaka Springs	5	8.21	8.21×10^4	8.10	8.10×10^4
Mud Spring	6	8.96	1.79×10^5	8.75	1.75×10^5
Forest Springs	7	8.31	4.15×10^4	8.13	4.07×10^4
Beecher Springs	8	11.2	7.73×10^5	10.9	7.35×10^5
Croaker Hole Spring	9	3.86	7.33×10^6	3.83	7.28×10^6
Salt Springs	10	8.51	7.02×10^6	8.50	6.99×10^6
Salt Springs Pickup	11	8.20	1.23×10^6	8.17	1.23×10^6
Orange Springs	12	49.1	5.66×10^5	48.8	5.60×10^5
Oklawaha River Pickup	13	20.4	5.50×10^4	20.4	5.27×10^4
do.	14	22.3	2.91×10^5	22.3	2.91×10^5
do.	15	23.6	4.44×10^5	23.6	4.44×10^5
do.	16	30.0	1.25×10^6	30.0	1.25×10^6
do.	17	30.6	1.32×10^6	30.6	1.32×10^6
Oklawaha River Pickup	18	40.7	1.04×10^6	40.6	1.03×10^6
do.	19	37.4	8.68×10^5	37.3	8.63×10^5
do.	20	30.7	5.32×10^5	30.6	5.31×10^5
do.	21	36.1	8.03×10^5	36.0	8.00×10^5
do.	22	32.7	6.34×10^5	32.6	6.31×10^5

Table 10-2 Continued

Spring	Drain Number	Calculated May 1985 Head (ft, NGVD)	Calculated May 1985 Discharge (ft^3/day)	Calculated May 2010 Head (ft, NGVD)	Calculated May 2010 Discharge (ft^3/day)
Oklawaha River Pickup	23	27.3	2.54×10^6	27.2	2.53×10^6
Oklawaha River Pickup	24	30.9	1.09×10^6	30.9	1.09×10^6
Hypothetical Spring	25	24.9	9.98×10^4	17.6	7.04×10^4
do.	26	26.2	1.05×10^5	21.2	8.47×10^4
do.	27	26.4	1.06×10^5	22.6	9.06×10^4
do.	28	26.2	1.05×10^5	23.2	9.27×10^4
do.	29	25.9	1.04×10^5	23.6	9.43×10^4
do.	30	25.5	1.02×10^5	23.7	9.48×10^4
do.	31	24.7	9.87×10^4	23.4	9.37×10^4
do.	32	23.1	9.24×10^4	22.3	8.93×10^4
Lake George	33	8.21	1.03×10^6	8.14	1.02×10^6
TOTAL SPRING DISCHARGE			3.07×10^7		3.04×10^7

Note: Refer to Table 9-1 for row and column locations and conductance and discharge head values for drains used in MODFLOW to simulate spring discharges.

the general head boundary conditions. In this revised, "drawdown" model, all of the starting heads and drain heads were set equal to 0.0. The general-head boundary source heads, located in layers three, four, and five, were set equal to 0.0 for the May 1985 simulation. The drawdowns predicted by Durden (1994a) for 1985 to 2010 for the upper Floridan aquifer north and east of the study area were subtracted from the 0.0 values for the general-head boundary source heads in layer three for the May 2010 simulation. The constant head nodes in layers one and two were activated, and layers two and three were treated as confined aquifers with constant thicknesses. The hydraulic conductivity and thickness of layer one were assigned values of $K_1 = 17.9$ ft/day and $b_1 = 35$ ft, respectively, so that the transmissivity of layer one was $T_1 = 625$ ft^2/day, based on Motz et al. (1993). The leakance values for layers one - four were the same as in the calibrated model, and the transmissivity values for layers two - five also were the same as in the calibrated model.

Evapotranspiration occurs from layers one, two, and three from the uppermost cells in the drawdown model. The maximum evapotranspiration rate and the extinction depth were assigned values of 0.00316 ft/day and 10.0 ft, respectively. This is equivalent to an evapotranspiration reduction rate of 0.000316 day^{-1}, which is consistent with evapotranspiration estimates made for east-central Florida by Tibbals (1990). Similarly, recharge in the drawdown model occurs to layers one, two, and three to the uppermost cells in the model. Recharge was assigned a value of 0.00316 ft/day so that recharge would be balanced by evapotranspiration when drawdowns were equal to 0.0 under the condition of no pumping.

10.2.2 Predicted 1985-2010 Water-Table Drawdowns

The drawdown model was run using the May 1985 and May 2010 well files, and the results were compared to estimate the drawdowns that will occur in layer one from May 1985 to May 2010. The results indicate that surficial aquifer drawdowns from 1985 to 2010 will range approximately from -1.6 ft (an increase in the water table) to 1.2 ft in the east-central part of the study area (see Figure 10-10). The increase in the water table is associated with the projected decrease in pumping at the Georgia Pacific facility in Palatka. The 1.2-ft drawdown is related to an increase in commercial and industrial pumping in southwestern Putnam County. In the GRU Murphree Well Field, the calculated water-table drawdown is 0.23 ft.

As a check, the modified, drawdown model predicts the same drawdowns in the upper Floridan aquifer (layer three) as the calibrated model, and it also predicts water-table drawdowns that compare favorably with the range of 0.2 to 0.5 ft predicted for 1988-2010 at individual wells in the GRU Murphree Well Field using an analytical model (Fischl 1994). Thus, the results of the modified, drawdown model appear to be reasonably accurate.

10.3 IMPACTS OF CHANGES IN PUMPING ON LAKE LEVELS

10.3.1 Lake-Level Declines in the UECB

In recent years, lake levels have declined by significant amounts in some parts of the UECB. Concerns about lake-level declines are exemplified by Brooklyn Lake, which is located near Keystone Heights in the UECB (see Figure 2-1). This lake is

