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SIMULATION OF THE EFFECTS OF GROUNDWATER WITHDRAWALS ON THE FLORIDAN AQUIFER SYSTEM IN EAST-CENTRAL FLORIDA: MODEL EXPANSION AND REVISION

by

Brian McGurk, P.G.
Paula Fischl Presley, P.G.

Professional Geologist
License No.: 882
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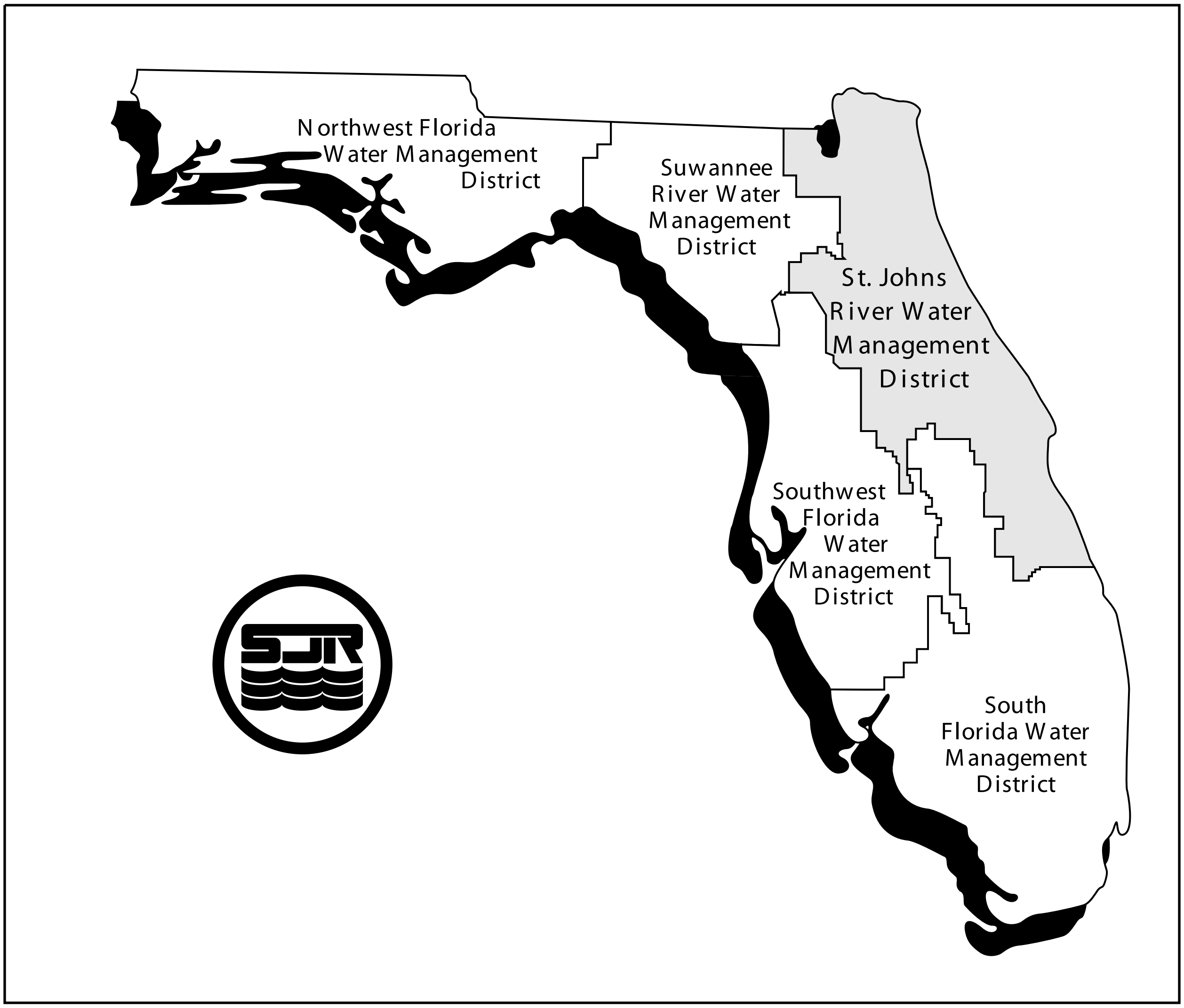

The St. Johns River Water Management District (SJRWMD) was created by the Florida Legislature in 1972 to be one of five water management districts in Florida. It includes all or part of 19 counties in northeast Florida. The mission of SJRWMD is to manage water resources to ensure their continued availability while maximizing environmental and economic benefits. SJRWMD accomplishes its mission through regulation; applied research; assistance to federal, state, and local governments; operation and maintenance of water control works; and land acquisition and management.

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EXECUTIVE SUMMARY

The east-central Florida (ECF) region is centered upon Orange and Seminole counties but includes most of Brevard, Lake, and Osceola counties plus parts of Marion, Polk, Sumter, and Volusia counties. A numerical groundwater flow model was developed for the ECF region that is a revision and expansion of several previous regional models that cover the area. The ECF model was calibrated to average, steady-state 1995 hydrologic conditions by quantitatively comparing simulated surficial aquifer system and Floridan aquifer system groundwater levels and springflow rates with observed values at corresponding locations. Other simulated fluxes were compared qualitatively to estimates of actual flux values. The model was also calibrated in a qualitative fashion to estimated predevelopment conditions by comparing simulated water levels and spring flows to available estimates.

The calibrated model was used to predict the potential changes to average surficial aquifer system and Floridan aquifer system water levels, and to average springflow rates as a result of projected 2020 magnitudes and locations of Floridan aquifer system withdrawals. Because all simulations represented estimated average conditions, climatic stresses and boundary conditions were kept the same as those used for the 1995 calibration. The results of a series of predictive simulations indicated that the cumulative effect of projected Floridan aquifer system pumping upon the Floridan aquifer system potentiometric surface extends throughout most of the ECF area and crosses municipal, county, and water management district boundaries. The predicted Floridan aquifer system potentiometric surface decline also has a direct effect upon Floridan aquifer system springflow rates. Although there is significant uncertainty in the magnitude of the predicted springflow declines, currently projected 2020 Floridan aquifer system withdrawals may cause average 2020 flow rates at several large springs that supply base flow to the Wekiva River to be below their adopted minimum average flow rates. The predicted change to the Floridan aquifer system potentiometric surface due to projected 2020 Floridan aquifer system pumping would ultimately have a widespread effect upon average surficial aquifer system water levels. Declines in average surficial aquifer system water levels would be limited to areas where both the Upper Floridan aquifer potentiometric decline is significant and the intermediate confining unit is relatively thin or breached by sinkhole formation. Upland lakes and wetlands in these areas could experience long-term water level declines. The boundary between the freshwater and the saltwater portions of the Floridan aquifer

system within the lower portion of the Upper Floridan aquifer and within the Lower Floridan aquifer could also be affected by a regional decline in Floridan aquifer system water levels resulting from Floridan aquifer system withdrawals. Potentiometric levels along this boundary could also be affected by projected 2020 Floridan aquifer system withdrawals.

CONTENTS

FIGURES

TABLES

SYMBOLS

b	aquifer layer thickness (ft)
b'	confining unit thickness (ft)
C_d	drain conductance (ft^2 / day)
C_{riv}	hydraulic conductance between an aquifer and a stream (ft^2 / day)
ET	evapotranspiration rate (ft^3 / day)
ET_{max}	the maximum rate at which ET can occur from either the unsaturated zone or the saturated zone, or both (ft^3 / day)
ET_{maxsat}	maximum allowed ET rate from the saturated zone (ft^3 / day)
ET_{min}	the minimum rate at which ET can occur from either the unsaturated zone or the saturated zone, or both (ft^3 / day)
ET_{sat}	ET from the saturated zone (ft^3 / day)
ET_{srf}	the specified water table elevation at which ETmax occurs (ft)
ET_{unsat}	ET from the unsaturated zone (ft^3 / day)
EXDEP	ET extinction depth (ft)
H_b	specified head at a general-head boundary (ft)
H_d	the elevation of the water body (spring pool) created by a spring discharge (ft)
H_m	estimated actual average Upper Floridan aquifer head in the area covered by a model grid cell containing a spring simulated as a drain (ft)
H_{riv}	the stage elevation of a stream (ft)
H_{sa}	model-simulated head at an active layer-one grid cell (ft)
H_{sd}	model-simulated head at a grid cell containing a spring simulated as a drain (ft)
H_{sr}	model-simulated head at a grid cell containing a stream simulated as a river (ft)
H_{sb}	model-simulated head value at the model grid cell along the boundary (ft)
K_h	horizontal hydraulic conductivity (ft^2 / day)
K_v	vertical hydraulic conductivity of streambed material (ft / day)
K_z	vertical hydraulic conductivity of aquifers and confining units (ft / day)
L	leakance (day^{-1})
L_{down}	annual rate of downward leakage from the Upper Floridan aquifer to the surficial aquifer system (in / yr)
L_{up}	annual rate of upward leakage from the Upper Floridan aquifer to the surficial aquifer system (in / yr)

l_h	horizontal distance between a specified head at a general-head boundary and a model-simulated head value at the model grid cell along the boundary (ft)
l_s	the length of a stream reach within a model grid cell (ft)
M	thickness of a streambed (ft)
N	annual rate of net recharge to the surficial aquifer system (in / yr)
P	annual precipitation rate (in / yr)
Q	lateral flow rate (ft^3 / day)
Q_d	drain discharge (ft^3 / day)
Q_{riv}	groundwater discharge rate to a stream (ft^3 / day)
Q_{swb}	groundwater flow from surface water bodies to the surficial aquifer system (in / yr)
R_{ag}	annual rate of agricultural and golf course irrigation derived directly from Floridan aquifer system withdrawals (in / yr)
R_{app}	annual rate at which water is applied to the land surface as irrigation (in / yr)
R_{bot}	elevation of a streambed (ft)
R_{mr}	annual precipitation rate minus annual rate of overland runoff (in / yr)
R_{psli}	annual rate of landscape irrigation using water derived from Floridan aquifer system public-supply withdrawals (in / yr)
R_{rib}	annual rate at which water is applied to rapid infiltration basins (in / yr)
R_{septic}	annual rate of septic tank effluent (in / yr)
R_{spray}	annual rate of landscape or sprayfield irrigation derived from reclaimed water distribution systems (in / yr)
R_{ssdli}	annual rate of landscape irrigation derived from Floridan aquifer system self-supplied domestic well withdrawals (in / yr)
R_u	annual rate of overland runoff (in / yr)
T	aquifer layer transmissivity (ft^2 / day)
$VCONT_{L2}$	vertical leakance between layers 2 and 3 (day^{-1})
W	width of a model grid cell face perpendicular to the direction of groundwater flow (ft)
W_s	width of a stream reach (ft)

ACKNOWLEDGMENTS

The authors wish to thank the staffs of the of the public water supply utilities in the east-central Florida region for all the support they have provided. In particular, staff from the city of Cocoa, Orange County, the Orlando Utilities Commission, Seminole County Utilities, and Florida Water Services supplied valuable information. The consulting firms PBWater, CH2M HILL, and Post Buckley Schuh & Jernigan also provided important data. Staff from the Water Supply Management Division of the St. Johns River Water Management District supplied invaluable analysis of water use data. Information and support from the groundwater and planning staffs of the South Florida Water Management District and the Southwest Florida Water Management District were greatly needed and appreciated. Appreciation is also extended to the staff of the U.S. Geological Survey Altamonte Springs subdistrict office, to technical peer reviewers, and to many others who provided technical guidance and assistance.

INTRODUCTION

The St. Johns River Water Management District (SJRWMD; Figure 1) completed an assessment of groundwater resources within its jurisdiction in 1994 (Vergara 1994). That assessment, commonly referred to as the Water Supply Needs and Sources assessment, resulted in the designation of significant portions of SJRWMD as Water Resource Caution Areas. These areas, which include most of the central Florida portion of SJRWMD, were designated based upon the likelihood of future water resource problems due to projected 2010 groundwater withdrawals. The assessment was revisited in 1998 (Vergara 1998), using the year 2020 as the planning horizon. SJRWMD has prepared a regional water supply plan (Vergara 2000) for the east-central Florida (ECF) area based upon the updated assessment as well as upon the results of ongoing groundwater-flow modeling efforts. This is a status report on the development of a regional groundwater flow model that has been used to predict potential steady-state changes in the groundwater flow system in the ECF area due to projected average 2020 withdrawals. This model has been developed in conjunction with the Volusia County and Vicinity regional model (Williams 2002, draft).

OBJECTIVES

The purpose of this project is to develop a numerical modeling tool that will be capable of

- Estimating the hydrologic characteristics of the fresh groundwater flow system in the ECF region
- Estimating potential changes to the groundwater flow system due to changes in groundwater withdrawals from the Floridan aquifer system throughout the ECF region

The ECF region is centered upon Orange and Seminole counties but includes most of Brevard, Lake, and Osceola counties plus parts of Marion, Polk, Sumter, and Volusia counties (Figure 2). The region includes areas located within the jurisdiction of three water management districts: the St. Johns River Water Management District, the Southwest Florida Water Management District (SWFWMD), and the South Florida Water Management District (SFWMD).

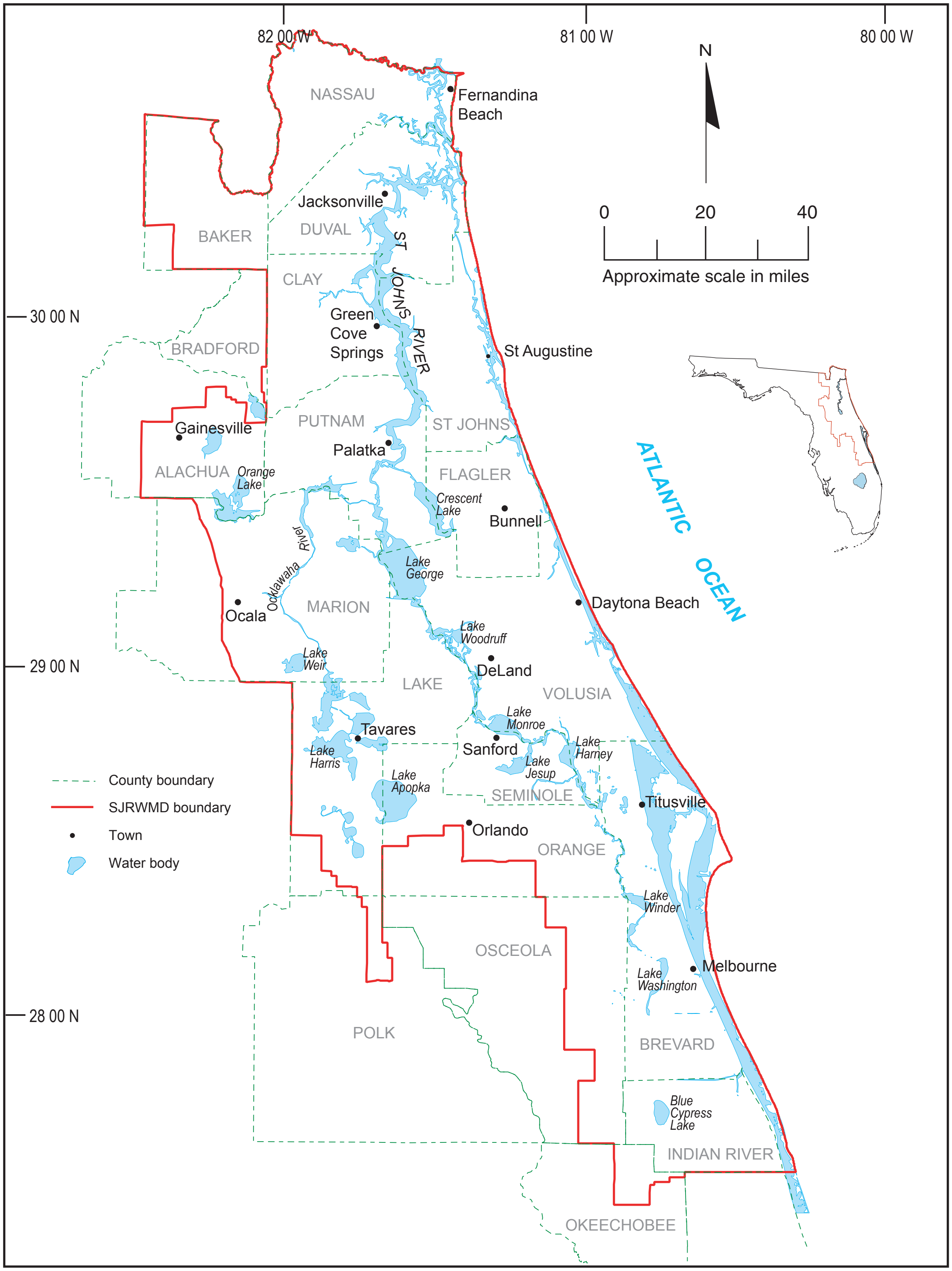


Figure 1. The St. Johns River Water Management District (SJRWMD)

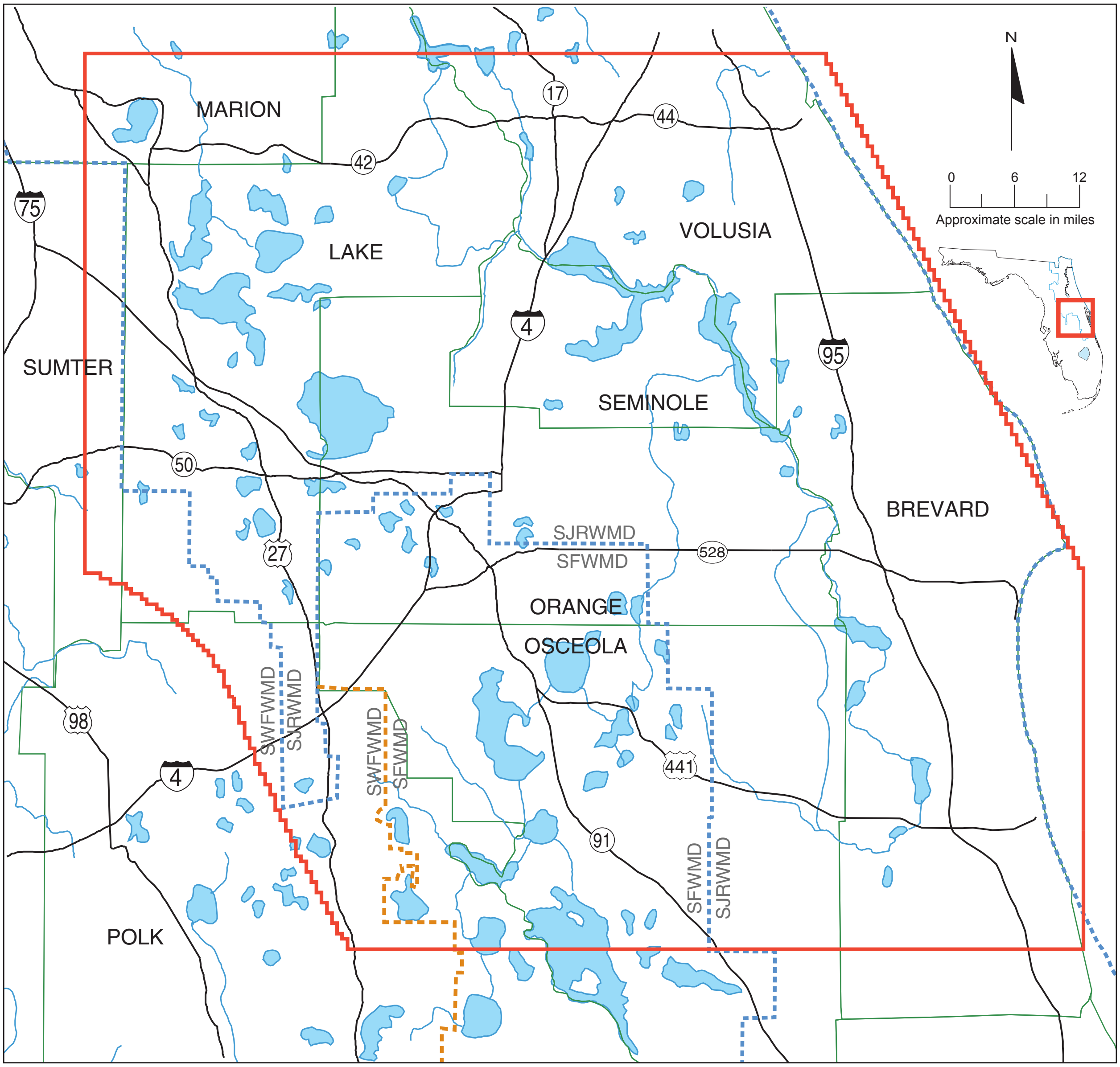


Figure 2. East-central Florida (ECF) project area — includes a portion of the Southwest Florida Water Management District (SWFWMD) and the South Florida Water Management District (SFWMD)

Legend

- Road
- ECF groundwater flow model boundary
- County boundary
- SJRWMD boundary
- SWFWMD/SFWMD boundary
- Water body

The specific objectives of the modeling study are to

1. Simulate the estimated steady-state flow conditions that existed prior to extensive groundwater development
2. Simulate the steady-state groundwater flow system under modern-day (1995) stressed conditions
3. Simulate the potential cumulative steady-state changes from projected increases in Floridan aquifer system withdrawals upon the following:
    - Floridan aquifer system potentiometric levels
    - Discharge from Floridan aquifer springs
    - Water levels in the surficial aquifer system

Model-simulated changes can be used to draw inferences regarding (1) potential decreases in lake and wetland water levels and the resulting effects upon vegetative communities, (2) effects of decreased flow in spring-fed streams upon ecological habitat, and (3) the potential for saltwater intrusion.

PREVIOUS STUDIES

The development of the regional-scale numerical models used for the water-supply planning process is part of a larger, ongoing process of data gathering, analysis, and evaluation that has been occurring for many years. As a result, the regional models have become dynamic tools that are revised as more information about the groundwater flow system becomes available and computer capabilities increase. The models used today were originally derived from models developed by the U.S. Geological Survey (USGS) for their Regional Aquifer System Analysis (RASA) program. Regional models constructed by Skipp (1988), Blandford and Birdie (1992, 1993), Birdie and Blandford (1994), and GeoTrans (1992a, b, and c) were based upon the regional model of Tibbals (1990). The modeling effort described in this report is a revision and expansion of these “second-generation” regional models. This effort is also being conducted in conjunction with a related modeling project that focuses upon the Volusia Groundwater Basin and overlaps with the ECF project area in Volusia County and parts of Lake and Seminole counties (Williams 2002). Significant knowledge of the groundwater flow system has also been gained by the studies conducted in recent years by Murray and Halford (1996), Yobbi (1996), O’Reilly (1998), Spechler and Halford (2001), and Sepulveda (2002). The developers of these models have made use of numerous groundwater hydrology publications by USGS, the Florida Bureau of Geology, water management districts, and others. The bibliography contains a list of references (including those describing regional models) that concern areas wholly or partially within the ECF area.

DATA COLLECTION SITES

Hydrologic data utilized in this project were obtained from numerous wells, rain gauges, and stream gauges located throughout the ECF region.

The locations of rainfall and stream gauging stations used in this study are shown in Figure 3. Information concerning these sites are summarized in Appendixes A and B. Lakes for which stage data were available are also identified in Appendix B. The location of groundwater observation and test wells used in the study are shown in Figures 4 and 5. Data describing these wells are listed in Appendix C.

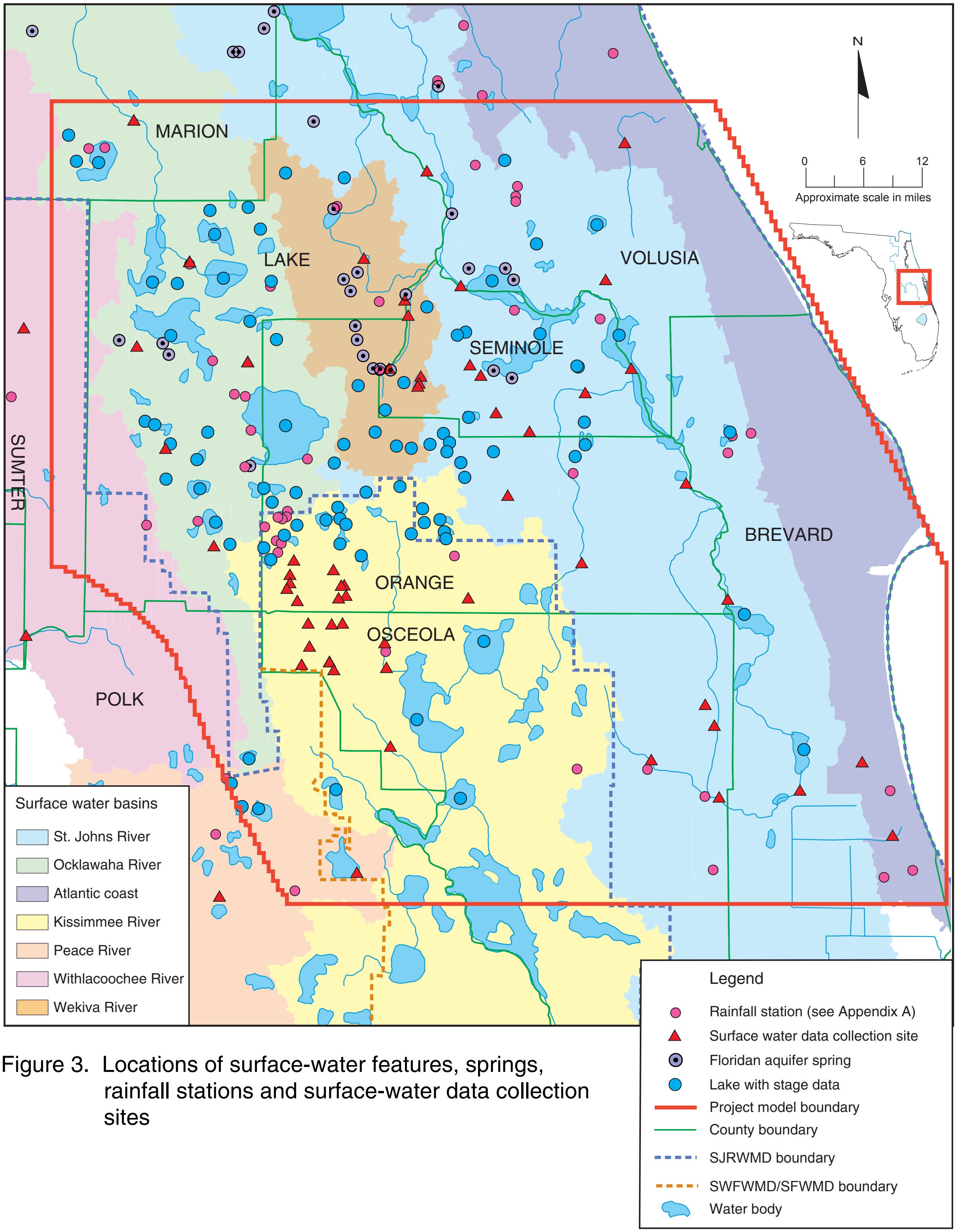


Figure 3. Locations of surface-water features, springs, rainfall stations and surface-water data collection sites

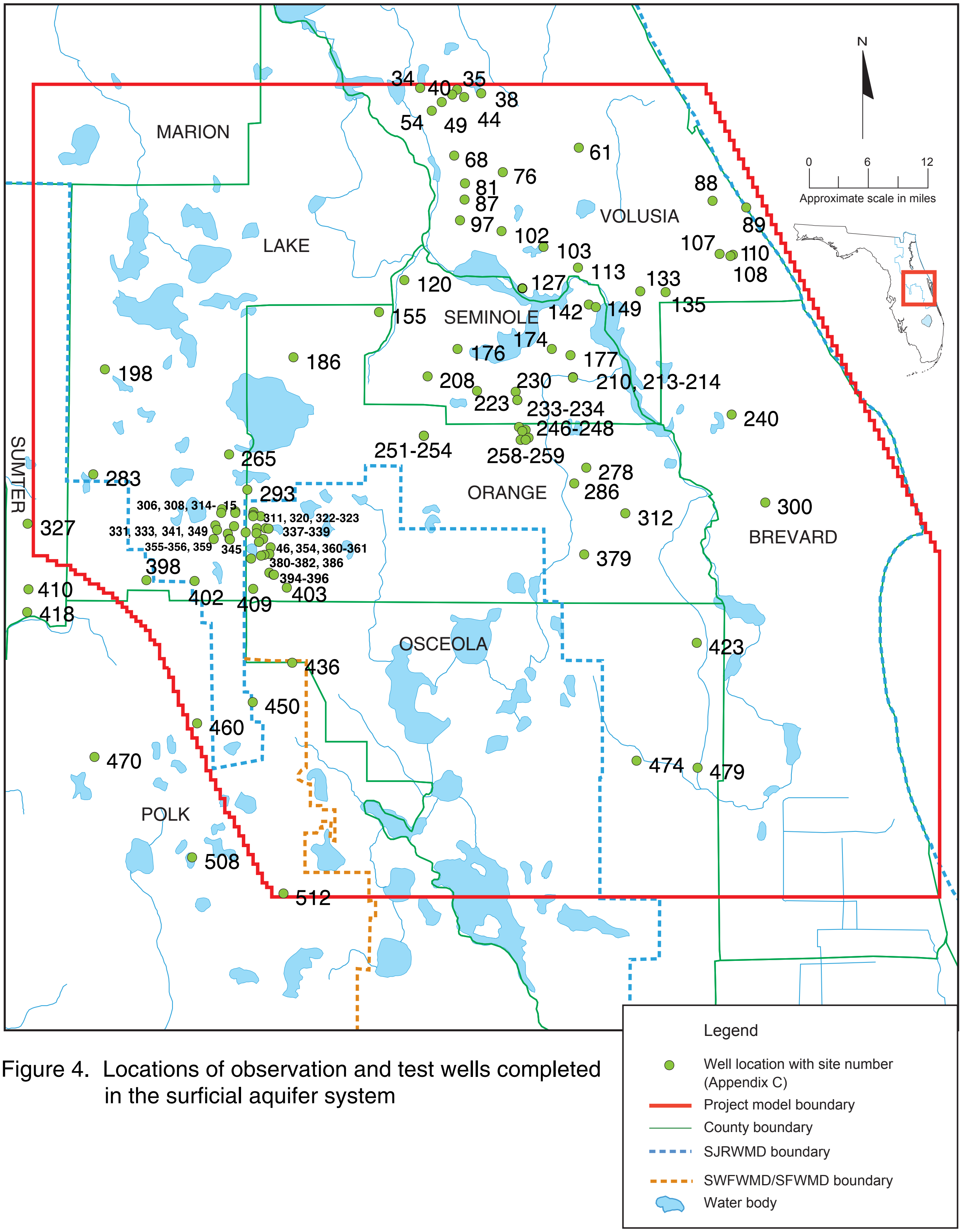


Figure 4. Locations of observation and test wells completed in the surficial aquifer system

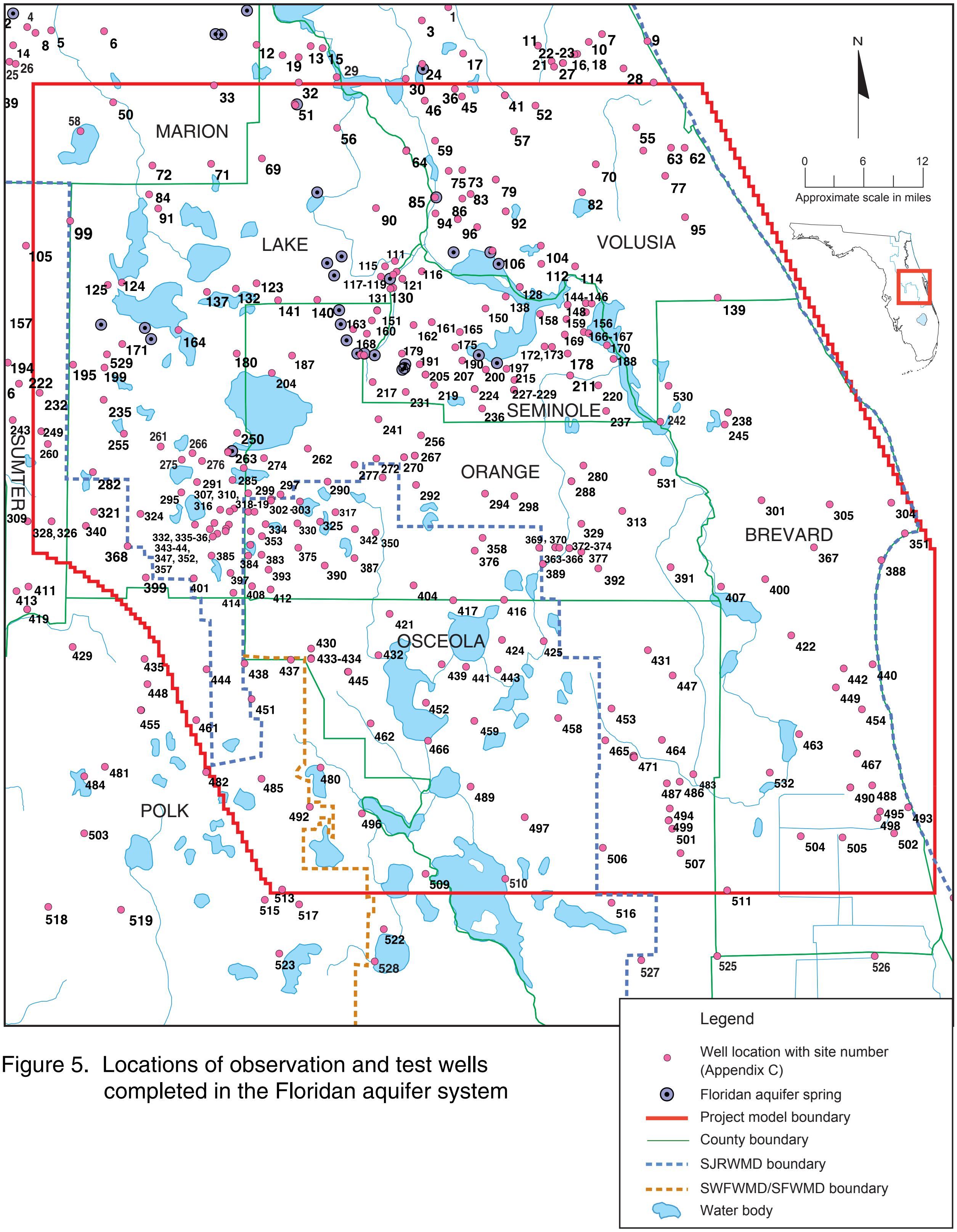


Figure 5. Locations of observation and test wells completed in the Floridan aquifer system

DESCRIPTION OF THE HYDROGEOLOGIC SYSTEM

The important climatic, topographic, and hydrogeologic characteristics of the ECF region can be organized into a basic structure or hydrogeologic framework. The major components of this framework are discussed in this chapter and developed into a conceptual model of groundwater flow.

CLIMATE

The study area climate is humid and subtropical, with warm, relatively wet summers and mild, relatively dry winters (Tibbals 1990). Most years have at least several days when the temperature drops below freezing, but minimum temperatures are rarely below 20ºF and maximum temperatures are rarely above 100ºF.

Rainfall represents the largest input of water to the hydrologic system, and it is unevenly distributed throughout time and space. Approximately 60% of the annual rainfall occurs from June through October (Rao et al. 1997). Most of this rainfall results from local thunderstorms that cover a relatively small area, although large-scale tropical storms or hurricanes occasionally pass through the region. Normal (1961–90) annual rainfall amounts measured at 12 sites within the region that have long-term data range from 46.07 inches per year (in / yr) at Lisbon in northern Lake County to 56.05 in / yr at De Land in western Volusia County (Appendix A). In addition to yearly fluctuations in rainfall amounts, long-term rainfall patterns vary. Tibbals (1990) discussed the evidence for a period of rainfall deficiency (compared to observed long-term averages at four stations) lasting from 1888 to approximately 1931.

Although evapotranspiration (ET) represents the largest water loss from the hydrologic system, there are few data available that represent direct ET measurements. Estimates of the upper and lower limits of average annual ET rates in the region have been made by Tibbals (1990) and Visher and Hughes (1975). The upper limit is approximately equal to the rate at which water can evaporate from an open body of water. This limit ranges from 46 in / yr in the northeastern part of the ECF region to 49 in / yr in the southwestern part (Tibbals 1990, Figure 5). Estimates of the minimum annual ET rate range from 25 in / yr to 35 in / yr (Knochenmus and Hughes 1976; Tibbals 1990; Sumner 1996). According to Tibbals (1990), the lowest ET rates occur where the water table lies beneath the root zone of most plants at depths of approximately 13 feet (ft) or greater. Sumner (1996) estimated annual ET for a 1-year period

(9/15/93 to 9/15/94) using short-term eddy-correlation measurements to calibrate ET estimation models. Sumner's estimate of annual ET of approximately 27 inches can be considered the lower limit from vegetated surfaces in the ECF region because his study area contained shallow-rooted plants, rapidly drained soils, and a deep water table.

TOPOGRAPHY AND SURFACE WATER FEATURES

Topographic relief and the nature of surface water features affect the distribution of recharge and discharge within the ECF groundwater flow system. These features are briefly discussed below.

Land surface elevations range from sea level at the coast to greater than 200 ft above the National Geodetic Vertical Datum of 1929 (NGVD, formerly called mean sea level) at hilltops in Lake and Polk counties. In general, the topography increases in elevation in a step-wise fashion westward from the coast to highland areas in Lake, Polk, and western Orange counties (Figure 6).

The major topographic features are, in general, oriented in a coast-parallel (northwest to southeast) direction. These features include hundreds of lakes and wetland areas, several major surface streams, and a number of highland "ridges." The highland areas are characterized by well-developed karst topography, with relatively high local relief, sinkhole lakes and ponds, dry depressions, and subsurface drainage. They are also covered by well-drained, sandy soil types that tend to limit overland runoff. The majority of the land area in the ECF region is relatively flat and covered by less well-drained soils. Swamps and wetlands cover much of the flatlands.

Surface water bodies within the study area include rivers and their tributaries, freshwater marshes and swamps, canals, lakes, coastal lagoons, and the Atlantic Ocean. Two major river systems collect overland runoff and shallow groundwater base flow from the flatlands in the ECF region. The St. Johns River flows northward, forming county boundaries in the eastern half of the ECF region (see Figure 3). The flow of one major tributary, the Wekiva River, consists mainly of water that discharges from Floridan aquifer springs located at its headwaters and throughout its course. The northward-flowing Ocklawaha River is another major tributary to the St. Johns River that drains much of the western one-quarter of the ECF region. Much of its course consists of the chain of large lakes located in Lake County and in westernmost Orange County. The headwaters of the Ocklawaha River are in the Green Swamp, a large area of swampy flatlands and small sandy ridges in

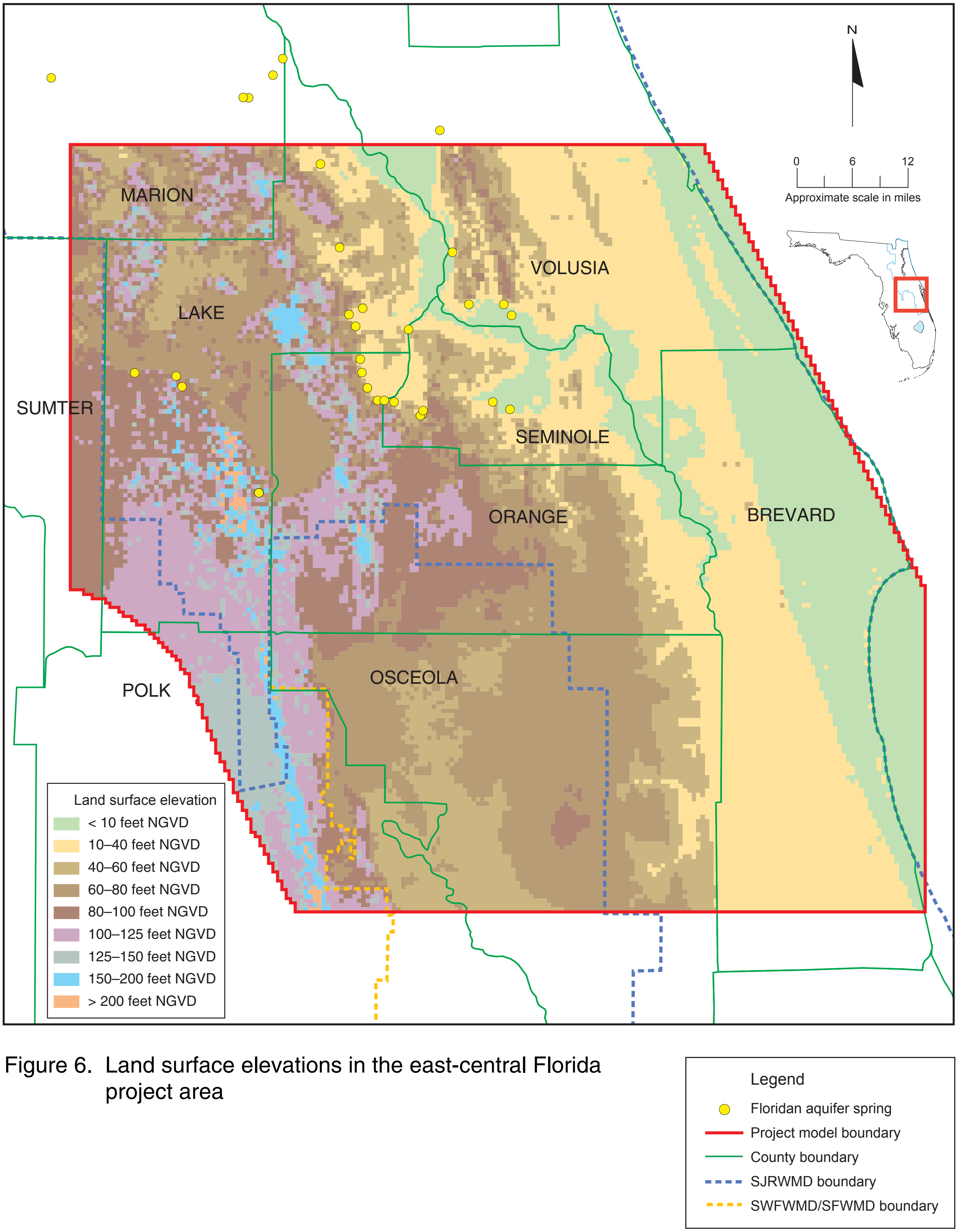


Figure 6. Land surface elevations in the east-central Florida project area

southern Lake and Sumter counties and northern Polk County. The Green Swamp forms the headwaters of several other rivers that flow from it in all directions (Pride et al. 1966). The Kissimmee River system and its headwater tributaries drain the south-central portion of the ECF region. As with the Ocklawaha River, most of the abundant large lakes in the Kissimmee basin are connected by either natural stream channels or man-made canals. Water levels in many of the lakes, streams, and interconnecting canals within both river systems are regulated by control structures. Long-term flow measurement records indicate that the St. Johns, Ocklawaha, and Kissimmee rivers account for approximately 85% of the total surface water discharge in the ECF region (USGS 1998).

Depth contours in the Atlantic Ocean generally increase to about 30 ft within approximately one-half mile from shore, then gradually increase to about 60 ft and level off for several miles. Offshore of Cape Canaveral, however, water depth is less than 60 ft for several miles.

The study area contains hundreds of lakes that are not connected to the major surface water drainage systems and have no surface streams or canals flowing in or out of them. These seepage lakes are most numerous in the highland areas of Lake County, eastern Marion County, western Orange and Seminole counties, eastern Polk County, and western Volusia County. They range in size from less than 1 acre to approximately several hundred acres and receive water from direct rainfall, overland runoff, and discharge from the surficial aquifer system. Seepage lakes are often sinkhole depressions that have filled with water. Water level fluctuations tend to be greater in seepage lakes located in upland areas than in other lakes because inflow from runoff and groundwater is relatively less constant (Schiffer 1996a).