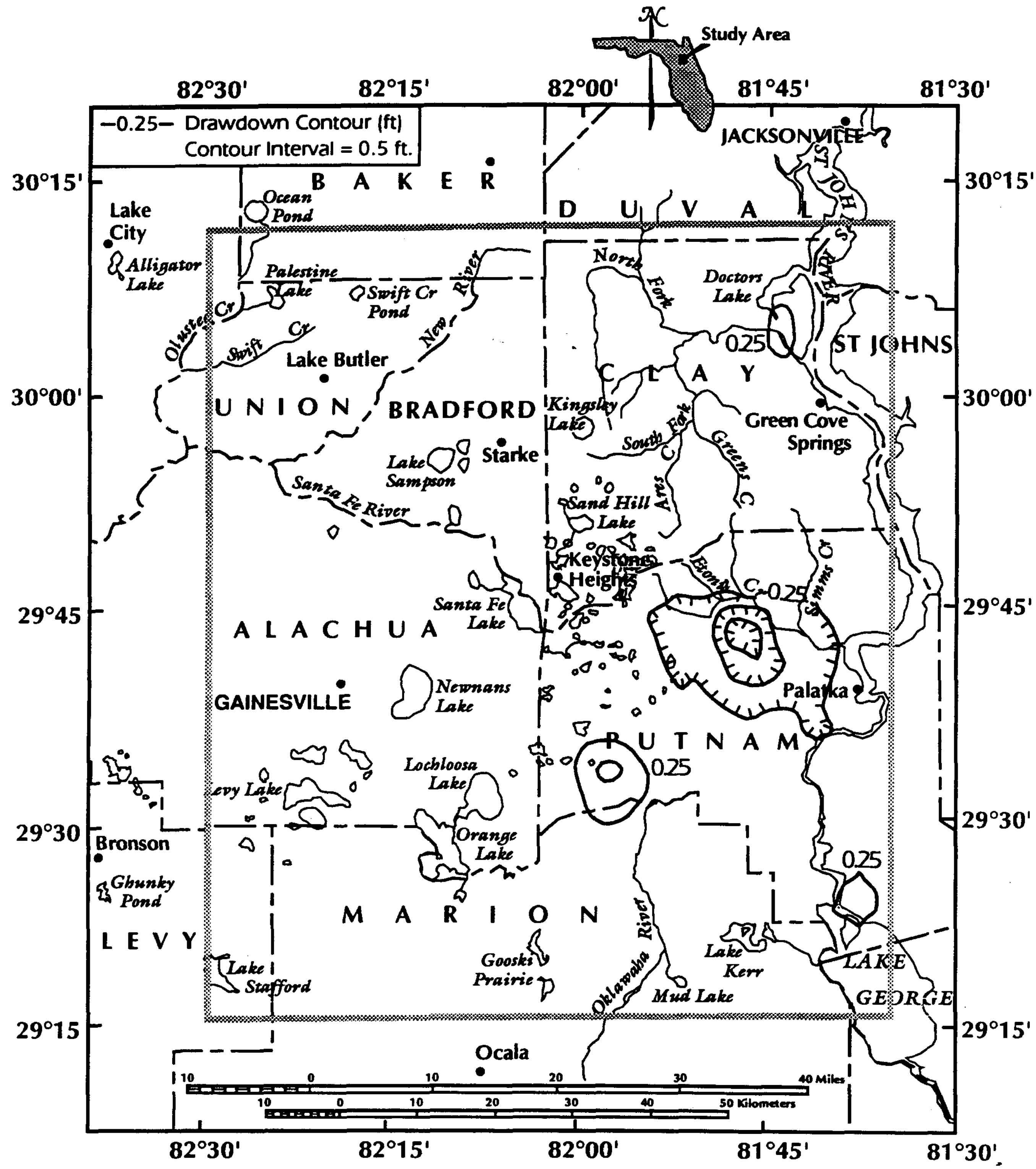


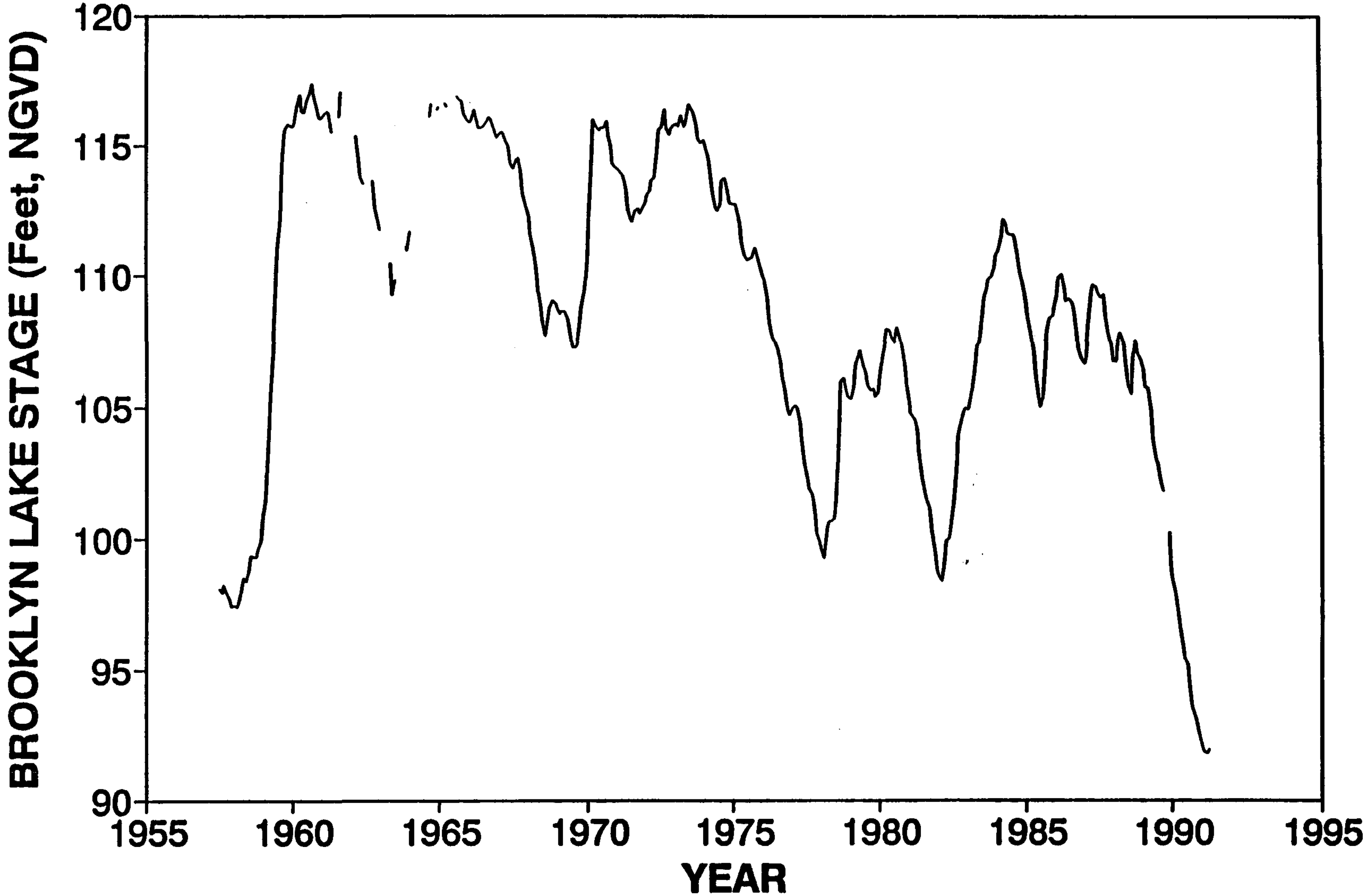
Figure 10-10. Predicted Drawdowns in the Water Table in the Surficial Aquifer Due to Changes in Pumping from May 1985 to May 2010

highly unstable due to fluctuations of more than 24 ft over the period of record from 1957 to 1991 (see Figure 10-11). The maximum lake-stage elevation during the period of record is 117.43 ft, NGVD, which occurred in October 1960. Prior to the period of record, a maximum of 118.2 ft., NGVD, was reached in 1948, according to Clark et al. (1963).

In previous studies (Motz el al. 1991a and 1993), below average rainfall over the past several years has been identified as the primary cause of lake-level declines in the UECB. For Brooklyn Lake, below average rainfall, declining ground-water levels in the upper Floridan aquifer, vertical leakage from the lake to the upper Floridan aquifer, and cessation of surface-water inflow since 1989 are the major, interrelated factors that have contributed to the lake's decline to record low levels (Motz and Fowler 1993). A comparison of the cumulative departure from mean annual rainfall at Gainesville (see Figure 10-12) with the Brooklyn Lake stage (Figure 10-11) indicates a general correlation between periods of low rainfall and lowered stages in Brooklyn Lake. Periods of below average rainfall in 1954-1956, 1961-1963, 1976-1978, and 1980-1981 were followed by lowered lake stages in 1957-1958, 1963, 1978, and 1982, respectively. Also, there appears to be a similar relation to below average rainfall in 1984-1985, 1987, and 1989-1990 and lowered lake stages in 1985, 1987, and 1991-1992, respectively.

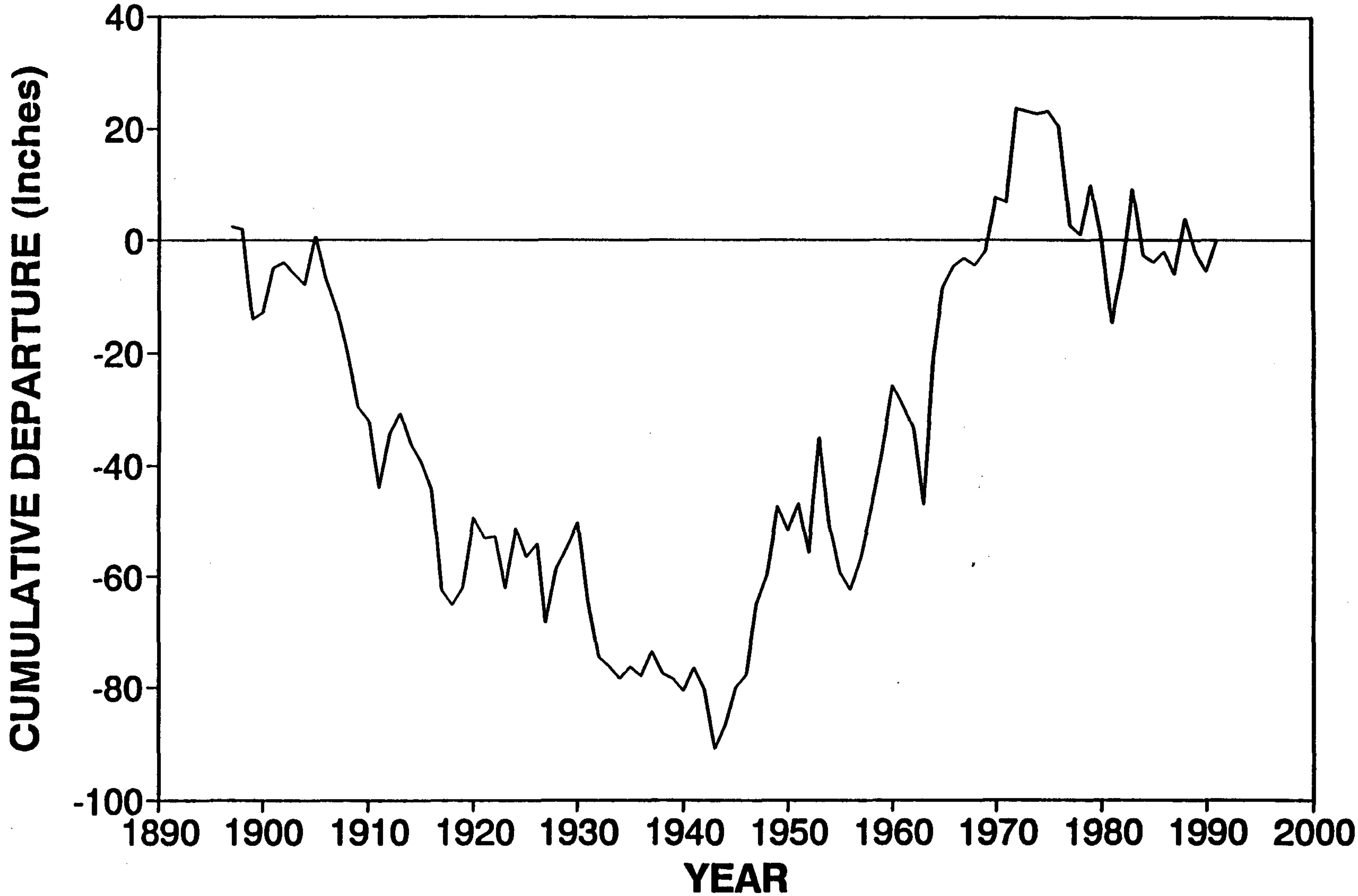
10.3.2 Double-Mass Curves

A double-mass curve is a graph that plots the cumulative values for each of two variables (Butler 1957). This type of hydrologic plot can be used to determine if



Source: Motz et al. (1993)