GROUNDWATER FLOW

The clastic and carbonate sediments beneath the study area can be grouped into three aquifers bounded by three confining layers (Figure 7). These hydrostratigraphic units apply throughout the study area and can be considered equivalent to the regional-scale hydrostratigraphic units that have been described by Miller (1986) and Tibbals (1990). The characteristics of each of these hydrostratigraphic units are described in the following sections.

<table>
<tr><th>Geologic Series / Stratigraphic Unit</th><th>Lithology and Thickness (feet)</th><th>Hydrostratigraphic Unit</th></tr>
<tr><td>Holocene, Pleistocene / undifferentiated</td><td>Interbedded sand, clay, marl, and peat / 0–150</td><td>Surficial aquifer system</td></tr>
<tr><td>Pliocene, Miocene / undifferentiated sediments, Hawthorn Group</td><td>Interbedded clay, sandy clay, and sand, often phosphatic, with some phosphatic limestone and dolostone / 0–250</td><td>Intermediate confining unit</td></tr>
<tr><td>Upper Eocene / Ocala Limestone</td><td>Predominantly soft to hard porous limestone, minor amounts of hard, crystalline dolostone / 0–300</td><td>Upper Floridan aquifer—upper zone</td></tr>
<tr><td rowspan="3">Middle Eocene / Avon Park Formation</td><td>Upper part: predominantly hard, crystalline dolostone with abundant fractures and solution cavities / 100–200</td><td>Upper Floridan aquifer—lower zone</td></tr>
<tr><td>Middle part: predominantly soft, porous limestone and dolomitic limestone, with minor amounts of hard crystalline dolostone / <100–700</td><td>Middle semiconfining unit</td></tr>
<tr><td>Lower part: soft to hard porous limestone and hard, fractured crystalline dolostone / 600–800</td><td rowspan="2">Lower Floridan aquifer</td></tr>
<tr><td>Lower Eocene / Oldsmar Formation</td><td>Soft to hard porous limestone and hard, fractured crystalline dolostone; minor amounts of peat, chert, anhydrite, and gypsum / 500–1,000</td></tr>
<tr><td>Paleocene / Cedar Keys Formation</td><td>Interbedded carbonate rocks and evaporites / 500–2,200</td><td>Lower confining unit</td></tr>
</table>

Figure 7. Geologic and hydrostratigraphic units within the east-central Florida project area

Surficial Aquifer System

The uppermost unit is the surficial aquifer system, which consists of Pleistocene to Recent (Holocene) age sand, silt, clayey sand, and shell beds. It is equivalent to the surficial aquifer system described by Tibbals (1990) for the entire ECF region. Thickness of the surficial aquifer system ranges from less than 20 ft in places where pre-Pleistocene sediments lie near the surface to as much as 150 ft where sands have filled sinkhole depressions in karstic areas, and in parts of Osceola and Brevard counties. The top of the surficial aquifer system (the water table) is generally at or within a few feet of land surface in swampy lowlands and in the flatlands that lie within much of the ECF region. In the highland ridge areas, the water table can be found several tens of feet below land surface.

The surficial aquifer system receives recharge from rainfall, irrigation water derived from either groundwater, nearby surface water bodies, or reclaimed water, and also from septic tank effluent. The largest rates of recharge occur where the soils of the unsaturated zone consist of permeable sand and overland runoff is minimal. The Floridan aquifer also supplies recharge to the surficial aquifer system in lowland areas where the potentiometric surface of the Floridan aquifer is higher than the water table. Water discharges from the surficial aquifer system via ET from the water table, by seepage to surface water bodies, by pumpage, and by downward leakage to the underlying Floridan aquifer system where the elevation of the water table is higher than the Floridan aquifer potentiometric surface.

A significant source of man-made recharge to the surficial aquifer system comes from reclaimed-water distribution systems. Reclaimed water is applied to the land surface in two ways: through rapid infiltration basins (RIBs) or by spray irrigation. RIBs are designed to act as recharge sites. They are usually located in areas with a deep water table and are maintained to prevent ponding and subsequent evaporation. Large-scale RIB sites are located in western Seminole County, Lake County, western Orange County, and northwestern Osceola County. At spray irrigation sites, municipal wastewater is used to irrigate crops such as citrus or hay, or for landscape irrigation. As long as irrigation at these sites is designed for plant use, significant recharge to the surficial aquifer system would only occur if irrigation exceeds the crop’s demand for water, or if the water table is shallow enough to be within the root zone.

Large-scale aquifer tests of the surficial aquifer system have been conducted at relatively few locations within the ECF region (Figure 8). Hydraulic conductivity data are more commonly reported from single-well slug tests. Reported horizontal hydraulic conductivity of the surficial aquifer system sediments ranges from 0.03 ft / day to 200 ft / day. Reported transmissivities from pump tests range from 90 square feet per day (ft2 / day) to 20,000 ft2 / day (Table 1). Most of these pump tests, however, were conducted on semiconfined shelly zones located near the base of the surficial aquifer system.

The salinity of groundwater from the surficial aquifer system is generally very low, except along the St. Johns River, where base flow is slightly to moderately brackish, and along the Atlantic coast. Use of the surficial aquifer system for potable or irrigation supply is very limited over most of the ECF region due to relatively low well yields and because wells completed in it commonly contain relatively high concentrations of dissolved iron. Significant amounts of potable water are withdrawn from the surficial aquifer system in northern and southern Brevard County, where permeable sandy shell beds exist at or near its base (Toth 1988).

Intermediate Confining Unit

The intermediate confining unit separates the surficial aquifer system from the underlying Floridan aquifer system throughout the ECF region. It consists of unconsolidated sand, silt, clay, and shell and consolidated beds of shell, limestone, and dolomite of Pliocene and Miocene age. A combination of published and unpublished data was used to construct an updated map of intermediate confining unit thickness. Digital elevation data representing the estimated top of the intermediate confining unit from Boniol et al. (1993) were updated over Lake, Orange, and Seminole counties and parts of Brevard, Osceola, Polk, Sumter, Marion, and Volusia counties using draft maps supplied by the Altamonte Springs subdistrict office of USGS. Some additional adjustments were made along the southern and western boundaries of the region using point data and maps from Duncan et al. (1994), Shaw and Trost (1984), Schiner (1993), Barcelo et al. (1990), Yobbi (1996), and Campbell (1989). The total thickness of the intermediate confining unit generally increases from north to south across the region (Figure 9). The Hawthorn Group, which comprises much of the unit's thickness, is absent throughout much of Volusia County and parts of northern Brevard and Seminole counties. In these areas, the intermediate confining unit consists of upper Miocene and Pliocene fine sand and calcareous silty clays. In western

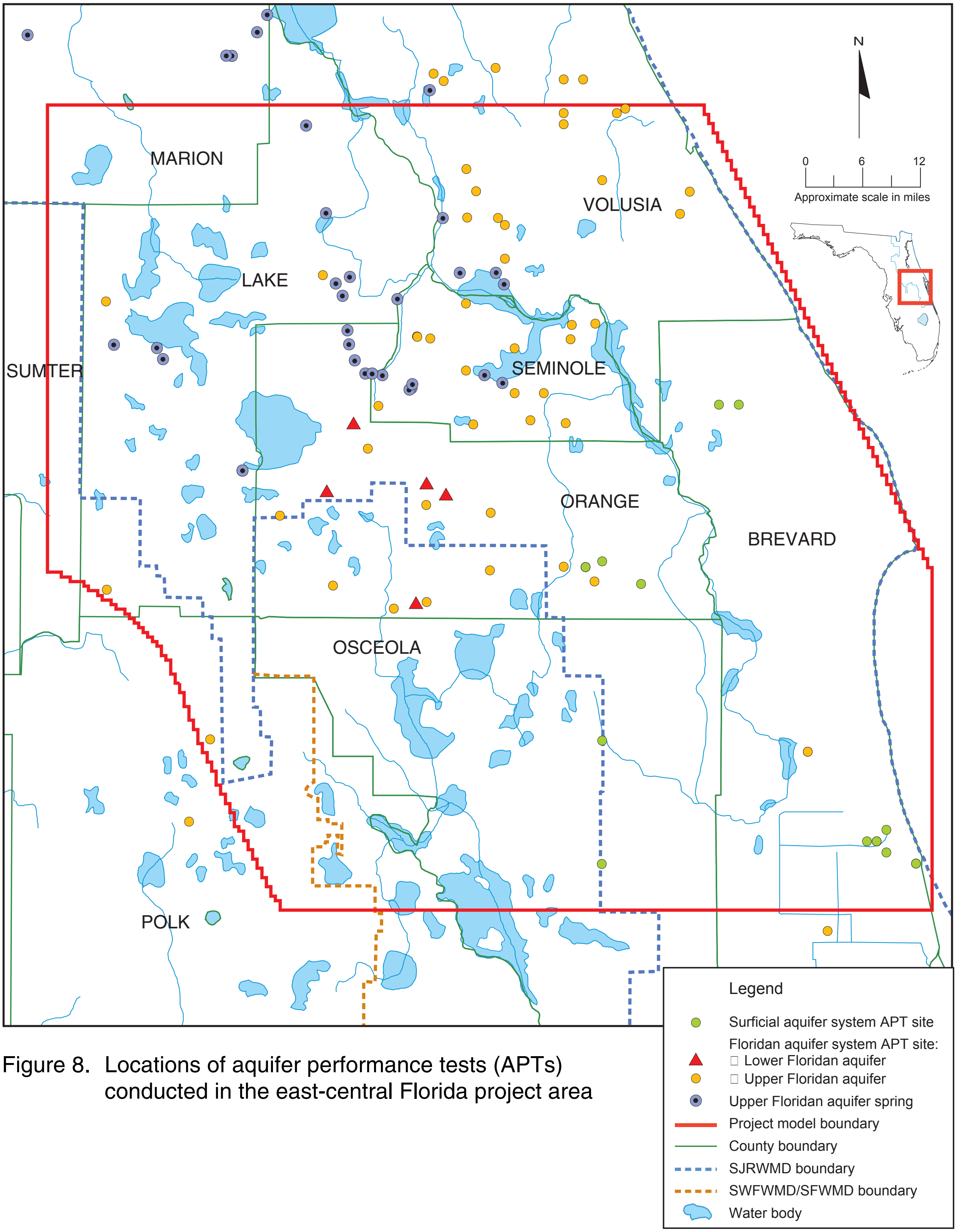


Figure 8. Locations of aquifer performance tests (APTs) conducted in the east-central Florida project area

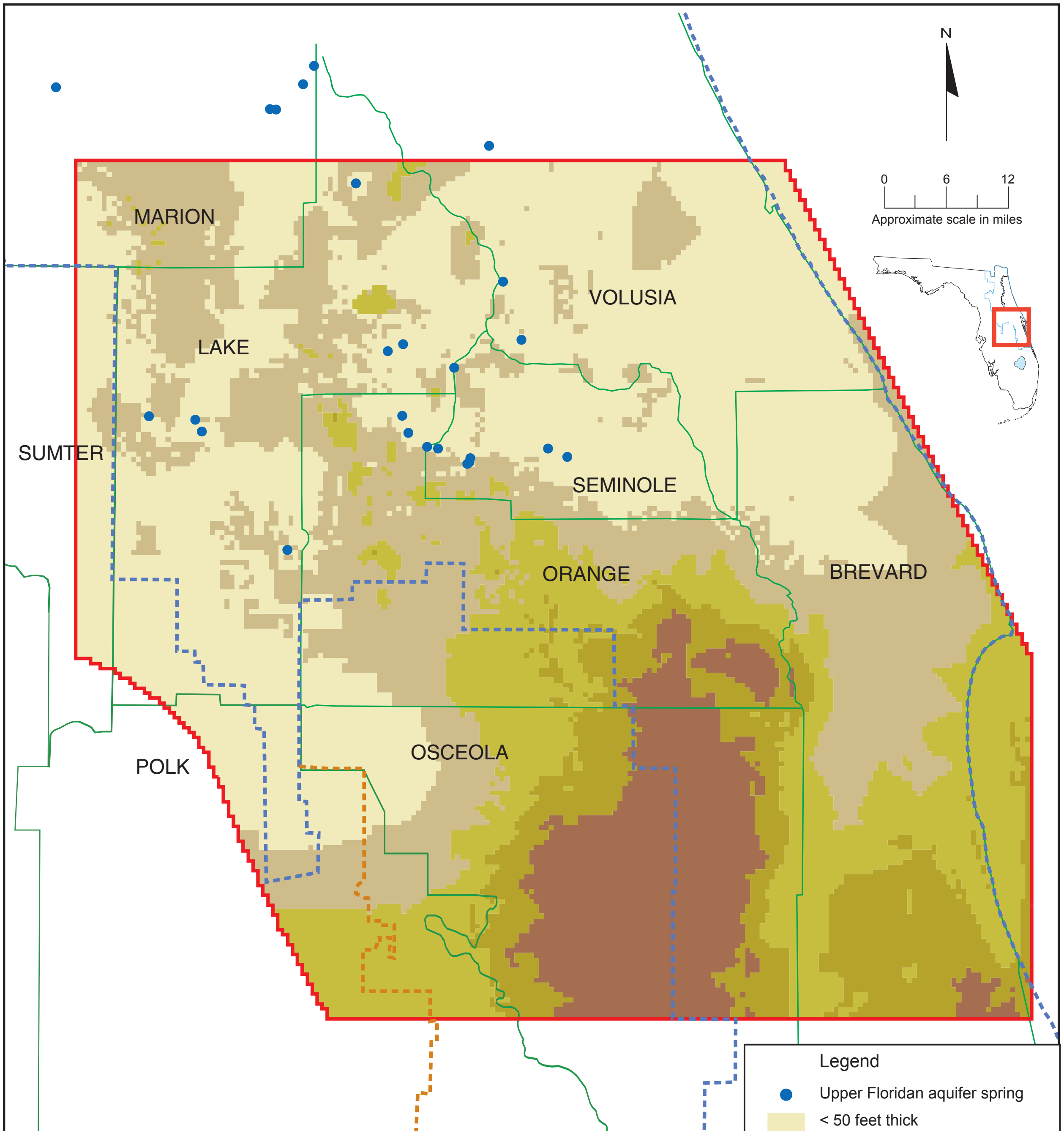


Figure 9. Generalized thickness of the intermediate confining unit

Table 1. Ranges of aquifer parameter values reported from aquifer performance tests conducted in the east-central Florida region

Hydrostratigraphic Unit	Parameter	Minimum Reported Value	Maximum Reported Value	Approximate Number of Tests	Source(s)*
Surficial aquifer system	Horizontal hydraulic conductivity	0.03 ft/day	200 ft/day	50	1,2,4,6
Surficial aquifer system	Transmissivity	90 ft^2/day	20,000 ft^2/day	30	2,5,6
Intermediate confining unit	Leakance	1 x 10^{-6}/day	0.8/day	38	5
Upper Floridan aquifer	Transmissivity	1,217 ft^2/day	530,000 ft^2/day	84	3,5
Lower Floridan aquifer	Transmissivity	200,535 ft^2/day	688,450 ft^2/day	10	5,7

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

*1=McGurk et al. (1989); 2=Phelps (1990); 3=Shaw and Trost (1984); 4=Spechler and Halford (2001); 5=Szell (1993); 6=Williams (1995); 7=St. Johns River Water Management District consumptive use permitting files

Orange County, southwestern Volusia County, and many parts of Lake County, some sinkhole depressions are totally filled with permeable sand, and the intermediate confining unit is very thin or essentially absent in these locations. The intermediate confining unit is also thin in the Green Swamp area of northern Polk County and southern Lake and Sumter counties and in the immediate vicinity of several of the Floridan aquifer springs located in southwestern Volusia County and in the Wekiva River Basin. The intermediate confining unit reaches a maximum thickness in the region of greater than 200 ft in eastern Osceola County. The thickness of the intermediate confining unit may differ markedly from that shown in Figure 9 at any particular location because of local erosional or karst features.

The hydraulic conductivity of the intermediate confining unit can be extremely variable because its lithology is highly variable. Horizontal hydraulic conductivity of sand, shell, or limestone / dolostone beds is relatively high in localized areas, but because Hawthorn Group clays are the dominant lithology, hydraulic conductivity in the unit as a whole is low. Estimates of leakance (ratio of vertical hydraulic conductivity to thickness of the intermediate confining unit) derived from aquifer tests conducted by pumping Upper Floridan aquifer wells range from 1 x 10-6 day-1 to 0.8 day-1

(Table 1). Most of these values are higher than the actual intermediate confining unit leakance because they were estimated using analytical solutions that assume all leakage to the pumped well passes through the intermediate confining unit from an overlying unpumped aquifer. In reality, leakage to the pumped well is also derived from deeper layers within the Floridan aquifer system.

Water levels measured at the few observation wells completed within the intermediate confining unit are consistently between those of the overlying surficial aquifer system and the underlying Floridan aquifer system. Because of this relationship, the intermediate confining unit is believed to receive recharge from the surficial layers and discharge to the Floridan aquifer wherever the water table is higher than the Floridan aquifer potentiometric surface. Where the Floridan aquifer potentiometric surface is higher than the water table, the reverse is true. As with the surficial aquifer system, salinity of the intermediate confining unit is usually low, except along the St. Johns River and along the coast. Few areas within the ECF region use the intermediate confining unit as a source of water. Permeable layers of sand, gravel, and carbonate rocks within the unit that can produce significant quantities of water are very limited, both spatially and in terms of quantity. Large-scale production is limited to a few wells in southeastern Orange County and southern Brevard County and in central and southern Polk County. Elsewhere, intermediate confining unit water use is restricted primarily to self-supply domestic wells.

Floridan Aquifer System

The Floridan aquifer system contains the thickest and most extensive aquifer layers in Florida. Estimation of changes in regional-scale groundwater flow patterns due to widespread pumping increases in the Floridan aquifer system is the focus of this study.

Stratigraphy and Hydrostratigraphy

The Floridan aquifer system is composed of permeable Paleocene-age and Eocene-age carbonate rocks. The geologic formations that comprise the Floridan aquifer system are, from bottom to top: the Cedar Keys Formation, the Oldsmar Formation, the Avon Park Formation, and the Ocala Limestone (Figure 7). These formations consist of interbedded limestone, dolomite, and dolomitic limestone in which the amount of primary porosity, secondary porosity, and secondary infilling of pores or fractures is highly variable with depth. Throughout nearly all of the ECF region, the Floridan aquifer system has been subdivided into three hydrostratigraphic subunits on the basis of relative hydraulic conductivity (Miller 1986; Tibbals 1990): the Upper Floridan aquifer, the middle semiconfining unit, and the Lower Floridan aquifer.

The Upper Floridan aquifer consists of the Ocala Limestone and approximately the upper one-third of the Avon Park Formation (Figure 7). The elevation of the top of the Upper Floridan aquifer varies between approximately 50 ft NGVD in Polk, Sumter, southern Lake, and Marion counties and –300 ft NGVD in Osceola County (Figure 10). The Ocala Limestone, however, has been removed by erosion in southwestern Volusia County, south-central Orange County, and part of northern Osceola County. In these areas, the Avon Park Formation makes up the top of the Upper Floridan aquifer. The elevation of the top of the Upper Floridan aquifer is very irregular due to previous subaerial erosion and sinkhole activity, and therefore the elevations depicted by Figure 10 may differ from that found at a particular location. Previous authors have mapped inferred faults in several locations along the St. Johns River and elsewhere based upon greater-than-usual differences in the elevation of the top of the Upper Floridan aquifer over relatively short distances and along linear topographic features. Miller (1986) notes that the faults can be mapped only for middle and late Eocene rocks (the Avon Park Formation and Ocala Group) and appear to die out with depth. As Scott (1988) pointed out, however, the nature of the Miocene and Eocene deposits makes it difficult to determine whether the origin of some of these features is actually due to structural (tectonic) processes or to depositional and erosional processes. Snyder et al. (1989) suggest that the apparent displacement of Miocene and Eocene sediments along the St. Johns River is due to very long-term subsidence caused by paleokarst solution collapse within the Eocene carbonates.

Permeability within the Upper Floridan aquifer is not uniform with depth. Numerous reports describing production well drilling and testing in the ECF region have documented the presence of a zone of hard, fractured dolostone within the Avon Park Formation containing abundant secondary porosity features. Several of these reports (e.g., Ardaman and Associates 1993; Boyle Engineering Corp. 1994; CH2M HILL 1996; Jammal and Associates 1990; Yovaish Engineering Sciences 1994) described this zone as a major source of production within the Upper Floridan aquifer and designated the base of this zone as the base of the Upper Floridan aquifer. Data from these reports and from other unpublished geophysical log data indicate that, in southwestern

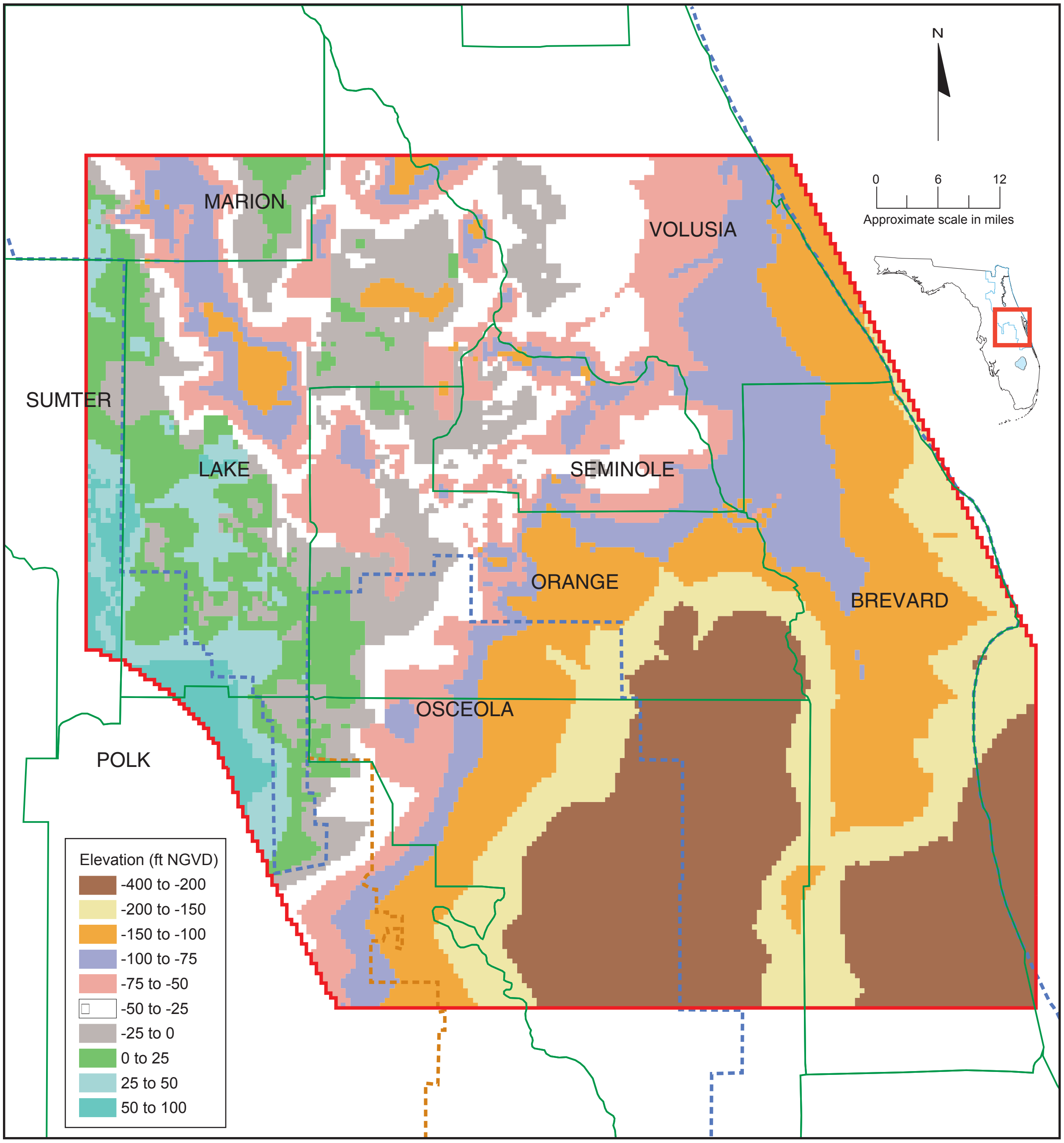


Figure 10. Generalized elevation of the top of the Upper Floridan aquifer (modified from Miller 1986)

Volusia County, Orange County, Osceola County, and Seminole County, the “dolostone zone” is in many places more productive than the overlying Ocala Limestone and uppermost Avon Park Formation rocks. The key lithologic and geophysical characteristics of the dolostone zone can also be observed in logs from wells located in Brevard, Lake, and Polk counties, indicating that the zone may exist throughout most of the ECF region. It is believed to be equivalent to the “Highly Permeable Dolomite Zone” that was mapped throughout much of the Southwest Florida Water Management District (SWFWMD) by Wolansky et al. (1980). In the immediate vicinity of major springs, the uppermost Upper Floridan aquifer probably is at least as permeable, if not more permeable, than the dolostone zone.

The elevation of the top of the dolostone zone (Figure 11) ranges from a high of approximately –150 ft NGVD near the intersection of Lake, Marion, and Sumter counties to below –700 ft NGVD in southern Brevard County. Thickness of the upper zone of the Upper Floridan aquifer ranges from less than 60 ft in southeastern Marion County to greater than 500 ft in southern Brevard County. Total thickness of the Upper Floridan aquifer (including the dolostone zone) ranges from less than 200 ft to more than 650 ft in the ECF region and generally increases from the northwest to the southeast.

The middle semiconfining unit is equivalent to middle semiconfining unit I mapped by Miller (1986) and consists of relatively soft, micritic limestone and dense, dolomitic limestone with little secondary porosity compared to the aquifer units above and below. The middle semiconfining unit is leaky, and its lithology is very similar to that of the overlying and underlying aquifer units. It is considered a semiconfining unit primarily because it lacks abundant fracture zones and solution cavities (Lichtler et al. 1968). A comparison of production well depths with maps of the top of the middle semiconfining unit produced by Tibbals (1990) and Miller (1986) has shown that many production wells in Lake, Orange, Osceola, and Seminole counties are completed to depths that are below the top of the middle semiconfining unit as previously mapped. The elevation of the top of the middle semiconfining unit as mapped by Miller (1986) and Tibbals (1990) lies at a higher elevation in some areas than the base of the dolostone zone of the Upper Floridan aquifer. The reason for this discrepancy is apparently because Miller used the top of a zone of relatively high resistivity on geophysical logs to pick the top of middle semiconfining unit I (see, for example, Miller 1986, Plate 17). High resistivity readings, along with log signatures that indicate abundant fractures, are main characteristics of the dolostone zone. The top of the middle semiconfining unit has been revised and remapped as part of this

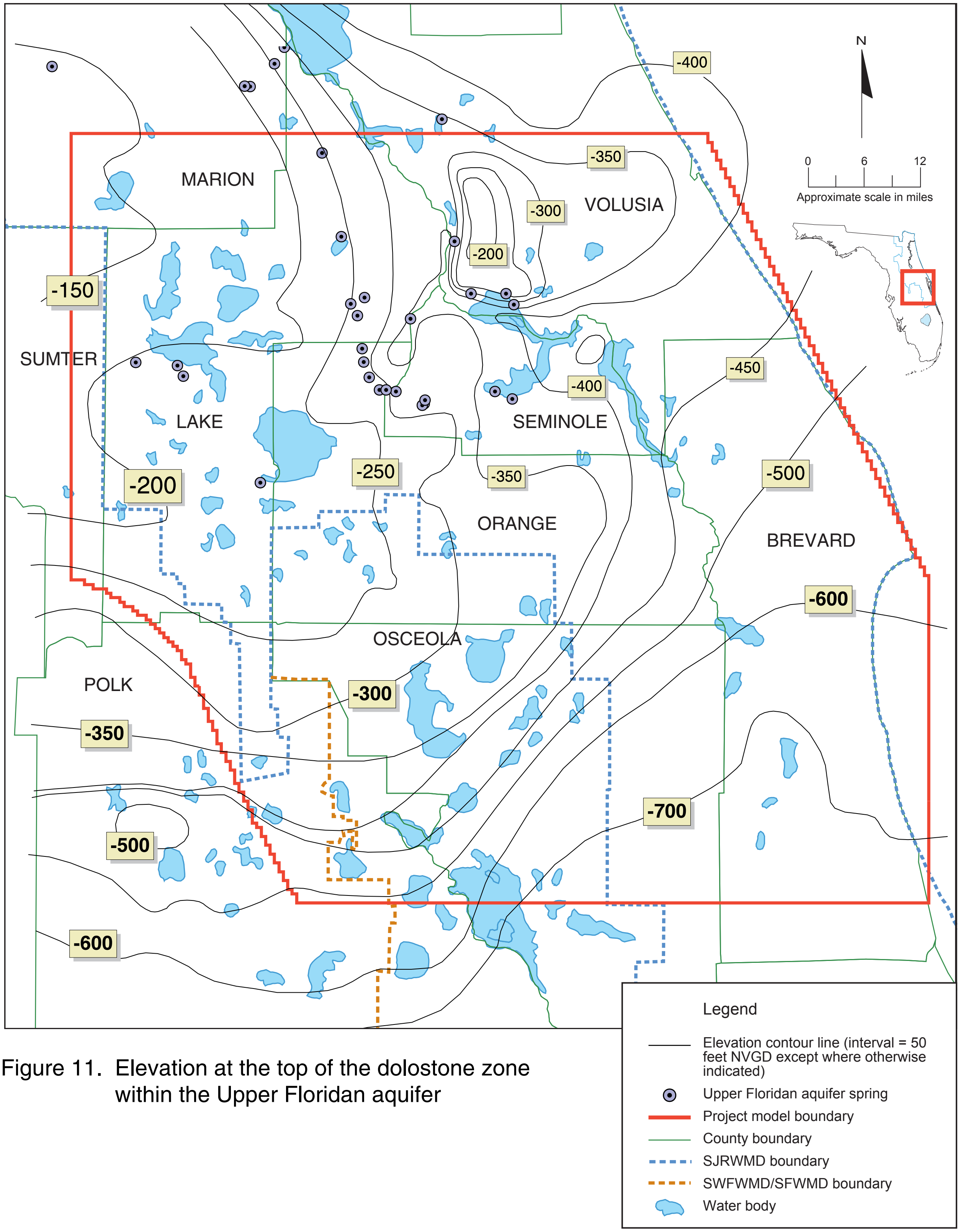


Figure 11. Elevation at the top of the dolostone zone within the Upper Floridan aquifer

study (Figure 12), in part by including this high-resistivity zone as part of the Upper Floridan aquifer and picking the base of the high-resistivity zone as the top of the middle semiconfining unit. The revised top of the middle semiconfining unit ranges from above –250 ft NGVD in northern Sumter County to below –800 ft NGVD in southern Brevard County. Total thickness of the revised middle semiconfining unit ranges from approximately 150 ft to approximately 650 ft and generally increases in a southward direction.

A second middle confining unit (middle confining unit II of Miller 1986) exists in the southwestern portion of the ECF region in Lake, Sumter, and Polk counties. This confining unit comprises the middle part of the Avon Park Formation in this area and consists of gypsiferous dolomite and dolomitic limestone. It forms an essentially non-leaky confining bed that separates freshwater from very highly mineralized water in the underlying rocks. The middle semiconfining unit overlies middle confining unit II in a northwest-southeast trending band from Marion County to southern Osceola County.

The geologic units comprising the Lower Floridan aquifer are the lower part of the Avon Park Formation, the Eocene Oldsmar Formation, and the upper part of the Paleocene Cedar Keys Formation. Lithology is similar to that of the Upper Floridan aquifer and middle semiconfining unit, but the upper part is characterized by abundant fractured dolostone zones and solution cavities. Scattered deep-well data suggest that permeability in the Lower Floridan aquifer is non-uniform with depth. Miller (1986) mapped a confining unit across most of Brevard and Osceola counties (middle confining unit VIII) that includes rocks within the middle part of the Oldsmar Formation. Miller (1986) and Duncan et al. (1994) also mapped a cavernous, high-permeability interval (the Boulder Zone) across most of Brevard County that lies beneath middle confining unit VIII. Data points are too limited to further map separate hydrogeologic subunits within the Lower Floridan aquifer, but lithologic and borehole data from a recently constructed test well in south-central Orange County suggest that middle confining unit VIII may actually extend farther to the northwest (McGurk and Sego 1999). The elevation of the top of the Lower Floridan aquifer ranges from above –500 ft NGVD in southeastern Marion County to below –1,300 ft NGVD in Brevard County (Figure 13). Total thickness of the Lower Floridan aquifer ranges from approximately 1,000 ft to greater than 2,000 ft and gradually increases in a southward direction.

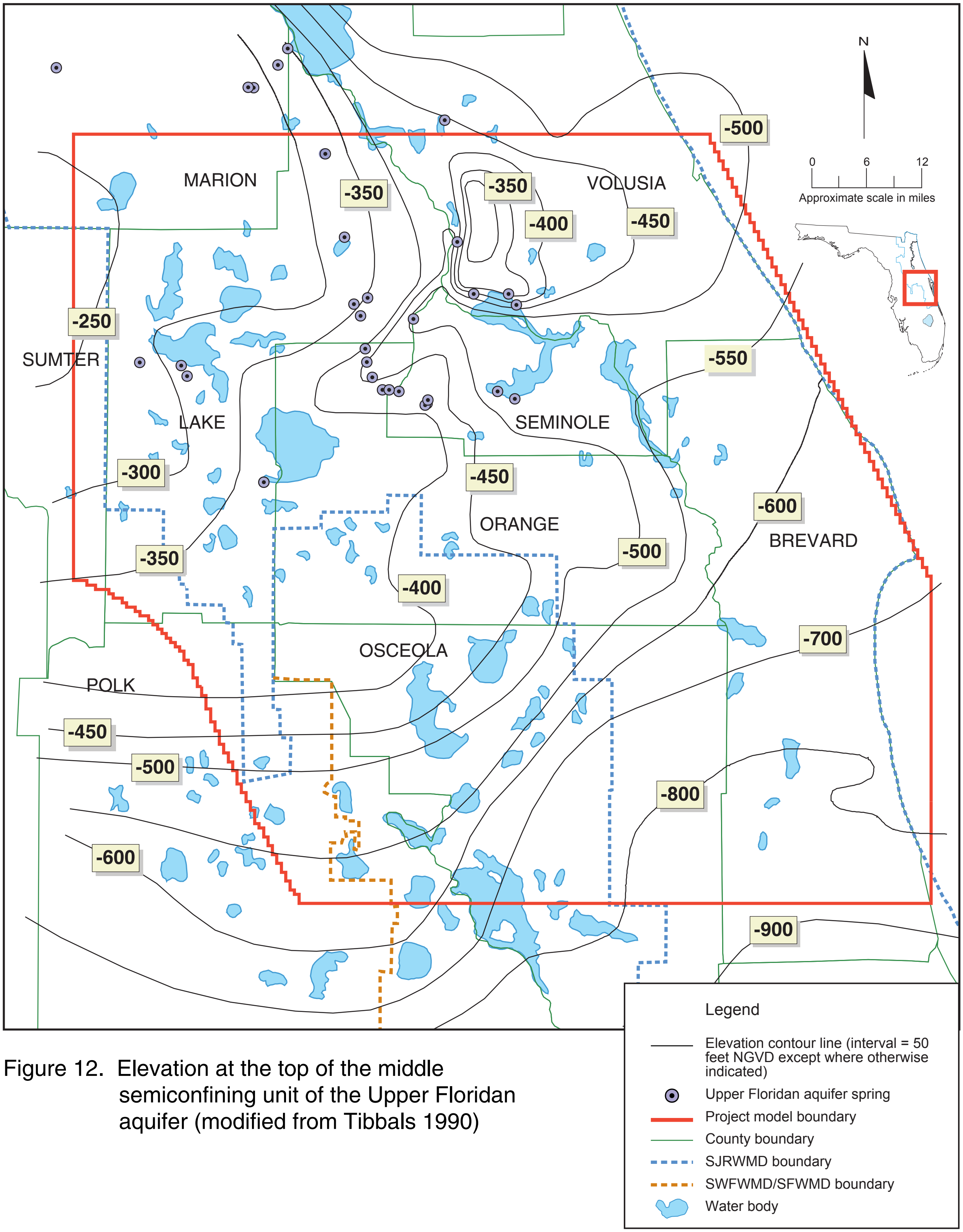


Figure 12. Elevation at the top of the middle semiconfining unit of the Upper Floridan aquifer (modified from Tibbals 1990)

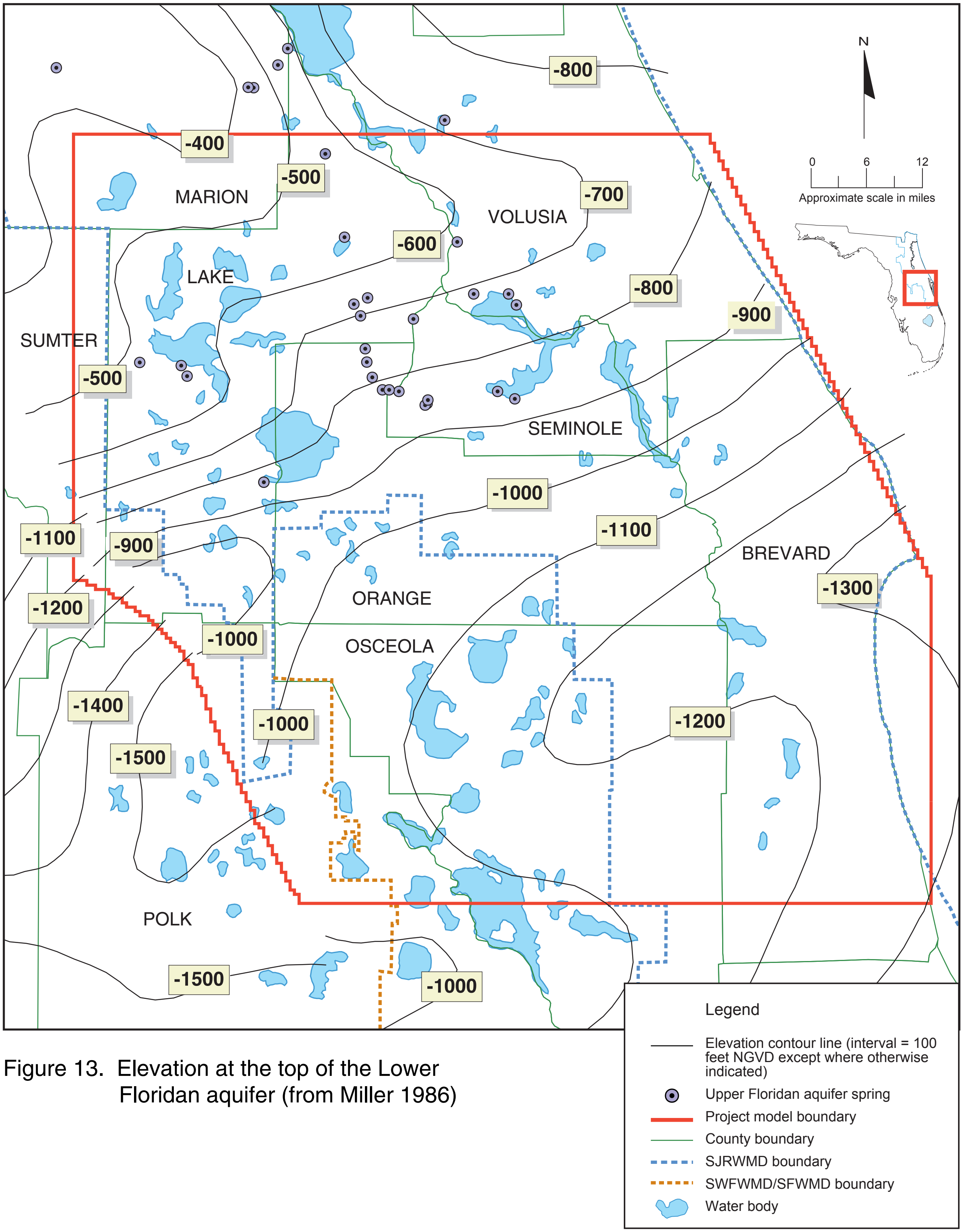


Figure 13. Elevation at the top of the Lower Floridan aquifer (from Miller 1986)

The lower confining unit underlies the Lower Floridan aquifer throughout the region. It is made up of poorly permeable to relatively impermeable carbonate rocks of the Cedar Keys Formation that contain abundant evaporite minerals. The top of the lower confining unit is equal to the base of the Floridan aquifer system; its elevation ranges from above –1,800 ft NGVD to below –3,000 ft NGVD within the project area (Figure 14).

Recharge and Discharge

Naturally-occurring recharge to the Floridan aquifer system is derived almost exclusively from downward leakage from the surficial aquifer system. A relatively small amount flows laterally into the ECF region from recharge areas along the Highlands Ridge to the south. Estimated rates of natural recharge range from less than 4 in / yr to greater than 12 in / yr (Figure 15). Low rates of recharge occur where the water levels in the surficial aquifer system are only slightly above the potentiometric surface of the Upper Floridan aquifer, or where the intermediate confining unit is sufficiently thick or of low enough permeability to significantly retard the downward movement of water. Low-rate recharge areas coincide with topographically low or flat areas where the water table is consistently near land surface, enhancing ET from the saturated zone. High rates of recharge occur where the vertical gradient between the surficial aquifer system and the Upper Floridan aquifer is the greatest and where the intermediate confining layer is thinnest or the most permeable. High-rate recharge areas coincide with highlands characterized by sandy ridges with deep water table soils and karst topography and where there are few perennial streams to collect overland runoff. The highest rates of recharge occur where sinkhole depressions collect overland runoff and surficial aquifer system base flow. An example of one such location is Wolf Sink in northeastern Lake County near Mount Dora, where a small stream (Wolf Branch) drains a nearly 5-square-mile (mi2) area and ends at the sink, providing a nearly direct connection to the Upper Floridan aquifer (Schiffer 1996b).