Figure 10-11. Brooklyn Lake Stage for 1957-1991

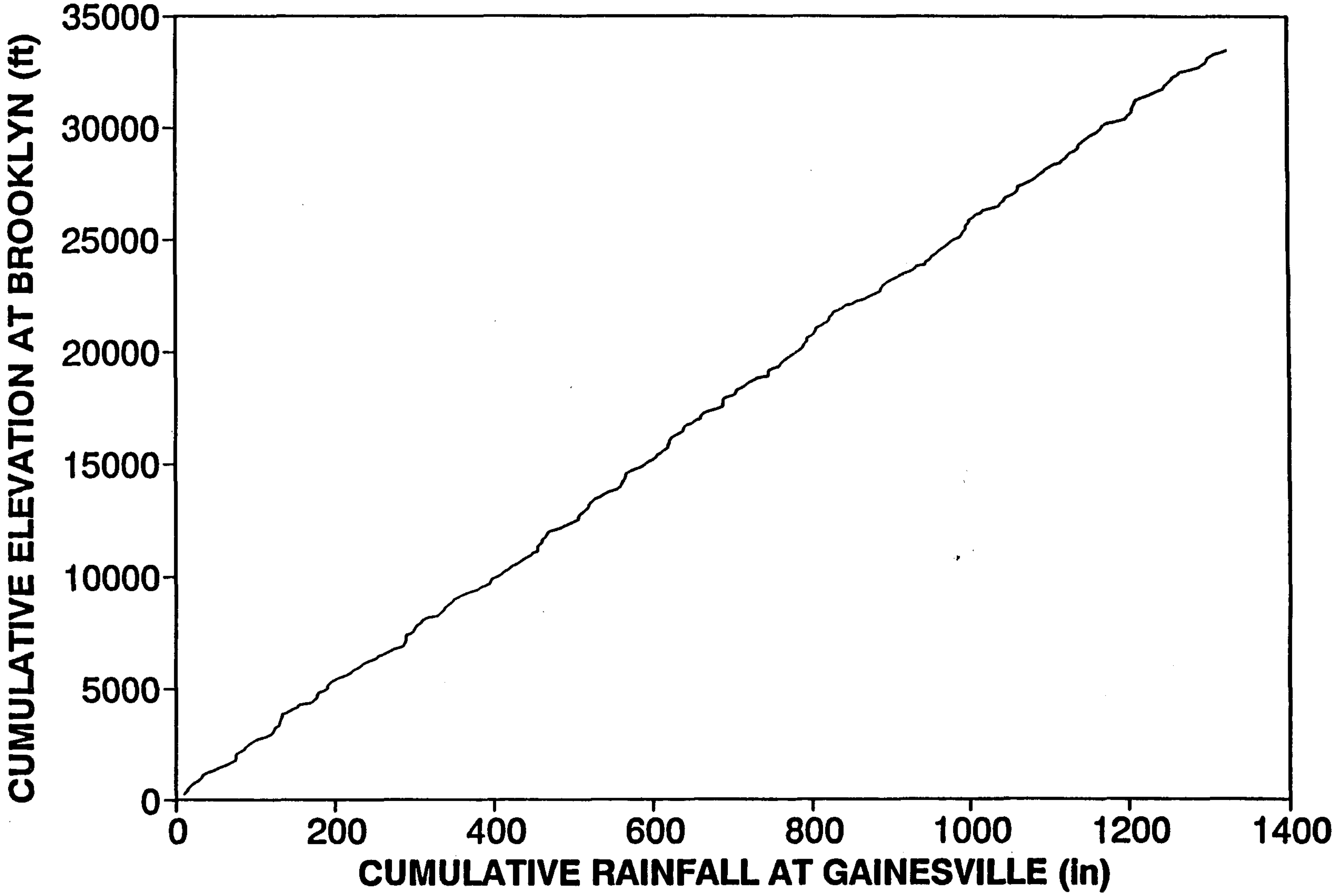


Source: Motz et al. (1993)

Figure 10-12. Cumulative Departure from Mean Annual Rainfall at Gainesville for 1897-1991 changes in the relation between two related parameters have occurred due to changes in their environment, i.e., that perhaps a third parameter not previously important has become significant in affecting one of the other parameters. A plot of cumulative monthly lake-stage elevation for Brooklyn Lake for the period 1965 (when the period of record became continuous) to 1991 versus cumulative monthly rainfall at Gainesville for the same period has a constant slope, which indicates a constant relation between these two parameters (see Figure 10-13). A plot of the cumulative elevation at Brooklyn Lake versus the water level in the upper Floridan aquifer in nearby well C-0120 for 1965-1991 also has a constant slope, which indicates that the relation between the stage of Brooklyn Lake and the upper Floridan aquifer water level at well C-0120 also did not change during 1965-1991 (see Figure 10-14). The double-mass curves for the Brooklyn Lake stage elevation versus Gainesville rainfall and water levels in the upper Floridan aquifer indicate that the relations between lake-stage elevation and these important parameters remained constant and that the Brooklyn Lake stage elevation apparently was not affected by the introduction of other parameters during the 1965-1991 period of record.

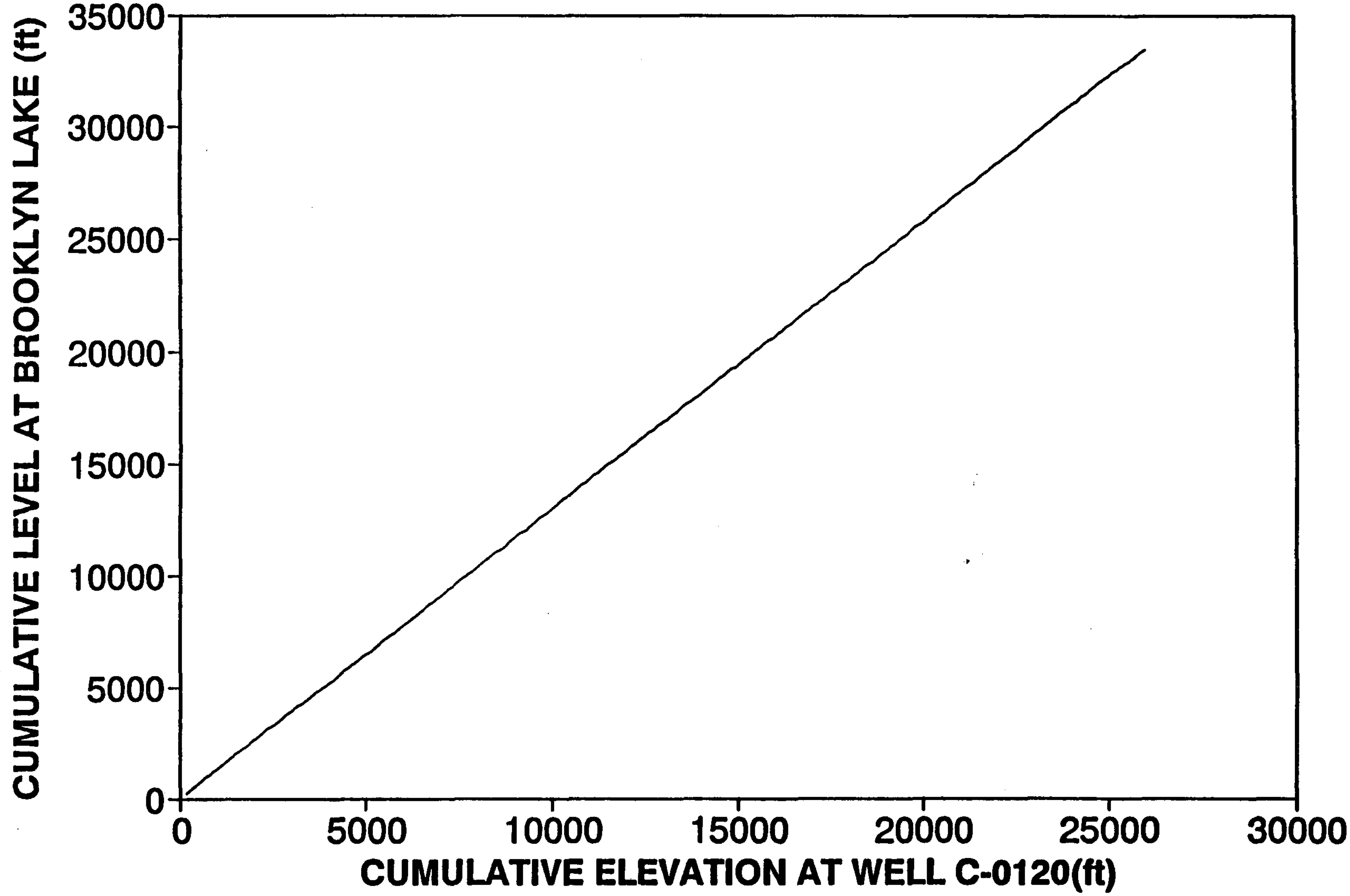
10.3.3 Lake-Stage Simulations

Water-budget and lake-stage simulations make it possible to consider the interconnection that exists among the components of a lake's water budget, which include precipitation, runoff, surface-water inflow, ground-water inflow, evapotranspiration, surface-water outflow, and vertical leakage to underlying aquifers. Such simulations can be used to estimate the effects on lake stage that could occur due to changes in



Source: Motz et al. (1993)

Figure 10-13. Double-Mass Curve for Brooklyn Lake Stage and Gainesville Rainfall for 1965-1991



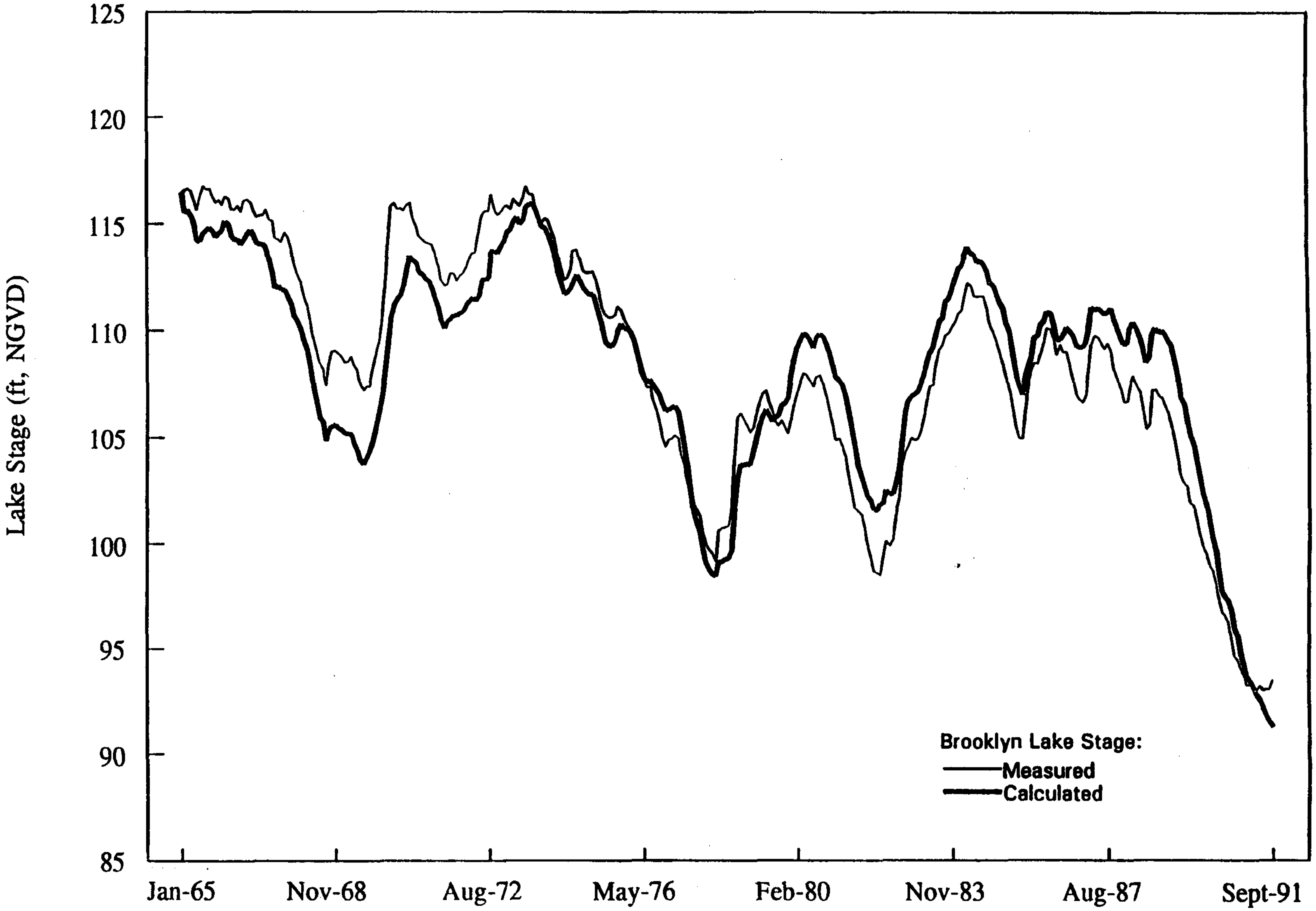
Source: Motz et al. (1993)

Figure 10-14. Double-Mass Curve for Brooklyn Lake Stage and Upper Floridan Aquifer Water Level at Well C-0120 for 1965-1991 components of the water budget. Based on a lake-stage simulation of Brooklyn Lake for 1965-1991, approximately 6.7 ft in the decline in the Brooklyn Lake stage elevation from 1965 to 1991 can be attributed to a downward trend of 9.2 ft in the water level in the upper Floridan aquifer (see Figure 10-15). Based on this result, a 1-ft change in elevation in the water level in the upper Floridan aquifer will result in an approximate change of 0.76 ft in the stage elevation of Brooklyn Lake (Motz et al. 1993). Coupling this result with drawdown predictions for the upper Floridan aquifer makes it possible to predict how lake-stage elevation will be affected by changes in pumping from 1985 to 2010.

10.3.4 Effects of Changes in Pumping

The calibrated ground-water model predicts that water-level changes in the upper Floridan aquifer in the Keystone Heights area due to the projected changes in pumping from May 1985 to May 2010 generally will be negligible (±1 ft) (see Figure 10-9). Specifically, in the vicinity of Brooklyn Lake, a decrease on the order of 0.03 ft is predicted for the water level in the upper Floridan aquifer. Combining this result with the result from the lake-stage simulation for Brooklyn Lake, which indicates that a 1-ft change in the water level in the upper Floridan aquifer will change the lake-stage elevation in Brooklyn Lake by 0.76 ft, indicates that the stage in Brooklyn Lake will be decreased by a negligible amount on the order of 0.02 ft due to the predicted drawdown in the upper Floridan aquifer due to the projected changes in pumping.

The lake-stage elevation of Brooklyn Lake will increase and/or decrease by amounts significantly greater than 0.02 ft due to other factors in the water budget such



Source: Motz et al. (1993)

Figure 10-15. Lake-Stage Simulation for Brooklyn Lake from 1965 to 1991 as rainfall, evaporation, and surface-water inflow. Thus, these results indicate that the presently projected changes in pumping from 1985 to 2010 will not significantly affect the lake-stage elevation in Brooklyn Lake.

11.0 SUMMARY AND CONCLUSIONS

11.1 SUMMARY

The north-central Florida regional ground-water flow model investigation was authorized by the St. Johns River Water Management District in August 1992 as a result of recommendations to investigate the regional decline in water levels in the upper Floridan aquifer and the impact on Brooklyn Lake and other lakes in the Upper Etonia Creek basin. The objective of the investigation was to determine the magnitude and causes of the regional decline in ground-water levels in the upper Floridan aquifer in an area extending westward from Duval County to Alachua County. The investigation consisted of five tasks: compilation and evaluation of hydrologic data; determination of natural effects and pumping effects; development of a regional ground-water flow model; development of recommendations for management strategies that would reduce the regional decline due to present and proposed pumping; and preparation of a report of findings.

The study area for this investigation covers approximately 3,450 square miles in north-central Florida centered on the Keystone Heights lake region in southwestern Clay County. All or parts of twelve counties are in the study area: all of Bradford and Clay counties, most of Alachua, Putnam, and Union counties, and smaller parts of Baker, Columbia, Duval, Levy, Marion, St. Johns, and Volusia counties. The study area is in the physiographic division of Florida known as the Central Highlands, except for the eastern edge, which is in the Coastal Lowlands division. The principal topographic features in the study area include Trail Ridge, which extends in a north-south direction through the center, swampy plains in the north, rolling plains in the west and south, and rolling, downward sloping lands in the eastern part. The center of the area is dominated by high sand hills and many lakes. The climate of north-central Florida is classified as humid subtropical, and it is characterized by warm, normally wet summers and mild, relatively dry winters. The mean annual rainfall for Gainesville is 50.92 inches, and over fifty percent of the annual rainfall occurs during the four months from June to September.

The ground-water system in north-central Florida generally consists of a surficial aquifer system that overlies a low permeability confining unit, which in turn overlies the Floridan aquifer system, a regionally extensive aquifer system. The surficial aquifer system consists of Pliocene, Pleistocene, and Holocene deposits, and it is under water-table conditions. The confining unit is called the upper confining unit for the Floridan aquifer system, and it is comprised of rocks of the Miocene age Hawthorn Group and, locally, deposits of Pliocene age. In some parts of the study area, a discontinuous artesian aquifer system called the intermediate aquifer system occurs in the Hawthorn Group within the upper confining unit of the Floridan aquifer system. The Floridan aquifer system in north-central Florida is made up of carbonate formations that consist of the Oligocene age Suwannee Limestone (where it is present), the late Eocene Ocala Limestone, the middle Eocene Avon Park Formation, the early Eocene Oldsmar Formation, and the Paleocene Cedar Keys Formation. In the eastern part of the study area, the Floridan aquifer system is comprised of two zones called the upper and lower Floridan aquifers that are separated by a relatively low permeability unit called the middle semiconfining unit. The upper Floridan aquifer is a zone of high permeability contained within the Ocala Limestone and the upper third of the Avon Park Formation. The lower Floridan aquifer is contained within the lower half of the Avon Park Formation, the Oldsmar Formation, and the upper third of the Cedar Keys Formation. The Fernandina permeable zone occurs at the base of the Oldsmar Formation in the northeast part of the study area.

In parts of Alachua, Bradford, and Union counties, the surficial deposits are very thin or not present, and the water table occurs in the Hawthorn Group. In parts of southwestern Alachua County and Marion County, the Hawthorn Group is not present, and the water table occurs in the surficial deposits that directly overlie the upper Floridan aquifer in these areas or in the upper Floridan aquifer itself. The Floridan aquifer system occurs under both artesian and non-artesian conditions in the study area. In areas where it is confined, it is overlain by the upper confining unit.

Maps of the potentiometric surface of the upper Floridan aquifer have consistently delineated a major ground-water mound in the upper Floridan aquifer in the central part of the study area centered on Keystone Heights. Its presence indicates that the lakes and surficial aquifer system in this area are a major source of recharge to the underlying Floridan aquifer system. The elevation of the potentiometric surface in the Keystone Heights area was greater than an estimated 90 ft, NGVD, prior to development, and it is on the order of more than 80 ft, NGVD, at the present. Regionally, from predevelopment time to 1985, the potentiometric surface of the upper Floridan aquifer declined on the order of 10 ft in a large part of the study area, 20 to 30 ft in northern Clay and Union counties, 30 to 40 ft in the northeastern part of the study area near Jacksonville, and more than 40 ft in the GRU Murphree Well Field in Gainesville.

The study area falls within three water management districts. Fifty-five percent of the area is in the St. Johns River Water Management District, forty percent is in the Suwannee River Water Management District, and five percent is in the Southwest Florida Water Management District. Ground-water use for the study area in these districts was compiled and projected for May 1985 and May 2010, respectively, to represent monthly periods when ground-water withdrawals would be greatest and the impact on ground-water levels at a maximum. Ground-water withdrawals were grouped into five major categories: public supply; self-supplied domestic; commercial and industrial; and thermoelectric power generation. In addition, direct recharge of surface water at several sites was considered also.

For May 1985, pumpage from the ground-water system in the study area was 54.8 mgd for public supply, 28.2 mgd for domestic self-supply, 63.1 mgd for commercial and industrial use, 55.4 mgd for agriculture, and 4.4 mgd for thermoelectric power generation. Excluding the pumpage for domestic self-supply, the total estimated pumpage from the ground-water system was 177.7 mgd, and recharge to the ground-water system at four site-specific locations was estimated to be 22.3 mgd. The net pumpage from the ground-water system is the difference between these numbers, or 155.4 mgd.