In the Orlando metropolitan area, drainage wells provide a significant man-made source of recharge to the Floridan aquifer system. Approximately 479 drainage wells have been completed to the Upper Floridan aquifer in and around Orlando (Figure 16), mainly for storm runoff removal and lake-level control. Total average daily flow into the Upper Floridan aquifer from these wells has been estimated at between 33 million gallons per day (mgd) and 52 mgd (Tibbals 1990; CH2M HILL 1997). The status of approximately 265 of

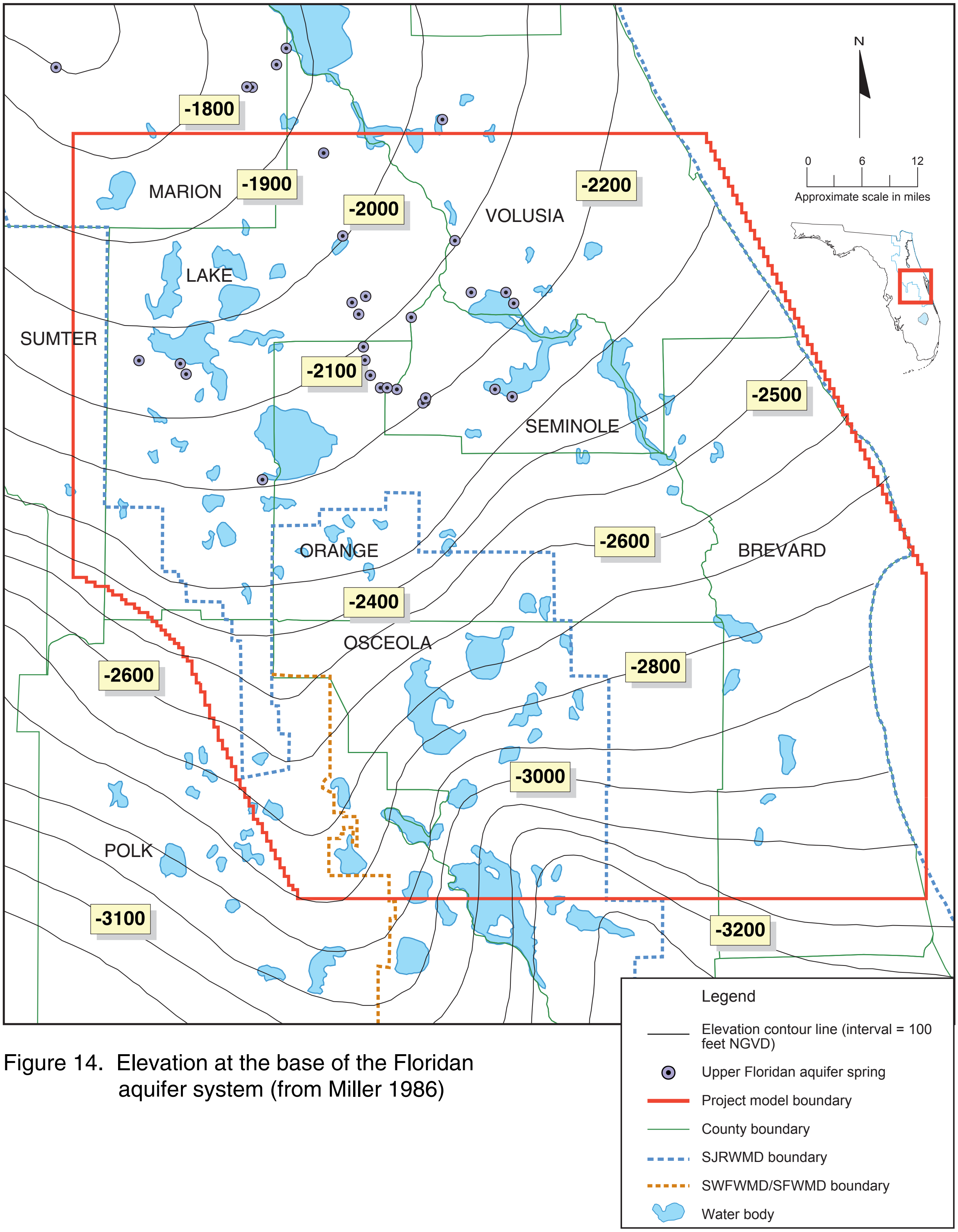


Figure 14. Elevation at the base of the Floridan aquifer system (from Miller 1986)

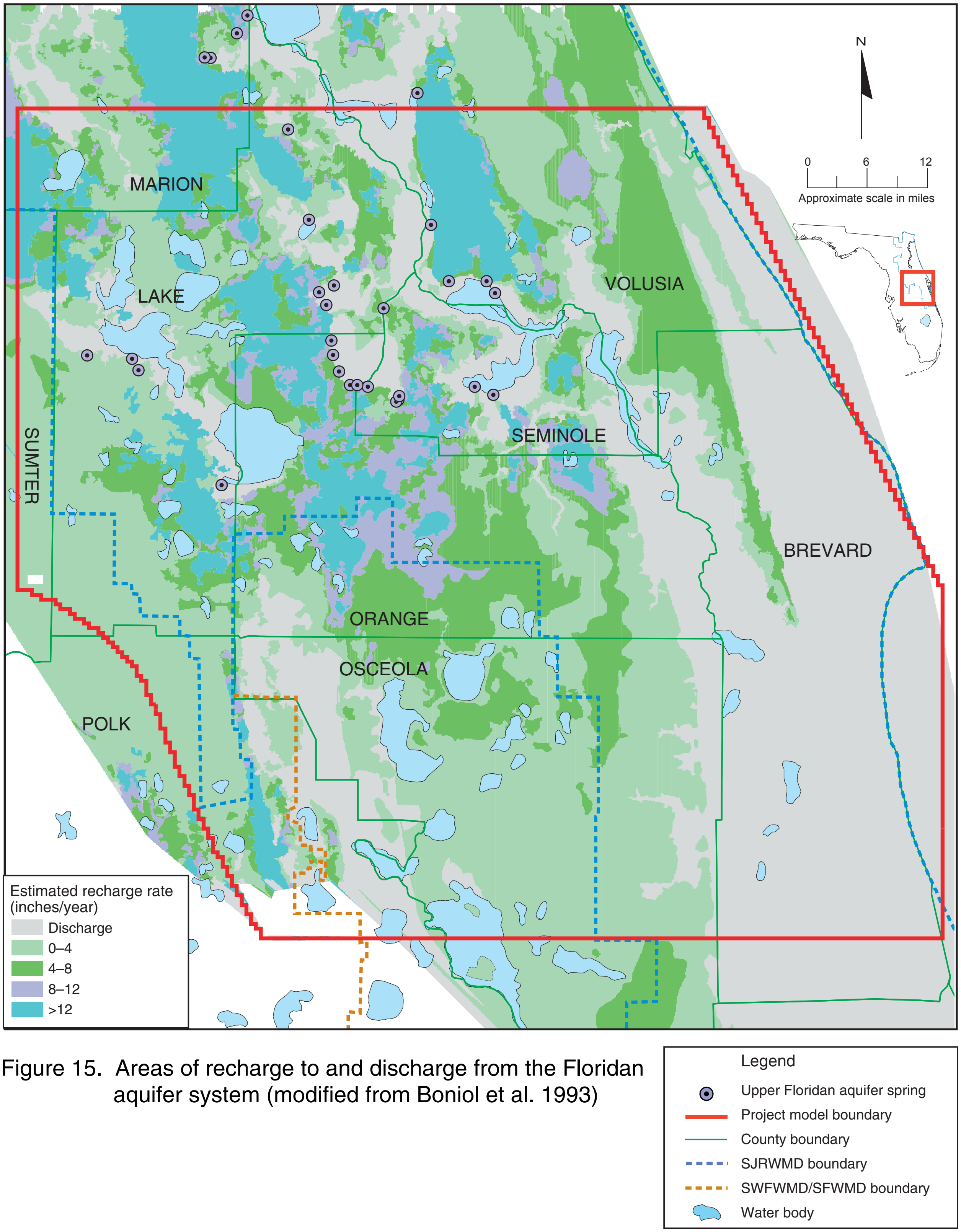


Figure 15. Areas of recharge to and discharge from the Floridan aquifer system (modified from Boniol et al. 1993)

the wells inventoried by CH2M HILL (1997) is unknown, but many may have been capped, plugged, or clogged with debris and no longer operate.

The locations of more than 380 abandoned artesian wells that were inventoried by Curtis (1998) are also shown on Figure 16. Most of these wells were completed into the Upper Floridan aquifer. When inventoried (1995), many were discharging at relatively low rates via leaking gate valves, corroded casings, or improperly installed well caps. Maximum potential flow rate estimates made at wells that were plugged or repaired in 1995 totaled approximately 16 mgd for counties within the ECF region (Curtis 1998). However, on an annualized basis, the actual total flow rate would have been much lower. This is because, once inventoried, each well was temporarily capped prior to repair or abandonment.

Natural discharge from the Floridan aquifer system occurs as diffuse upward leakage to the surficial aquifer system and as spring flow. Water leaks upward to the surficial aquifer system through the intermediate confining unit wherever the Floridan aquifer potentiometric surface is greater than that of the surficial aquifer system (delineated as discharge areas on Figure 15). The rate of upward leakage depends upon the thickness and vertical hydraulic conductivity of the intermediate confining unit. Most of the natural discharge from the Floridan aquifer system occurs from springs. There are 23 documented springs in the ECF region that discharged at an average rate of approximately 601 cubic feet per second (cfs) (388 mgd) in 1995 (Table 2). Average discharge rates for 1995 measured at individual springs ranged from less than 1 cfs at Sulphur and Droty springs to 150 cfs at Blue Spring in southwestern Volusia County. Approximately 42% of the total spring flow discharges from springs in the Wekiva River Basin. Most of the base flow to the Wekiva River is derived from Floridan aquifer springs. The relatively few discharge measurements made at submerged Apopka (Gourdneck) Spring have varied considerably over its period of record. Rosenau et al. (1977) reported a discharge of 28.6 cfs from a 1971 measurement. Several measurements made by USGS in the 1980s exceeded 58 cfs. More recently, a contractor for SJRWMD conducted 14 discharge measurements from the spring orifice at periodic intervals between 1997 and 1999 (D. Rao, SJRWMD, pers. comm. 1998; Karst Environmental Services 1999a, b, c). The average of these measurements is 29.8 cfs. Because no 1995 discharge measurements were made at this spring, the listed 1995 flow rate was estimated using a regression equation developed by SJRWMD (Table 2). The regression is based upon the relation between measured spring flow, water level in the Upper Floridan aquifer at nearby observation well 264, and the level of Lake Apopka

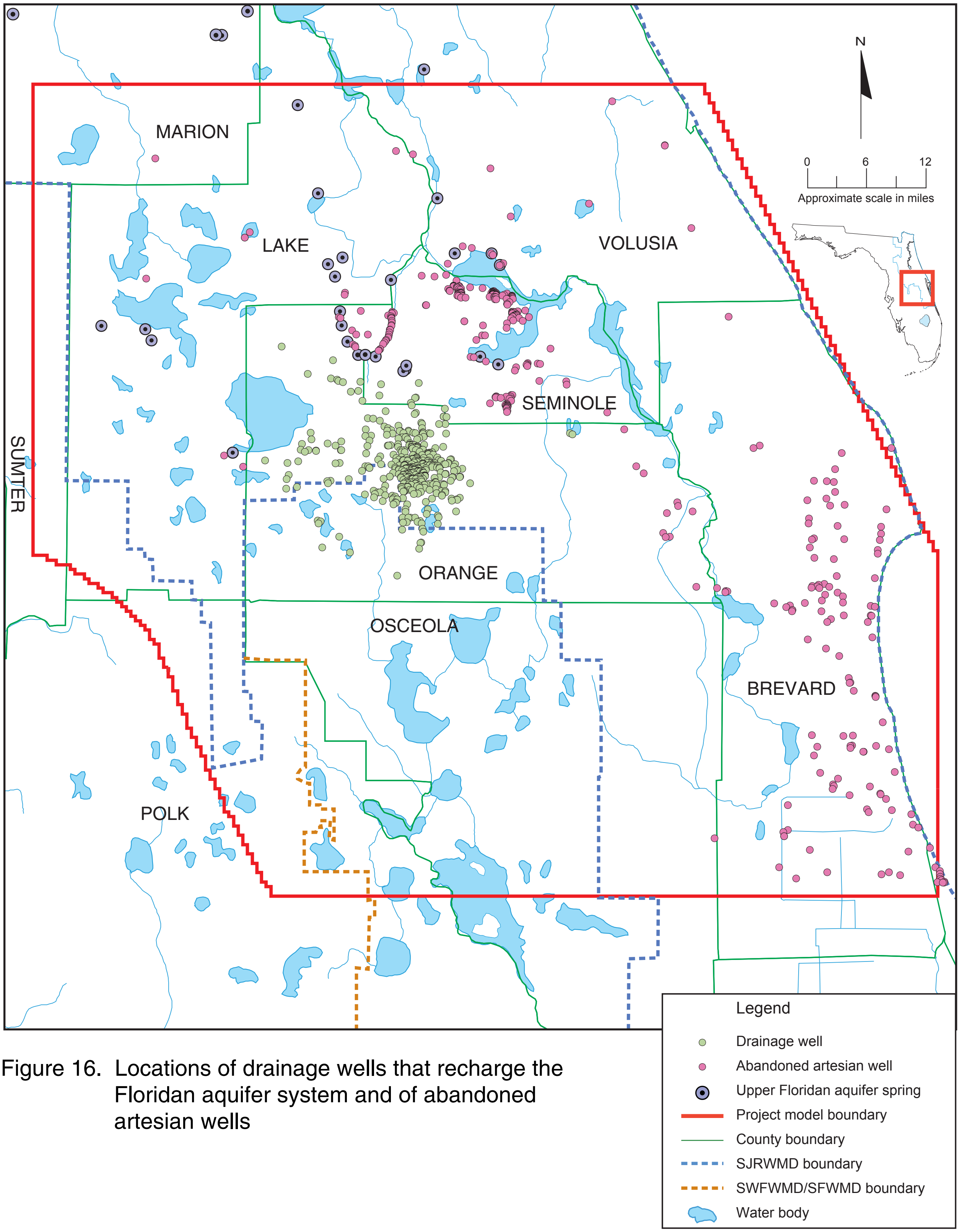


Figure 16. Locations of drainage wells that recharge the Floridan aquifer system and of abandoned artesian wells

Table 2. Location and discharge from Upper Floridan aquifer springs in the east-central Florida region for estimated predevelopment and average 1995 conditions

Spring	Spring Location		Model Location		Estimated Predevelopment Flow (cfs)	Average Measured 1995 Flow (cfs)*	Source of Predevelopment Flow Estimates
	Latitude	Longitude	Row	Column			
Alexander Spring	290450	813430	5	57	100	104	T
Alexander Creek	290450	813400	5	58	30	33[†]	T
Camp La-No-Che	285702	813224	24	62	1	1[†]	T
Blue (Volusia County)	285638	812024	24	87	160	150	T
Gemini	285144	811839	37	91	8	8	T
Green	285145	811455	37	99	1	2[†]	R
Messant	285121	812956	38	67	20	16	MH
Seminole	285044	813122	39	63	40	39	MH
Droty	284940	813038	42	65	1	1[†]	A
Island	284922	812503	42	77	10	6[†]	MH
Sulphur (Camp)	284634	813010	49	66	2	1	MH
Bugg	284509	815406	52	15	18	11	R
Rock	284520	812958	52	67	70	61	MH
Blue (Lake County)	284455	814941	53	25	3	3[†]	T
Holiday	284424	814905	54	26	4	4[†]	T
Witherington	284353	812922	56	68	4	4[†]	T
Wekiwa	284243	812736	59	71	80	73	MH
Miami	284236	812634	59	74	6	6	MH
Lake Jesup	284236	811605	59	96	1	1[†]	MH
Starbuck	284148	812328	61	81	17	15	T
Clifton	284156	811414	61	100	2	1[†]	MH
Palm	284127	812334	62	80	10	6	T
Sanlando	284119	812344	62	80	23	23	T, MH
Apopka (Gourdneck)	283400	814051	79	43	44	32[‡]	A
Total					654	601	

Note:
A = average of all available measurements
cfd = cubic feet per day
cfs = cubic feet per second
ft msl = feet mean sea level
MH = Murray and Halford (1996)
R = Rosenau et al. (1977)
T = Tibbals (1990)

*Measurement error for spring discharge is typically ± 10% except for submerged Apopka and Island springs, which have a measurement error of ± 25%.
Data from Rao and Clapp 1996; USGS 1996, 1997, 1998; and SJRWMD unpublished data files.

[†]Multiple measurements not made during 1995; historic median flow used.

[‡]Calculated using the following equation: Q(cfs) = 2.3473 dh + 15.136, where H = difference between Lake Apopka water level and water level in Upper Floridan aquifer well L-0199 (ft); for 1995, average dh = 7.28 ft (D. Rao, SJRWMD, written com. 1998).

(D. Rao, SJRWMD, pers. comm. 1998). Use of this equation using the average 1995 water levels (365 daily values) for well 264 and for Lake Apopka yields an estimated average 1995 flow rate for Apopka Spring of 32 cfs.

Undocumented spring discharge may occur along the St. Johns River from Lake Harney downstream and along the lower reaches of the Wekiva River. The intermediate confining unit is thin in these areas (see Figure 9). Tibbals (1990) and Murray and Halford (1996) simulated spring flow of 54 cfs and 35 cfs, respectively, along the St. Johns River from Lake Harney to Lake Jesup using regional groundwater flow models. Murray and Halford (1996) simulated 9 cfs near the convergence of the Wekiva and St. Johns rivers. Due to wind action and extremely low stream gradients, documenting these flows along the St. Johns River by comparing upstream and downstream flow measurements would be impractical (Tibbals 1990).

Hydraulic Characteristics

The data available concerning Floridan aquifer system aquifer hydraulic characteristics derived from aquifer tests include information on Upper Floridan aquifer transmissivity, Lower Floridan aquifer transmissivity, and specific-capacity and normalized well yield data. Reported transmissivity of the Upper Floridan aquifer ranges from approximately 1,200 ft2 / day to 530,000 ft2 / day from 84 tests (Table 1 and Figure 8). Lower Floridan aquifer transmissivity estimates range from approximately 200,000 ft2 / day to 670,000 ft2 / day from 10 aquifer performance tests. The relatively few Lower Floridan tests that have been conducted to date were located within or near the Orlando area. Field estimates of vertical hydraulic conductivity of the middle semiconfining unit have been made at two sites. At the Bull Creek Wildlife Management Area in eastern Osceola County, estimates ranged from 0.005 ft / day to 2 ft / day (PBS&J 1990). At the Cocoa wellfield in eastern Orange County, vertical hydraulic conductivity was estimated to be no greater than 0.05 ft / day (Phelps and Schiffer 1996).

Potentiometric Levels

Throughout nearly all of the ECF region, the Floridan aquifer system is sufficiently confined so that water levels in wells completed within it are above the top of the aquifer. The Floridan aquifer system is unconfined only in small, isolated areas in the immediate vicinity of several springs (e.g., Rock Springs and Wekiva Spring), where limestone is at or within a few feet of land surface. The large number of wells completed within the Upper Floridan aquifer allow contour maps to be constructed of its potentiometric surface. Johnston et al. (1980) constructed a map of the estimated average predevelopment potentiometric surface of the Upper Floridan aquifer throughout Florida. In the ECF region (Figure 17), elevations of the estimated average predevelopment potentiometric surface ranged from less than 10 ft NGVD along the coast and along the St. Johns River in western Volusia County to approximately 130 ft NGVD in northern Polk County. Subsequent authors (Miller 1986; Tibbals 1990; Murray and Halford 1996) have published slightly revised maps of the estimated predevelopment potentiometric surface. The major differences between these maps and that of Johnston et al. (1980) are the shapes of the 50 ft NGVD contour in western Seminole County and the addition of a 10-ft NGVD contour along the St. Johns River in northeastern Seminole County. In Orange County, Johnston et al. (1980) used water level data from Stringfield (1936). Because most of Stringfield’s water level data points in the Orlando area were drainage wells, the actual predevelopment surface of the Upper Floridan aquifer in that area may have been somewhat different than that depicted by Figure 17. USGS publishes potentiometric surface maps of the Upper Floridan aquifer for May and September of each year. Figure 18 is a map of the estimated average 1995 potentiometric surface of the Upper Floridan aquifer made by combining and averaging digitized versions of the May 1995 and September 1995 published maps (Knowles et al. 1995 and O’Reilly et al. 1996, respectively) using a geographic information system (GIS). Comparing Figure 17 with Figure 18 reveals that the general shapes of the two potentiometric surfaces are similar. However, the magnitude of the 1995 surface is less than that of the predevelopment surface, especially in Brevard, Orange, Osceola, and Seminole counties.

Large areawide potentiometric surface maps have not been made for the Lower Floridan aquifer within the ECF region because of the scarcity of observation wells completed within the Lower Floridan aquifer. Previous water level comparisons between the Upper Floridan aquifer and the Lower Floridan aquifer have indicated a slight downward gradient in the Orlando area (Lichtler et al. 1968; Tibbals 1990). Hydrographs of water levels from recently constructed observation well clusters indicate that a vertically upward gradient exists within the Floridan aquifer system in Seminole County and near Wekiva Springs in northwestern Orange County (Figure 19). Potentiometric levels within the middle semiconfining unit have been measured at only a few places within the ECF region.

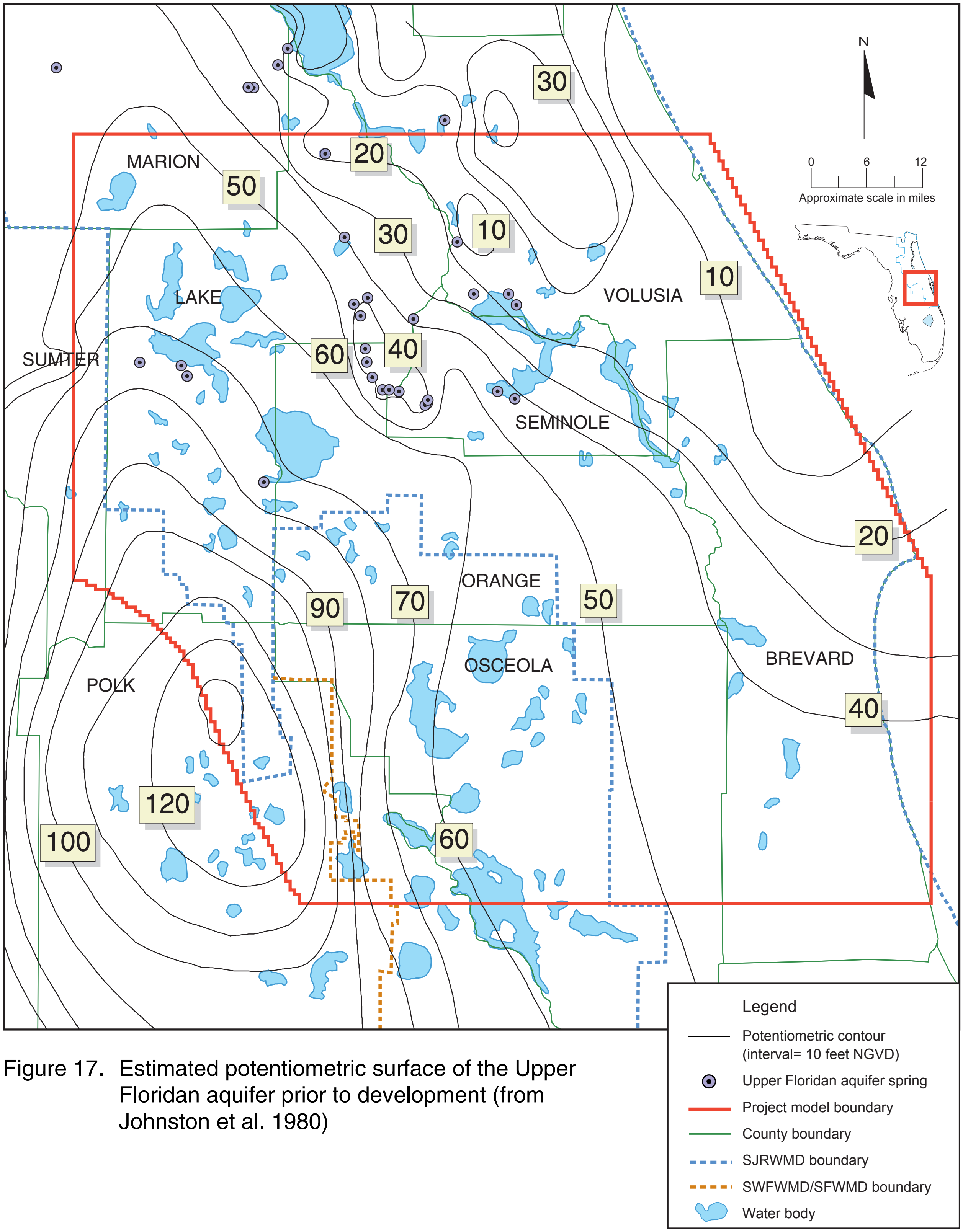


Figure 17. Estimated potentiometric surface of the Upper Floridan aquifer prior to development (from Johnston et al. 1980)

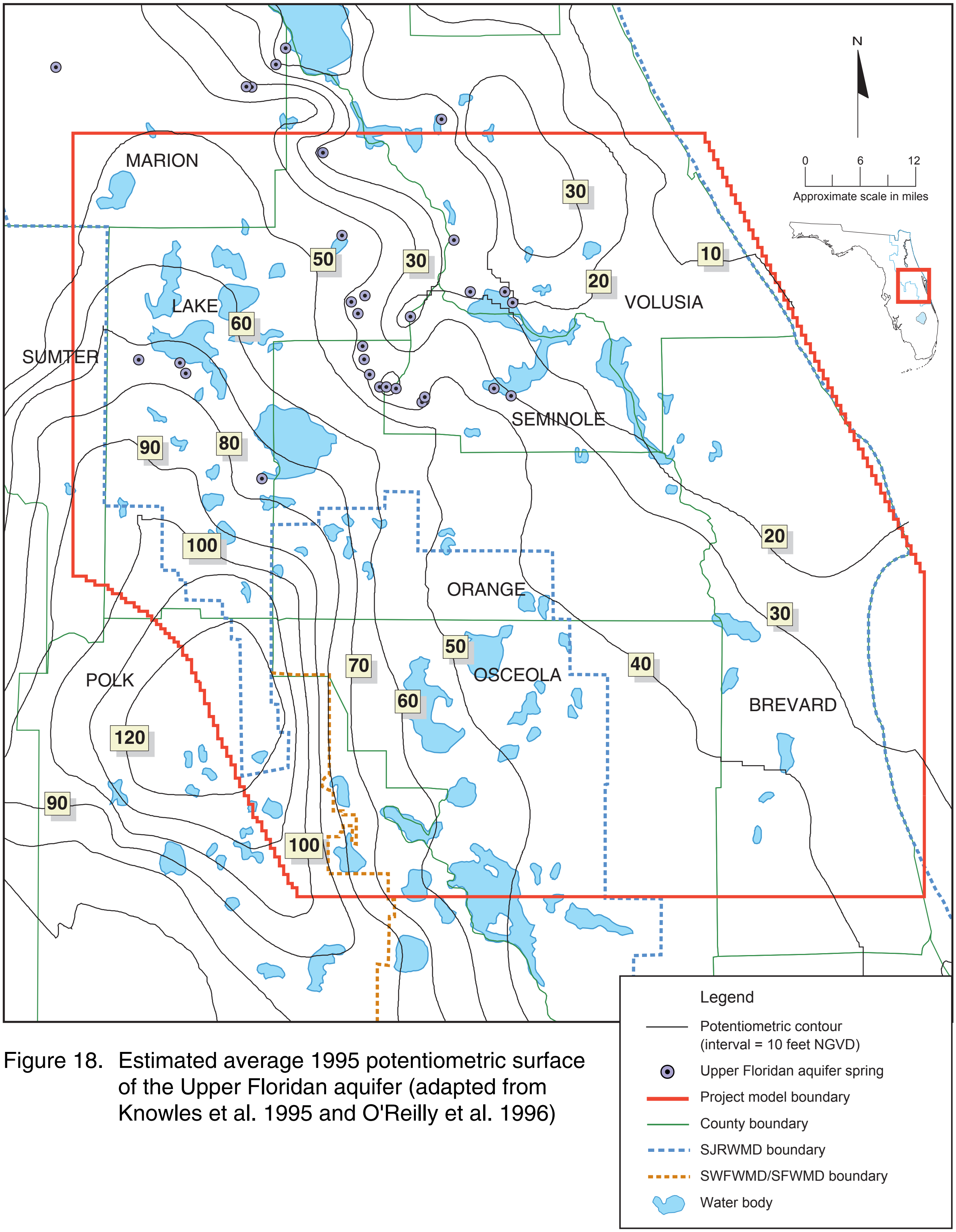


Figure 18. Estimated average 1995 potentiometric surface of the Upper Floridan aquifer (adapted from Knowles et al. 1995 and O'Reilly et al. 1996)

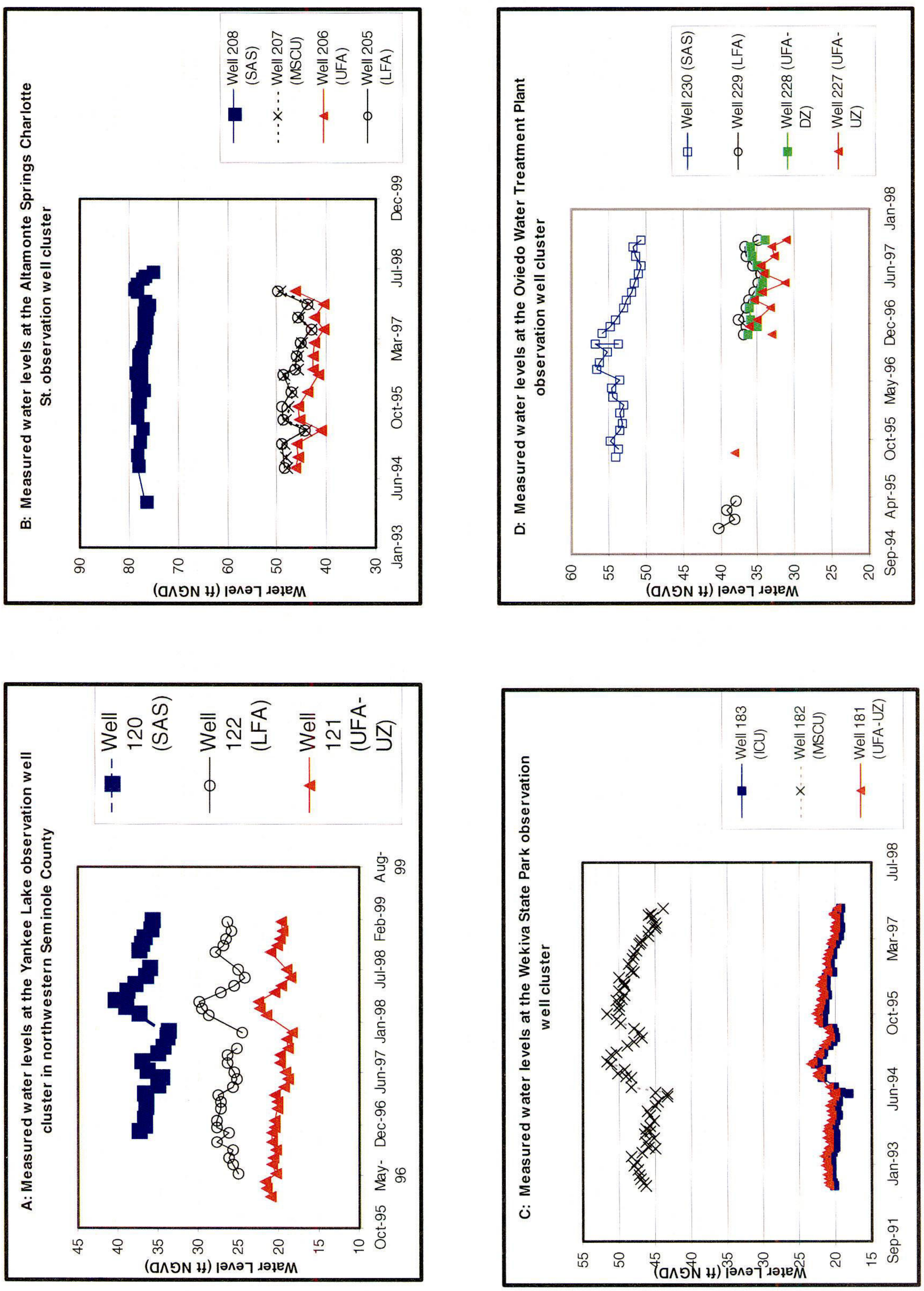


Figure 19. Hydrographs of water levels at selected observation well clusters

Historic and Projected Water Use

Most of the water used in the ECF region is withdrawn from the Floridan aquifer system (Florence and Moore 1997; SFWMD 2000; Marella 1999). The groundwater withdrawn from the Floridan aquifer system has been used for agricultural irrigation, commercial/industrial, recreational, and domestic (household) uses. Domestic uses are both self-supplied and derived from public-water supplies. In some areas, agricultural irrigation has historically been the largest user of water from the Floridan aquifer system. For example, Stubbs (1937) documented potentiometric declines of several feet between 1913 and 1937 in northern and central Seminole County due to extensive use of approximately 2,000 artesian wells to irrigate truck farms. Over the past several decades, however, public-water supply withdrawals have surpassed agricultural withdrawals in Orange, Seminole, and Volusia counties (Table 3). The average annual withdrawal rates that have been projected for 2020 indicate that this trend will continue. Significant portions of the projected increases in irrigation withdrawals in Lake and Seminole counties between 1995 and 2020 are for recreational (golf course) irrigation. In terms of spatial patterns, public water supply use is centralized, with wellfields located within and around populated areas (Figure 20). In contrast, agricultural wells are more diffuse and are spread throughout the entire model domain (Figure 21).

Water Quality

The water quality characteristics of the Floridan aquifer system within the ECF region were described in detail by Tibbals (1990) and Murray and Halford (1996). Within and near recharge areas, the aquifer system contains fresh (low salinity), relatively hard water dominated by calcium, magnesium, and bicarbonate ions. In discharge areas (Figure 15), the aquifer system generally contains brackish water dominated by sodium, sulfate, and chloride ions; salinity increases with depth. In low recharge areas, or areas that are transitional between recharge and discharge, freshwater overlies brackish or saline water. In Volusia County and parts of northern and eastern Seminole County, brackish water underlies freshwater in high recharge areas as well.

The thickness of the transition zone between fresh and saline water varies considerably from place to place. Results of packer testing conducted at a test well in south-central Orange County (McGurk and Sego 1999) indicated

Table 3. Historic and projected average annual groundwater withdrawals from selected counties within the east-central Florida region (in million gallons per day)

County	1970	1985	1995	2020
Agricultural and Recreational Irrigation				
Brevard	47.9	100.3	90.7	84.4
Lake	13.4	28.8	53.2	79.6
Orange	11.2	47.9	30.5	37.8
Osceola	8.0	40.0	41.6	44.8*
Seminole	3.4	23.2	9.5	15.6
Volusia	6.9	36.6	27.7	32.5
Total	90.8	276.8	253.2	294.7
Public Supply				
Brevard	3.5	9.2	15.0	16.0
Lake	10.0	15.3	22.6	70.6
Orange	65.8	122.6	165.0	328.2
Osceola	2.7	5.7	19.2	38.0*
Seminole	6.3	34.9	50.7	94.8
Volusia	19.2	36.4	48.8	90.9
Total	107.5	224.1	321.3	638.5
Self-Supplied Commercial, Industrial, and Power Generation				
Brevard	0.4	0.5	2.1	0.9
Lake	19.4	12.2	10.2	13.6
Orange	7.0	15.2	20.1	6.9
Osceola	0.2	3.2	0.8	1.5*
Seminole	0.5	5.0	0.1	0.2
Volusia	1.0	0.8	1.1	1.0
Total	28.5	36.9	34.4	24.1
Self-Supplied Domestic				
Brevard	3.4	5.6	5.2	2.1
Lake	3.3	8.5	6.0	1.3
Orange	7.6	6.1	12.9	10.5
Osceola	2.0	4.8	6.8	5.5*
Seminole	2.7	3.6	8.6	2.1
Volusia	3.7	5.3	3.6	12.0
Total	22.7	33.9	43.1	33.5
Total for all uses	249.5	571.7	652.0	946.0

*East-central Florida model portion only.

Source: Marella 1995, 1999; Vergara 1998; SFWMD 1998

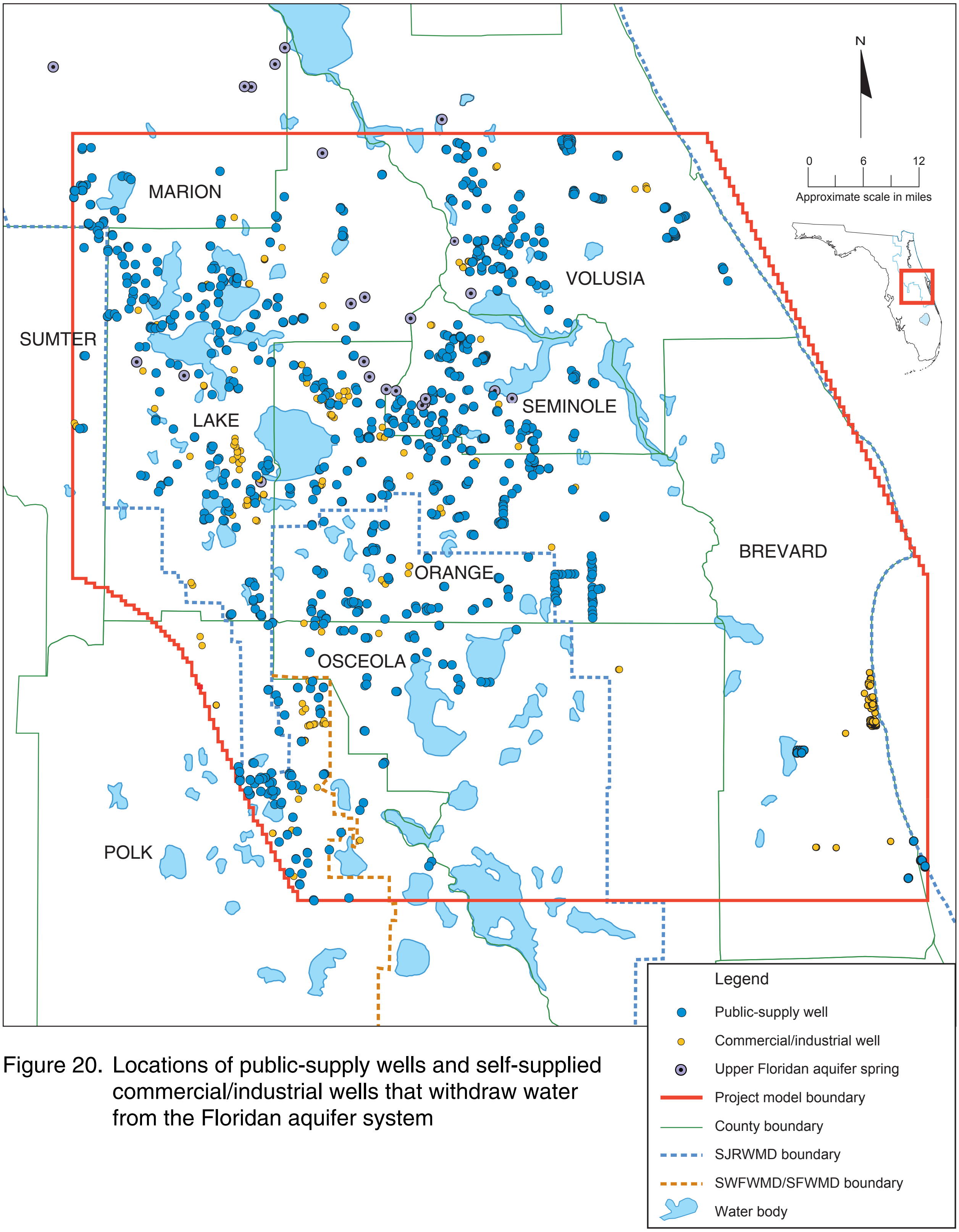


Figure 20. Locations of public-supply wells and self-supplied commercial/industrial wells that withdraw water from the Floridan aquifer system

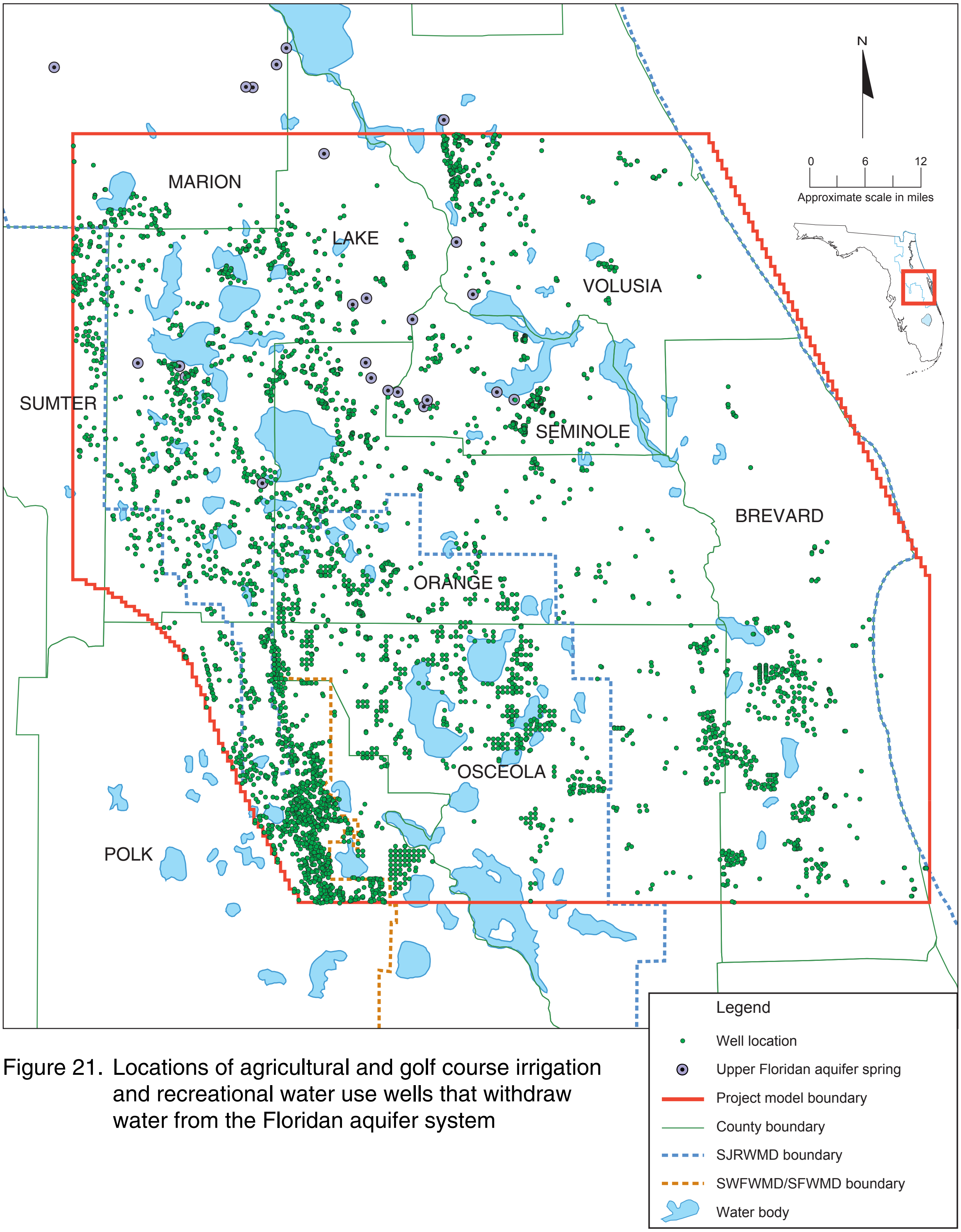


Figure 21. Locations of agricultural and golf course irrigation and recreational water use wells that withdraw water from the Floridan aquifer system

water containing a chloride concentration of less than 100 milligrams per liter (mg/L) from a fractured dolostone flow zone at approximately –1,900 ft NGVD. At the same test well, water samples collected from a zone less than 100 ft lower in elevation contained water with a chloride concentration that exceeded 3,000 mg/L. At this well location, the base of the Floridan aquifer system was estimated to occur at an elevation of approximately –2,000 ft NGVD. By contrast, in central and southern Brevard County, brackish water exists throughout the entire thickness of the Upper Floridan aquifer and saline water exists throughout the entire thickness of the Lower Floridan aquifer (Duncan et al. 1994). McGurk et al. (1998) used chloride concentration data from 645 production, observation, and test wells, plus estimates of the elevation of the 5,000-mg/L chloride isochlor at 86 time-domain electromagnetic (TDEM) survey sites (Blackhawk Geosciences 1992; Subsurface Detection Investigations 1995) to examine and map salinity changes with depth. A map was constructed of the estimated elevation of the 5,000-mg/L isosurface across the ECF region (Figure 22). The 5,000-mg/L isosurface was interpreted by McGurk et al. (1998) to approximately represent the boundary line between moderately brackish water and very brackish to saline water. Water quality data from test wells that have penetrated the transition zone in the ECF region indicate that the vertical distance between water with a chloride concentration of 5,000 mg/L and water with a chloride concentration of 10,000 mg/L is relatively short (Figure 23; see also Phelps and Schiffer 1996, Figure 12). Therefore, the 5,000-mg/L isosurface can be interpreted to represent the midpoint of the transition zone and the base of the freshwater flow system.