For May 2010, pumpage from the ground-water system in the study area is projected to be 83.6 mgd for public supply, 30.5 mgd for domestic self-supply, 49.5 mgd for commercial and industrial use, 65.0 for agriculture, and 4.1 mgd for thermoelectric power generation. Excluding pumpage for domestic self-supply, the total pumpage from the ground-water system is projected to be 202.2 mgd, and recharge to the ground-water system at the four site-specific locations is projected to be 31.0 mgd. The projected net pumpage from the ground-water system is the difference between these numbers, or 171.2 mgd.

From May 1985 to May 2010, pumpage is projected to increase from 54.8 to 83.6 mgd for public supply and from 55.4 to 65.0 mgd for agriculture. Pumpage is projected to decrease from 63.1 to 49.5 mgd for commercial and industrial use and from 4.4 to 4.1 mgd for thermoelectric power generation. Recharge to the ground-water system at the four site-specific locations is projected to increase from 22.3 to 31.0 mgd.

Hydrogeologic, rainfall, and water-use data for the study area were evaluated to investigate the causes of declines in the water levels in the upper Floridan aquifer in parts of the study area over the past twenty to thirty years. Using historical water-level data for the upper Floridan aquifer, water-level changes in the study area were determined for the time period from 1960 to 1992. Water levels in the upper Floridan aquifer declined from 1960 to 1992 throughout most of the study area. The northwest part of the study area experienced an approximate decline of 8.5 ft. In the center of the region, the net declines ranged from 6 to 12 ft. The drawdowns were greatest in the northeast part of the study area and increased toward the City of Jacksonville. Near Orange Park, drawdowns were on the order of 12 to 15 ft. In the southwest, net ground-water declines ranged from 0 to 15 ft from 1960 to 1992, and in the southeast, net declines ranged from 2 to 6 ft. It appears that much of the study area experienced a regional decline in water levels in the upper Floridan aquifer from 1960 to 1992.

In Clay County, the upper Floridan aquifer has experienced significant drawdowns over the past sixty years. The greatest declines occurred in the northeast corner of the study area where net drawdowns ranged from 24 to 28 ft. Water levels in two wells near Keystone Heights both declined a total of 12 ft. From northeast Clay County toward the southeast, net drawdowns ranged from 12 to 28 ft. Water-level measurements for wells in the southwest corner of Clay County are not available prior to the late 1950's. However, based on actual drawdowns from 1960 to 1990 and estimated drawdowns using linear regression, the ground-water levels may have declined approximately 20 ft from 1934 to 1992 near Keystone Heights.

Multiple regression analysis was used to determine how changes in rainfall, evaporation, and ground-water pumpage from the upper Floridan aquifer may have caused short-term changes in water levels in the upper Floridan aquifer. The analysis was based on the monthly changes in hydraulic heads, end of the month rainfall totals, estimated monthly potential evaporation rates, and monthly withdrawals from 1985 to 1990. The numerous ground-water withdrawal points in the study area were grouped into 10 pumping centers, and an eleventh pumping center was used to represent the ground-water pumpage in Duval County, which is located outside the study area. Geometric means were used to determine the locations of the pumping centers. By varying the combinations of independent variables, many different regression relations were used to examine monthly changes in ground-water levels at five wells in the study area. The independent variables were current and previous monthly rainfalls, current and previous monthly potential evaporation rates, and current and previous monthly water pumpage from the pumping centers. Based on comparing the estimated ground-water levels in the upper Floridan aquifer with observed ground-water levels, it was determined that the regression relations developed for the wells adequately predicted the changes in ground-water levels from 1986 to 1990.

The USGS modular three-dimensional finite-difference model MODFLOW was used to simulate the ground-water system in the study area. An initial, or preliminary, simulation was made of the predevelopment potentiometric surface of the upper Floridan aquifer. Subsequently, a simulation was made of the May 1985 potentiometric surface using water-level data for more current conditions. The hydrogeologic system was considered to consist of five layers, or aquifer units, separated by confining units. Layer one represents the surficial deposits and the water-table aquifer, which are present in most, but not all, of the study area. Layer two represents the Hawthorn Group, which generally acts as the upper confining unit for the Floridan aquifer system. However, in some areas where the surficial deposits are absent, the Hawthorn Group is the uppermost hydrologic unit. In these areas, the water table is in the Hawthorn Group, and it was necessary to treat the Hawthorn Group as an aquifer unit in order to include this feature of the hydrologic system. Layer three represents the upper Floridan aquifer, which is unconfined in parts of the southwest part of the study area and confined everywhere else. Layers four and five represent the lower Floridan aquifer.

The study area was discretized into 53 rows and 54 columns that ranged in size from 5,000 to 20,000 ft. Layer one was assigned constant head nodes in the area where it is present, and inactive cells in the area where it is not present. Layer two was assigned active cells in the area where it is overlain by layer one, constant head cells in the area where it is the uppermost hydrologic unit, and inactive cells in the areas where it is absent. All of the cells in layers three, four, and five were active cells. The water table in layer one (and layer two, where it is the uppermost hydrologic unit) was represented as a constant-head source bed. Elevations for the water table were calculated using a model that relates the water-table elevation to land-surface elevation, which was based on data selected from 146 wells in the region that were considered to be representative of average rainfall conditions.

The predevelopment potentiometric surface of the upper Floridan aquifer was simulated, with the vertical leakance of layer one equal to 5.0×10^{-4} day^{-1}. The hydraulic conductivity of layer two was equal to 5.0×10^{-3} ft/day. The vertical leakance for layer two represents the leakance of the upper confining unit, and it is a calibration parameter that was adjusted during the calibration process. The transmissivity for layer three, which represents the upper Floridan aquifer, also was a calibration parameter. The vertical leakance for layer three, which represents the leakance for the middle semiconfining unit, ranges from 5.0×10^{-5} day^{-1} in the eastern part of the study area to 1.0×10^{-2} day^{-1} in the western part. The transmissivities in layers four and five were set equal to 100,000 ft^2/day. Thirty-three drains in layer three were used to represent spring discharges along the St. Johns River and its tributaries. Recharge to the active cells in layer three is 12 inches/year,and the maximum evapotranspiration rate from the active cells in layer three is 37.0 inches/year. General head boundary conditions were assigned around the peripheries of layers three, four, and five.

The ground-water flow model was calibrated by calculating the potentiometric surface for layer three and comparing it to the estimated predevelopment potentiometric surface in the upper Floridan aquifer and to the May 1985 potentiometric surface in the upper Floridan aquifer. Values for the transmissivities in layer three, vertical leakance in layer two, and conductances for the drains and general head boundaries in layer three were adjusted until the observed and calculated head differences in layer three were within reasonable agreement.

For the predevelopment model simulation that was considered calibrated, the mean of the differences between the calculated and observed heads is 0.251 ft, and the standard deviation of the differences is 2.19 ft. Values for the vertical leakance in layer two range from 1.0×10^{-6} to 1.0×10^{-3} day^{-1}, and the values of transmissivity in layer three range from 50,000 to 1,000,000 ft^2/day. In the predevelopment simulation, inflows to and outflows from the ground-water system are 6.60 inches/year.

The May 1985 potentiometric surface and water-use data were used with MODFLOW to simulate conditions that existed in May 1985 in the upper Floridan aquifer. In the May 1985 simulation, pumping occurs from 305 cells in layers three and four, and direct recharge occurs via wells in four cells. The net pumping rate is 2.08×10^7 ft^3/day. For the May 1985 simulation that was considered calibrated, the mean of the differences between the observed and calculated heads is 0.592 ft, and the standard deviation of the differences is 3.36 ft. Values for the vertical leakance in layer two range from 1.0×10^{-6} to 1.0×10^{-2} day^{-1}, and the values of transmissivity in layer three generally range from 50,000 to 1,000,000 ft^2/day. In the May 1985 simulation, inflows to and outflows from the ground-water system are 7.29 inches/year.

To verify the calibration parameters in the May 1985 simulation, the aquifer parameters for the May 1985 simulation were used to simulate the observed predevelopment potentiometric surface. The MODFLOW files for the predevelopment simulation representing the hydrologic units, aquifer discretization, the water table in layers one and two, the observed predevelopment potentiometric surface, recharge and evapotranspiration, and the general head boundary conditions were used, along with the aquifer parameters and spring discharge head and conductance values that resulted from the 1985 simulation. In this modified predevelopment simulation, the mean of the differences between the observed and calculated heads is 0.454 ft, and the standard deviation of the differences is 4.31 ft.

The calibrated May 1985 simulation and the projected pumping rates for May 2010 were used to predict the potentiometric surface in the upper Floridan aquifer for May 2010. In the May 2010 simulation, pumping occurs from 319 cells in layers three and four, and direct recharge occurs via four cells. The net pumping rate for May 2010 is 2.29×10^7 ft^3/day, which is 10.0 percent greater than the net pumping rate for May 1985. The potentiometric surface in the upper Floridan aquifer for May 2010 was predicted using the MODFLOW files from the May 1985 simulation and the well file representing the May 2010 ground-water pumpage. The general head boundary conditions used for the May 1985 simulation were adjusted for the 2010 simulation to reflect predicted drawdowns for 2010 in the adjacent areas north and east of the study area. In the May 2010 simulation, inflows to and outflows from the ground-water system are 7.45 inches/year, which is only 2.19 percent greater than the inflows and outflows simulated for May 1985.

A transient simulation was performed by varying the May 1985 pumping rate and calculating heads as a function of time. Pumping rates were calculated for June, July, August, and September 1985 for agricultural, commercial and industrial, public supply, and thermoelectric power generation uses. The net pumping rate at the 309 wells in the model in 1985 decreased from 2.077×10^7 ft^3/day in May to 1.197×10^7 ft^3/day in September 1985. Results obtained by comparing simulated heads in the model with observed water-level data at selected wells in the study area indicate that the transient simulation was only moderately successful.

11.2 RESULTS

Two major factors, rainfall and ground-water pumpage, were evaluated as the potential causes of the changes in ground-water levels in the upper Floridan aquifer. The cumulative rainfall departures for Jacksonville and Gainesville show two distinct trends in precipitation during the period from 1960 to 1992. A period of consistently above average rainfall occurred from 1969 to 1972, and a period of below average rainfall occurred from 1973 to 1992. Although the decline in rainfall is moderate compared to the period of above average rainfall, the below average rainfall experienced over the past 19 years likely has impacted ground-water levels in the upper Floridan aquifer.

Ground-water pumpage from the upper Floridan aquifer has increased over the past 20 to 30 years in the vicinity of the study area. From 1970 to 1990, ground-water use in the study area and adjacent areas increased from 242 to 435 mgd, which is nearly an 80 percent increase over a 20-year period. The largest ground-water withdrawals in the study area are by Gainesville Regional Utilities, which pumped 19.13 mgd in 1991, and Georgia Pacific in Palatka, which pumped 15.54 mgd in 1991. The areas of greatest drawdown in the potentiometric surface of the upper Floridan aquifer generally coincide with the areas where pumpage is greatest. The most obvious impact of pumping is the cone of depression extending out from the City of Jacksonville; this feature has expanded farther outward in distance as a function of time.

Current low ground-water levels can be explained in terms of recent low rainfall. However, the long-term continuous declines in ground-water levels in the upper Floridan aquifer over the past 30 to 60 years in many parts of north-central Florida cannot be explained entirely by changes in rainfall. Unfortunately, data for long-term ground-water pumpage are not available, but from 1970 to 1990, ground-water use increased nearly 80 percent for counties in and adjacent to the study area, and it undoubtedly is a major factor. The long-term analysis and the short-term multiple regression analysis of changes in ground-water levels in the upper Floridan aquifer indicate that both rainfall and ground-water pumpage have contributed to the declines in ground-water levels in north-central Florida.

The calculated potentiometric surfaces for May 1985 and May 2010 were compared to predict water-level changes in the upper Floridan aquifer due to the projected pumping changes in the study area from May 1985 to May 2010. Predicted water-level changes due to projected changes in pumping are negligible (± 1 ft) over a large part of the study area. In the east-central part of the study area, water levels in the upper Floridan aquifer are predicted to <u>increase</u> by as much as 5 ft due to the projected decrease in pumping at the Georgia Pacific facility near Palatka. In the GRU Murphree Well Field in Gainesville, the predicted drawdown is 19.0 ft, and in the northeast part of the study area, drawdowns on the order of 12.0 ft are predicted due to the increased pumping in the Orange Park area and in the Jacksonville area adjacent to but outside the study area. The total spring discharge from the upper Floridan aquifer calculated for May 2010 (3.04×10^7 ft^3/day) is only slightly less than the total spring discharge calculated for May 1985 (3.07×10^7 ft^3/day).

Drawdowns due to changes in pumping from May 1985 to May 2010 were calculated for layer one by modifying the calibrated MODFLOW model so that drawdowns due to the May 1985 and May 2010 pumping rates could be calculated separately and then compared in order to estimate changes that will occur from May 1985 to May 2010 in the water-table in the surficial aquifer. In this revised "drawdown" model, all of the starting heads and drain heads were set equal to 0.0 so that no drawdowns occurred when the model was run unless pumping stresses were applied or changes occurred in the general head boundary conditions. The constant head nodes in layers one and two were activated, and layers two and three were treated as confined aquifers with constant thicknesses. The transmissivity of layer one was assigned a value of $T_1 = 625$ ft^2/day, and the leakance values for layers one - four and transmissivity values for layers two - five were the same as in the calibrated model. The evapotranspiration and recharge rates were assigned similar values so that recharge would be balanced by evapotranspiration when drawdowns were equal to 0.0 under the condition of no pumping.

The drawdown model was run using the May 1985 and May 2010 well files, and the results were compared to estimate the drawdowns that will occur in layer one from May 1985 to May 2010. The results indicate that surficial aquifer drawdowns from 1985 to 2010 will range approximately from -1.6 ft (an <u>increase</u> in the water-table) at the Georgia Pacific facility near Palatka to 1.2 ft in the east-central part of the study area. In the GRU Murphree Well Field, the calculated water-table drawdown is 0.23 ft. The results of the modified "drawdown" model appear to be reasonably accurate, because the modified "drawdown" model predicts the same drawdowns in the upper Floridan aquifer as the calibrated model, and it also predicts water-table drawdowns that compare favorably with the range of drawdowns predicted for individual wells in the Murphree Well Field using an analytical model.

In recent years, lake levels have declined by significant amounts in some parts of the Upper Etonia Creek Basin in the Keystone Heights area. Brooklyn Lake, for example, is considered highly unstable due to fluctuations of more than 24 ft over the period of record from 1957 to 1991. Below average rainfall, declining ground-water levels in the upper Floridan aquifer, vertical leakage from the lake to the upper Floridan aquifer and cessation of surface-water inflow since 1989 are the major, interrelated factors that have contributed to the lake's decline to record low levels. Based on a lake-stage simulation of Brooklyn Lake for 1965-1991, a 1-ft change in elevation in the water level in the upper Floridan aquifer will result in an approximate change of 0.76 ft in the stage elevation of Brooklyn Lake.

The calibrated ground-water model predicts that the water level in the upper Floridan aquifer in the Keystone Heights area will decrease on the order of 0.03 ft due to the projected changes in pumping from May 1985 to May 2010. Coupling this result with the result from the lake-stage simulation for Brooklyn Lake indicates that the stage in Brooklyn Lake will be decreased by a negligible amount on the order of 0.02 ft due to the predicted decrease in the water level in the upper Floridan aquifer, which is due to the projected changes in pumping. The lake-stage elevation of Brooklyn Lake will increase and/or decrease by amounts significantly greater than

0.02 ft due to other factors in the water budget such as rainfall, evaporation, and surface-water inflow. Thus, these results indicate that the presently projected changes in pumping from 1985 to 2010 will not significantly affect the lake-stage elevation in Brooklyn Lake.

11.3 RECOMMENDATIONS

Based on the results of this investigation, several recommendations can be made towards reducing the regional decline in ground-water levels due to pumping:

The largest increase in pumping is in the public-supply category, in which pumpage is projected to increase approximately 53 percent from 54.8 to 83.6 mgd from 1985 to 2010. The greatest drawdowns in the study area will occur in the vicinity of the GRU Well Field in Gainesville and in the northeast part of the study area due to increases in pumping in the Orange Park and Jacksonville areas. If reductions in pumping increases in these areas could be achieved, drawdowns in water levels in the upper Floridan aquifer could be reduced proportionally.

The largest decrease in pumping is in the commercial and industrial category, in which pumpage is projected to decrease approximately 22 percent from 63.1 to 49.5 mgd, due largely to a major reduction in pumpage at the Georgia Pacific facility near Palatka. More efficient use of ground water by other commercial and industrial users should be encouraged. Instead of estimating ground-water pumpage, commercial and industrial users should be required to meter and report pumpage on a monthly basis.

Agricultural use is projected to increase approximately 17 percent from 55.4 to 65.0 mgd. Better estimates for agricultural crop and land use are needed in order to improve water-use estimates. Agricultural practices that reduce water use should be encouraged.

Domestic self-supply is a major category that makes up approximately 16 percent of the total ground-water pumpage. Pumpage in this category is projected to increase approximately 8 percent from 28.2 to 30.5 mgd. However, more accurate determinations of pumping in this category are needed in order to assess its impact. This includes determining spatial locations, pumping rates, and aquifer units that are being pumped.

In an overall sense, major improvements in the availability of water-use data are needed. To support SJRWMD's ground-water modeling program, accurate pumping data compatible with numerical model requirements should be available based on spatial locations and categories for the entire District. Discrepancies between "permitted" and "actual" pumping rates should be eliminated by requiring pumping to be metered and reported on a timely basis and consumptive use permit files to be updated with actual rather than projected or estimated data. In addition, the availability of water-table measurements and maps for the District and better delineation of hydrogeologic regimes such as the intermediate aquifer in the Hawthorn Group in the Keystone Heights area and the Fernandina Permeable Zone in the northeast part of the study area also would benefit future modeling efforts in the District.

12.0 REFERENCES

Anderson, P.F. 1990. *PREMOD: A preprocessor for MOD3D,* Version 2.7. Geotrans, Inc.

Andrews, W.J. 1990. *Transmissivity and well yields of the Upper Floridan aquifer in Florida*. Florida Geological Survey Map Series no. 132. Tallahassee, Florida, 1 sheet.

Arrington, D.V. 1985. *Geology of the Interlachen Karstic Highlands*. Master of Science Thesis, University of Florida Department of Geology. Gainesville, Florida, 130 pp.

Batten, R.L. 1987. Geological time scale. In: *McGraw-Hill Encyclopedia of Science and Technology*, vol. 8, 29-31.

Bentley, C.B. 1977. *Surface-water and ground-water features, Clay County, Florida*. U.S. Geological Survey Water Resources Investigations Report 77-87. Tallahassee, Florida, 59 pp.

Bermes, B.J., G.W. Leve and G.R. Tarver. 1963a. *Geology and groundwater resources of Flagler, Putnam, and St. Johns counties, Florida*. Florida Geological Survey Report of Investigations Report no. 32. Tallahassee, Florida, 97 pp.

__________. 1963b. *Ground water records of Flagler, Putnam, and St. Johns counties, Florida*. Florida Geological Survey Information Circular no. 37. Tallahassee, Florida.

Blandford, T.N. and T.R. Birdie. 1992. *Regional Ground Water Flow Modeling for East-Central Florida with Emphasis on Orange and Seminole Counties*. St. Johns River Water Management District Technical Publication SJ92-SP17. Palatka, Florida.