Within most of the ECF region, the thickness of the freshwater flow system corresponds to the thickness of the Floridan aquifer system with chloride concentrations of less than 5,000 mg/L. This thickness is greatest within a northwest to southeast-trending area that includes southeastern Marion County, northern and central Lake County, western Orange County, and central Osceola County (Figure 24), where it exceeds 2,100 ft. The freshwater flow system thickness is least along the coast of northern Brevard County and along the St. Johns River near and downstream of Lake Harney where very brackish or saline water exists within the Upper Floridan aquifer. Freshwater thickness is probably much less than 2,100 ft south and west of the line shown on Figure 24 that demarcates the inferred eastern extent of middle confining unit II of Miller (1986). The limited data available suggest that beneath middle confining unit II, the concentration of total dissolved solids may be too high to consider the groundwater fresh, even though the chloride concentration is very low.

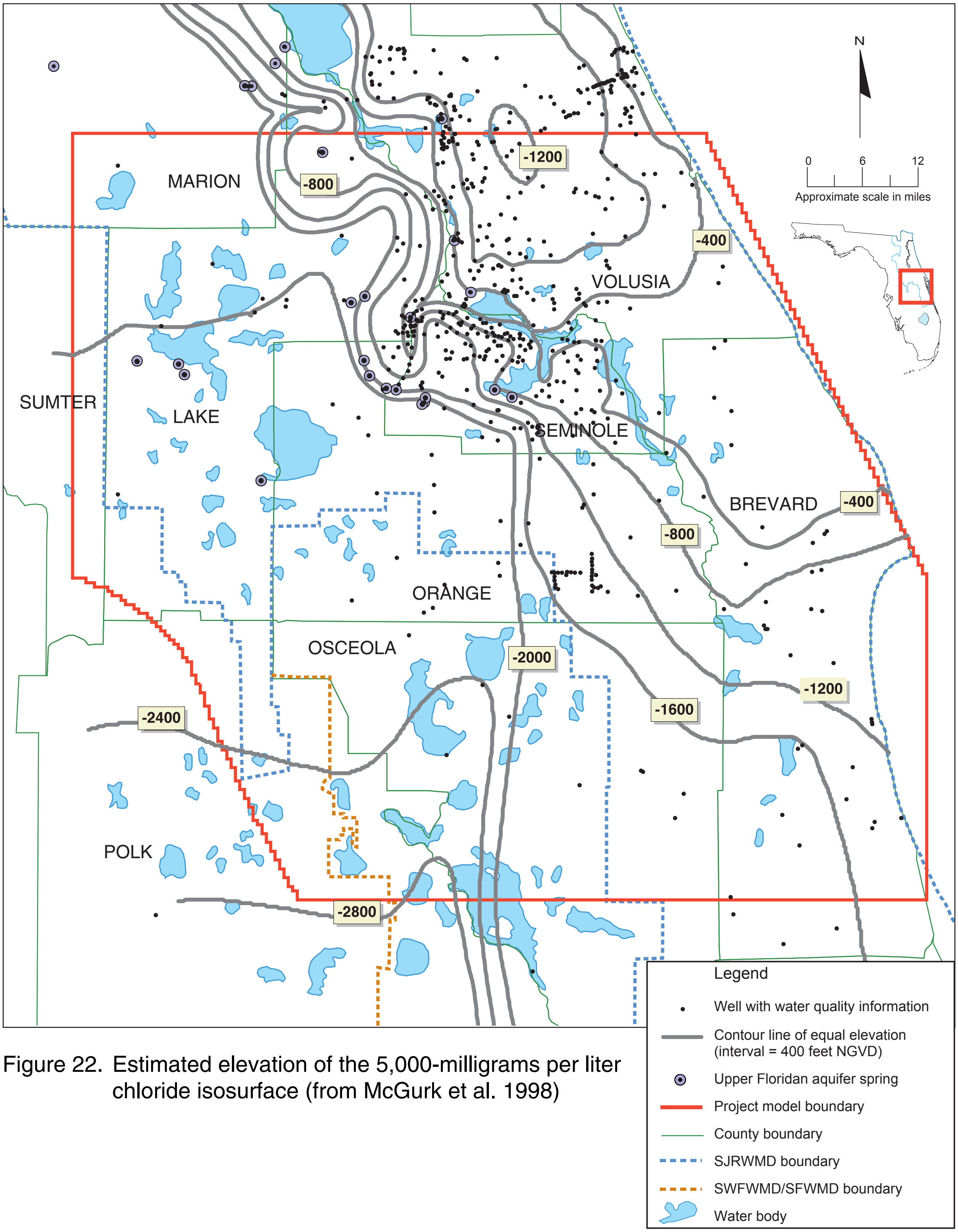


Figure 22. Estimated elevation of the 5,000-milligrams per liter chloride isosurface (from McGurk et al. 1998)

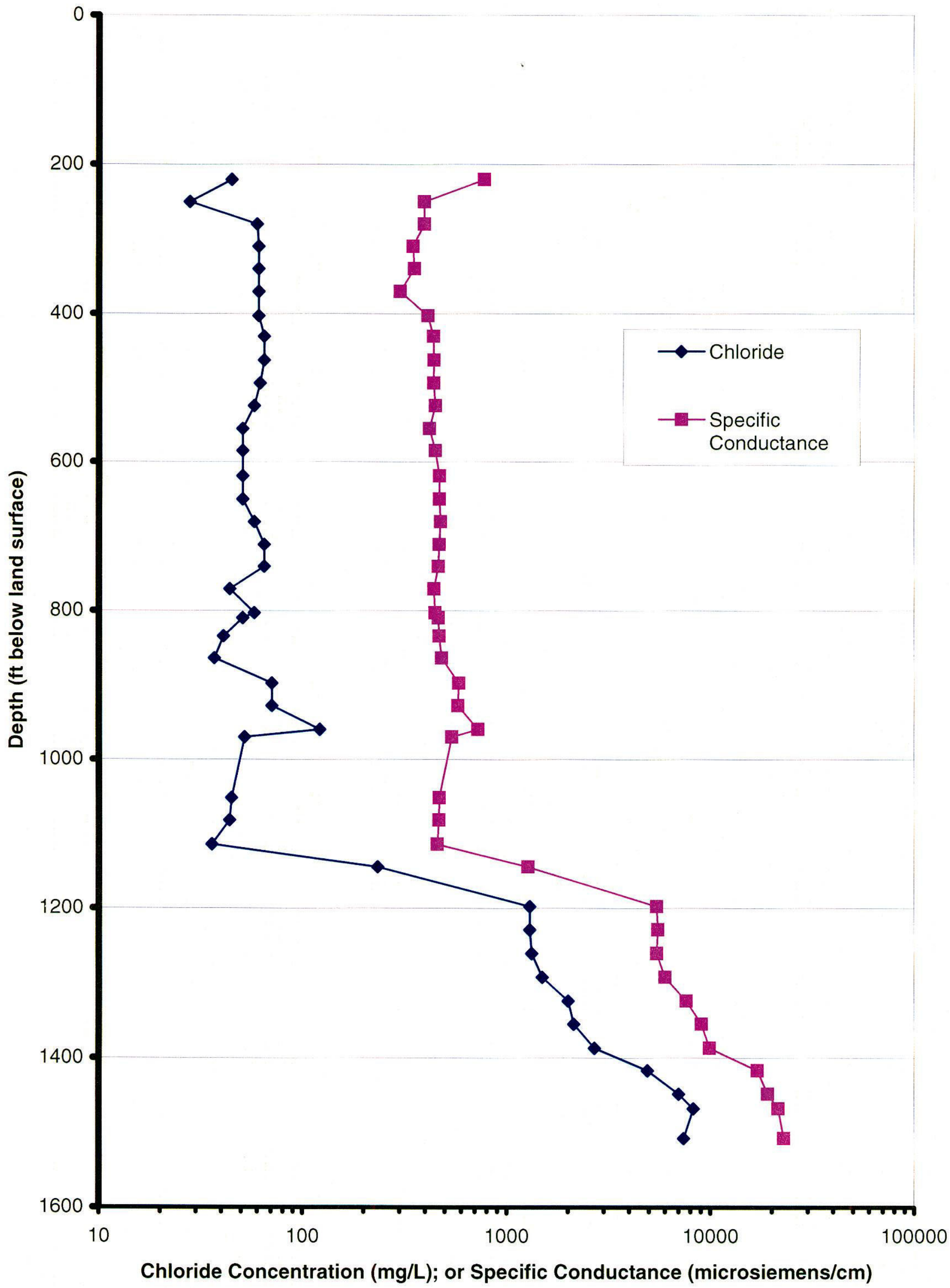


Figure 23. Chloride concentration and specific conductance versus depth at well 288 in eastern Orange County (data collected during drilling of test well)

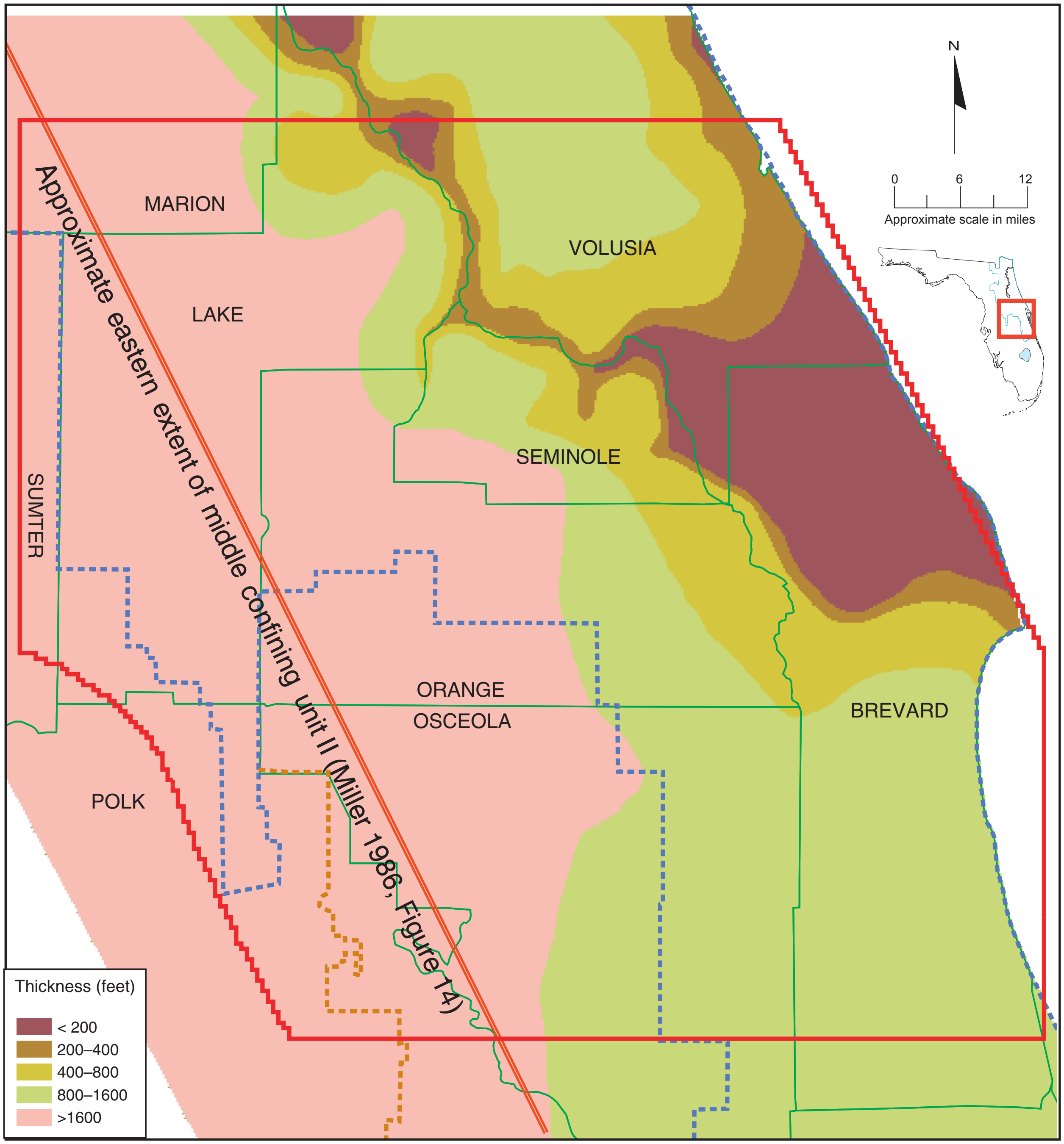


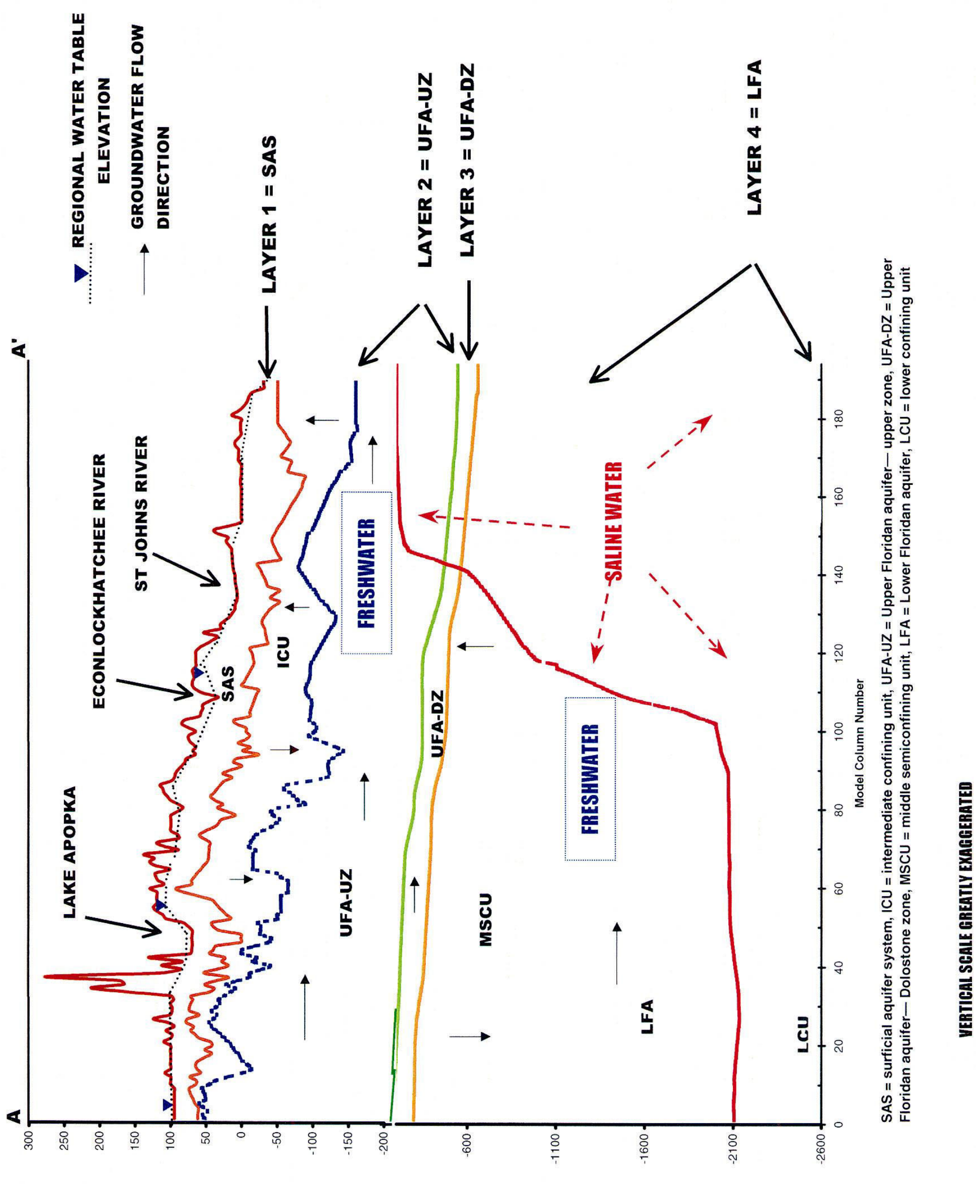
Figure 24. Thickness of the Floridan aquifer system containing chloride concentrations less than 5,000 milligrams per liter (from McGurk et al. 1998)

CONCEPTUAL MODEL OF GROUNDWATER FLOW

In order to construct a numerical model that can adequately simulate groundwater flow in the ECF region, the details of the hydrogeologic framework have been simplified into a conceptual model that incorporates the important regional-scale features of the groundwater flow system. Hydrogeologic section A–A' (Figure 25) is aligned along model row 80 of the numerical model grid that is discussed later in this report. The conceptual model consists of three aquifers separated by two semiconfining units and underlain by a confining unit. Groundwater flow has been conceptualized as quasi-three-dimensional. That is, horizontal flow occurs only within the aquifer layers and vertical flow occurs only between the aquifer layers. The three aquifers were discretized into four model layers. These are the surficial aquifer system (model layer 1), the Upper Floridan aquifer (model layers 2 and 3), and the Lower Floridan aquifer (model layer 4). Model layer 2 represents the upper part of the Upper Floridan aquifer, including the Ocala Formation and the uppermost part of the Avon Park Formation. Model layer 3 represents the dolostone zone within the Avon Park Formation. Vertical flow occurs between model layers 1 and 2 through the intermediate confining unit, between model layers 2 and 3, and between model layers 3 and 4 through the middle semiconfining unit. Horizontal flow within the semiconfining units is not simulated. These units act as membranes to transmit flow vertically between the aquifer layers above and below. No flow occurs between the Lower Floridan aquifer and the lower confining unit. There is also no vertical exchange of flow between the freshwater flow system and those portions of the aquifer layers containing saline water.

The surficial aquifer system is conceptualized as an unconfined aquifer. This means that simulated layer 1 water levels represent the elevation of the regional water table surface. The surficial aquifer system is recharged by infiltration of water derived from rainfall through the unsaturated zone. Although horizontal flow within the surficial aquifer system is simulated, it is recognized that the direction and magnitude of the surficial aquifer system horizontal gradient is, in many places, more detailed than can be simulated by a regional-scale model. Detailed simulation of the shape of the water table surface is beyond the scope of this study.

ET occurs from both the unsaturated zone above the surficial aquifer system and the saturated zone within the surficial aquifer system. The model can simulate ET from the groundwater flow system only. Therefore, total ET is the sum of that amount simulated by the model from the saturated zone plus



SAS = surficial aquifer system, ICU = intermediate confining unit, UFA-UZ = Upper Floridan aquifer— upper zone, UFA-DZ = Upper Floridan aquifer— Dolostone zone, MSCU = middle semiconfining unit, LFA = Lower Floridan aquifer, LCU = lower confining unit

Figure 25. Hydrogeologic cross section along model row 80 showing the conceptual model of regional groundwater flow in east-central Florida

an estimated amount from the unsaturated zone. Total annual ET should not, on the average, exceed the average annual free-water surface evaporation.

The Floridan aquifer system is recharged by downward movement of water from the surficial aquifer system wherever the elevation of the water table is higher than the potentiometric surface of the Upper Floridan aquifer. Similarly, water discharges from the Floridan aquifer system wherever the potentiometric surface of the Upper Floridan aquifer is greater than the water table elevation. Discharge from model layer 2 within the Upper Floridan aquifer is concentrated at springs. Permeability is assumed to be higher in model layer 2 than in model layer 3 in the vicinity of the larger (first- and second-magnitude) springs. The base of the freshwater flow system occurs at the top of the lower confining unit of the Floridan aquifer system or at the elevation of the 5,000-mg/L chloride isosurface, where it is present within the aquifer system. The saltwater interface boundary, as represented by the 5,000-mg/L chloride isosurface, is equivalent to the midpoint of the transition zone between freshwater and saline water.

SIMULATION OF GROUNDWATER FLOW

The conceptual model and the hydrologic data discussed in previous sections were used to construct a numerical model of groundwater flow within the fresh groundwater flow system. The model simulates predevelopment and postdevelopment (1995) average, steady-state conditions. The model was used to evaluate the average, steady-state changes to the regional groundwater flow system due to projected average Floridan aquifer system withdrawals in the year 2020.

COMPUTER CODE SELECTION

The USGS MODFLOW computer code (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996) was used to simulate the groundwater flow system. This code has been used and accepted for analyzing regional and subregional-scale groundwater flow problems worldwide (Anderson and Woessner 1992). Nearly all of the published regional groundwater flow modeling studies concerning central Florida have used the MODFLOW code or its USGS forerunner (Trescott 1975). MODFLOW's modular format facilitates the incorporation of various types of stresses, such as pumping, recharge, and ET.

MODEL DESIGN

The use of the MODFLOW code requires the flow system to be divided into discrete blocks, or grid cells. The numerical equations of groundwater flow are solved for each grid cell to produce simulated water levels, or head values. Flow between cells depends upon the head gradient and upon the horizontal and vertical hydraulic conductivity values assigned to the cells. The ECF model domain encompasses roughly the area between latitude 275430 to 290700 and longitude 803000 to 820115. However, the northeastern and southwestern corners of this area grid are not considered part of the model domain (Figure 26). The model domain was discretized into a grid containing 174 rows and 194 columns. The dimensions of each grid cell are 2,500 ft by 2,500 ft (cell area of 6,250,000 ft2).

The model area was discretized vertically using GIS ARC/INFO software. Contour maps of each of the hydrostratigraphic units plus the 5,000-mg/L chloride isosurface were converted into ARC/INFO grids. Each grid was then joined with the model grid, resulting in a series of top and bottom aquifer and

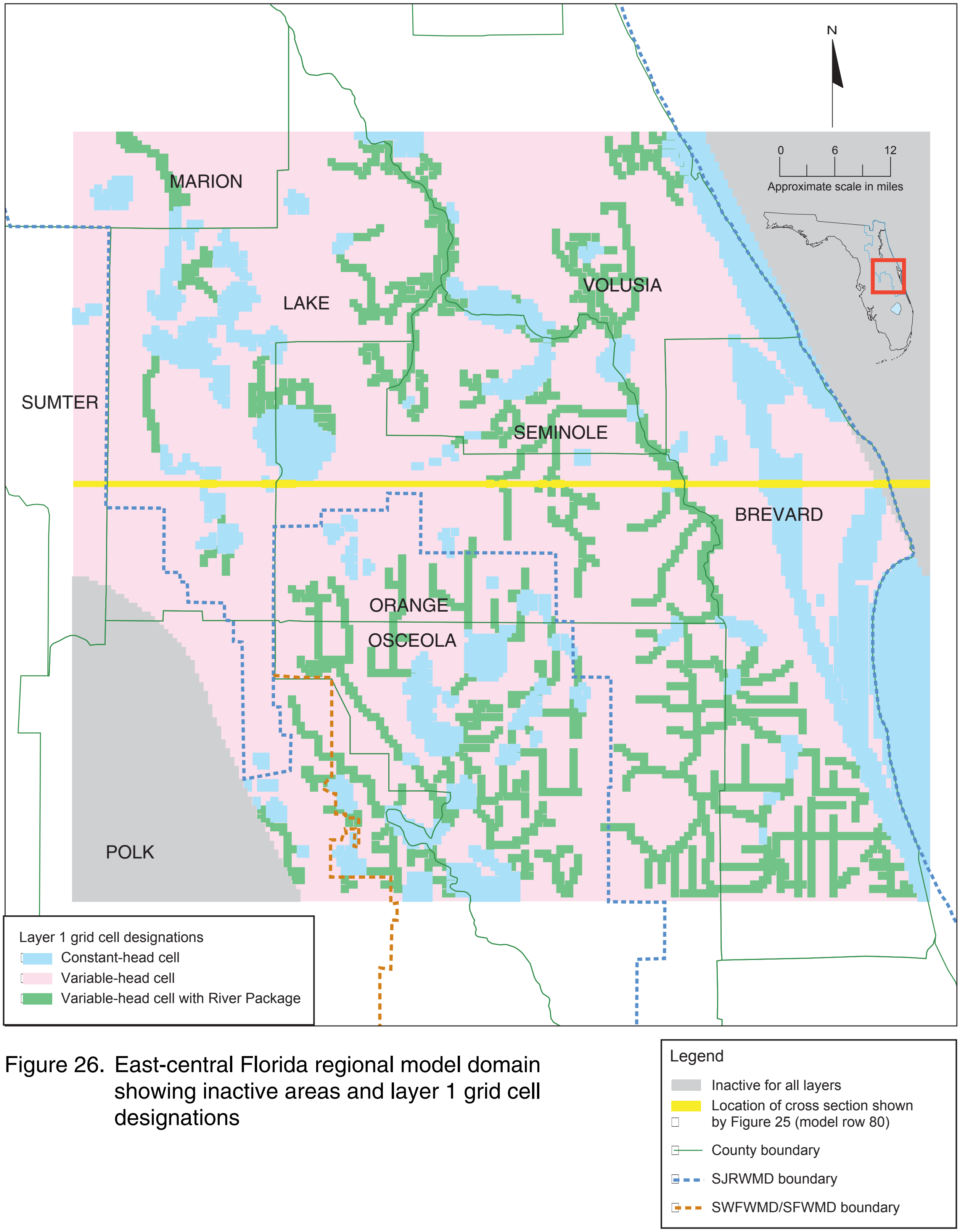


Figure 26. East-central Florida regional model domain showing inactive areas and layer 1 grid cell designations

confining unit elevation values, as well as a saline water interface elevation for each grid cell. At cell locations where the saline water interface elevation was calculated to be above an aquifer layer bottom elevation, the bottom elevation of the flow domain was recomputed to equal the saline water interface elevation. Model grid cells where the saline water interface elevation value was calculated to be within 20 ft of the top of an aquifer layer were considered to be saline and therefore inactive. Head in layer 1 at model grid cells covered by large water bodies was not computed by the model. This designation includes large lakes, coastal lagoons, and the ocean. Layer 1 head values at these cells (Figure 26) were specified as constant throughout the simulations, in part because the stage elevations of these water bodies are, in part, functions of upstream surface water flow and tidal fluctuations. Simulation of these processes is beyond the scope of this modeling project. Therefore, flow to and from large surface water bodies is also simulated by the model via flow to and from constant-head cells.

As a result of (1) exclusion of the northeastern and southwestern corners of the grid from the model, (2) exclusion of grid cells with less than 20 ft of freshwater thickness from the model, and (3) assignment of constant-head values to layer 1 cells located at large surface water bodies, there are 24,793 variable-head cells in layer 1; 28,509 variable-head cells in layer 2; 25,538 variable-head cells in layer 3; and 20,571 variable-head cells in layer 4 (Figures 26, 27, and 28). The top of the surficial aquifer system was not assigned an elevation because it is equivalent to the water table elevation and is simulated by the model. For use in simulation of evapotranspiration, a topographic elevation was assigned to each grid cell, however, using a digital elevation model of land surface topography at 5-ft contour intervals. The value assigned was equal to the topographic elevation corresponding to the midpoint of the grid cell.

HYDROLOGIC DATA INPUT

There are several types of input data required for the model. These include information needed to assign boundary conditions, applied stresses, and aquifer and confining unit properties (Table 4).

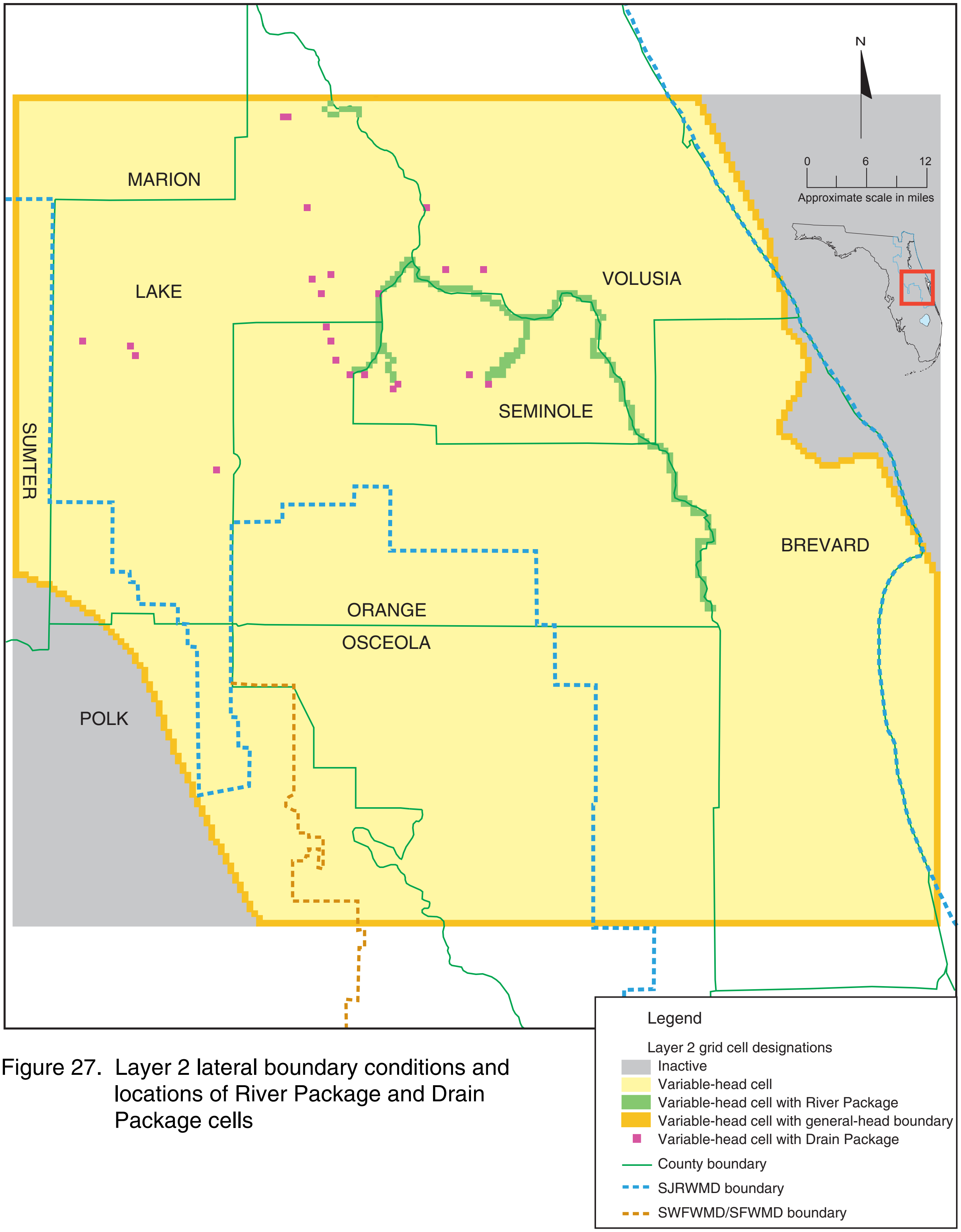


Figure 27. Layer 2 lateral boundary conditions and locations of River Package and Drain Package cells

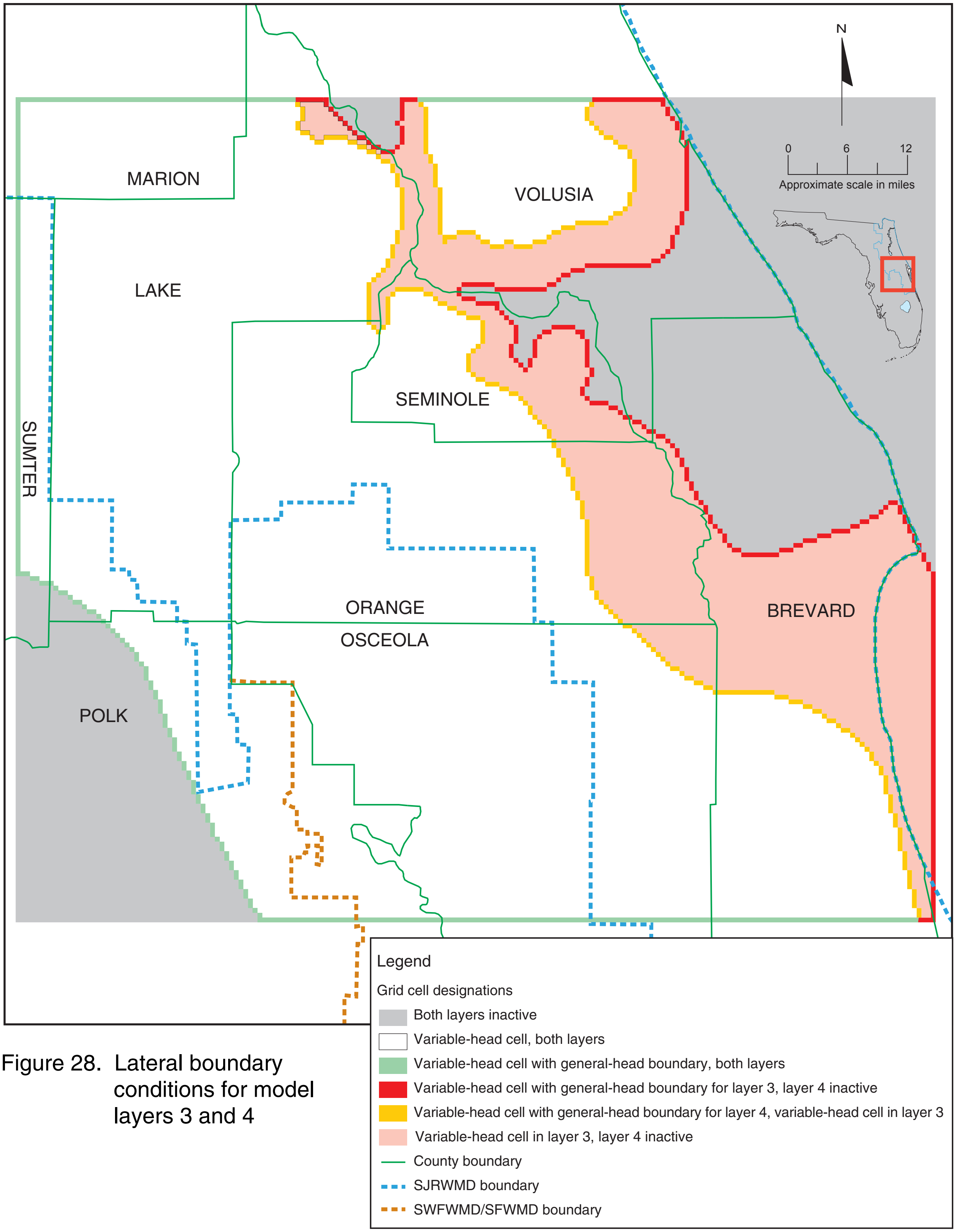


Figure 28. Lateral boundary conditions for model layers 3 and 4

Table 4. Summary of model input data

Hydrostratigraphic Unit/Model Unit	Type of Data Required for Active Model Grid Cells	Data Item Needed to Estimate MODFLOW Input Item	MODFLOW Input Item Applied to All Cells in Model Unit	MODFLOW Input Item Applied Only to Boundary Condition and/or Applied Stress Cells
Surficial aquifer system/layer 1	Major soil type and depth to water table	X		
	Land use (1995)	X		
	Soil Conversation Service curve number	X		
	Total 1995 precipitation	X		
	Total 1995 overland runoff	X		
	Total 1995 flow to rapid infiltration basins or from septic tanks	X		
	Total 1995 applied irrigation (reclaimed or potable)	X		
	Recharge			X
	Land surface elevation			X
	Average free-water surface evaporation			X
	Evapotranspiration extinction depth			X
	Average 1995 stream stage			X
	Streambed elevation			X
	Streambed vertical hydraulic conductivity	X		
	Streambed thickness	X		
	Streambed conductance			X
	Fixed head at constant-head cells			X
	Horizontal hydraulic conductivity		X	
	Elevation of top of ICU (base of layer 1)		X	

Table 4—*Continued*

Hydrostratigraphic Unit/Model Unit	Type of Data Required for Active Model Grid Cells	Data Item Needed to Estimate MODFLOW Input Item	MODFLOW Input Item Applied to All Cells in Model Unit	MODFLOW Input Item Applied Only to Boundary Condition and/or Applied Stress Cells
Intermediate confining unit (ICU)	Vertical hydraulic conductivity	X		
	Leakance		X	
Upper Floridan aquifer—upper zone (layer 2)	Top elevation		X	
	Bottom elevation*		X	
	Horizontal hydraulic conductivity		X	
	Vertical hydraulic conductivity	X		
	Leakance between layer 2 and layer 3		X	
	Fixed GHB head			X
	Distance from model edge to GHB head	X		
	GHB conductance			X
	Drain conductance			X
	Spring pool elevation			X
	Average 1995 stream stage			X
	Streambed elevation			X
	Streambed vertical hydraulic conductivity	X		
	Streambed thickness	X		
	Streambed conductance			X
	Well discharge and/or drainage well recharge			X

Table 4—*Continued*

Hydrostratigraphic Unit/Model Unit	Type of Data Required for Active Model Grid Cells	Data Item Needed to Estimate MODFLOW Input Item	MODFLOW Input Item Applied to All Cells in Model Unit	MODFLOW Input Item Applied Only to Boundary Condition and/or Applied Stress Cells
Upper Floridan aquifer—dolostone zone /layer 3	Bottom elevation*		X	
	Horizontal hydraulic conductivity		X	
	Vertical hydraulic conductivity	X		
	Fixed GHB head	X		
	Distance from model edge to GHB head			X
	GHB conductance			X
	Well discharge and/or drainage well recharge			X
Middle semiconfining unit (MSCU)	Vertical hydraulic conductivity	X		
	Leakance		X	
Lower Floridan aquifer /layer 4	Top elevation		X	
	Bottom elevation*		X	
	Horizontal hydraulic conductivity		X	
	Vertical hydraulic conductivity	X		
	Fixed GHB head			X
	Distance from model edge to GHB head	X		
	GHB conductance			X
	Well discharge and/or drainage well recharge			X

Note: GHB = general-head boundary

*Bottom elevation of layers 2, 3, and 4 were adjusted at some cells where 5,000-milligrams per liter chloride isosurface elevation was higher

Boundary Conditions

Boundary conditions were estimated and applied at the sides of the model domain for the Floridan aquifer system layers, along rivers and their major tributaries, at springs, and at the water table to account for loss of water due to ET. The base of the model is a zero-prescribed flux boundary. Wherever the freshwater flow system extends throughout the entire thickness of the Floridan aquifer system, the lower confining unit acts as an impermeable, no-flow boundary at the base of the Lower Floridan aquifer. A no-flow bottom boundary also exists at cells where the saline water interface equals the layer bottom, or where the saline water interface lies within the middle semiconfining unit below layer 3.

Lateral Boundaries

Clearly defined hydrogeologic boundaries do not exist within the Floridan aquifer system in the project area. The Floridan aquifer system extends not only well beyond the model domain, it underlies all of peninsular Florida. Therefore, realistic conditions must be set up and applied along the lateral sides of the domain in order to represent flow that occurs across these artificial boundaries. Potentiometric surface maps of the Upper Floridan aquifer (Figures 17 and 18) were used to locate model boundaries and to help in defining these conditions. On a regional scale, flow directions within the Upper Floridan aquifer will be perpendicular to the potentiometric contours shown on Figures 17 and 18. The southwestern, southern, and eastern model boundaries were located where they are in part because the contours are oriented so that flow across the boundaries would be relatively insignificant. Another reason for locating these boundaries where they are (as well as the remaining sides of the model) was to minimize predicted potentiometric changes at the boundaries due to projected future withdrawals.

Choices for lateral boundary condition assignments are limited to three types: (1) prescribed potentiometric levels (heads), (2) prescribed flow rates, or (3) head-dependent flux. The third type was chosen for application along all lateral boundaries for two reasons. First, there was not enough available information to independently estimate the flow rates along the boundaries where the orientation of potentiometric contours indicates significant flow (the northwestern boundary and parts of the northern boundary). The head-dependent flux condition allows the model to compute a boundary flow rate based upon (1) the difference between known heads near to, but outside of, the model (available from potentiometric maps) and model-calculated heads at the boundary; and (2) a conductance value that can be easily related to aquifer hydraulic conductivity. Therefore, available information was used to estimate the boundary conditions along all sides of the domain. Second, the locations of projected future withdrawals indicated a potential for predicted potentiometric changes (drawdowns) to reach the lateral boundaries. Using a prescribed head boundary condition would not allow heads near the boundaries to change due to future pumping and would tend to lessen the predicted potentiometric decrease within the model. Using a prescribed zero flux along the southwestern, southern, and eastern boundaries would tend to cause the opposite problem: an exaggeration of predicted potentiometric decrease within the model. Therefore, lateral boundary conditions were assigned based upon knowledge of hydraulic conditions within the Floridan aquifer system. The general-head boundary (GHB) package (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996) was used to assign a head-dependent-flux condition at lateral boundaries for aquifer layers 2, 3, and 4 (Figures 27 and 28). Within each of these layers, flow across the lateral boundaries is described by the following equation:

$$Q = \left(K_h * b * W\right) * \frac{\left(H_b - H_{sb}\right)}{L_h} \qquad \textbf{(1)}$$

where

Q = the lateral flow rate (cubic feet per day [ft^3/ day]),
K_h = the horizontal hydraulic conductivity (ft / day),
b = the aquifer layer thickness (ft)
W = the width of the cell face perpendicular to the flow (2,500 ft for all cells)
H_b = the specified GHB head (ft)
H_{sb} = the model-simulated head at the grid cell along the model boundary (ft)
L_h = the distance between H_{sb} and H_b (ft)

The quantities Q and H_{sb} are computed by the model. K_h represents the value input for each grid cell located along the boundary, and b is the difference between the layer top and the layer bottom (computed as previously described). The quantity KbW/L_h is equal to the boundary conductance and is an input to the GHB package. Because the hydraulic gradient between H_b and H_{sb} is assumed to be linear (McDonald and Harbaugh 1988), L_h varies between two and four grid cell lengths (5,000 to 10,000 ft), depending upon the shapes of the estimated predevelopment and average 1995 potentiometric surfaces (Figures 17 and 18) in the area surrounding each boundary grid cell. At lateral boundaries located within the freshwater flow system, values for H_b in Upper Floridan aquifer layers 2 and 3 are equal and were derived from the estimated predevelopment and average 1995 potentiometric surfaces for the predevelopment and average 1995 calibrations, respectively. Values for H_b in Lower Floridan aquifer layer 4 were arbitrarily set at 2 ft below layer 3 H_b values in Floridan aquifer system high recharge areas (Boniol et al. 1993). Layer 4 H_b values were assigned 2 ft higher than layer 3 H_b values in obvious Floridan aquifer system discharge areas. In Floridan aquifer system low recharge areas, or where Floridan aquifer system discharge is thought to occur at low rates, layer 4 H_b values equal those of layers 2 and 3. Along the model's southwestern boundary in Polk County, however, layer 4 H_b values were set at 10 to 20 ft lower than layer 3 H_b values. In this area, middle semiconfining unit II of Miller (1986) is believed to separate the Lower Floridan aquifer from the Upper Floridan aquifer to a greater degree than elsewhere in the model. Evidence for a 10- to 20-ft vertical head difference was available from Stewart (1966, Table 7) and from water-level data collected during recent drilling of test well 533 in southeastern Lake County (SJRWMD 2000).

The GHB package was also used along the seaward boundary between saltwater and freshwater within the interior of the grid for layers 2, 3, and 4. As described previously, this boundary represents the midpoint of the transition zone between freshwater and saline water. In east-central Florida, this transition zone is relatively thick. Within it, mixing of fresh and saline water occurred in an equilibrium condition prior to the onset of historical groundwater withdrawals. A certain amount of fresh and saline water was added to the transition zone to replace brackish water naturally discharged in lowlands along the St. Johns River. Pumping-induced drawdown on the freshwater side of this boundary causes increased mixing of saline, brackish, and fresh water due to the pressure imbalance across it. As a result of this increase in mixing, the transition zone becomes wider. Because this process is controlled in part by density differences, the MODFLOW code cannot simulate it very accurately. The GHB package was used in order to obtain the best estimate of potential water-level and flux changes near the seaward boundary. Assigning zero-flux conditions would assume no increase in mixing and result in an overestimation of predicted drawdown in the interior of the model. Prescribed head conditions would result in the opposite effect of overestimating flux across the boundary and underestimating drawdown in response to future withdrawals.