Brown, D.P. 1984. *Impact of development on availability and quality of ground water in eastern Nassau County, Florida, and southeastern Camden County, Georgia*. U.S. Geological Survey Water Resources Investigations Report 83-4190. Tallahassee, Florida, 113 pp.

Bush, P.W. and R.H. Johnston. 1988. *Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama.* U.S. Geological Survey Professional Paper 1403-C. Washington, D.C., 80 pp.

Butler, S.S. 1957. *Engineering Hydrology.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 356 pp.

Caprara, M.R. 1993. *Estimation of phreatic-surface elevations for a regional groundwater flow model, north central Florida.* Bachelor of Science in Civil Engineering High Honors Paper, University of Florida Department of Civil Engineering. Gainesville, Florida. 29 pp.

Chow, V.T., D.R. Maidment and L.W. Mays. 1988. *Applied hydrology.* McGraw-Hill, New York, 572 pp.

Clark, W.E., R.H. Musgrove, C.G. Menke and J.W. Cagle, Jr. 1962. *Interim report on the water resources of Alachua, Bradford, Clay, and Union counties, Florida.* Florida Geological Survey Information Circular no. 36. Tallahassee, Florida, 92 pp.

__________. 1963. *Hydrology of Brooklyn Lake near Keystone Heights, Florida.* Florida Geological Survey Report of Investigations no. 33. Tallahassee, Florida, 43 pp.

__________. 1964. *Water resources of Alachua, Bradford, Clay, and Union counties, Florida.* Florida Geological Survey Report of Investigations no. 35. Tallahassee, Florida, 170 pp.

Domenico, P.A. and F.W. Schwartz. 1990. *Physical and chemical hydrogeology.* John Wiley & Sons, New York.

Durden, D.W. 1990. *Computer simulation of the predevelopment and current Floridan aquifer system in northeast Florida.* Master of Engineering Thesis, University of Florida Department of Civil Engineering. Gainesville, Florida, 164 pp.

__________. 1994a. *Finite-Difference Simulation of the Floridan Aquifer System in Coastal Northeast Florida and Camden County, Georgia.* St. Johns River Water Management District Technical Publication (draft). Palatka, Florida.

__________. 1994b. *MODVIEW: A Graphical-Kernel System Program for Evaluating MODFLOW Data.* St. Johns River Water Management District Technical Publication (draft). Palatka, Florida.

Durden, D.W. and L.H. Motz. 1991. *Computer simulation of the predevelopment and current Floridan aquifer system in northeast Florida.* St. Johns River Water Management District Technical Publication SJ91-4. Palatka, Florida, 128 pp.

Fairchild, R.W. 1972. *The shallow-aquifer system in Duval County, Florida.* Florida Bureau of Geology Report of Investigations no. 59. Tallahassee, Florida, 50 pp.

Faulkner, G.L. 1973. *Geohydrology of the cross-Florida barge canal area with special reference to the Ocala vicinity.* U.S. Geological Survey Water Resources Investigations Report 1-73. Tallahassee, Florida, 117 pp.

Fernald, E.A. and D.J. Patton, Editors. 1984. *Water resources atlas of Florida.* Florida State University Institute of Science and Public Affairs. Tallahassee, Florida, 291 pp.

Fischl, P. 1994. *Projected aquifer drawdowns: Murphree Wellfield, Gainesville Regional Utilities, Alachua County, Florida.* St. Johns River Water Management District Professional Paper SJ94-PP2. Palatka, Florida, 17 pp.

Florence, B.L. 1990. *Annual water use survey: 1988.* St. Johns River Water Management District Technical Publication SJ 90-4. Palatka, Florida, 128 pp.

__________. 1991. *Annual water use survey: 1989.* St. Johns River Water Management District Technical Publication SJ 91-6. Palatka, Florida, 126 pp.

__________. 1992. *Annual water use survey: 1990.* St. Johns River Water Management District Technical Publication SJ 92-4. Palatka, Florida, 122 pp.

Franks, B.H. 1980. *The surficial aquifer at the U.S. Naval Station near Mayport, Florida.* U.S. Geological Survey Open-File Report 80-765. Tallahassee, Florida, 13 pp.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater.* Prentice-Hall. Englewood Cliffs, New Jersey, 604 pp.

Gay, J.D. 1993. *Temporal and spatial changes in groundwater levels in the upper Floridan aquifer in north-central Florida and the factors that relate to these changes: rainfall and groundwater pumpage.* Master of Engineering Report, University of Florida Department of Environmental Engineering Sciences. Gainesville, Florida, 76 pp.

GeoTrans, Inc. 1992. *Wekiva Basin Ground Water Flow and Solute Transport Modeling Study Phase I: Regional Ground Water Flow Model Development.* St. Johns River Water Management District Technical Publication SJ92-SP19. Palatka, Florida.

Geraghty & Miller, Inc. 1991. *Numerical Modeling of Ground-Water Flow and Sea Water Intrusion, Volusia County, Florida.* St. Johns River Water Management District Technical Publication SJ92-SP5. Palatka, Florida.

Haan, C.T. 1977. *Statistical methods in hydrology.* Iowa State University Press, Ames, Iowa, 365 pp.

Hayes, E.C. 1981. *The surficial aquifer in east-central St. Johns County, Florida.* U.S. Geological Survey Water Resources Investigations Report no. 81-14. Tallahassee, Florida, 19 pp.

Healy, H.G. 1966. *Water levels in artesian and nonartesian aquifers of Florida, 1961-62.* U.S. Geological Survey Information Circular no. 48. Tallahassee, Florida, 53 pp.

__________. 1968. *Water levels in artesian and nonartesian aquifers of Florida, 1963-64.* U.S. Geological Survey Information Circular no. 52. Tallahassee, Florida, 68 pp.

__________. 1971. *Water levels in artesian and nonartesian aquifers of Florida, 1967-68.* U.S. Geological Survey Information Circular no. 68. Tallahassee, Florida, 61 pp.

__________. 1972. *Water levels in artesian and nonartesian aquifers of Florida, 1969-70.* U.S. Geological Survey Information Circular no. 73. Tallahassee, Florida, 61 pp.

__________. 1974. *Water levels in artesian and nonartesian aquifers of Florida, 1971-72.* U.S. Geological Survey Information Circular no. 85. Tallahassee, Florida, 94 pp.

__________. 1976. *Water levels in artesian and nonartesian aquifers of Florida, 1973-74.* U.S. Geological Survey Water Resources Investigations Report 76-101. Tallahassee, Florida, 115 pp.

__________. 1978. *Water levels in artesian and nonartesian aquifers of Florida, 1975-76.* U.S. Geological Survey Open-File Report 80-693. Tallahassee, Florida, 115 pp.

__________. 1980. *Water levels in artesian and nonartesian aquifers of Florida, 1977-78.* U.S. Geological Survey Open-File Report 78-458. Tallahassee, Florida, 99 pp.

Hoenstine, R.W. and E. Lane. 1991. *Environmental geology and hydrogeology of the Gainesville area, Florida.* Florida Geological Survey Special Publication no. 33. Tallahassee, Florida, 70 pp.

Huang, C.-T. 1994. *Revised Spring Conductance Coefficients: Wekiva River Basin Ground Water Flow Model.* St. Johns River Water Management District Technical Publication SJ94-PP3. Palatka, Florida.

Hubbert, M.K. 1940. The theory of ground-water motion. *Journal of Geology*, 48(8):785-944.

Hunn, J.D. and L.J. Slack. 1983. *Water resources of the Santa Fe River Basin, Florida.* U.S. Geological Survey Water Resources Investigations Report 83-4075. Tallahassee, Florida.

Huntsberger, D.V. and P. Billingsley. 1973. *Elements of statistical inference.* Allyn and Bacon, Inc. Boston, Massachusetts, 349 pp.

Jenab, S.A., V.R. Donthamsetti and D. Clapp. 1986. *Rainfall analysis for northeast Florida part II: summary of monthly and annual rainfall data.* St. Johns River Water Management District Technical Publication SJ86-4. Palatka, Florida, 107 pp.

Johnston, R.H. and P.W. Bush. 1988. *Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama.* U.S. Geological Survey Professional Paper 1403-A. Washington, D.C., 24 pp.

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

Kane, B.C. 1984. *Origin of the Grandin (Plio-Pleistocene) sands, western Putnam County, Florida.* Master of Science Thesis, University of Florida Department of Geology. Gainesville, Florida.

King, F.H. 1899. *Principles and conditions of the movement of groundwater.* U.S. Geological Survey 19th Annual Report, Part 2, pp. 59-294.

Kohler, M.A. 1954. *Lake and pan evaporation in water-loss investigations: Lake Hefner studies*. U.S. Geological Survey Professional Paper no. 269. Washington, D.C.

Krause, R.E. and R.B. Randolph. 1989. *Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina.* U.S. Geological Survey Professional Paper 1403-D. Washington, DC, 65 pp.

Leach, S.D. 1978. *Source, use and disposition of water in Florida, 1975*. U.S. Geological Survey Water Resources Investigations Report 78-17. Tallahassee, Florida, 90 pp.

__________. 1983. *Source, use and disposition of water in Florida, 1980.* U.S. Geological Survey Water Resources Investigations Report 82-4090. Tallahassee, Florida, 337 pp.

Leach, S.D. and H.G. Healy. 1980. *Estimated water use in Florida, 1977.* U.S. Geological Survey Water Resources Investigations Report 79-112. Tallahassee, Florida, 76 pp.

Leve, G.W. 1966. *Groundwater in Duval and Nassau counties, Florida.* Florida Geological Survey Report of Investigations Report no. 43. Tallahassee, Florida, 91 pp.

Lopez, M.A. and J.D. Fretwell. 1992. *Relation of change in water levels in surficial and Upper Floridan aquifers and Lake Stage to climatic conditions and well-field pumpage in northwest Hillsborough, northeast Pinellas, and south Pasco counties, Florida*. U.S. Geological Survey Water Resources Investigations Report 91-4158. Tallahassee, Florida, 94 pp.