For model grid cells along the seaward boundary, L_h varies between two and four grid cell lengths also, depending upon the shape of the estimated elevation of the 5,000-mg / L chloride isosurface. For these cells, H_b represents the saltwater head value that would ideally result in a no-flow condition across this boundary for predevelopment conditions. Initial H_b values along this boundary were set equal to H_{sb} values determined from initial predevelopment calibration simulations that treated the saltwater interface as a no-flow boundary. The boundary condition was then changed to a GHB for both the average 1995 and the predevelopment calibrations, with the saltwater head H_b value assumed to remain unchanged from predevelopment to 1995. Some adjustment of these H_b values was required until simulated flow across the saltwater interface boundary was insignificant for predevelopment conditions.

Springs

Discharge from 23 named Upper Floridan aquifer springs, plus estimated discharge from the Upper Floridan aquifer into Alexander Springs Creek in Lake County, was simulated with the Drain Package (Table 2 and Figure 27). The Drain Package calculates discharge using the following equation (Murray and Halford 1996):

$$Q_d = C_d \left(H_{sd} - H_d \right) \tag{2}$$

where

Q_d = the drain discharge (ft^3 / day)
C_d = the drain conductance (ft^2 / day)
H_{sd} = the model-simulated head at the grid cell containing the spring (ft)
H_d = the elevation of the water body (spring pool) created by the spring discharge (ft)

Equation 2 is a “one-way” head-dependent-flux boundary condition. If the simulated head (H_{sd}) drops below the spring pool elevation (H_d), the drain ceases to discharge. Flow will not be reversed into the aquifer to become recharge. The magnitude of the drain conductance depends upon the hydraulic characteristics of the convergent flow pattern in and around the immediate vicinity of the drain (McDonald and Harbaugh 1988). Plausible ranges for drain conductance values were estimated for each spring by altering and rearranging Equation 2:

$$C_d = \frac{Q_d}{(H_m - H_d)} \tag{3}$$

where

H_m = the estimated actual average Upper Floridan aquifer head in the area covered by the grid cell containing the spring (ft)

The average measured values of Q_d, H_d, and H_m for the 1995 calibration period were tabulated for each spring. H_m values were estimated by overlaying the May 1995 and September 1995 Upper Floridan aquifer potentiometric surface maps (Knowles et al. 1995 and O'Reilly et al. 1996, respectively) on the model grid. Equation 3 was then used to produce a range of estimated C_d values for each spring. Input values for C_d were adjusted during model calibration only within these ranges. The assigned C_d and H_d values were kept the same for both the average 1995 and the predevelopment calibrations.

Stream Flow

Discharge of groundwater to rivers and streams was simulated using the MODFLOW River Package. This package calculates flow rates using two equations that are very similar to Equation 2 (adapted from equation set 65 of McDonald and Harbaugh 1988):

$$Q_{riv} = C_{riv}\,(H_{riv} - H_{sr}), \text{ for } H_{sr} > R_{bot} \tag{4}$$

and

$$Q_{riv} = C_{riv}\,(H_{riv} - R_{bot}), \text{ for } H_{sr} < \text{or} = \text{to } R_{bot} \tag{5}$$

where

Q_{riv} = the discharge rate to the stream (ft^3 / day)
H_{riv} = the stage elevation of the stream (ft)
H_{sr} = the model-simulated head at the grid cell containing the stream (ft)
R_{bot} = the elevation of the streambed (ft)
C_{riv} = the hydraulic conductance between the aquifer and the stream (ft^2 / day), or $K_v l_s W_s / M$
K_v = the vertical hydraulic conductivity of the streambed material (ft / day)

l_s = the length of the stream reach within each grid cell (ft)
W_s = the width of the stream reach (ft)
M = the thickness of the streambed (ft)

Input required for the River Package includes values for C_{riv}, H_{riv}, and R_{bot}. Discharge is simulated as long as H_{sr} is greater than H_{riv}. In the ECF model, River Package cells were located only along streams where groundwater discharge is expected to occur. Therefore, R_{bot} was made equal to H_{riv} at all River Package cells so that, if H_{sr} drops below H_{riv}, discharge ceases, but recharge does not occur.

Groundwater discharge to rivers and streams from the surficial aquifer system (layer 1) was simulated at model grid cells located along the valleys of the major streams, including their larger tributaries (Figure 26). Where available, data collected at USGS gauging stations were used to specify H_{riv}. Along streams where stage data were not available, GIS was used to overlay the model grid on 1:24,000-scale topographic map coverages and H_{riv} was estimated from the map coverage. Initial values of C_{riv} were determined by measuring W using the same GIS methodology used to estimate H_{riv} and assuming values of 2,500 ft, 1 ft / day, and 1 ft, respectively, for l_s, K_v, and M. C_{riv} values were adjusted during calibration.

It has been postulated (Tibbals 1990; Murray and Halford 1996) that a very good hydraulic connection with the Upper Floridan aquifer exists along the St. Johns River due to either undocumented spring flow or dredging of the river channel for navigation. Therefore, groundwater discharge from model layer 2 directly to surface water bodies was also simulated using the River Package at model grid cells located along the St. Johns River valley (Figure 27). River package values for layer 2 cells were obtained using the same methodology as that used for layer 1 River Package cells, the only difference being that initial values for K_v were derived from initial estimates of intermediate confining unit leakance. Assigned values for C_{riv} and H_{riv} were kept the same for both the average 1995 and the predevelopment calibrations.

Evapotranspiration

ET from the saturated zone of the surficial aquifer system (ET_{sat}) was simulated using the MODFLOW ET Package. This package calculates ET_{sat} on a cell-by-cell basis using the following equations (adapted from Equations 75–77 of McDonald and Harbaugh 1988):

$$ET_{sat} = ET_{maxsat} \text{ where } H_{sa} \geq ET_{srf}\,; \tag{6}$$

$$ET_{sat} = 0 \text{ where } H_{sa} < ET_{srf} - \text{EXDEP}; \tag{7}$$

$$ET_{sat} = ET_{maxsat} * \left[\frac{H_{sa} - \left(ET_{srf} - \text{EXDEP}\right)}{\text{EXDEP}} \right] \tag{8}$$

where H_{sa} lies between ET_{srf} and (ET_{srf} – EXDEP);

where

H_{sa} = the model-simulated head at each active layer 1 grid cell (ft)
ET_{maxsat} = the maximum allowed ET rate from the saturated zone (ft / day), or $ET_{max} - ET_{min}$
EXDEP = the ET extinction depth (ft)
ET_{srf} = the specified water table elevation at which ET_{maxsat} occurs (ft)

This approach assumes that, at each model grid cell, ET varies linearly between a maximum value (ET_{maxsat}) when the simulated water table surface is at or above a specified elevation (the "ET surface"), and zero when the simulated water table is below a specified extinction depth. The ET surface value for each grid cell was assigned as equal to the assigned land surface elevation. The maximum rate at which ET can occur from either or both the unsaturated or saturated zone (ET_{max}) was assumed to be equal to the estimated average annual evaporation from a free water surface. ET_{max} values were assigned on a cell-by-cell basis (Figure 29) using areal distributions mapped by Visher and Hughes (1975) and Tibbals (1990).

Maximum saturated ET (ET_{maxsat}) rates were assumed to equal ET_{max} minus an assumed minimum amount of ET from the unsaturated zone above the water table (ET_{min}) equal to 27 in / yr. The minimum ET estimate was derived from climatological data collected at a site with shallow-rooted vegetation, a well drained soil, and a deep water table below the soil horizon (Sumner 1996). At this site, the data were used to develop evapotranspiration models for a year-long period with average rainfall conditions. The models were calibrated using eddy correlation measurements of actual ET collected at the site within the same period (September 1993 to September 1994). According to Sumner (1996), the data from this site probably define the lower limit of ET from vegetated surfaces in central Florida. This same minimum ET estimate was

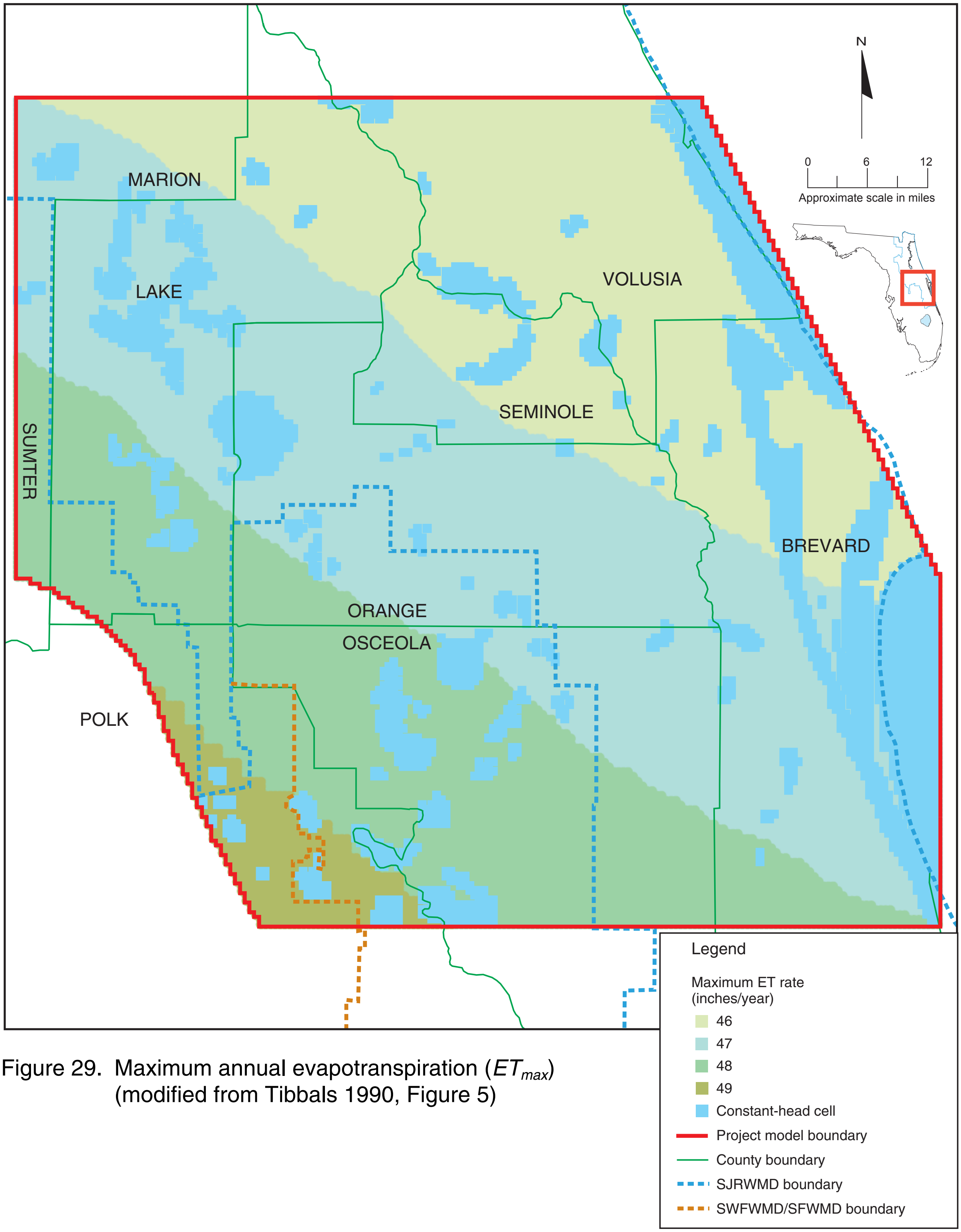


Figure 29. Maximum annual evapotranspiration (ET_{max}) (modified from Tibbals 1990, Figure 5)

also applied to areas where the water table is expected to be very shallow in order to account for evaporation from vegetative canopy surfaces and from water temporarily ponded above the water table.

Initially, unique values for ET extinction depth were estimated for each of three soil zones that were based upon reported depth to the seasonal high water table (see discussion on applied recharge below). During calibration, it became apparent that modelwide simulated heads and fluxes are only slightly sensitive to realistic changes in the extinction depth values. Therefore, because little is known concerning detailed spatial distribution of extinction depth at the regional scale, a single, modelwide depth of 6 ft below the ET_{srf} value was used.

Applied Stresses

Stresses applied to the model include well withdrawals from different depths within the Floridan aquifer system (layers 2, 3, and 4), recharge to the Upper Floridan aquifer (layers 2 and 3) through drainage wells and recharge to the surficial aquifer system (layer 1).

Groundwater Withdrawals

Total groundwater withdrawals from the Floridan aquifer system within the ECF model area in 1995 were estimated to be 565 mgd. Public water supply use totaled 321 mgd; commercial/industrial use, 30 mgd; and agricultural, golf course, and recreational uses, 177 mgd. In addition, approximately 36 mgd was withdrawn for self-supplied domestic use and approximately 2 mgd of discharge was estimated from 381 abandoned artesian wells inventoried as of September 30, 1995 (Curtis 1998). The primary irrigated agricultural crop within the model domain is citrus, with over 28,000 acres of citrus within the SJRWMD portion alone. Greenhouse and nursery irrigation are a distant second, with over 3,000 acres in the SJRWMD portion of the model.

Due to their regulatory role in consumptive use permitting, SJRWMD, SFWMD, and SWFWMD all maintain databases that contain location, casing depth, total depth, status, and withdrawal rate information on permitted wells. These databases, plus the abandoned artesian well inventory (Curtis 1998), provided much of the information used to prescribe well withdrawal rates using the MODFLOW Well Package. Information contained in consultant reports, or supplied directly by public-water supply utilities, supplemented these data. Permitted well information used in the model is listed in Appendix D.

Records of public water supply metered pumpage at water treatment plant were obtained from the SJRWMD Division of Water Supply Management. Records from individual wells or wellfields were obtained from those suppliers that have more than one wellfield per water treatment plant. Average pumping rates were then distributed to each well based upon capacity or pump run-time data. If those data were not available, the average rates were distributed evenly among the appropriate wells. The same process was applied to the commercial/industrial wells to arrive at withdrawal rates for each well location. However, permitted average withdrawal rates were used for several commercial/industrial users for which no metered pumpage data were available. The error associated with distributing metered water treatment or wellfield flows is probably negligible because most wells attributed to particular wellfields or plants are located within the same model grid cell.

Average 1995 public supply and commercial/industrial water use data for wells located within SFWMD and SWFWMD were obtained from water use staff of each respective district. The SFWMD data were applied in a similar fashion as the SJRWMD data. The SWFWMD data, however, were provided on a well-by-well basis; therefore, no distribution of withdrawal was needed.

Groundwater withdrawals for agricultural and golf course irrigation are generally not metered. Withdrawal estimates for those wells located within the SJRWMD portion of the ECF model were made using irrigation application rates and acreages used for the SJRWMD *Annual Water Use Survey 1995* (Florence and Moore 1997). Average 1995 water use withdrawal rates for each SJRWMD agricultural well were calculated based upon the number of permitted wells per permit, the permitted acres, and the irrigation application rate. The irrigation application rate was calculated based upon estimated ET requirements for each crop and the efficiency of the irrigation method (Florence and Moore 1997). Three irrigation methods were assumed: (1) flood irrigation with 50% efficiency, (2) spray irrigation with 75% efficiency, and (3) drip irrigation with 80% efficiency. Therefore, this methodology assumes that the crop irrigation requirement is a percentage of the total amount withdrawn. For example, a nursery using spray irrigation withdraws 1.333 times (1/0.75) the amount needed by the crop.

For projects that irrigate with both groundwater and surface water, the calculation included the number of permitted surface water pumps. The resulting pumpage attributed to surface water use was not included in the model. For some crops in some counties, the resulting total estimated agricultural withdrawal did not reasonably match the total groundwater withdrawal reported for that crop in Florence and Moore (1997). The assumption was made that this discrepancy is primarily because an agricultural project's permitted acres are often different than its actual irrigated acres. Therefore, for those crops, the acreage value used in the withdrawal calculation was adjusted by a factor such that the total acreage by crop for each county was similar to the corresponding acreage reported by Florence and Moore (1997). Average 1995 agricultural water use data for SFWMD and SWFWMD were supplied by each water management district on a well-by-well basis. Therefore, no distribution of withdrawals was needed for these estimates. SFWMD also supplied additional average 1995 agricultural withdrawal estimates on a grid cell-by-grid cell basis. These withdrawals represent irrigation projects not included in the SFWMD database because of their small size or because a permit is not required.

Wells identified in consumptive use permit files or consultant reports as used only for backup purposes were included in the well file, but assigned an average 1995 flux of zero. This group includes those identified with several consumptive use permits contained within the area supplied by the Conserve II project's reclaimed water sprayfields.

The locations of self-supplied domestic withdrawals from the Floridan aquifer system were incorporated into the model using a GIS to compare 1995 land use, public-water supply service area boundaries, and public-supply well locations (see discussion below for recharge estimation). Countywide withdrawal rates for Floridan aquifer system self-supplied pumpage were obtained from Vergara (1998) and Marella (1999) (Table 3). For most of the counties represented in the ECF model, these rates were divided evenly among the model grid cells identified as having self-supplied domestic withdrawals. As mentioned above, Brevard County self-supplied domestic withdrawals were assumed to be derived from the surficial aquifer system. Only small portions of Polk and Marion counties are within the model domain. Therefore, the average self-supplied domestic pumpage rate computed for Lake, Orange, Osceola, Seminole, and Volusia counties was applied to self-supplied domestic cells in these two counties.

Groundwater withdrawals were apportioned to model layers 2, 3, and 4 by comparing each well's reported casing and total depths (where available) to the associated layer tops and bottoms for the corresponding model grid cell and assigning the withdrawal to the appropriate layer. Wells with no available casing and total depth information were assumed to be completed only within the upper portion of the Upper Floridan aquifer (layer 2). Most of the wells lacking depth data are used for agricultural or commercial/industrial uses; depth information was available for 82% of public-supply wells. All pumpage located and estimated on a grid cell-by-grid cell basis, such as self-supplied domestic and SFWMD below-database threshold withdrawals, were assigned to model layer 2. Withdrawals from wells open to more than one layer were distributed evenly among the corresponding layers. Withdrawals from layer 2 are the most widespread (Figure 30), and they also constitute the largest percentage of average 1995 pumpage (62%). Layer 3 withdrawals (Figure 31) constitute 20% of total 1995 pumpage. Layer 4 withdrawals (Figure 32), which are used mainly for public supply in the Orlando metropolitan area, make up 18% of the total 1995 pumpage. Wells open to both the Upper Floridan aquifer and the Lower Floridan aquifer (either layers 3 and 4 or all three Floridan aquifer system layers) comprise only a very small percentage (less than 1%) of the total number of wells, with an estimated total 1995 withdrawal rate of 13 mgd.

Artificial Recharge From Drainage Wells

Recharge to the Upper Floridan aquifer from drainage wells was also simulated using the MODFLOW Well Package. Drainage well locations were determined using the database developed by CH2M HILL (1997). Recharge was applied only to those wells identified as active in that inventory. Drainage wells with an unknown status are distributed over approximately the same area as the active wells (see Figure 16). Therefore, the error associated with prescribing recharge to only the active drainage wells is probably insignificant.

The average 1995 flows to these wells were estimated by adjusting the calculated long-term average recharge rate attributed by CH2M HILL (1997) to each drainage well type using 1995 rainfall data. This adjustment was carried out by determining the ratio of the 1995 rainfall total attributed to each model grid cell to the long-term average annual rainfall for Orlando (50.80 in/year, Rao et al. 1997). For street runoff drainage wells, the calculated long-term average recharge rate of 7.09 mgd (CH2M HILL 1997, Table 12) was first divided equally among the 104 active street runoff wells. The

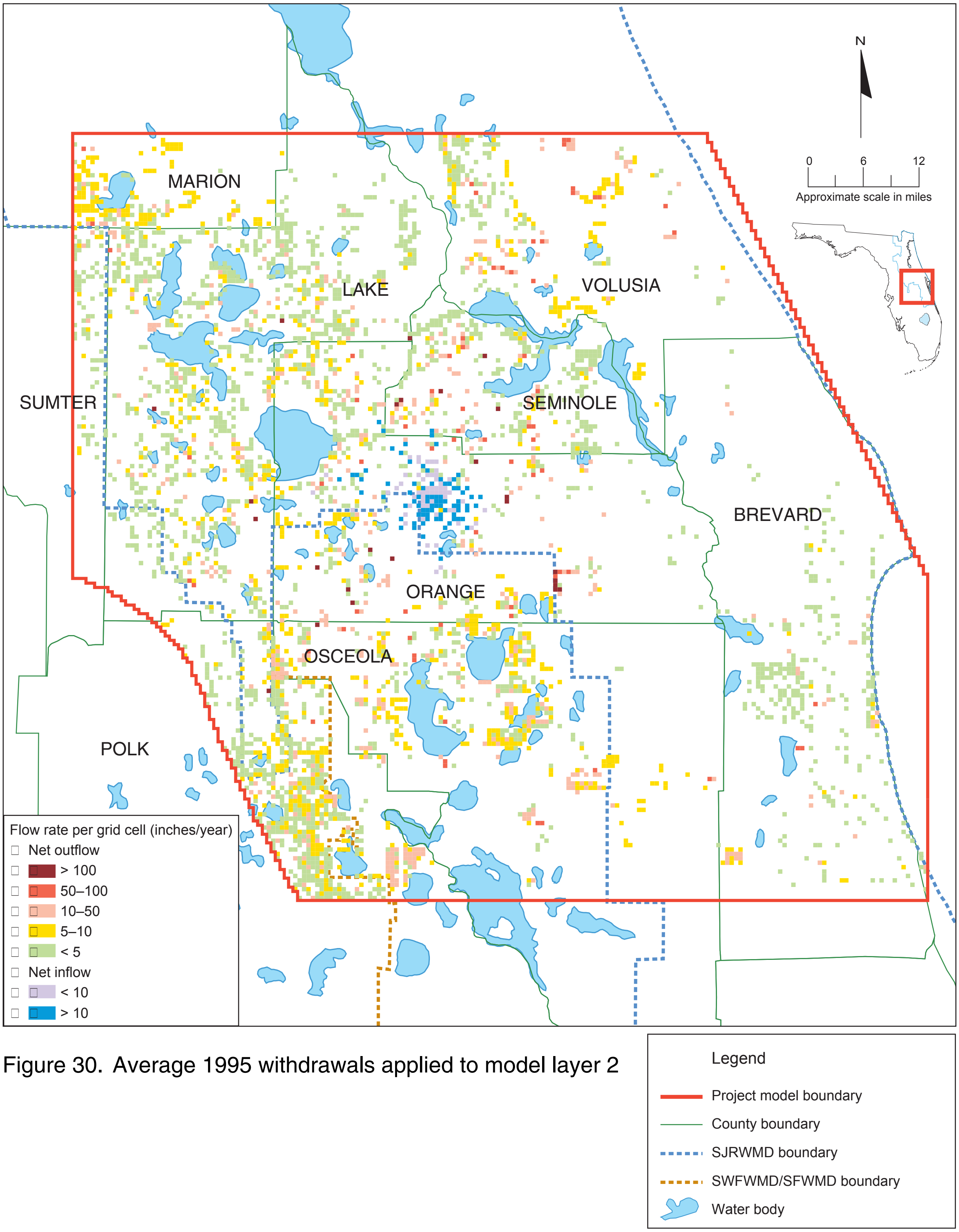


Figure 30. Average 1995 withdrawals applied to model layer 2

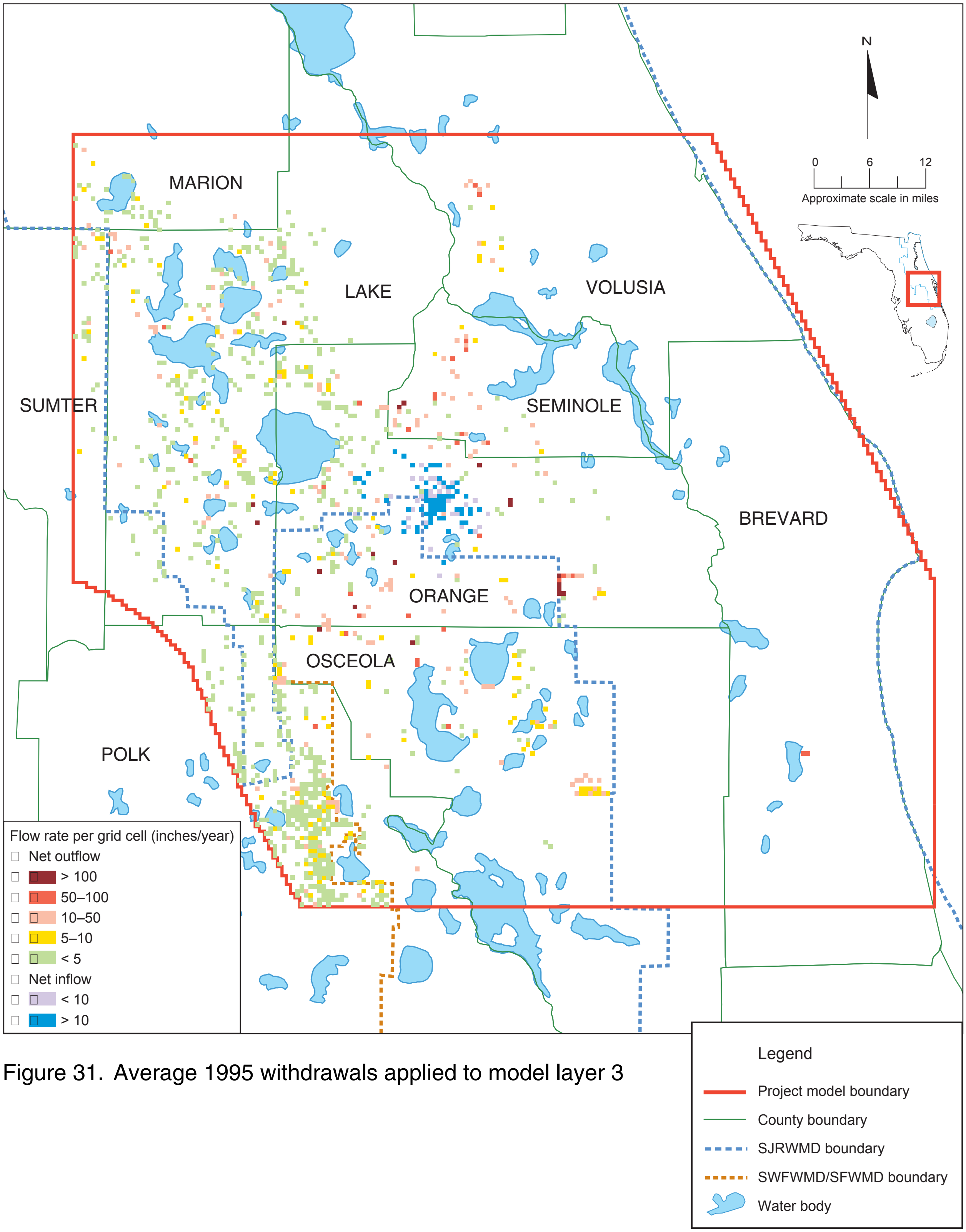


Figure 31. Average 1995 withdrawals applied to model layer 3

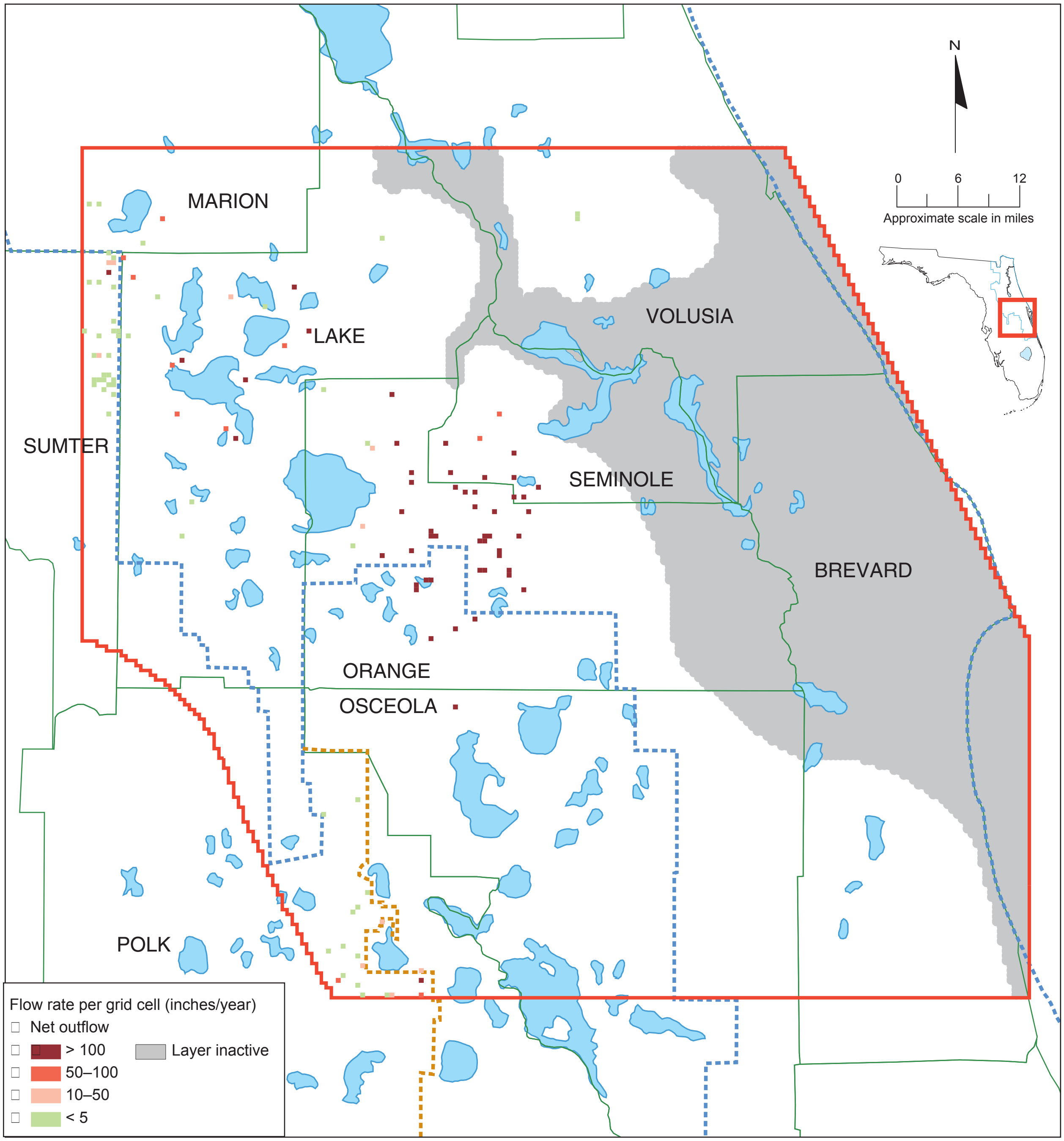


Figure 32. Average 1995 withdrawals applied to model layer 4

Legend

- Project model boundary
- County boundary
- SJRWMD boundary
- SWFWMD/SFWMD boundary
- Water body

resulting flow rate was then multiplied by the rainfall ratio. The total recharge applied to street runoff wells totaled 6.2 mgd. The remaining 110 wells were identified as used for either lake outflow, wetland outflow, or wet pond outflow. The median of the range of estimated recharge through these wells (CH2M HILL 1997, Table 11) was divided equally among the wells. This value was then adjusted for 1995 measured rainfall in the same fashion used to assign recharge to the street runoff wells. Due to the complexity of individual lake drainage basin hydrology, estimates of recharge through these wells are not considered as accurate as those for street runoff wells. Therefore, applied recharge at corresponding model grid cells was adjusted during calibration.

Recharge Applied to the Surficial Aquifer System

Recharge to the surficial aquifer system was applied directly as a prescribed flux to model layer 1 using the MODFLOW Recharge Package. Recharge rates were estimated by developing an algorithm that incorporates the appropriate portions of the following steady-state water budget for the surficial aquifer system:

$$P + R_{rib} + R_{septic} + R_{app} + L_{up} + Q_{swb} = ET_{unsat} + ET_{sat} + L_{down} + R_u + Q_{riv} \qquad \textbf{(9)}$$

where

P = precipitation
R_{rib} = water applied to rapid infiltration basins (RIBs)
R_{septic} = septic tank effluent
R_{app} = water applied to the land surface as irrigation
L_{up} = upward leakage from the Upper Floridan aquifer to the surficial aquifer system
Q_{swb} = groundwater flow from surface water bodies to the surficial aquifer system
ET_{unsat} = evapotranspiration from the unsaturated zone
ET_{sat} = evapotranspiration from the saturated zone
L_{down} = downward leakage from the surficial aquifer system to the Upper Floridan aquifer
R_u = overland runoff
Q_{riv} = groundwater discharge rate from the surficial aquifer system to surface water bodies (areally averaged)

(Units for all terms are in inches per year.)

Five of the terms contained in Equation 9 are flows that are simulated by the ECF model. The terms L_{up} and L_{down} are calculated by the ECF model for each grid cell as flow between layers 1 and 2. Q_{swb} is calculated by the ECF model as flow from constant-head cells to layer 1, and Q_{riv} is calculated either by the River Package or as flow from layer 1 to constant-head cells. ET_{sat} is calculated by the ECF model using the MODFLOW ET Package as described previously. Total 1995 values for each of the six other terms in Equation 9 were estimated for each grid cell and distributed across the active model domain.

Precipitation (*P*): Daily rainfall data from 59 stations with complete records for 1995 were tabulated and distributed spatially to grid cells using the Thiessen polygon method (Figure 33). The rainfall polygons were estimated using a larger set of rainfall data stations that also encompassed the Volusia County regional model domain (Williams 2002). In both models, each grid cell is associated with a particular rainfall station for which the 1995 daily rainfall totals were tabulated.

Flow to rapid infiltration basins (R_{rib}): Flow through RIBs was assumed to pass through the unsaturated zone to the surficial aquifer system without losses due to ET. Locations and application rates for R_{rib} estimates were obtained from municipalities and utilities within the region. Some depressional lakes in the Deltona area of southwestern Volusia County that receive focused runoff were conceptualized as RIBs in the same manner as the Volusia County and Vicinity model (Williams 2002). Estimated R_{rib} application rates per grid cell range from 2.0 in / yr to greater than 350 in / yr at Conserve II, located along the Orange County–Lake County border south of Lake Apopka (Figure 34). Modelwide, total 1995 RIB application was estimated at 42.5 mgd.

Septic tank effluent (R_{septic}): The spatial distribution of septic tank effluent was estimated using a GIS by comparing 1995 land-use polygons with public-water supply service area boundaries and the locations of public-water supply wells. Model grid cells where residential, commercial, or institutional land-use polygons cover more than approximately 25% of the cell's area, but are not included within a public-water supply service area boundary (or within the same grid cell as a public supply well representing a small public supply not associated with a public-water supply service area) were assumed to have (1) self-supplied domestic withdrawals from the Floridan aquifer system and (2) septic tank effluent (R_{septic}). The R_{septic} flow rate was assumed to equal 50% of the estimated self-supplied domestic well withdrawal rate

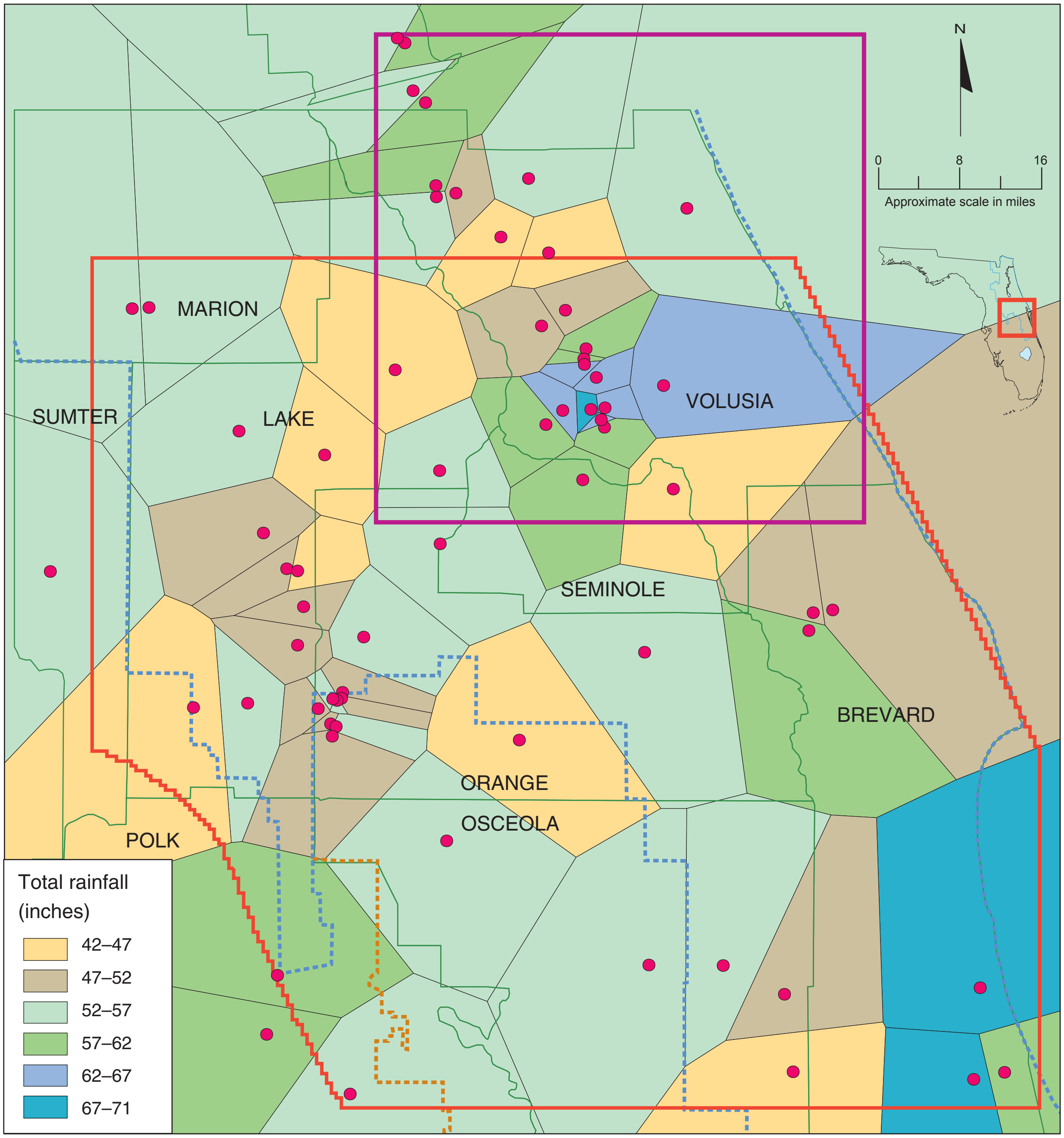


Figure 33. Theissen polygon distribution of total rainfall for 1995

Legend
- Rainfall station with complete data for 1995
- Volusia County and vicinity model boundary
- Project model boundary
- County boundary
- SJRWMD boundary
- SWFWMD/SFWMD boundary

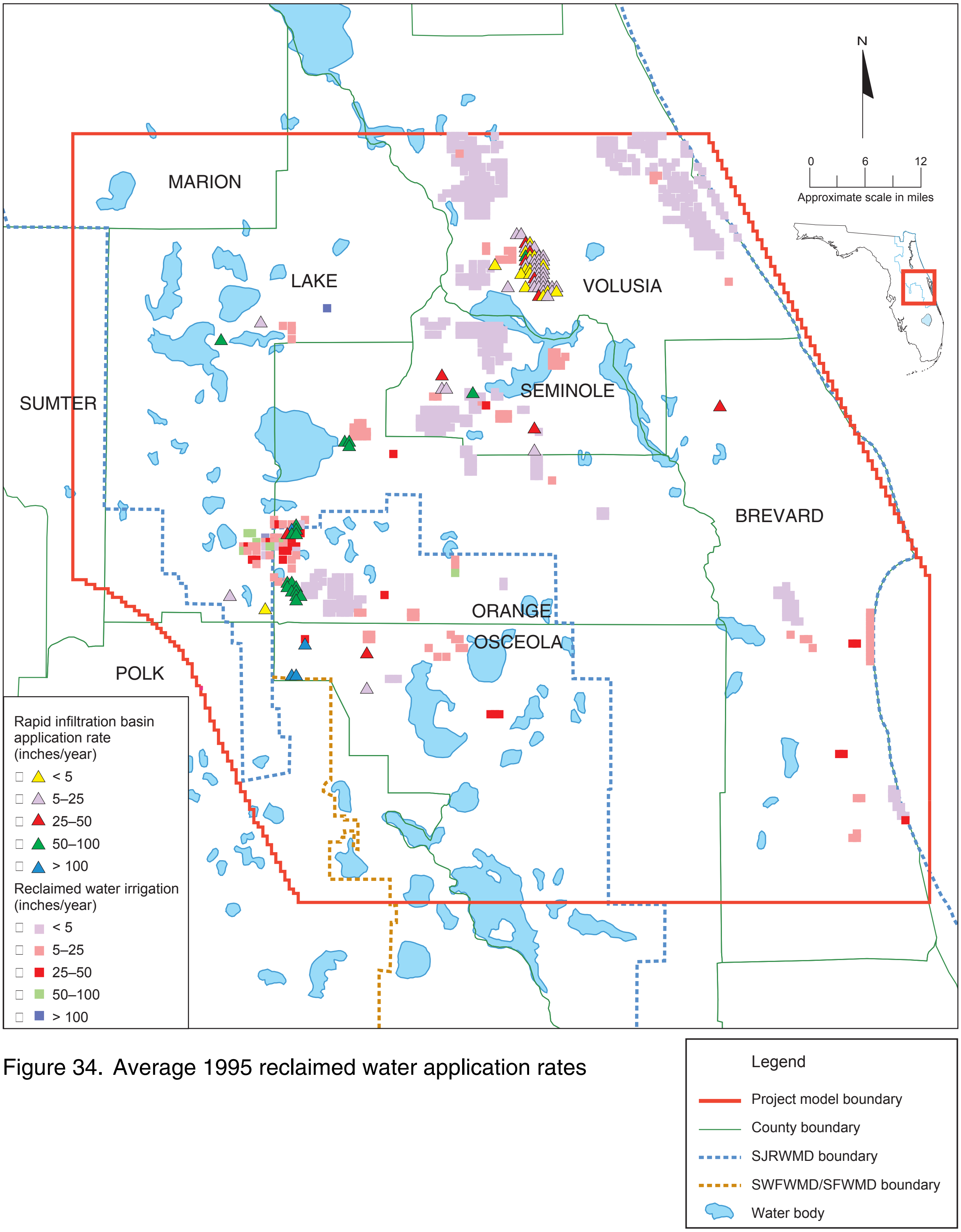


Figure 34. Average 1995 reclaimed water application rates

assigned to the cell. The resultant daily volumetric rate was then averaged over the cell's area and converted to a linear flux in inches per year.

The assumptions inherent in this procedure are (1) the available 1995 land use GIS coverage is sufficient to identify the spatial distribution of septic tanks, (2) wastewater service areas are essentially equivalent to public-water supply service areas, and (3) septic tank usage is associated with self-supplied domestic well withdrawal from the Floridan aquifer system. Two exceptions were made to this methodology. First, significant septic tank usage is known to occur within Deltona's public-water supply service area in southwestern Volusia County. Separate estimates of R_{septic} locations and rates were obtained for this area (S.A. Williams, SJRWMD, pers. com. 2001). Second, R_{septic} fluxes were not applied to model grid cells in Brevard County because in that county, self-supplied domestic well withdrawal was assumed to be derived solely from either the surficial aquifer system or the intermediate confining unit. R_{septic} flow rates range from 0.4 in / yr per cell to 4.9 in / yr per cell (Figure 35) and total 28.5 mgd modelwide.