Lynne, G.D. and C.F. Kiker. 1991. *Needs and sources planning in the St. Johns River Water Management District: Agricultural land and water use projections for 1995 and 2010.* University of Florida Institute of Food and Agricultural Sciences, Food and Resource Economics Department. Gainesville, Florida.

MacNeil, F.S. 1950. *Pleistocene shore lines in Florida and Georgia*. U.S. Geological Survey Professional Paper 221-F. Washington, D.C., 106 pp.

Marella, R.L. 1981. *Annual water use survey - 1979.* St. Johns River Water Management District Technical Publication SJ 81-3. Palatka, Florida, 164 pp.

__________. 1982. *Annual water use survey - 1980.* St. Johns River Water Management District Technical Publication SJ 82-5. Palatka, Florida, 165 pp.

__________. 1983a. *Annual water use survey - 1981.* St. Johns River Water Management District Technical Publication SJ 83-9. Palatka, Florida, 95 pp.

__________. 1983b. *Annual water use survey - 1982. Part I.* St. Johns River Water Management District Technical Publication SJ 84-2. Palatka, Florida, 53 pp.

__________. 1984. *Annual water use survey - 1983.* St. Johns River Water Management District Technical Publication SJ 84-5. Palatka, Florida, 103 pp.

__________. 1985a. *Annual water use survey - 1984.* St. Johns River Water Management District Technical Publication SJ 85-7. Palatka, Florida, 113 pp.

__________. 1985b. *Annual water use survey - 1984 Supplement.* St. Johns River Water Management District Technical Publication SJ 85-7, Supplement Data. Palatka, Florida, 48 pp.

__________. 1986a. *Annual water use survey - 1985.* St. Johns River Water Management District Technical Publication SJ 86-5. Palatka, Florida, 53 pp.

__________. 1986b. *Annual water user survey: 1985 Supplement.* St. Johns River Water Management District Technical Publication SJ 86-5, Supplement Data. Palatka, Florida, 117 pp.

__________. 1988a. *Water withdrawals, use and trends in the St. Johns River Water Management District: 1986.* St. Johns River Water Management District Technical Publication SJ 88-7. Palatka, Florida, 131 pp.

__________. 1988b. *Water withdrawals, use and trends in Florida, 1985.* U.S. Geological Survey Water Resources Investigations Report 88-4103. Tallahassee, Florida, 43 pp.

__________. 1990. *Annual water use survey: 1987.* St. Johns River Water Management District Technical Publication SJ 90-4. Palatka, Florida, 126 pp.

__________. 1992a. *Water withdrawals, use and trends in Florida: 1990.* U.S. Geological Survey Water Resources Investigations Report 92-4140. Tallahassee, Florida, 38 pp.

__________. 1992b. *Factors that affect public-supply water use in Florida, with a section on projected water use to the year 2020.* U.S. Geological Survey Water Resources Investigations Report 91-4123. Tallahassee, Florida.

McDonald, M.G. and A.W. Harbaugh. 1988. *A modular three-dimensional finite-difference ground-water flow model.* U.S. Geological Survey Techniques of Water Resources Investigations Report, Book 6, Chapter Al. Washington, D.C.

McGurk, B.E. 1992. *Ground Water Resource Evaluation of the Floridan Aquifer System in Western Volusia and Southeastern Putnam Counties, Florida.* St. Johns River Water Management District Technical Publication (draft). Palatka, Florida.

Miller, J.A. 1986. *Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina.* U.S. Geological Survey Professional Paper 1403-B. Washington, D.C., 91 pp.

Missimer & Associates, Inc. 1991. *Hydrogeologic impact assessment in support of the consumptive use permit application for the Goldhead Sand Plant, Florida Rock Industries, Inc., Keystone Heights, Florida.* Consulting Report. Jacksonville, Florida, 62 pp. and 4 appendices.

Moore, D.L. and D.A. Smith. *Water supply needs and sources 1990-2020.* Southwest Florida Water Management District. Brooksville, Florida.

Motz, L.H. 1989. *Review of pumping tests at Gold Head Sand Mine*, Report submitted to St. Johns River Water Management District, Palatka, Florida. March 22, 11 pp.

Motz, L.H. and M.S. Fowler. 1993. Lake-level declines in Karst Lake during droughts. In: *Proceedings of the 1993 national conference on hydraulic engineering and international symposium on engineering hydrology.* American Society of Civil Engineers. San Francisco, California, July 25-30.

Motz, L.H., J.P. Heaney, W.K. Denton, M.S. Fowler, and G. Leiter. 1993. *Upper Etonia Creek hydrological study, Phase II Final report (revised).* University of Florida Departments of Civil Engineering and Environmental Engineering Sciences. Gainesville, Florida, 175 pp.

Motz, L.H., J.P. Heaney, W.K. Denton and G. Leiter. 1991a. *Upper Etonia Creek hydrologic study, Phase I Final report.* St. Johns River Water Management District Special Publication SJ 91-SP5. Palatka, Florida, 100 pp.

__________. 1991b. Groundwater Seepage from Karst Lakes in Florida, USA. In: *New technologies in urban drainage: UDT '91*, ed. Č. Maksimović, 171-176. Elsevier Applied Science. London.

Phelps, G.G. 1987. *Effects of surface runoff and treated wastewater recharge on quality of water in the Florida aquifer system, Gainesville area, Alachua County, Florida.* U.S. Geological Survey Water Resources Investigations Report 87-4099. Tallahassee, Florida, 57 pp.

Pirkle, E.C., W.A. Pirkle and W.H. Yoho. 1977. *The Highland heavy-mineral sand deposit on Trail Ridge in northern peninsula Florida.* Florida Bureau of Geology Report of Investigations no. 84. Tallahassee, Florida, 50 pp.

Pirkle, E.C., W.H. Yoho and C.W. Hendry, Jr. 1970. *Ancient sea level stands in Florida.* Florida Bureau of Geology Bulletin no. 52. Tallahassee, Florida, 61 pp.

Pride, R.W. 1973. *Estimated use of water in Florida, 1970.* Florida Bureau of Geology Information Circular no. 83. Tallahassee, Florida, 31 pp.

Puri, H.S. and R.O. Vernon. 1964. *Summary of the geology of Florida and a guide book to the classic exposures.* Florida Geological Survey Special Publication no. 5. Tallahassee, Florida, 312 pp.

Rosenau, J.C., G.L. Faulkner, C.W. Hendry, Jr. and R.W. Hull. 1977. *Springs of Florida.* Florida Bureau of Geology Bulletin no. 31 (revised). Tallahassee, Florida, 461 pp.

Ross, F.W. and D.A. Munch. 1980. *Hydrologic investigations of the potentiometric high centered along the Crescent City Ridge, Putnam County, Florida.* St. Johns River Water Management District Technical Publication SJ 80-3. Palatka, Florida, 75 pp. and appendix.

Ryder, P.D. 1985. *Hydrology of the Floridan aquifer system in west-central Florida.* U.S. Geological Survey Professional Paper 1403-F. Washington, DC, 63 pp.

Schiner, G.R. and E.C. Hayes. 1985. *Potentiometric surface of the Upper Floridan aquifer in the St. Johns River Water Management District and vicinity, Florida, May 1985.* U.S. Geological Survey Open-File Report 85-491. Tallahassee, Florida, 1 sheet.

Scott, T.M. 1983. *The Hawthorn formation of northeastern Florida: Part I The geology of the Hawthorn Formation of northeastern Florida.* Florida Bureau of Geology Report of Investigation no. 94. Tallahassee, Florida, 90 pp.

__________. 1988. *The lithostratigraphy of the Hawthorn group (Miocene) of Florida.* Florida Geological Survey Bulletin no. 59. Tallahassee, Florida.

Sheaffer, S.M. 1993. *Estimation of ground-water use: north central Florida regional ground-water model.* Bachelor of Science in Civil Engineering High Honors Paper, University of Florida Department of Civil Engineering. Gainesville, Florida, 30 pp.

Shultz, J.R. and A.B. Cleaver. 1955. *Geology in engineering.* John Wiley, New York, 592 pp.

Snell, L.J. and W. Anderson. 1970. *Water resources of northeast Florida (St. Johns River Basin and adjacent coastal areas).* Florida Bureau of Geology Report of Investigation no. 54. Tallahassee, Florida, 77 pp.

Southeastern Geological Society. 1986. *Hydrogeological units of Florida.* Florida Geological Survey Special Publication no. 28. Tallahassee, Florida, 9 pp.

Stieglitz, E.H. 1986. *Estimated water use in the Southwest Florida Water Management District: 1985.* Southwest Florida Water Management District, Brooksville, Florida, 52 pp.

Stringfield, V.T. 1936. *Artesian water in the Florida peninsula.* U.S. Geological Survey Water Supply Paper 773-C. Washington, DC.

Tibbals, C.H. 1990. *Hydrology of the Florida aquifer system in east-central Florida.* U.S. Geological Survey Professional Paper 1403E. Washington, DC, 98 pp.

Tolmann, C.F. 1937. *Groundwater.* McGraw-Hill. New York, 593 pp.

White, W.A. 1970. *The geomorphology of the Florida peninsula.* Florida Bureau of Geology Geological Bulletin no. 51. Tallahassee, Florida, 164 pp.

Williams, S.A. 1988. *POSTMOD: A Postprocessor for MODFLOW, Version 2.1.* International Ground Water Modeling Center, Indianapolis, Indiana.

__________. 1992a. *Revision and Recalibration of a Regional Flow Model of the Volusia Ground Water Basin.* St. Johns River Water Management District Technical Publication (draft). Palatka, Florida.

__________. 1992b. *Development and Application of a Regional Ground Water Flow Model of the Surficial Aquifer System in the Titusville/Mims Area of Brevard County, Florida.* St. Johns River Water Management District Technical Publication (draft). Palatka, Florida.