Applied irrigation (R_{app}): Water applied to the land surface as irrigation is composed of four components:

$$R_{app} = R_{ag} + R_{spray} + R_{psli} + R_{ssdli} \qquad \textbf{(10)}$$

where

R_{ag} = agricultural and golf course irrigation derived directly from Floridan aquifer system groundwater withdrawal
R_{spray} = landscape irrigation or sprayfield irrigation derived from reclaimed water distribution systems
R_{psli} = landscape irrigation using water derived from Floridan aquifer system public-water supply withdrawal
R_{ssdli} = landscape irrigation derived from Floridan aquifer system self-supplied domestic well withdrawal

(Units for all terms are in inches per year.)

Agricultural and golf course irrigation (R_{ag}) values equal 100% of the Floridan aquifer system groundwater withdrawal for irrigation estimated for each model grid cell. Average 1995 R_{ag} values per grid cell range from less than 0.1 in / yr to 123 in / yr (Figure 36) and total 159.0 mgd modelwide. The spatial distribution of irrigation using reclaimed water (R_{spray}) and water derived from Floridan aquifer system public-water supplies (R_{psli}) was estimated using

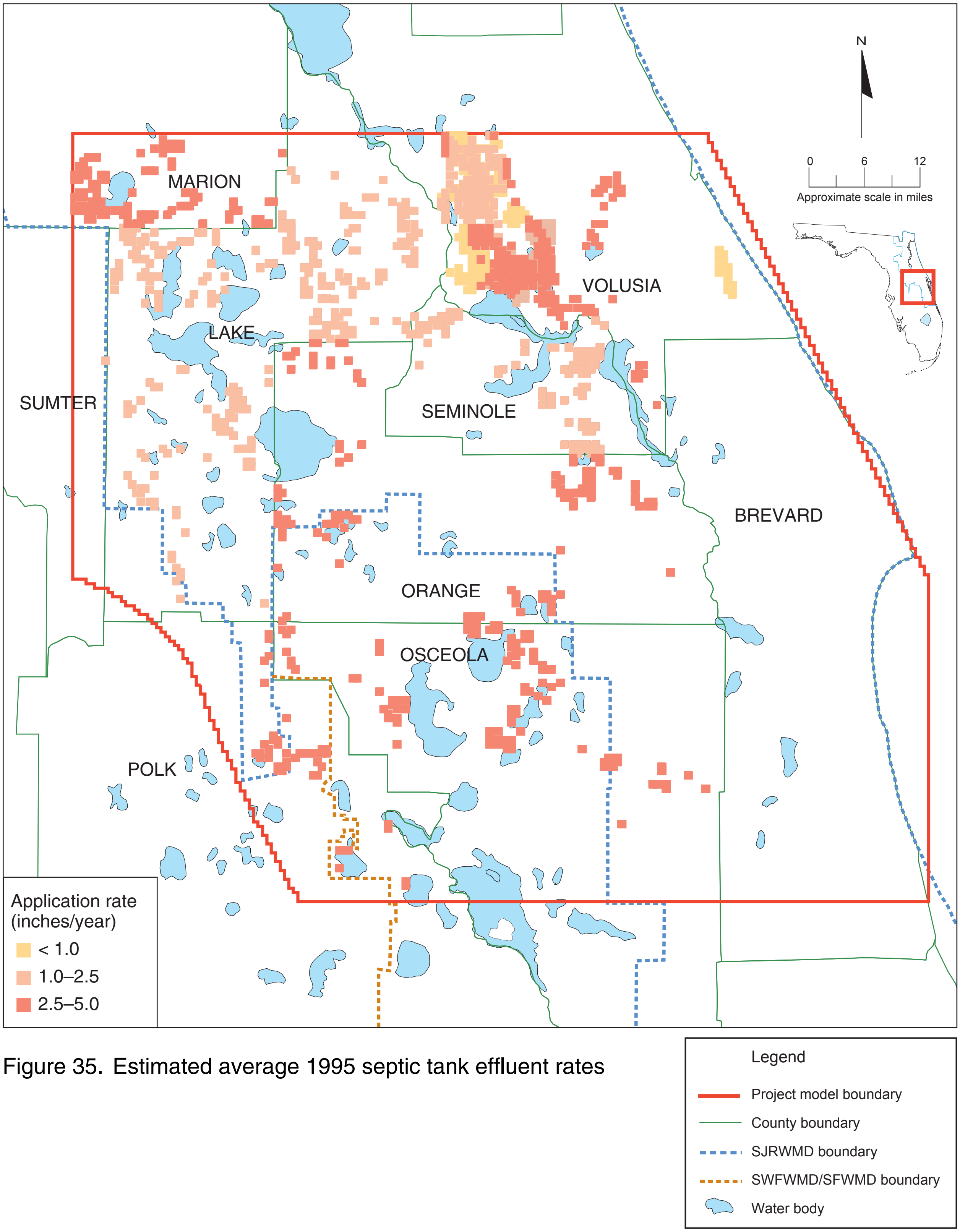


Figure 35. Estimated average 1995 septic tank effluent rates

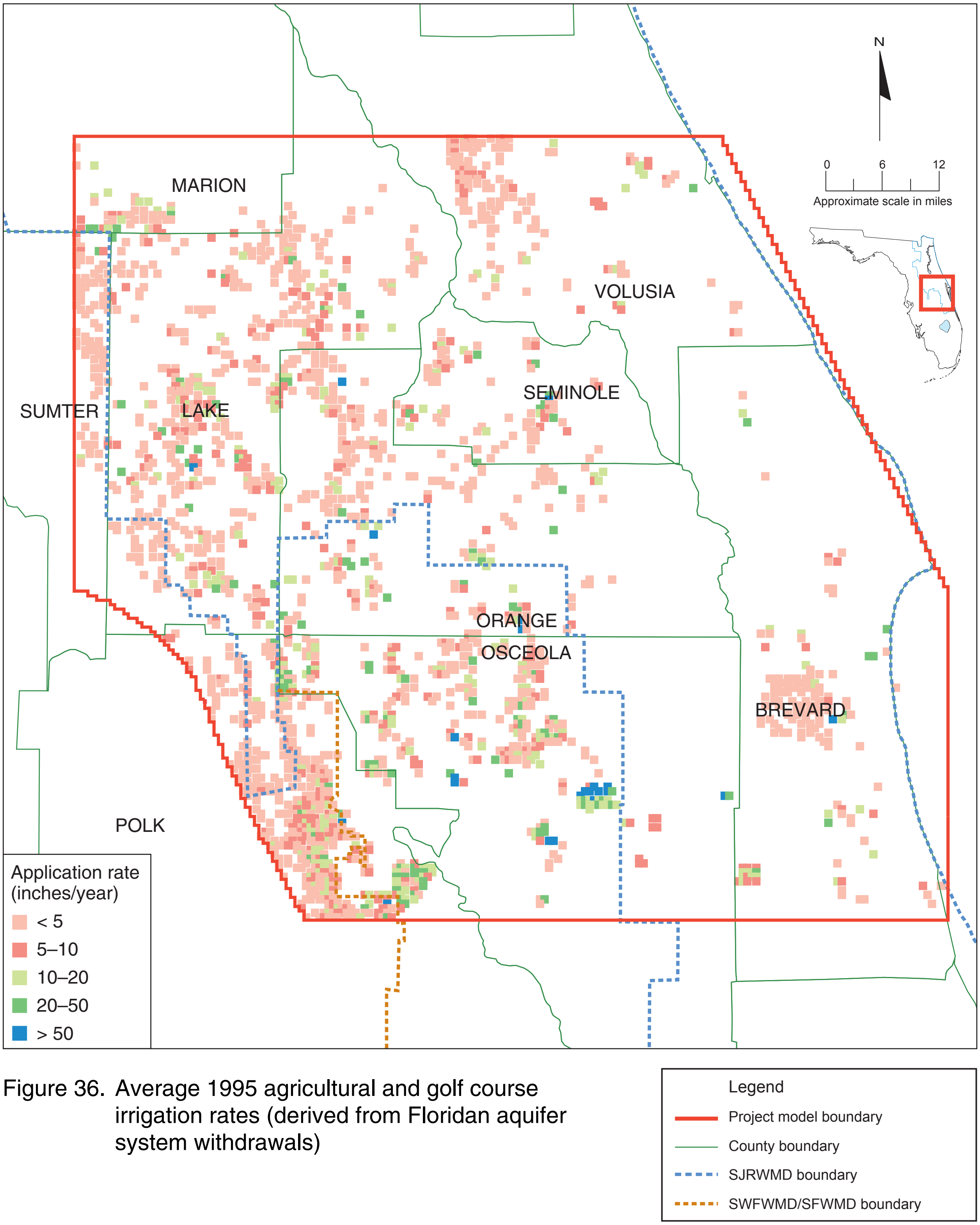


Figure 36. Average 1995 agricultural and golf course irrigation rates (derived from Floridan aquifer system withdrawals)

procedures similar to that used for R_{septic}. For R_{spray}, average daily reclaimed water flow rates were obtained for wastewater facilities throughout the project area by the District's Water Supply Management Division. For Conserve II (the large-scale reclaimed water distribution facility located along the border between southwestern Orange County and southeastern Lake County), detailed flow rates and distribution (turnout) locations were also obtained (PBWater, written com. 1999). Additional detailed R_{spray} flow rates and distribution locations were available for the Reedy Creek Improvement District in southwestern Orange County and northwestern Osceola County (Montgomery Watson 1996). Average 1995 flow rates are listed in Appendix E according to reuse category. Using maps of each facility's location and service area (where available), plus GIS 1995 land-use coverages, these flow rates were distributed evenly among those model grid cells containing the appropriate land use. Average 1995 R_{spray} values per grid cell range from 0.2 in / yr to 117 in / yr at Conserve II. Reclaimed water irrigation modelwide was estimated at 44.4 mgd. This total is less than the total listed in Appendix E because reclaimed water withdrawn from the surficial aquifer system was not included, the distribution systems of some wastewater utilities are located outside of the model boundary, and the sprayfield locations of some utilities are unknown.

Estimates of the percentage of most of the project area's public-water supply utility's 1995 average daily flow (ADF) that is used for landscape irrigation were obtained by the District's Water Supply Management Division via a utilitywide survey. The percentages ranged from approximately 13% to 60%. Utilitywide R_{psli} values were calculated by multiplying these percentages by each utility's ADF. The average of these percentages (39%) was used to estimate R_{psli} for those utilities not listed in the survey results but located within the model domain. The appropriate spatial distribution of R_{psli} was then determined by evenly distributing the resulting utilitywide values among those model grid cells containing residential, commercial, institutional, or recreational land use polygons within each public-water supply service area boundary. Average 1995 R_{psli} values per grid cell range from 0.1 in / yr to 11.1 in / yr (Figure 37). Summed over the model domain, the public supply landscape irrigation rate was 121.7 mgd.

The spatial distribution of landscape irrigation derived from Floridan aquifer system self-supplied domestic well withdrawal (R_{ssdli}) was estimated using the same procedure used for R_{septic}. The modelwide self-supplied domestic landscape irrigation rate was 20.3 mgd.

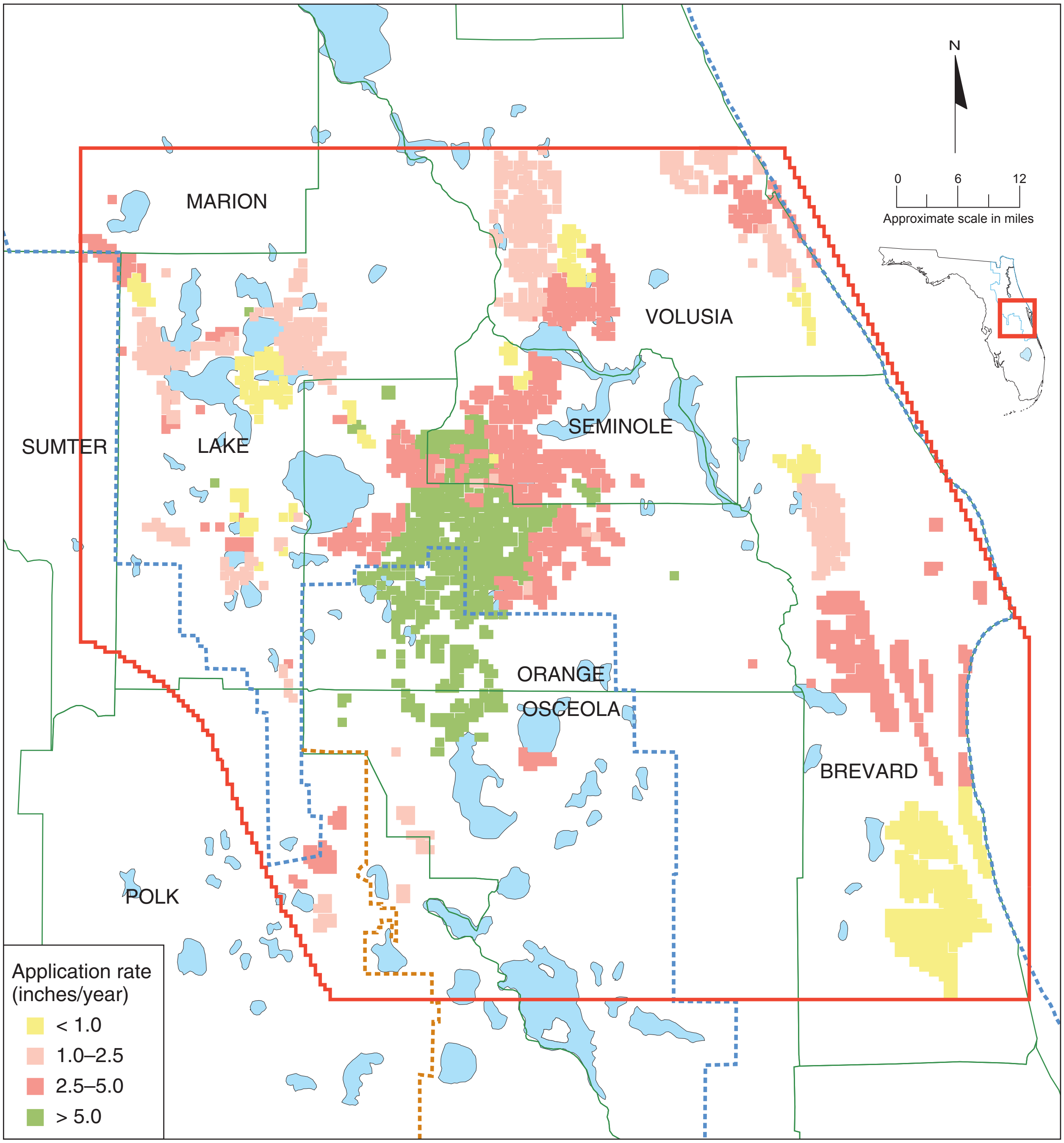


Figure 37. Average 1995 public-water supply landscape irrigation rates

Volumetric flow rates for R_{ag}, R_{spray}, R_{psli}, and R_{ssdli} were converted to linear flux rates (inches per year) in the same manner as septic tank effluent. At all applicable grid cells, the values for these four irrigation types were summed to obtain an estimate of applied irrigation (R_{app}). Average 1995 R_{app} values per grid cell range from less than 0.1 in / yr to 123 in / yr. The total applied irrigation rate modelwide equals 345.4 mgd.

Evapotranspiration from the unsaturated zone (ET_{unsat}): Both the rate of unsaturated zone ET and the net rate of recharge to the water table depend in part upon the thickness of the unsaturated zone. In order to estimate the unsaturated zone thickness, values for land-surface elevation and depth to high water table were computed using ARC / INFO grids of topography and water table depth. The latter grid was developed from detailed soil-survey maps and the corresponding depth to high water table recorded in county soil surveys. Three soil areas were identified and mapped based upon similar high water table depths (Figure 38):

- Soil Area 1—Water, wetlands, and any other lands where the high water table is less than or equal to 2 ft below land surface (bls)
- Soil Area 2—Land where the high water table is more than 2 ft bls, but within the soil horizon
- Soil Area 3—Land where the high water table is below the soil horizon

In soil area 1, ET_{unsat} was assumed to equal the minimum ET rate (ET_{min}) of 27 in / yr. Applied irrigation, therefore, is assumed to be applied directly to the water table surface in these areas. In soil areas 2 and 3, water applied as irrigation was assumed to be either evaporated or used by crops above the water table at most grid cells. However, at some grid cells in soil areas 2 and 3, the sum of ET_{min} plus R_{app} exceeded ET_{max}. At these cells, the portion of R_{app} greater than $ET_{max} - ET_{min}$ was assumed to reach the water table as recharge. During calibration, total modeled ET was calculated by adding simulated ET_{sat} and ET_{unsat} on a cell-by-cell basis; maps of total modeled ET were compared visually to the soil areas map (Figure 38).

Overland runoff (R_u): Runoff varies spatially according to topography, landcover, and soil type. R_u values for 1995 were estimated for each grid cell using a method similar to the U.S. Soil Conservation Service (SCS) curve number (CN) method (USDA 1986; Grove et al. 1998). Using 1995 land use data, a land use code was estimated for each grid cell. A CN value was also computed by combining the land use identifier with hydrologic soil group information using a methodology used by SWFWMD that is similar to the SCS method **(**M. Crowell, SWFWMD, written com. 1997**)**. The CN was used in

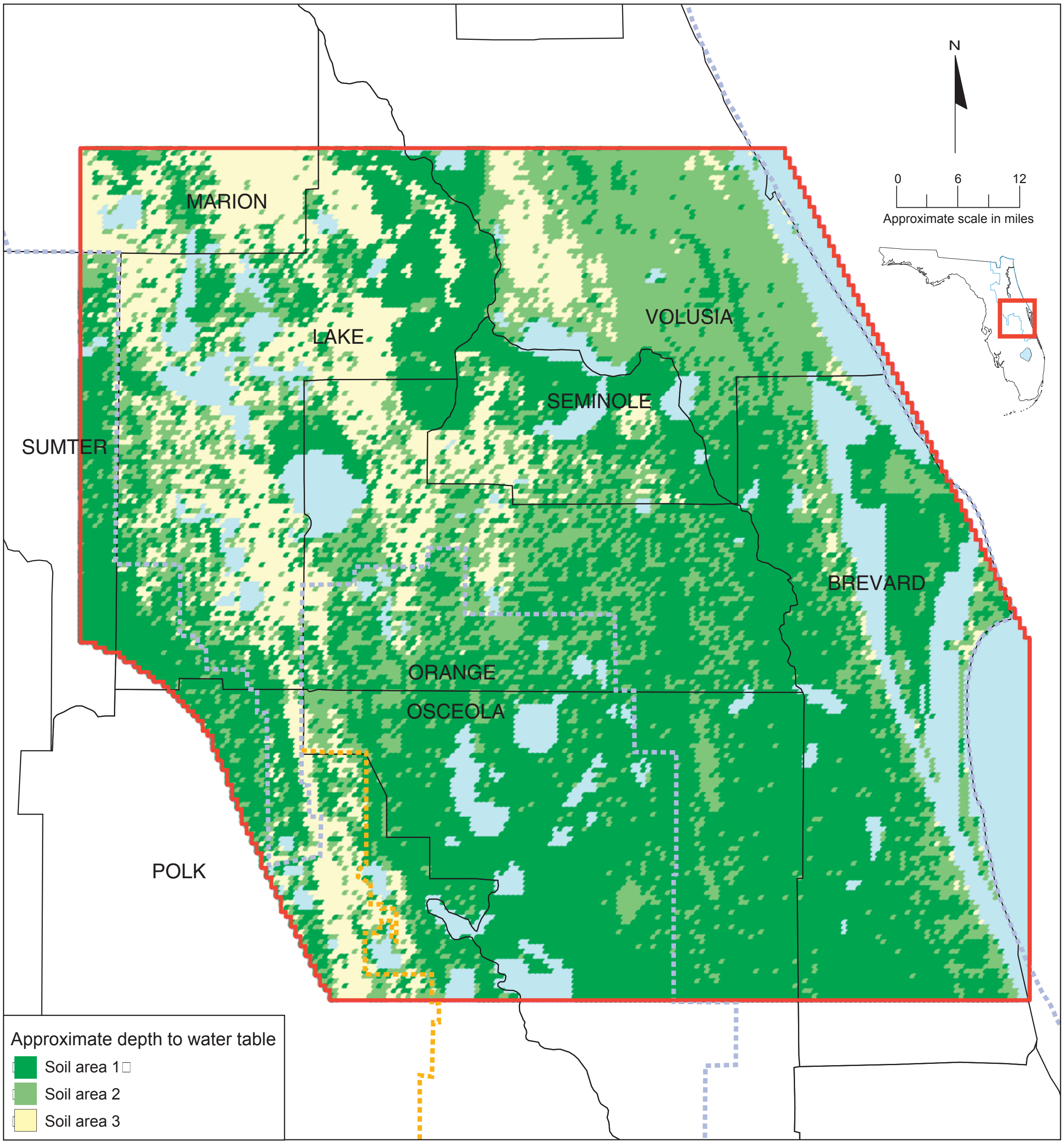


Figure 38. Soil area delineation, based upon estimated depth to the regional water table

conjunction with the corresponding daily rainfall station data to compute daily overland runoff estimates. Those estimates were then summed to produce 1995 R_u values for each grid cell. Average antecedent moisture conditions were assumed for the daily runoff calculations. It was recognized that, particularly in suburban areas, land use and hydrologic soil group can vary significantly within the area covered by a single model grid cell. Therefore, CN values were used to some extent as a calibration parameter. The spatial distributions of CN values (Figure 39) and total 1995 runoff (Figure 40) resemble the soil areas map of Figure 38.

Net recharge calculation: The net recharge rate to model layer 1 was calculated using one of two methodologies:

1. For areas with the water table at shallow depths (soil area 1):

$$N = \left(R_{mr} + R_{app} + R_{rib} + R_{septic}\right) - ET_{min} \qquad \textbf{(11)}$$

where

N = net recharge to the surficial aquifer system (inches / year)
R_{mr} = precipitation minus overland runoff ($P - R_u$)

or

2. For areas with an intermediate or deep water table depth (soil areas 2 and 3), one of two equations was used:

$$N = \left(R_{mr} + R_{rib} + R_{septic}\right) - ET_{min} \qquad \textbf{(12)}$$

where R_{app} is less than or equal to ($ET_{max} - ET_{min}$)

or

$$N = \left\{R_{mr} + R_{rib} + R_{septic} + \left[R_{app} - \left(ET_{max} - ET_{min}\right)\right] - ET_{min}\right\} \qquad \textbf{(13)}$$

where R_{app} is greater than ($ET_{max} - ET_{min}$)

A significant amount of applied irrigation was estimated to return to the groundwater system as recharge. For model grid cells in soil area 1, all irrigation is included as recharge. For these cells, the total estimated recharge due to irrigation equaled 112.5 mgd. For model grid cells located in soil

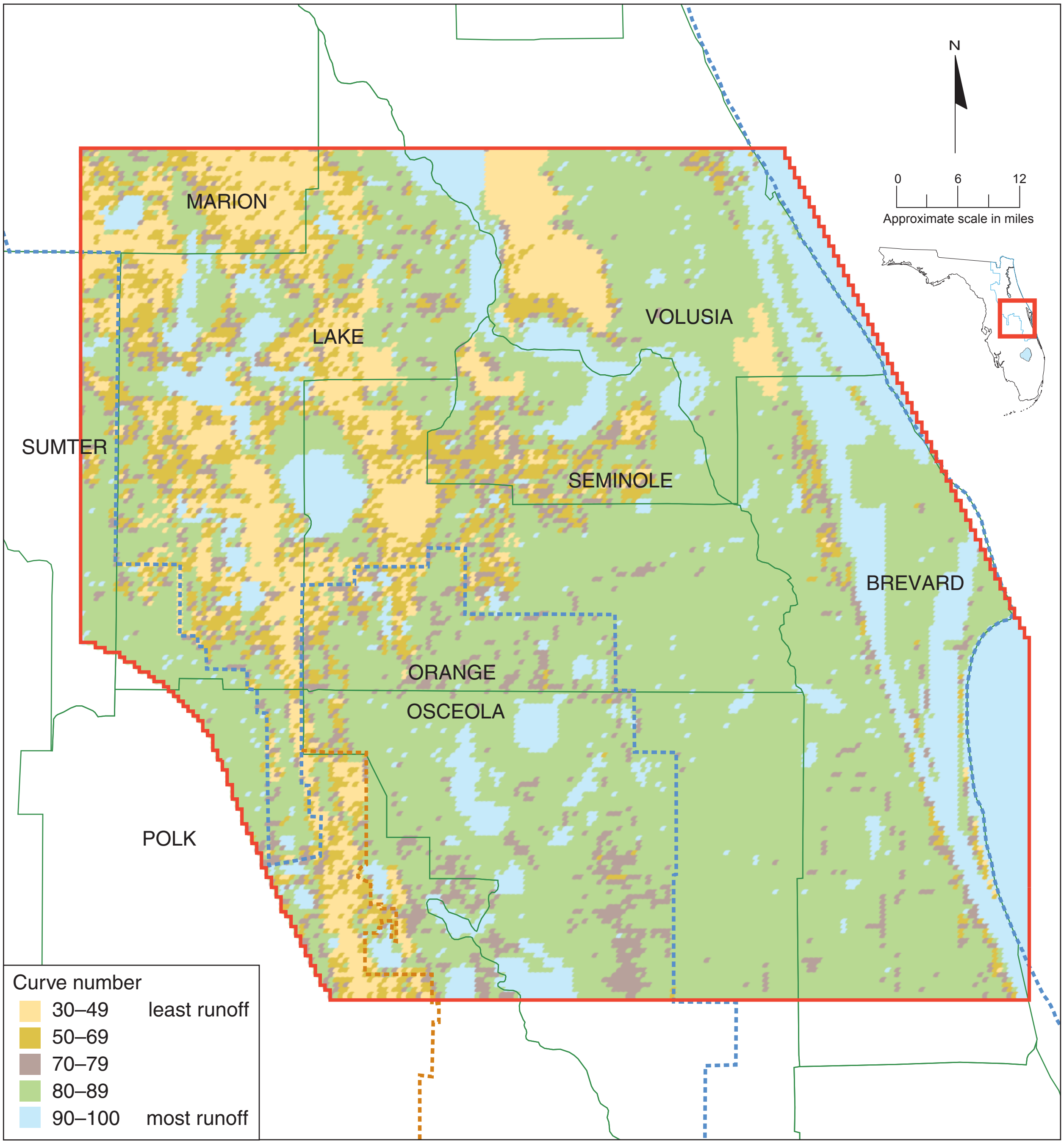


Figure 39. Soil Conservation Service curve numbers, used for estimation of total overland runoff

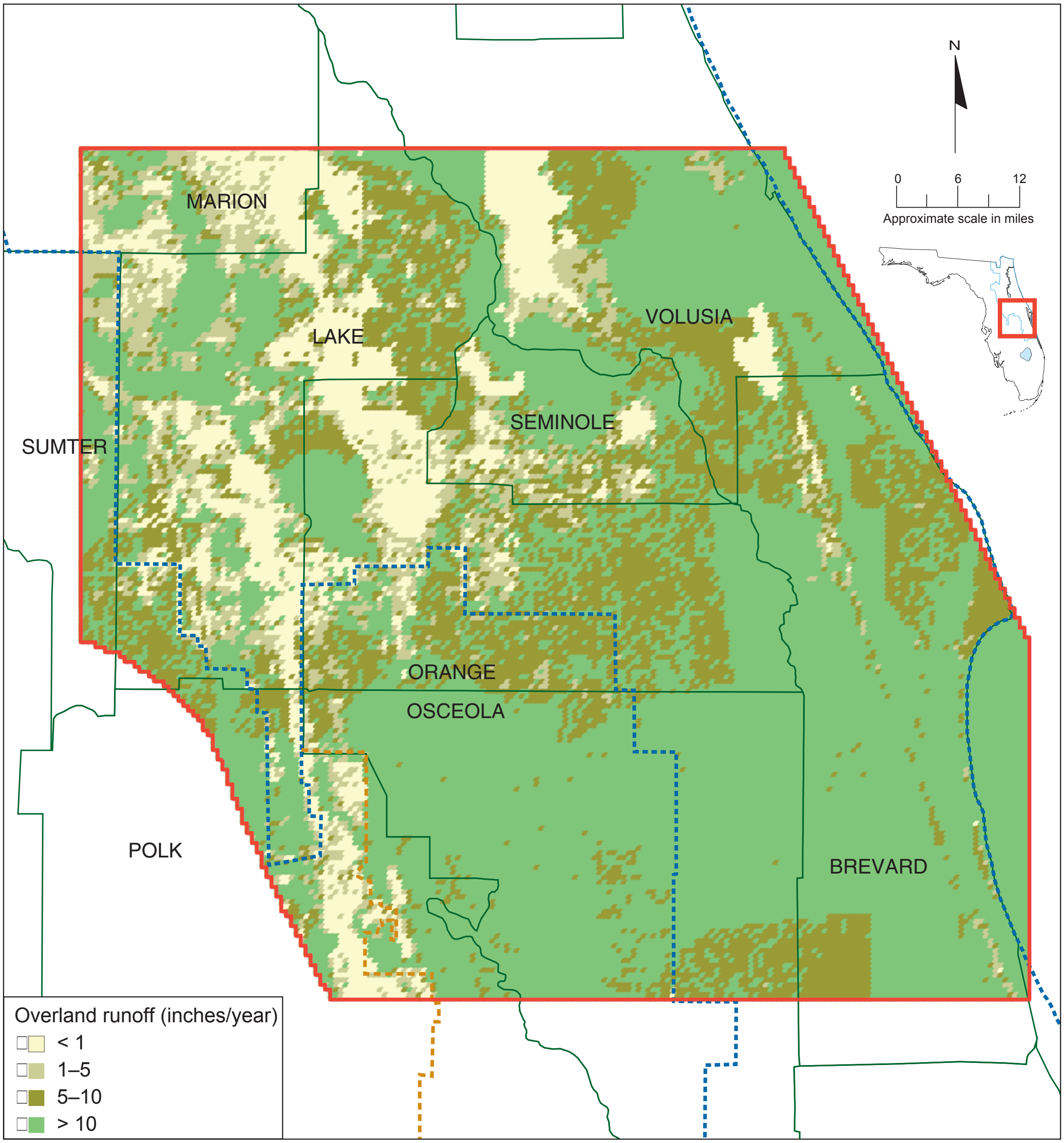


Figure 40. Total 1995 overland runoff

areas 2 and 3 where R_{app} was greater than the difference between ET_{max} and ET_{min}, an additional 18.5 mgd of recharge was derived from applied irrigation. Therefore, 131.0 mgd (38%) of the modelwide total irrigation rate of 345.4 mgd was assigned as recharge. The remaining irrigation withdrawal amount (214.0 mgd) was a component of ET_{unsat}. Modelwide, ET_{unsat} was estimated at approximately 7,400 mgd, or 28 in / yr.

The ultimate fate of most of the Floridan aquifer system withdrawals applied to the model was accounted for by the recharge algorithm and by totaling wastewater treatment plant flows (Appendix E). Agricultural and golf course irrigation withdrawals were accounted for in the recharge algorithm as described above. Thirty-nine percent of the ADF from public water supplies was used for lawn irrigation and also included in the recharge estimation process. The remaining 61% (approximately 196 mgd) is very close in magnitude to the total wastewater treatment plant ADF of 190 mgd listed in Appendix E. These wastewater discharges were, for the most part, included in the recharge algorithm as reclaimed water irrigation or RIB flows, discharged to surface water bodies either directly or indirectly through percolation ponds, or evaporated directly from surface water bodies. Self-supplied domestic withdrawals were incorporated into the recharge equations as either lawn irrigation or septic tank discharges. Self-supplied commercial, industrial, and recreational pumpage was assumed to be either discharged to surface water bodies or evaporated directly from surface water bodies. Abandoned free-flowing well discharges were assumed to flow directly to surface water bodies.

The same values for R_{mr}, ET_{min}, and ET_{max} were used for both the predevelopment and average 1995 simulations. For predevelopment conditions, R_{app}, R_{septic}, and $R_{rib} = 0$. The resulting spatial distribution of 1995 recharge applied to the surficial aquifer system (model layer 1) shown by Figure 41 is affected mainly by the spatial distribution of 1995 rainfall (Figure 33) and the soil areas (Figure 38).

Aquifer and Confining Unit Characteristics

Input data representing hydrostratigraphy, such as aquifer layer and confining unit top and bottom elevations, were initially estimated from various sources and assigned to model grid cells. After initial adjustments were made to some arrays, these elevation data were not changed during calibration. Initial arrays representing the top of the middle semiconfining unit, the top of the Lower Floridan aquifer (Figure 13), and the bottom of the

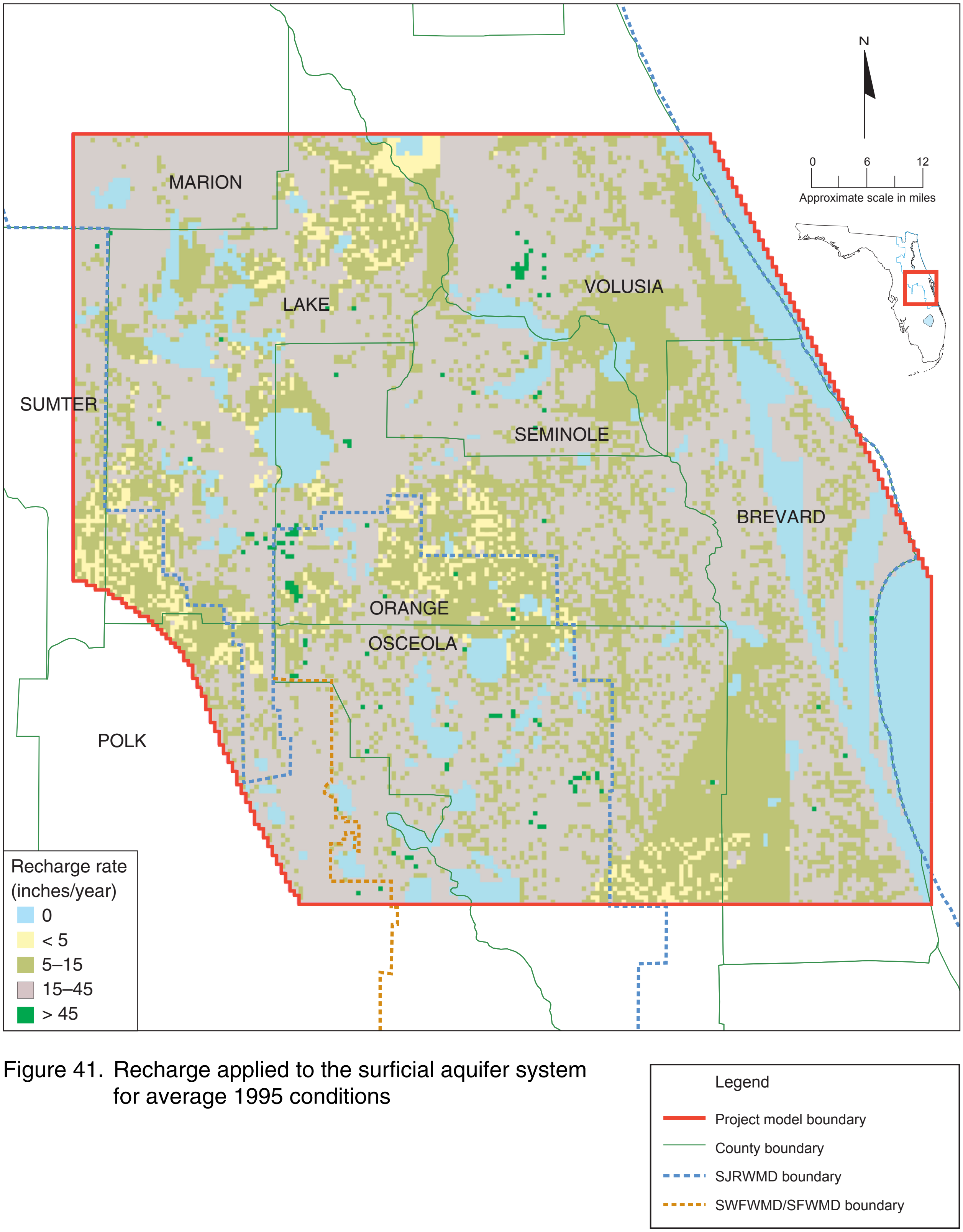


Figure 41. Recharge applied to the surficial aquifer system for average 1995 conditions

Lower Floridan aquifer (Figure 14) were derived from digitized contour maps of the corresponding plates of Miller (1986). As described previously, digital maps representing the top of the dolostone zone (layer 3, Figure 11) and the revised top of the middle semiconfining unit (Figure 12) were prepared using point data from various consultant reports, unpublished data from SJRWMD (2000), and Florida Geological Survey files, as well as information from Wolansky et al. (1980).

Initial values for hydraulic conductivity of the aquifer layers and confining units were derived from calibrated transmissivity and leakance values that were assigned to the previous versions of the ECF model and the Wekiva River Basin model (Blandford and Birdie 1992 and GeoTrans 1992a, respectively). Initial parameter values were also derived by reviewing regional modeling reports that described areas of the domain not covered by those models. These reports include those by Grubb and Rutledge (1979), Tibbals (1990), Planert and Aucott (1985), Ryder (1985), HydroGeologic (1997), Yobbi (1996), McGurk (1998), Williams (1995, 1997), and O'Reilly (1998). Initial input values for layer 1 (surficial aquifer system) horizontal hydraulic conductivity were derived from both calibrated regional models (where available) and literature sources. Horizontal hydraulic conductivity values for layers 2, 3, and 4 were calculated from the transmissivity values using the following equation:

$$K_h = \frac{T}{b} \tag{14}$$

where

K_h = aquifer layer horizontal hydraulic conductivity (ft / day)

T = aquifer layer transmissivity derived from previous regional models (ft^2 / day)

b = aquifer layer thickness (ft)

Horizontal isotropy was assumed for all four model layers. That is, horizontal hydraulic conductivity was assumed to be equal in the row and column directions. No regional-scale data on horizontal anisotropy exist within the model area, and the assumption of isotropic conditions is consistent with previous models.

Vertical hydraulic conductivity values were also derived from regional models. Values for the intermediate confining unit and the middle semiconfining unit were calculated from available leakance values using the following equation:

$$K_z = L * b' \qquad \textbf{(15)}$$

where

K_z = vertical hydraulic conductivity (ft / day)
L = leakance (day^{-1})
b' = confining unit thickness (ft)

The K_z values were then used to calculate a conductance term (VCONT in the MODFLOW code) to represent the vertical connection between aquifer layers. For the conductance between layers 1 and 2 and between layers 3 and 4, VCONT is equivalent to the leakance values of the intermediate confining unit and the middle semiconfining unit, respectively. For the conductance between layers 2 and 3, the vertical conductance was calculated using the following equation:

$$\mathrm{VCONT}_{L2} = 1 \;/\; \{[(b_2 / 2) / K_{z2}] + [(b_3 / 2) / K_{z3}]\} \qquad \textbf{(16)}$$

where

$VCONT_{L2}$ = vertical conductance between layers 2 and 3 (day^{-1})
b_2 = thickness of layer 2 (ft)
b_3 = thickness of layer 3 (ft)
K_{z2} = vertical hydraulic conductivity of layer 2 (ft / day)
K_{z3} = vertical hydraulic conductivity of layer 3 (ft / day)

K_h values and aquifer and confining unit top and / or bottom elevations were input directly to the model. K_z values were used to calculate VCONT terms, which were then used for model input arrays.

STEADY-STATE MODEL CALIBRATION

Calibration Criteria and Targets

The predevelopment and 1995 calibration simulations were conducted in an iterative fashion until the differences between simulated and observed conditions were minimized for both time periods. For each calibration period, simulated potentiometric levels and simulated groundwater flow rates were compared to measured and estimated values. Hydraulic parameters that were adjusted most often during calibration were aquifer layer K_h and semiconfining unit K_z. These parameters were adjusted using the following criteria as guidelines:

1. The vertical anisotropy (K_h / K_z ratio) within layers 2 and 3 varies between approximately 100:1 and 1000:1.
2. The vertical anisotropy (K_h / K_z ratio) between Floridan aquifer system layers (2, 3, or 4) and the semiconfining units can be much greater than 1000:1.
3. Layer 3 K_h is greater than layer 2 K_h, except in Volusia County, where they are approximately equal, and in the vicinity of large springs, where layer 2 K_h is greater than layer 3 K_h.
4. K_z of the intermediate confining unit is generally higher in areas where karstic sinkhole depressions are abundant than in areas where no sinkhole depressions are apparent on 1:24,000-scale topographic maps.
5. Transmissivity values derived from aquifer tests generally represent the lower end of a reasonable range for model-scale values.
6. Simulated recharge to the Floridan aquifer system at any particular cell should not exceed a rate equal to ($P - ET_{min}$), except in cells dominated by karstic sinkhole depressions and surrounded by areas of higher topography, where infiltration of overland runoff from areas located in adjacent cells can cause higher recharge rates.
7. Layer 1 K_h is generally less than layer 2 K_h.

Additional parameters that were adjusted less often than those above include
- Aquifer layer K_z
- Spring conductance
- ET extinction depth
- Boundary heads along saltwater GHB boundaries
- River bed conductance
- Flow at lake-level control drainage wells
- Two terms used in the recharge estimation algorithm: ET_{min} and CN value

Calibration targets were both quantitative and qualitative. Targets included the following:
- Achieve an average absolute difference between average 1995 measured water levels from 203 Upper Floridan aquifer wells and simulated layer 2 and layer 3 water levels at corresponding grid cells of less than or equal to 2.50 ft.
- Achieve an average absolute difference between average 1995 measured water levels from 100 lakes and surficial aquifer system wells and

simulated layer 1 water levels at corresponding grid cells of less than 4.00 ft.

- Achieve a mean error for both layer 1 and layer 2 head residuals of less than ± 1 ft for the 1995 calibration.
- Minimize the root mean square error (standard deviation of the residuals) for both layers 1 and 2 for the 1995 calibration.
- Simulate average 1995 Upper Floridan aquifer spring flows within ± 10% at first- and second-magnitude springs (± 25% at submerged Apopka and Island springs).
- Approximate the shape and gradients expressed by the estimated predevelopment Upper Floridan aquifer potentiometric surface.
- Approximate the shape and gradients expressed by the estimated average 1995 Upper Floridan aquifer potentiometric surface.
- Approximate on a regional scale the spatial pattern of depth from land surface to the water table that is expressed by Figure 38.
- Approximate on a regional scale the spatial pattern of average water level values derived from measurements made at 32 Lower Floridan aquifer observation and production wells between 1995 and 1999.
- Approximate the estimated predevelopment Upper Floridan aquifer spring flows as well as possible.
- Simulate the magnitude and spatial distribution of the following fluxes as well as possible in comparison with previously published estimates:
  - Total ET
  - Recharge / discharge to / from the Upper Floridan aquifer
  - Lateral boundary flows within the Floridan aquifer system
  - Base flow to streams

The model was calibrated to average, 1995 steady-state conditions for the following reasons:

1. Model results will be used to evaluate the effects of long-term changes in average withdrawal rates from the Floridan aquifer system, rather than the short-term, transient effects of, for example, drought-induced pumping changes.
2. Seasonal rainfall patterns during 1995 were typical of average conditions (Figure 42), with the least rain falling during the winter and spring and the greatest rainfall amounts occurring in the summer. Water level and, in most cases, springflow measurements made during May and September reflect the lowest and highest values for the year, respectively. Therefore, averages of May and September data points reflect annual averages.

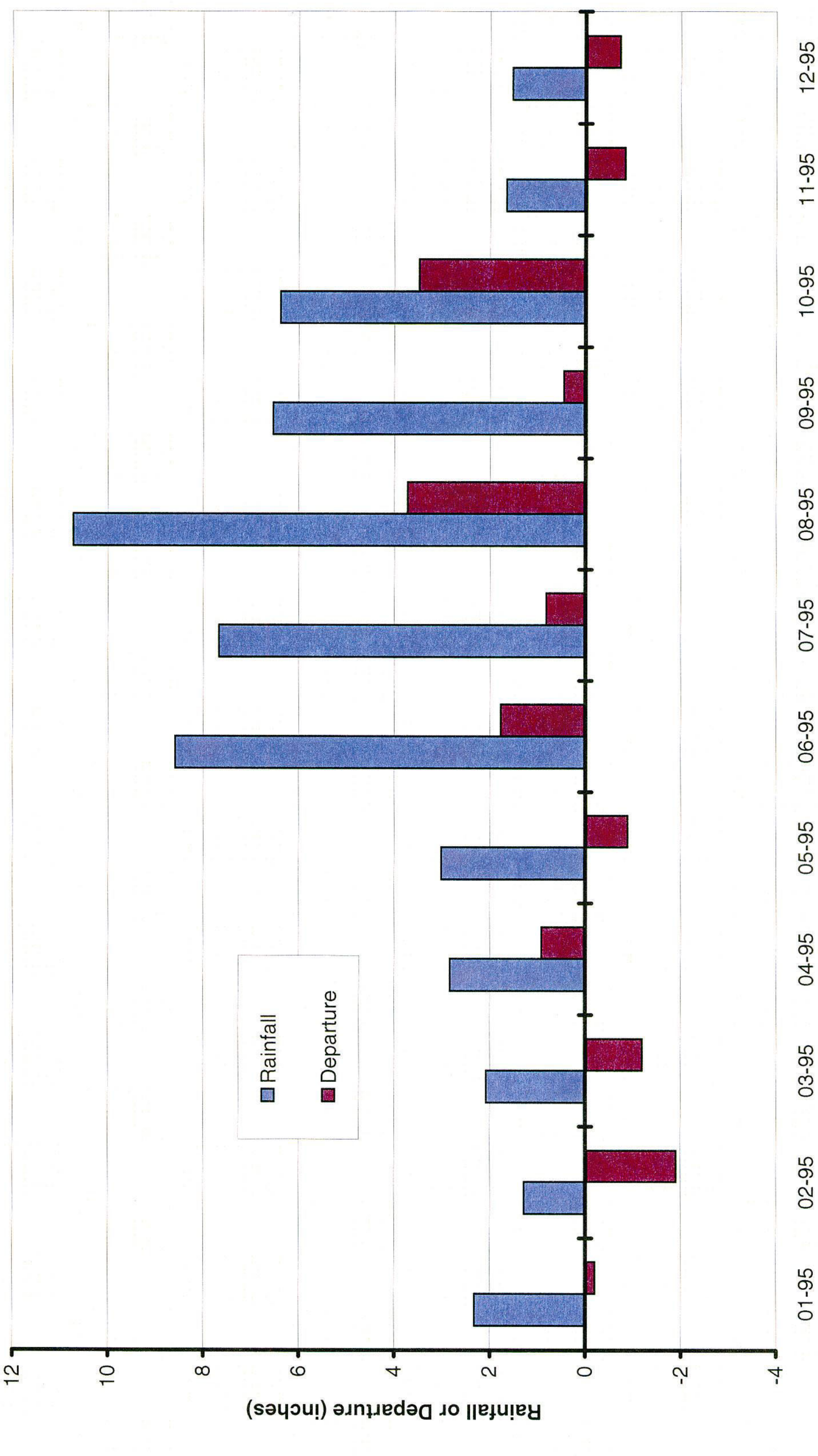


Figure 42. Average 1995 monthly rainfall and departure from normal at 12 NOAA stations

3. The averaged 1995 departures from normal rainfall for the 12 NOAA rainfall stations with available data within the project area were lower than the corresponding average departures for all years during the 1990s except for 1992, 1993, and 1998. Seasonal rainfall patterns in 1998, however, were not typical of average conditions. The winter months in 1998 were unusually wet and were followed by an extreme drought period with a dryer than normal summer. The 1995 calibration period was chosen rather than the calibration period for 1992 or 1993 because significantly more calibration data and detailed water use estimates were available for 1995.

Calibration Results

The calibrated model produces simulated water levels that are generally in agreement with measured values (Figures 43–46). Most of the large layer 1 residuals (Figure 47) are located along ridge areas where the majority of layer 1 data points are clustered. Large land surface elevation changes over short distances are common in these areas, causing significant grid-scale error at some of the data points. (Grid-scale error refers to the difference between the land surface elevation at a well point versus the calculated average land surface elevation for the corresponding grid cell.) Most of the larger Upper Floridan aquifer residuals occur in ridge areas as well (Figure 48), or they are located in areas of high horizontal gradient in the Upper Floridan aquifer potentiometric surface. The simulated 1995 water table elevations (Figure 49) mimic topography on a regional scale. The spatial pattern of depth from land surface to the 1995 water table (Figure 50) resembles the soil area map (see Figure 38). Surficial aquifer system water levels are, however, significantly different from observed data in several areas. The simulated water table is significantly below land surface in south-central Volusia County and in parts of the Upper St. Johns River Basin, particularly where River Package cells were located. The simulated water table is also significantly above land surface in scattered areas along the flanks of upland ridges or in some depressional lake areas within the upland ridges and in some wetland areas along the St. Johns River where River Package cells were not located.

The shape and horizontal gradients expressed by the simulated layer 2 potentiometric surface representing estimated predevelopment conditions (Figure 51) match the map produced by Johnston et al. (1980) fairly well. Similarly, the simulated 1995 layer 2 potentiometric surface (Figure 52) compares favorably with the average 1995 Upper Floridan aquifer potentiometric surface. The simulated 1995 layer 3 potentiometric surface

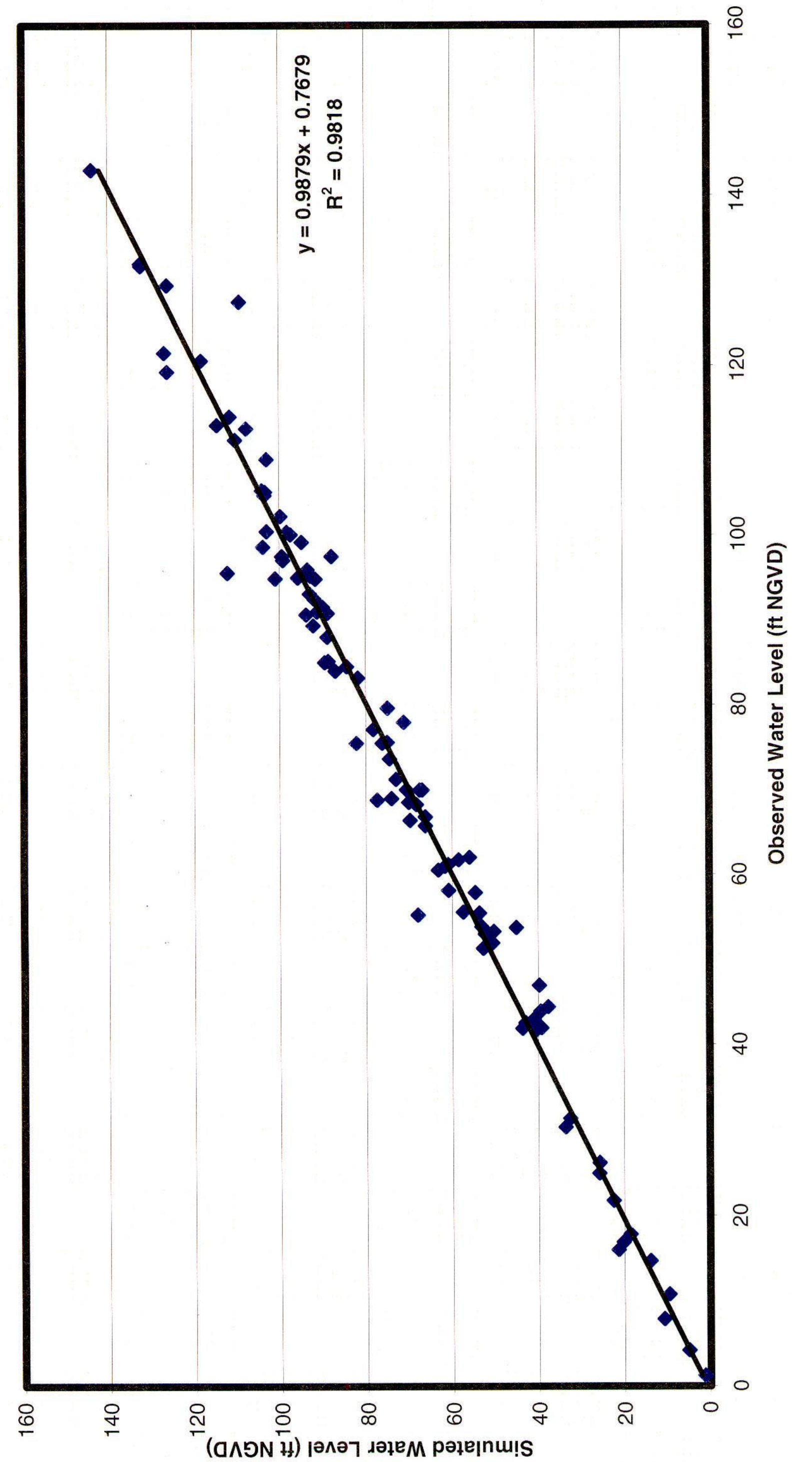


Figure 43. Observed versus simulated layer 1 (surficial aquifer system) water levels, average 1995 conditions

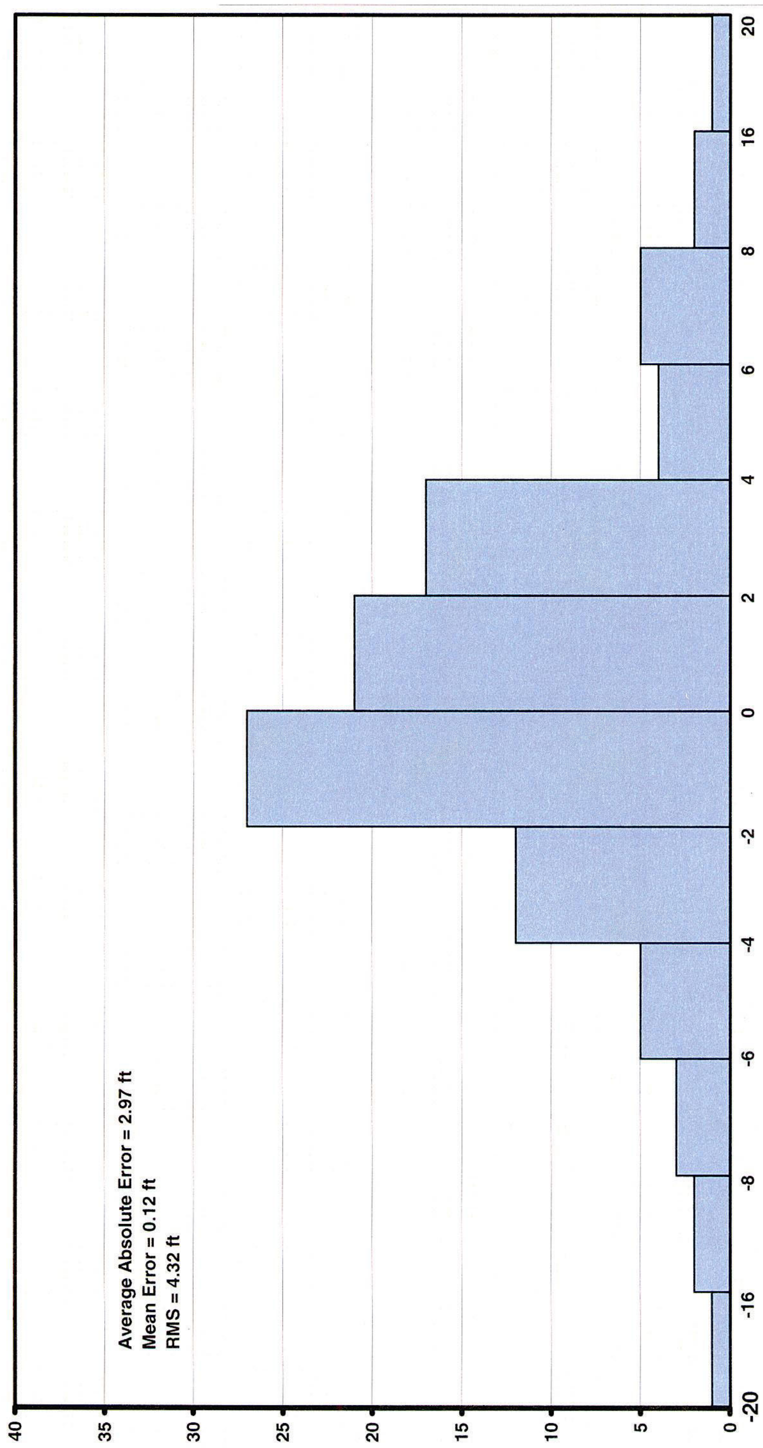


Figure 44. Layer 1 water level residuals for 1995 calibration

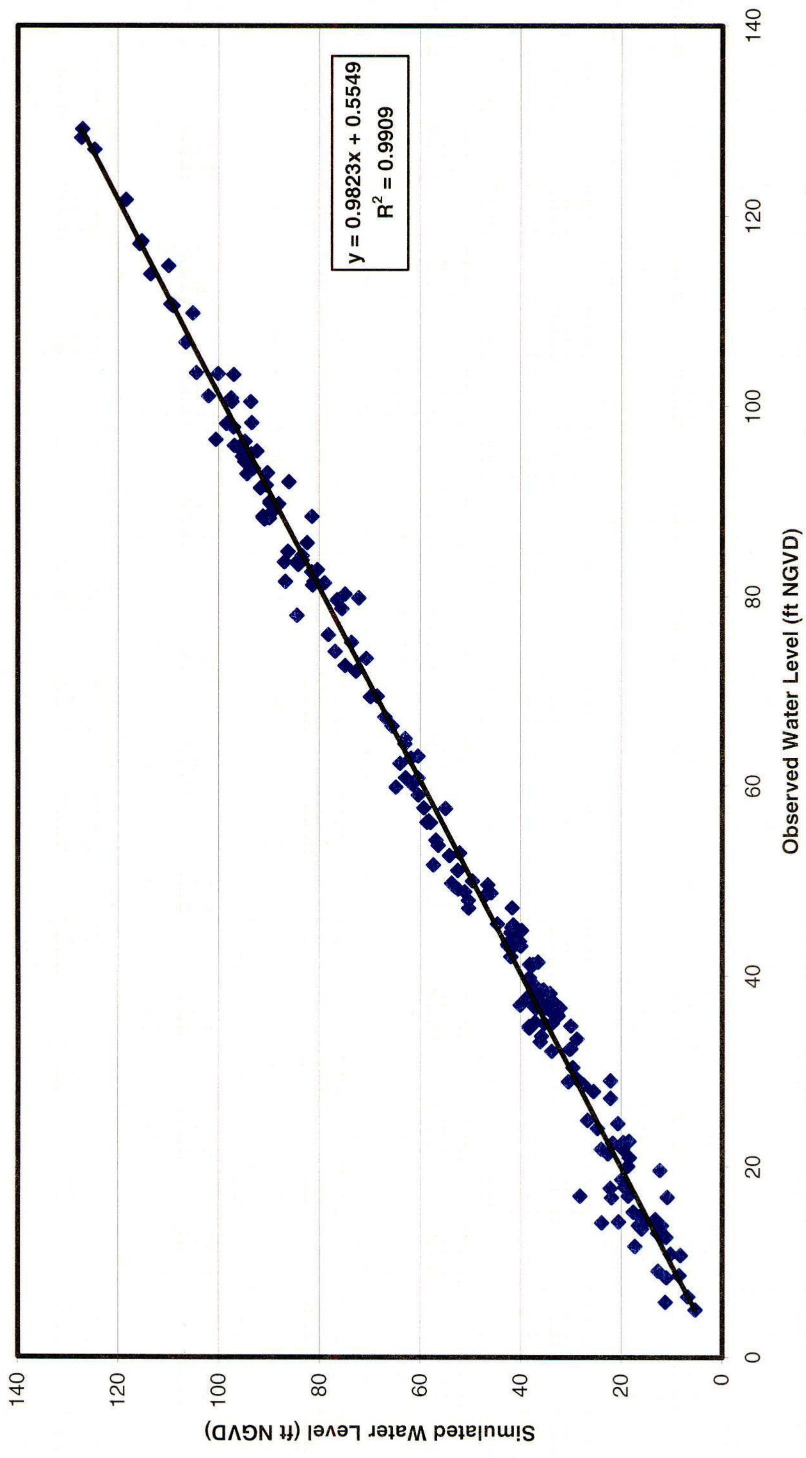


Figure 45. Observed versus simulated Upper Floridan aquifer (layers 2 and 3) water levels: average 1995 calibration

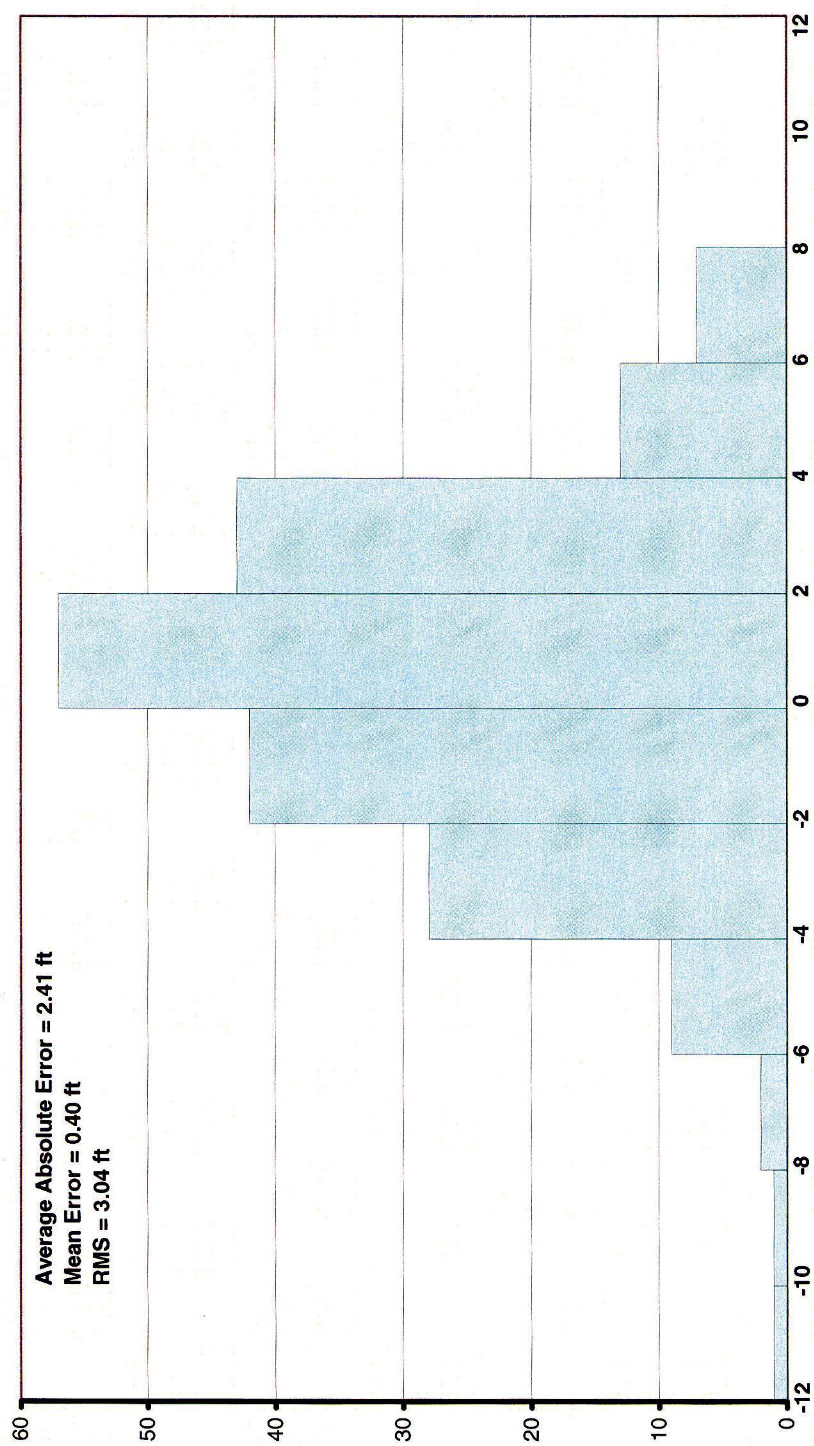


Figure 46. Layer 2 and layer 3 water level residuals for 1995 calibration

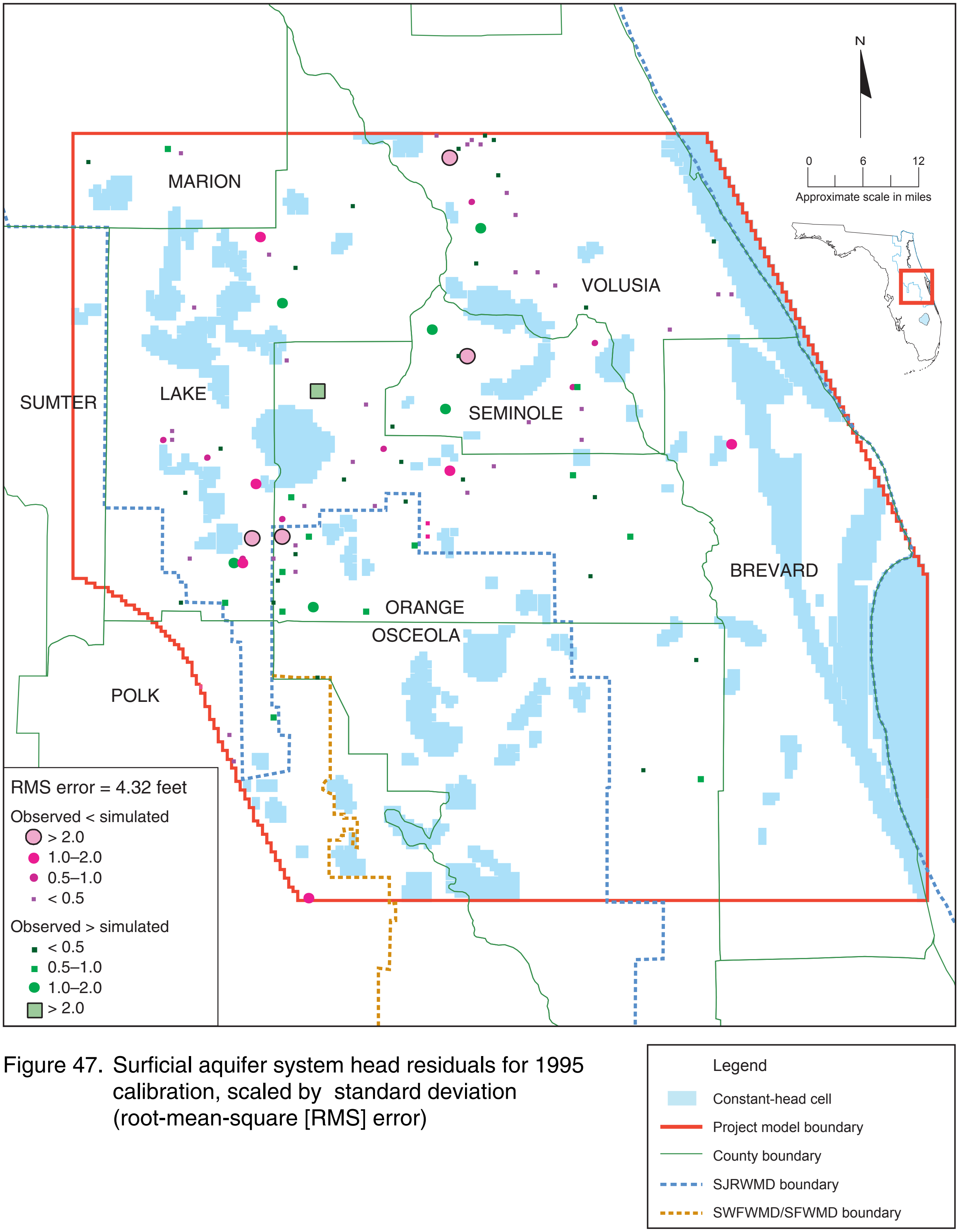


Figure 47. Surficial aquifer system head residuals for 1995 calibration, scaled by standard deviation (root-mean-square [RMS] error)

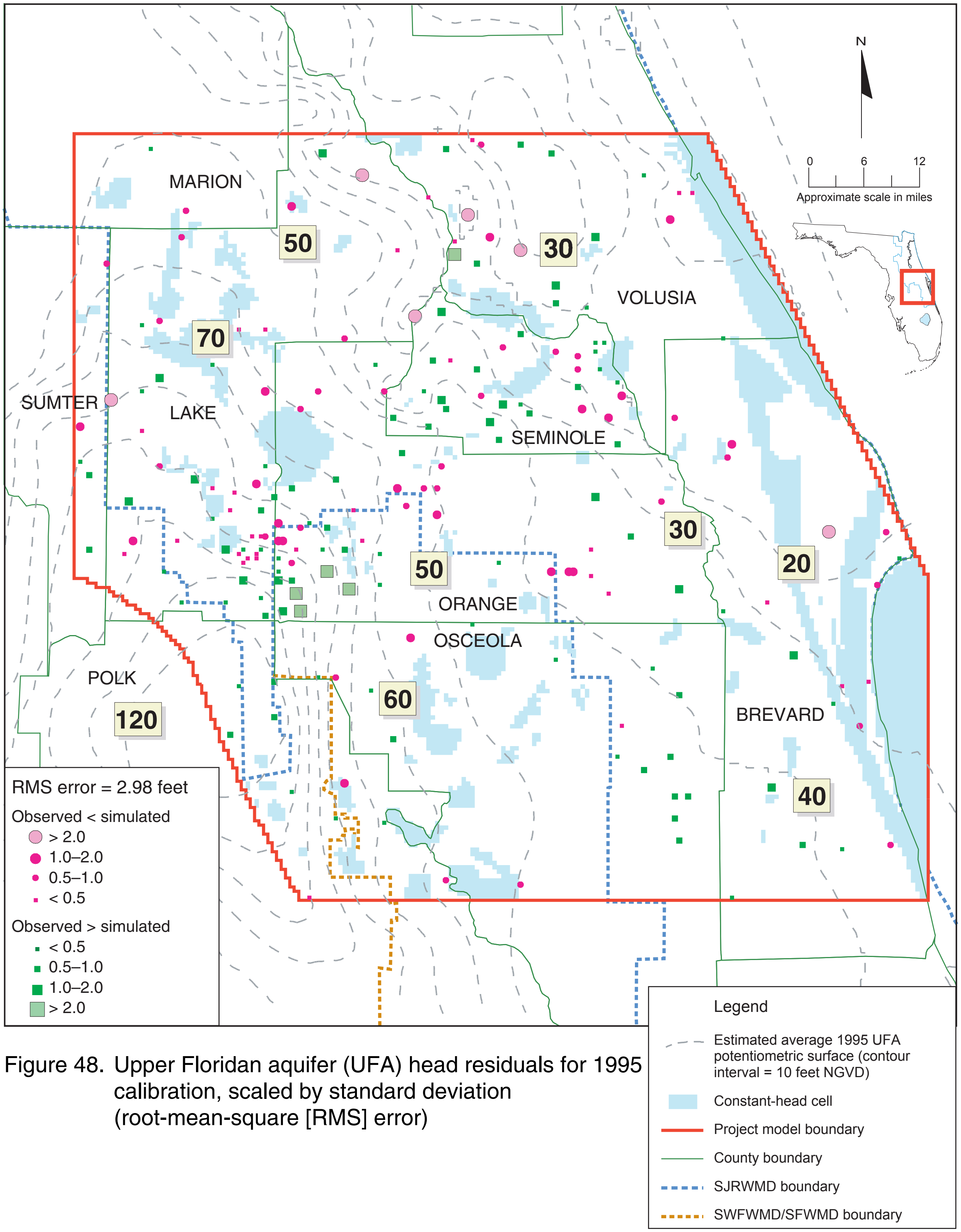


Figure 48. Upper Floridan aquifer (UFA) head residuals for 1995 calibration, scaled by standard deviation (root-mean-square [RMS] error)

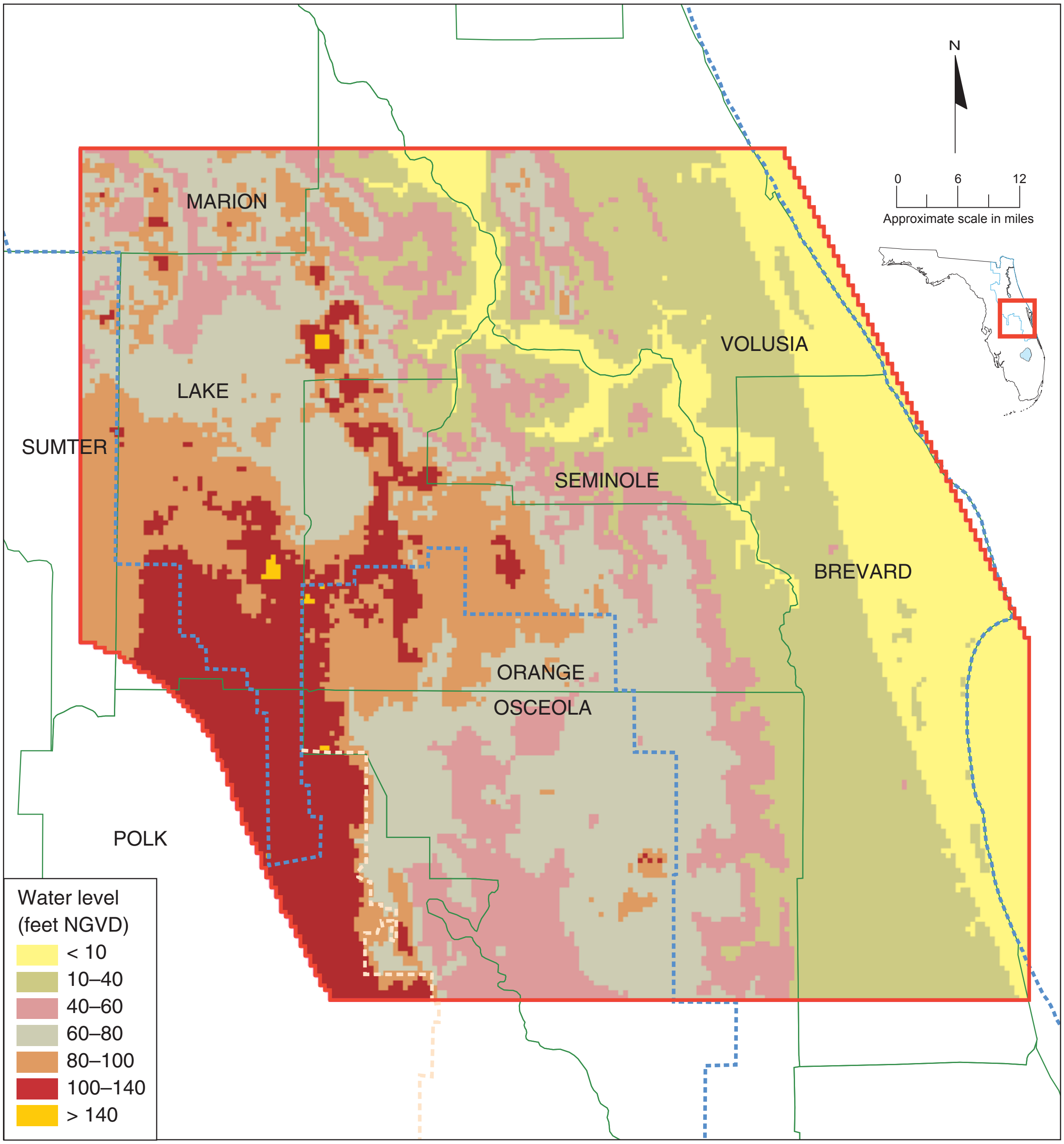
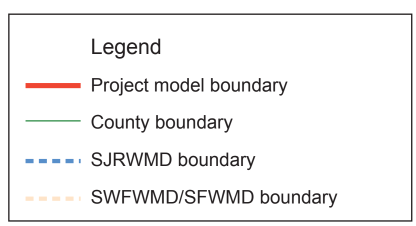


Figure 49. Simulated surficial aquifer system (layer 1) water levels for average 1995 conditions



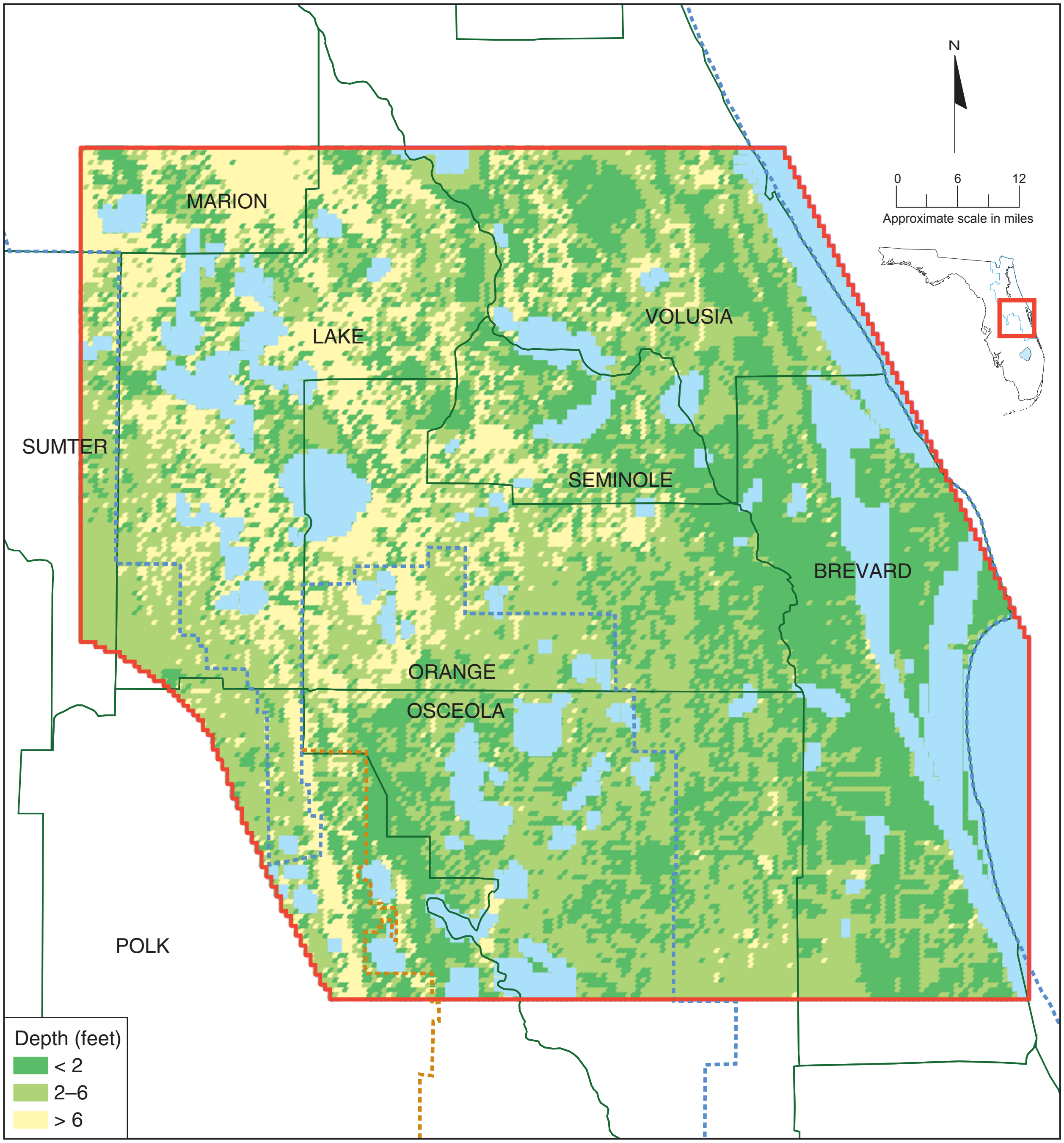
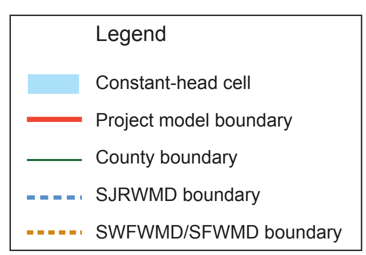


Figure 50. Average topographic elevation minus simulated layer 1 water level for average 1995 conditions



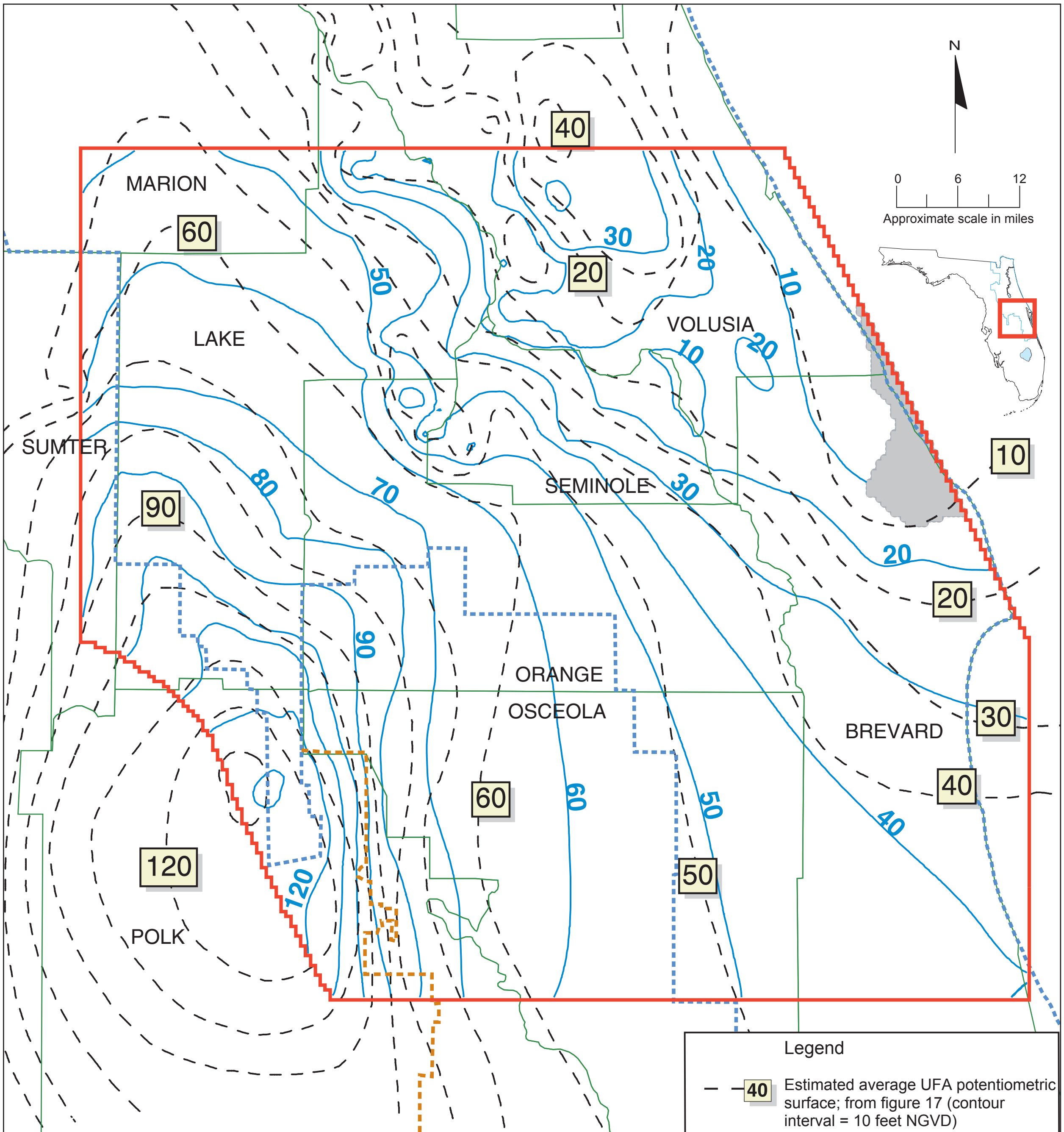


Figure 51. Predevelopment Upper Floridan aquifer (UFA) potentiometric surface and simulated layer 2 predevelopment potentiometric surface

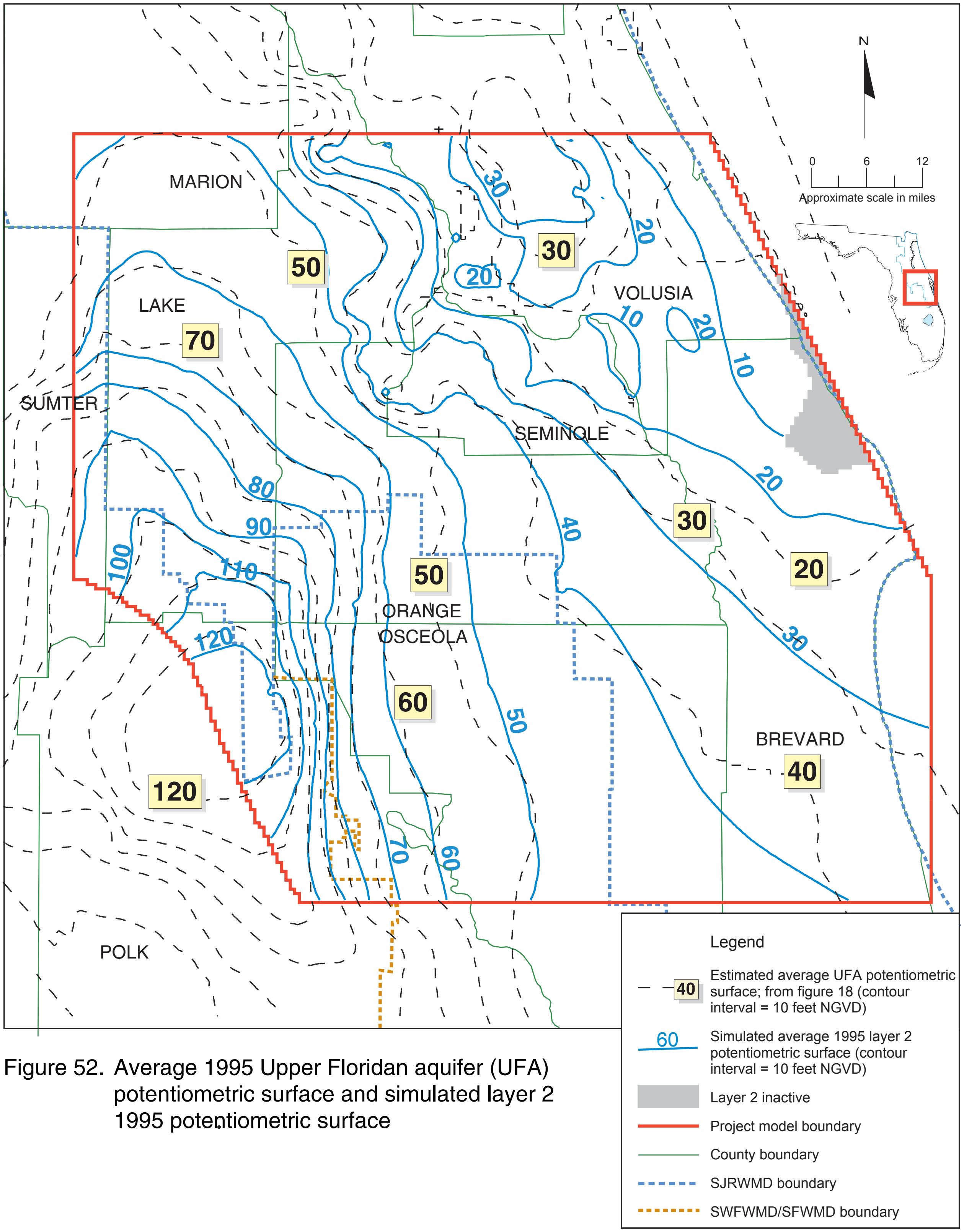


Figure 52. Average 1995 Upper Floridan aquifer (UFA) potentiometric surface and simulated layer 2 1995 potentiometric surface

(Figure 53) is similar to the layer 2 surface, differing only along the St. Johns River valley and near where layer 3 is inactive due to the location of the saltwater interface. The simulated 1995 layer 4 (Lower Floridan aquifer) potentiometric surface (Figure 54) is a subdued reflection of the Upper Floridan aquifer potentiometric surface. Layer 4 water levels are lower than layer 2 and layer 3 water levels in the southwestern corner of the model and in central Volusia County. Both of these areas contain potentiometric highs. Layer 4 water levels are higher than those in layers 2 and 3 along the potentiometric low areas near the St. Johns River. The simulated layer 4 water levels match the observed average Lower Floridan aquifer water levels fairly well, particularly those for which 1995 data were available. Differences between simulated and observed Lower Floridan aquifer water levels may be greater for those wells with average values from 1996 to 1999 because of differing climatic conditions.

Simulated Upper Floridan aquifer spring flows match the observed or estimated 1995 flows within ± 10% at all first- and second-magnitude springs except for Apopka Spring, where the simulated flow is approximately 18% higher than the 1995 estimate (Table 5). The percent difference between estimated / measured and simulated exceeds 20% at several small springs, none of which is large enough to have a significant effect upon the groundwater flow system outside of its immediate area. The simulated predevelopment spring flows are, in general, higher than the estimated predevelopment flows. The estimated predevelopment flows are derived from measurements made no earlier than the 1930s. However, it is known that some development occurred in the ECF region prior to that time (Sellards 1908; Sellards and Gunter 1913; Stringfield 1936; Stubbs 1937). Therefore, actual predevelopment spring flow could have been higher than the estimated flows listed on Tables 2 and 5. Modelwide, simulated spring flows dropped from approximately 681 cfs to 599 cfs between predevelopment and 1995 conditions, and estimated / measured spring flows dropped from approximately 654 cfs to approximately 601 cfs between predevelopment and 1995.

The predominant source of water to the groundwater flow system is the infiltration of local rainfall, rather than lateral inflow from outside of the model domain. Prescribed recharge to layer 1 and ET discharge from layer 1 are the largest components of the simulated overall volumetric budgets for predevelopment and average 1995 conditions (Table 6). Modelwide, recharge accounts for almost 97% of total input for predevelopment conditions and 95% for 1995 conditions; the remainder comes from layer 1 constant heads,

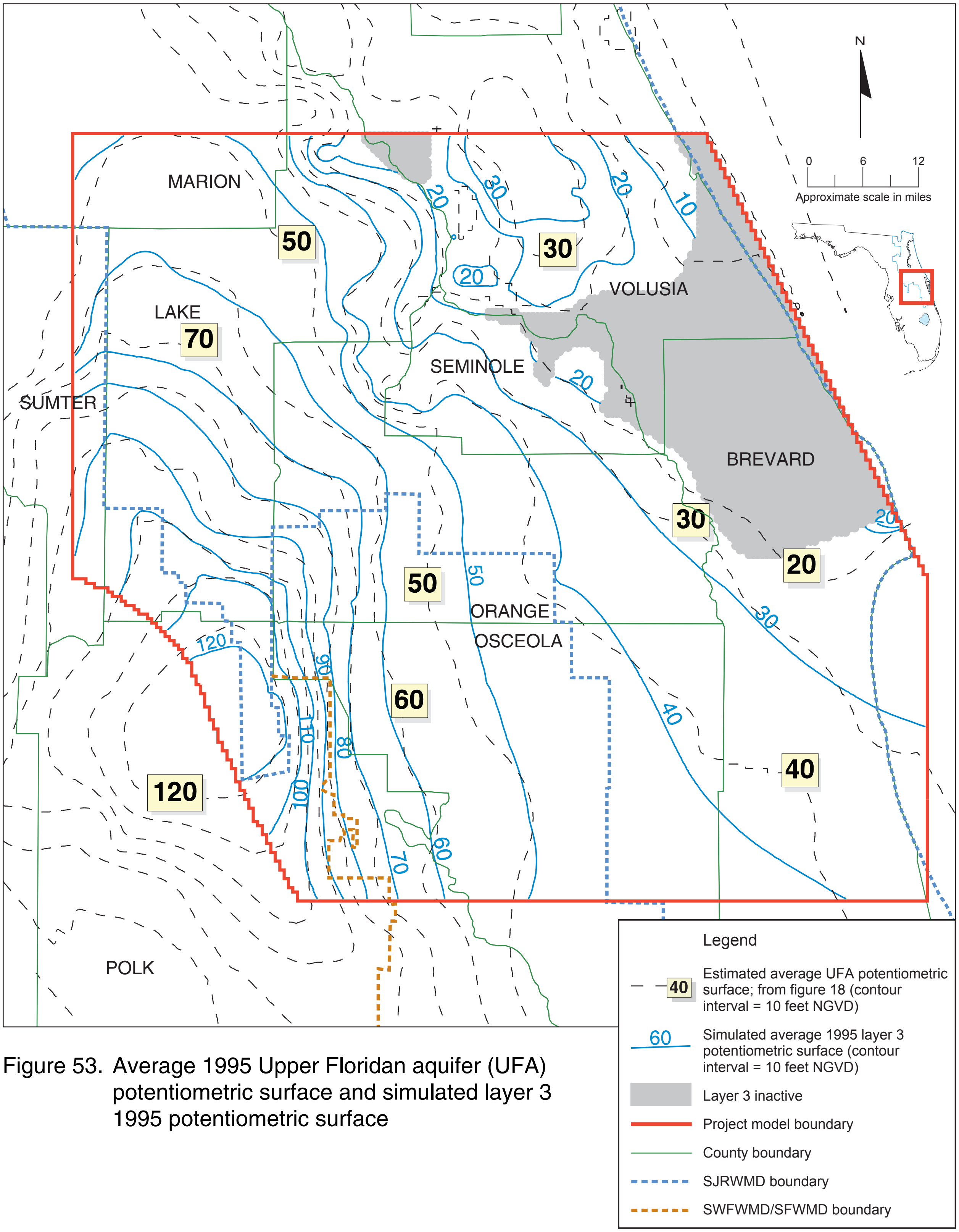


Figure 53. Average 1995 Upper Floridan aquifer (UFA) potentiometric surface and simulated layer 3 1995 potentiometric surface

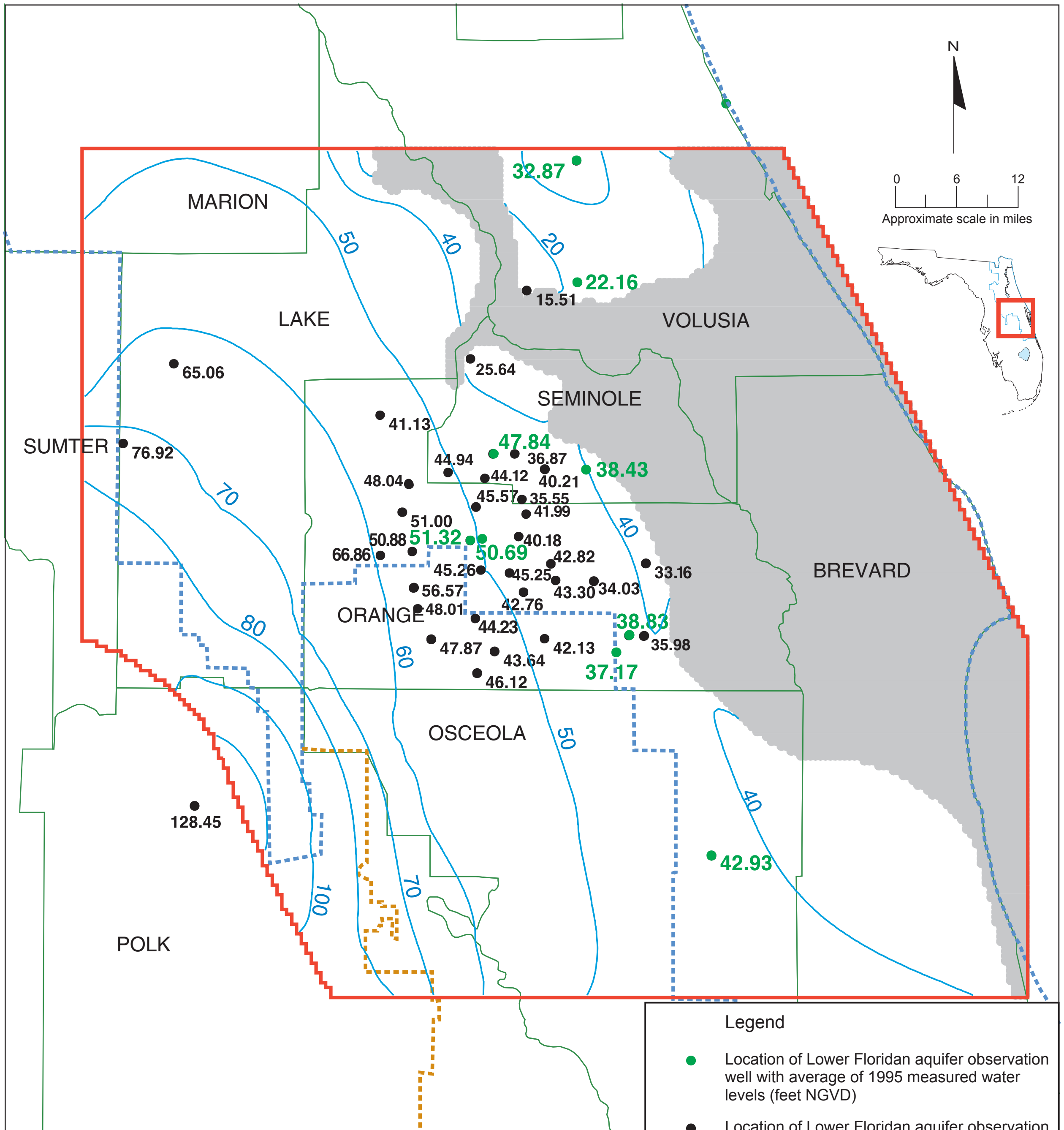


Figure 54. Simulated layer 4 potentiometric surface and observed Lower Floridan aquifer water levels, average 1995 conditions

Table 5. Comparison between measured or estimated spring flows and simulated spring flows for predevelopment and average 1995 conditions

Spring	Predevelopmen Conditions			1995 Average Conditions			Simulated Percent Change, Predevelopment to 1995
	Estimated Flow (cfs)	Simulated Flow (cfs)	Percent Difference	Measured Flow (cfs)	Simulated Flow (cfs)	Percent Difference	
Blue (Volusia County)	160	159	0.3	150.4	150.5	−0.1	5.6
Alexander	100	97	3.1	102.4	96.7	5.6	0.2
Wekiva	80	90	−12.5	73.0	76.7	−5.1	14.7
Rock	70	72	−2.5	61.4	59.0	3.9	17.8
Apopka	44	52	−17.4	32.2	38.2	−18.6	26.1
Seminole	40	45	−13.2	38.9	37.8	2.9	16.6
Alexander Creek	33	31	5.2	33.0	31.2	5.3	0.1
Palm and Sanlando	33	39	−19.6	28.2	27.9	1.2	29.4
Messant	20	18	9.7	16.4	16.0	2.2	11.2
Bugg	18	13	25.6	10.7	11.0	−2.6	15.7
Starbuck	17	20	−18.1	14.9	14.8	0.8	26.4
Gemini	10	8	15.0	8.1	7.8	3.4	7.9
Island	10	9	7.5	6.4	7.6	−18.2	18.2
Miami	6	8	−35.7	6.2	6.6	−6.4	19.0
Holiday	4	3	27.5	3.1	1.6	47.1	43.5
Blue (Lake County)	3	5	−55.5	3.2	3.1	3.9	34.1
Sulphur	2	1	37.3	0.8	1.0	−29.6	17.3
Witherington	2	3	−42.2	2.2	2.3	−4.7	19.0
Clifton	2	2	−2.7	1.7	1.7	0.2	17.1
Camp La-No-Che	1	1	−10.4	1.0	0.9	5.8	14.7
Green	1	2	−87.5	1.9	1.8	4.1	4.9
Lake Jesup	1	1	−8.6	1.0	0.9	8.9	16.1
Droty	1	1	−22.5	0.7	0.8	−11.3	9.2
Total	657	681	−3.7	597.8	595.9	−0.3	12.6

Note: cfs = cubic feet per second

Table 6. Simulated modelwide volumetric water budgets for predevelopment and average 1995 conditions

	Predevelopment	1995	Increase	Decrease
Total by Source and Sink Type (in million gallons per day)				
Inflow				
Constant heads*	15	27	12	
Wells	0	33	33	
Lateral boundaries	121	174	53	
Recharge	4,254	4,458	204	
Total inflow	4,390	4,692	302	0
Outflow				
Constant heads*	228	201		27
Wells	0	565	565	
Springs	440	385		55
Rivers	423	400		24
Evapotranspiration	2,928	2,838		90
Lateral boundaries	370	303		67
Total outflow	4,390	4,692	565	263
Linearized Over Model Domain (in inches per year)				
Inflow				
Constant heads*	0.0	0.1	0.0	
Wells	0.0	0.1	0.1	
Lateral boundaries	0.4	0.6	0.2	
Recharge[†]	13.8	14.5	0.7	
Total inflow	14.3	15.2	1.0	0.0
Outflow				
Constant heads*	0.7	0.7		0.0
Wells	0.0	1.8	1.8	
Springs	1.4	1.3		0.1
Rivers	1.4	1.3		0.1
Evapotranspiration[†]	9.5	9.2		0.3
Lateral boundaries	1.2	1.0		0.2
Total outflow	14.3	15.2	1.8	0.7

Note: Individual numbers may not match totals.

*Includes vertical and horizontal flow to/from constant-head cells in layer 1 representing large surface water bodies.
[†]Recharge and evapotranspiration not simulated at layer 1 constant-head cells.

lateral inflow, and (for 1995) drainage wells. ET accounts for 67% of predevelopment outflow and 60% of 1995 outflow. Volumetric flow rates decrease downward with each model layer (Table 7). The largest budget component for each Floridan aquifer system model layer is vertical inflow from either prescribed recharge or the overlying aquifer. For both predevelopment and 1995 conditions, the net vertical flow between the three pairs of adjoining aquifer layers (1-2, 2-3, and 3-4) was downward. However, for 1995 conditions, the net downward flows are significantly greater than for predevelopment in response to Floridan aquifer system well withdrawals. Well pumpage from layers 2, 3, and 4 also results in decreased spring flow, river discharge, and lateral boundary outflow.

Total ET for 1995 was calculated on a cell-by-cell basis by adding the simulated ET to the estimated ET_{unsat} (ET_{min} + R_{app}) value. The resulting spatial distribution of total ET (Figure 55) compares favorably with the soil area distribution shown by Figure 38. Modelwide, total 1995 ET averages 38.9 inches and simulated ET averages 9.2 inches (Table 6). Wherever total ET equals 27 in / yr (the assumed value for ET_{min}), there is no model-simulated ET from the water table because the simulated layer 1 water level was below the assigned extinction depth of 6 ft bls. Areas of low total ET shown on Figure 55 are similar in areal extent to soil area 3, where the water table, on average, lies below the soil horizon. Areas of relatively high model-simulated ET compare well over most of the model with soil area 1, where the water table is usually near land surface. Figure 55 does not match Figure 38 well in southeastern Osceola County and southwestern Brevard County, where simulated layer 1 water levels range from land surface to several feet below land surface (see Figure 50). Total 1995 ET exceeds the estimated average free-water surface evaporation (ET_{max}) at scattered locations. Many of the model grid cells where 1995 ET exceeds 49 inches were designated as parts of either soil area 2 or soil area 3; however, the simulated water table is within 2 ft of land surface. Irrigation applied (R_{app}) at a large percentage of these cells is less than a few inches per year. At most of the other cells where 1995 ET exceeds 49 inches (located in soil area 1), the estimate of applied irrigation is many inches per year. Therefore, overestimation of ET may be due to both errors in soil area designation and overestimation of applied irrigation. Many of these model grid cells are also within rainfall polygons (see Figure 32) with higher than average 1995 rainfall. Because the ET_{max} values are based upon long-term average data, it is possible that the actual 1995 ET_{max} values were higher than shown by Figure 37 in areas that experienced higher than average rainfall in 1995.

Table 7. Simulated layer-by-layer volumetric water budgets for predevelopment and average 1995 conditions (in million gallons per day)

Layer	Flux Type	Volumetric Flow Rates		Increase	Decrease	Net Change
		Predevelopment	1995			
1	**Inflow**					
	Recharge	4,254	4,458	204		
	Upward leakage from layer 2	229	169		60	
	Lateral flow from constant-head cells	4	6	2		
	Total inflow	4,487	4,633			146
	Outflow					
	Evapotranspiration	2,928	2,838		90	
	Downward leakage to layer 2	1,128	1,379	251		
	River discharge	313	301		12	
	Lateral flow to constant-head cells	118	115		3	
	Total outflow	4,487	4,633			146
2	**Inflow**					
	Downward leakage from layer 1	1,128	1,379	251		
	Upward leakage from layer 3	473	459		14	
	Downward leakage from constant-head cells	9	21	12		
	Lateral inflow along freshwater boundary	64	68	4		
	Lateral inflow along saltwater boundary	0	0			
	Drainage wells	0	23	23		
	Total inflow	1,674	1,950			276
	Outflow					
	Downward leakage to layer 3	613	732	119		
	Wells	0	332	332		
	Springs	440	385		55	
	Upward leakage to layer 1	229	169		60	
	Upward leakage to constant-head cells	109	86		23	
	Lateral outflow along freshwater boundary	172	146		26	
	Lateral outflow along saltwater boundary	1	1			
	River discharge	110	99		11	
	Total outflow	1,674	1,950			276

Table 7—*Continued*

Layer	Flux Type	Volumetric Flow Rates		Increase	Decrease	Net Change
		Predevelopment	1995			
3	**Inflow**					
	Downward leakage from layer 2	613	732	119		
	Upward leakage from layer 4	193	178		15	
	Lateral inflow along freshwater boundary	25	28	3		
	Lateral inflow along saltwater boundary	7	35	28		
	Drainage wells	0	10	10		
	Total inflow	838	983			145
	Outflow					
	Upward leakage to layer 2	473	459		14	
	Wells	0	123	123		
	Downward leakage to layer 4	266	320	54		
	Lateral outflow along freshwater boundary	88	80		8	
	Lateral outflow along saltwater boundary	11	1		10	
	Total outflow	838	983			145
4	**Inflow**					
	Downward leakage from layer 3	266	320	54		
	Lateral inflow along freshwater boundary	22	23	1		
	Lateral inflow along saltwater boundary	3	19	16		
	Total inflow	291	362			71
	Outflow					
	Wells	0	109	109		
	Upward leakage to layer 3	193	178		15	
	Lateral outflow along freshwater boundary	91	72		19	
	Lateral outflow along saltwater boundary	7	3		4	
	Total outflow	291	362			71

Note: 1 mgd equals approximately 1.55 cubic feet per second.

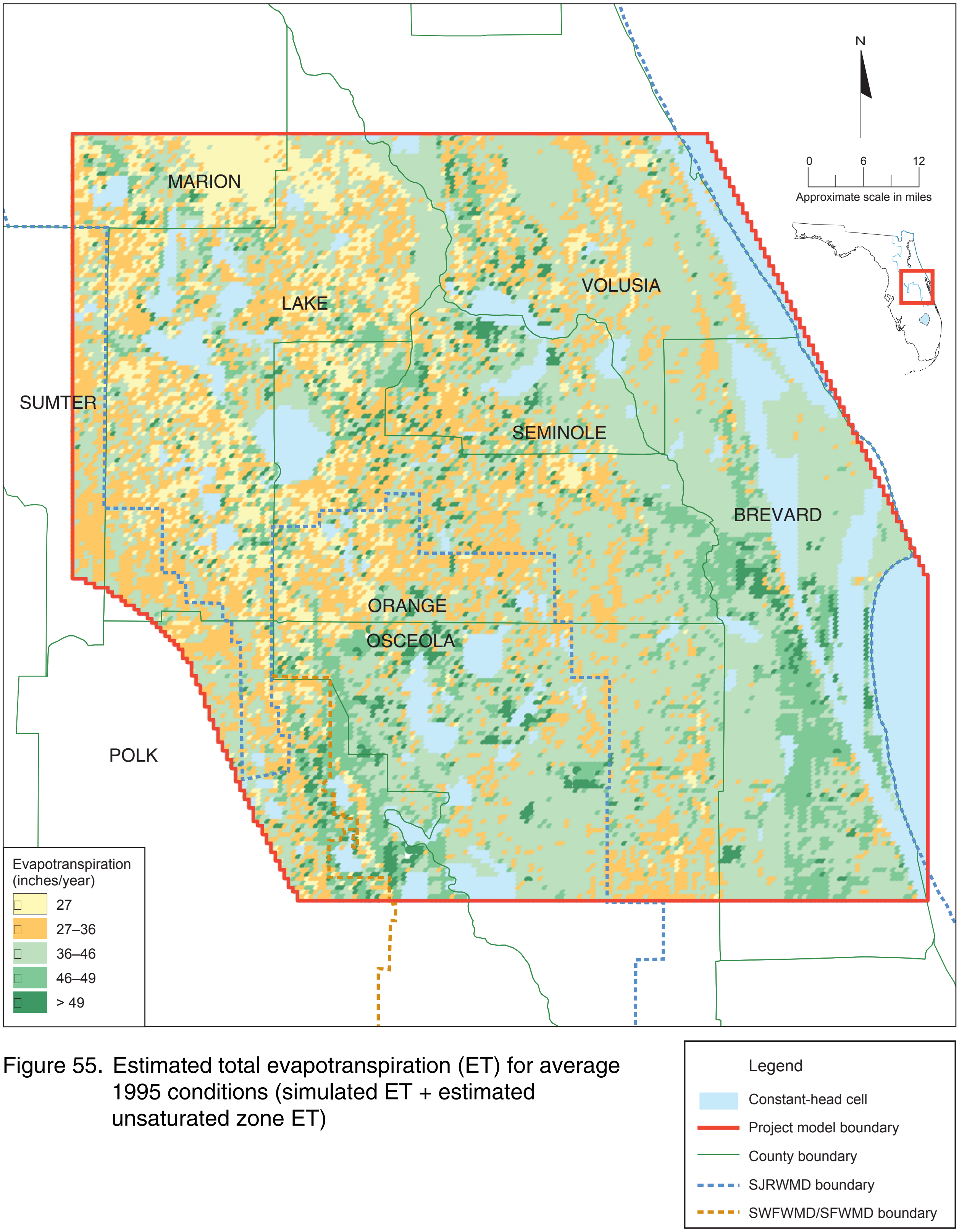


Figure 55. Estimated total evapotranspiration (ET) for average 1995 conditions (simulated ET + estimated unsaturated zone ET)

The spatial distribution of simulated vertical flow between the Upper Floridan aquifer and the surficial aquifer system (Figure 56) is consistent with maps generated by previous investigations (see Figure 15). The highest rates of simulated downward flow (recharge) to the Upper Floridan aquifer occur along ridge areas where (1) the difference in head between the surficial aquifer system (layer 1) and layer 2 is greatest (causing a large downward vertical gradient), and (2) the intermediate confining unit is relatively thin. Within these areas, flow rates range from approximately 12 in / yr to greater than 50 in / yr at grid cells dominated by karstic sinkhole depressions where overland runoff from surrounding, topographically higher areas can collect and infiltrate. Recharge to the Floridan aquifer also exceeds 50 in / yr at the locations of several large-scale RIB sites. Areas with relatively low simulated recharge rates coincide with areas of relatively high overland runoff to surface water systems and high ET. The highest rates of upward flow from the Upper Floridan aquifer to the surficial aquifer system occur along the St. Johns River valley where the intermediate confining unit is also relatively thin. The exchange of water between the surficial aquifer system and the Upper Floridan aquifer is minimal in southeastern Orange County, central and eastern Osceola County, and southern Brevard County where the intermediate confining unit is relatively thick (see Figure 9).

The spatial distribution of vertical flow between Upper Floridan aquifer layers 2 and 3 (Figure 57) generally resembles that shown by Figure 56 for layers 1 and 2. Some of the highest downward flow rates to layer 3 occur in Orlando where significant drainage well inflow occurs to layer 2 and in western and southwestern Orange County where large-scale artificial recharge projects are located. The highest rates of simulated upward flow from layer 3 to layer 2 occurs near the saltwater interface boundary and along the St. Johns River. Upward flow also occurs around springs and wellfield locations in Lake, Orange, Osceola, and eastern Volusia counties. Simulated vertical flow rates between the Upper Floridan aquifer (layer 3) and the Lower Floridan aquifer (layer 4) are less than those simulated for the higher layers (Figure 58). The highest downward flow rates are in western and central Orange County, including Orlando, where the simulated Upper Floridan aquifer potentiometric surface is enhanced by drainage well inflow. Relatively low upward flow rates were simulated across central and eastern Osceola County, eastern Orange County, Seminole County, and near the Wekiva and St. Johns rivers in northwest Orange and northeastern Lake counties.

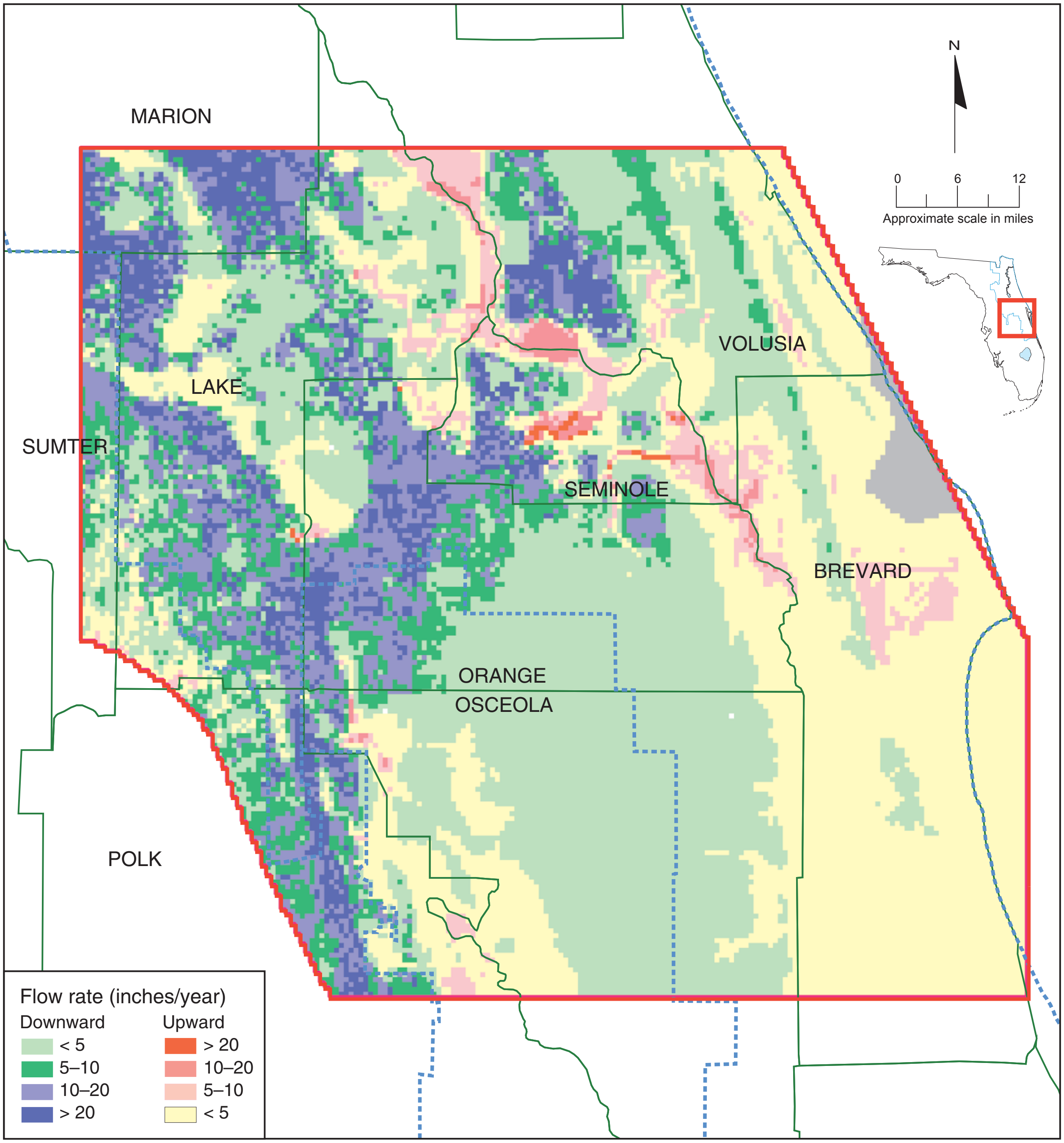


Figure 56. Simulated vertical flow between layer 1 (surficial aquifer system) and layer 2 (Upper Floridan aquifer—upper zone) for average 1995 conditions

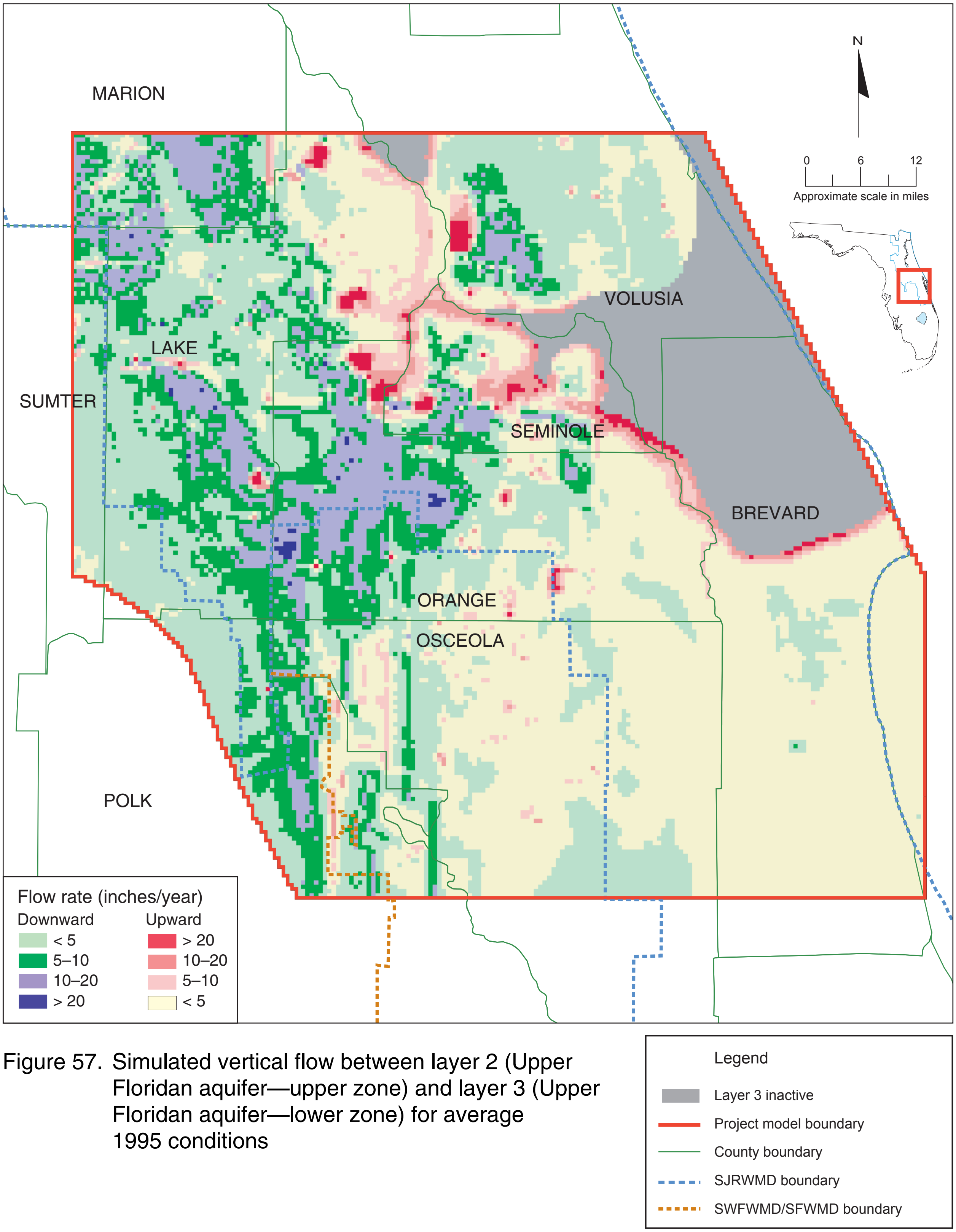


Figure 57. Simulated vertical flow between layer 2 (Upper Floridan aquifer—upper zone) and layer 3 (Upper Floridan aquifer—lower zone) for average 1995 conditions

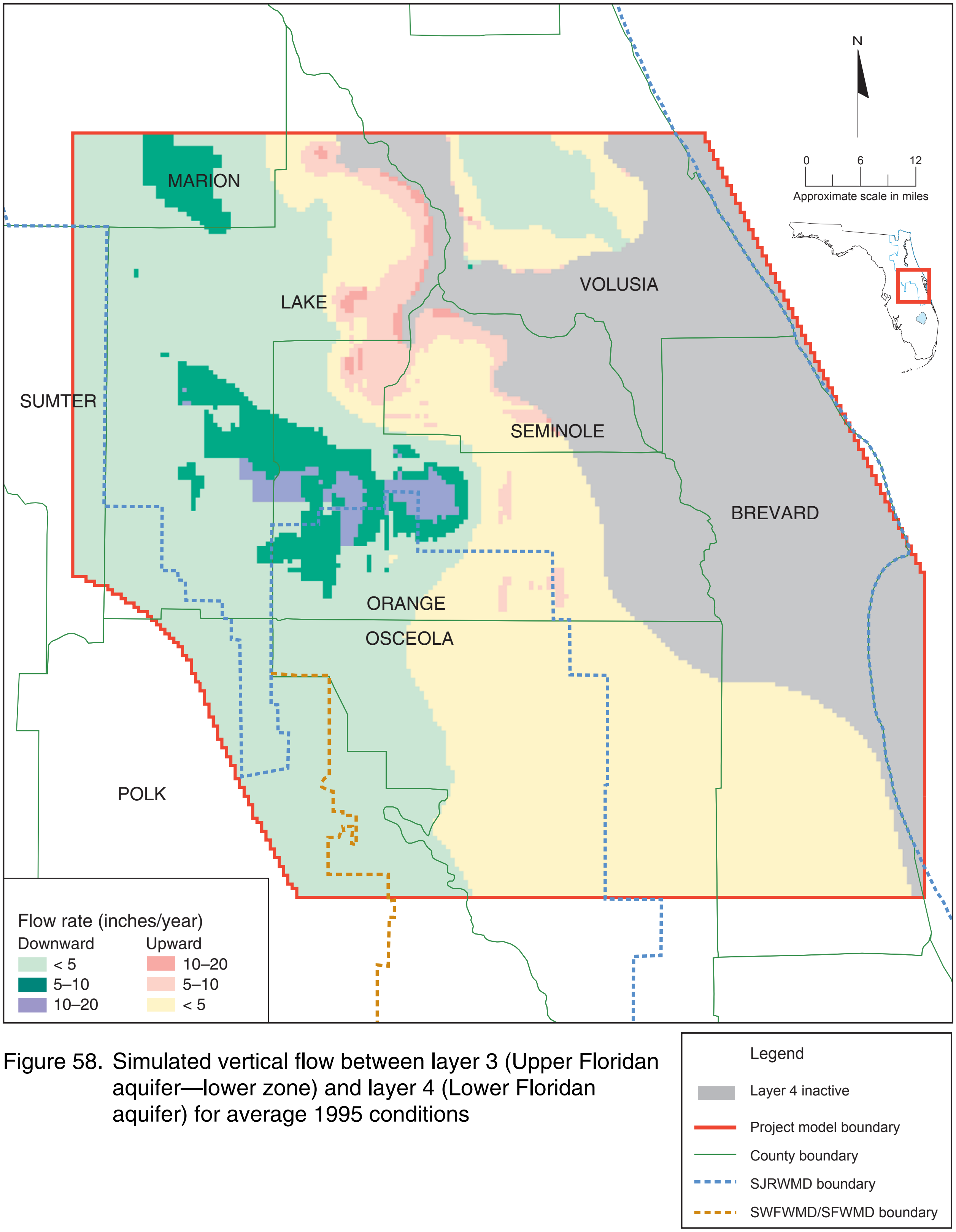


Figure 58. Simulated vertical flow between layer 3 (Upper Floridan aquifer—lower zone) and layer 4 (Lower Floridan aquifer) for average 1995 conditions

Although simulated lateral boundary flows are relatively small compared to vertical flow rates modelwide, they are significantly high at individual grid cells (Figures 59–64). Predevelopment layer 2 and layer 3 lateral inflow rates exceed 25 in / yr (averaged over the area of the grid cell at the boundary) at scattered locations along the southern, southeastern, and northern boundaries (Figures 59 and 60). Predevelopment layer 2 and layer 3 outflow rates exceed 25 in / yr mainly in the northwestern corner of the model domain. Simulated net flow in all three layers across the saltwater interface boundary is small for predevelopment conditions. For 1995 conditions, lateral inflow is simulated along a greater portion of the southern boundary than for predevelopment (Figures 62–64).

The change in simulated lateral flow rates between predevelopment and 1995 is most apparent, however, along the saltwater interface boundary in layers 3 and 4 (compare Figures 60 and 61 with Figures 63 and 64). Total net flow across this boundary in layer 3 changes from approximately 3.4 mgd outward for predevelopment to 34.6 mgd inward for 1995 conditions. Likewise, net flow across the layer 4 saltwater interface boundary reverses from approximately 4.3 mgd outward for predevelopment to 15.8 mgd of inflow for 1995 conditions. As described previously, these inflows represent increased mixing of very brackish to saline water with freshwater within the freshwater-saltwater transition zone. The increased mixing is in response to the decrease in head on the freshwater side of the zone. As a result, the midpoint of the transition zone would gradually shift toward the freshwater side, causing the transition zone to become wider than in predevelopment conditions. Without subsequent changes in fresh groundwater withdrawals, an eventual equilibrium condition would be reached in which there is no transfer of water across the midpoint. The northwestern corner of the model is located within the groundwater recharge area for Silver Springs, which is located approximately 8 miles north of the model boundary near Ocala (Faulkner 1973). The simulated 1995 lateral outflow from all three Floridan aquifer system layers along this corner (model row 1, columns 1–22 and model rows 1–22, column 1) was approximately 189 cfs, which is 12.5% of the estimated 1995 annual mean flow at Silver Springs (USGS 1997).

The calculated overland runoff and simulated groundwater discharge to surface water bodies for 1995 conditions was compared to reported mean annual streamflow data for surface water data collection sites along major streams (Table 8). Total overland runoff was calculated by first converting the average R_u value for the portion of the model located within each stream basin to a volumetric flow rate by multiplying it by the area of a single model

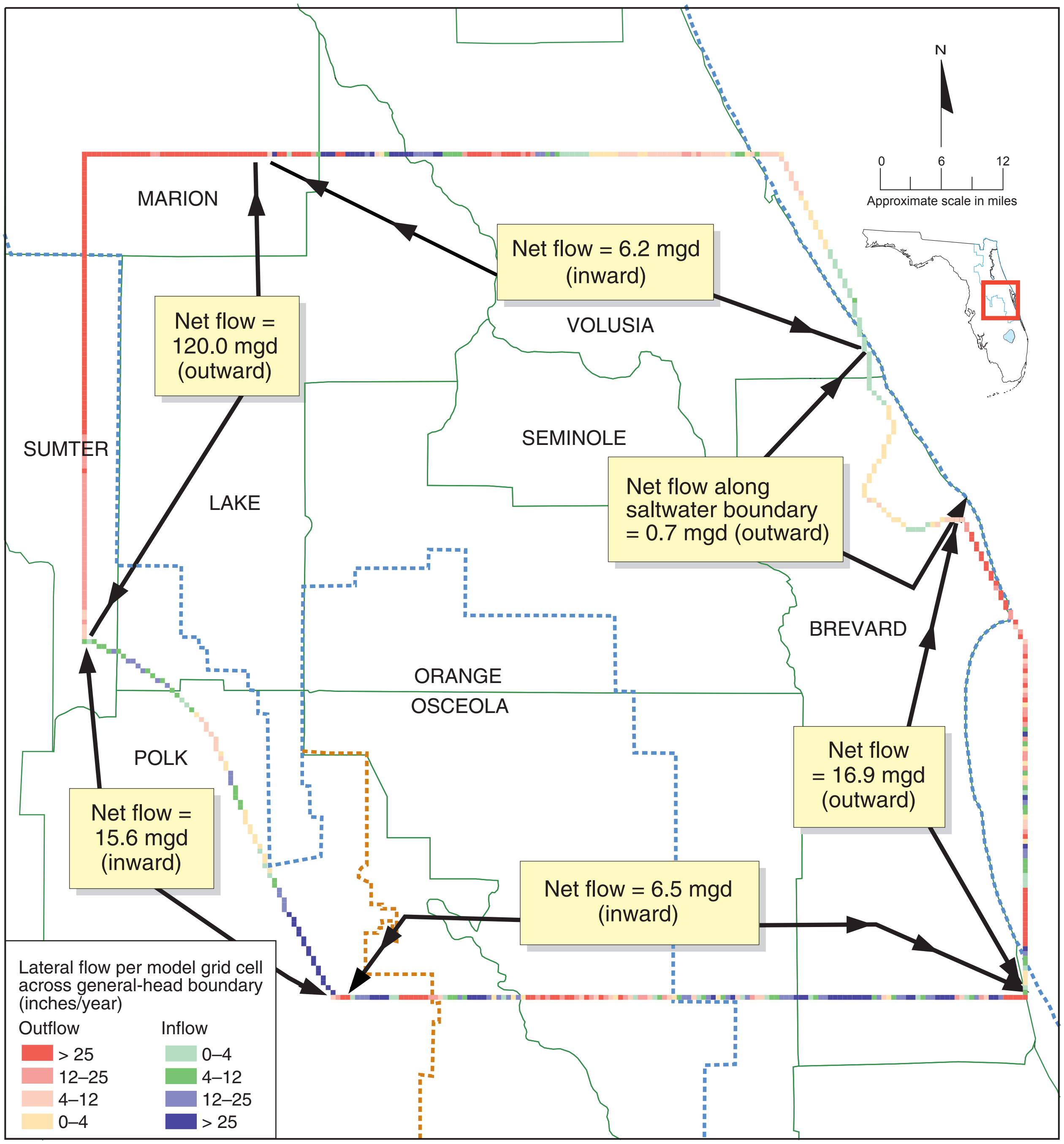


Figure 59. Simulated layer 2 (Upper Floridan aquifer—upper zone) lateral boundary flows, predevelopment conditions

Legend

County boundary

SJRWMD boundary

SWFWMD/SFWMD boundary

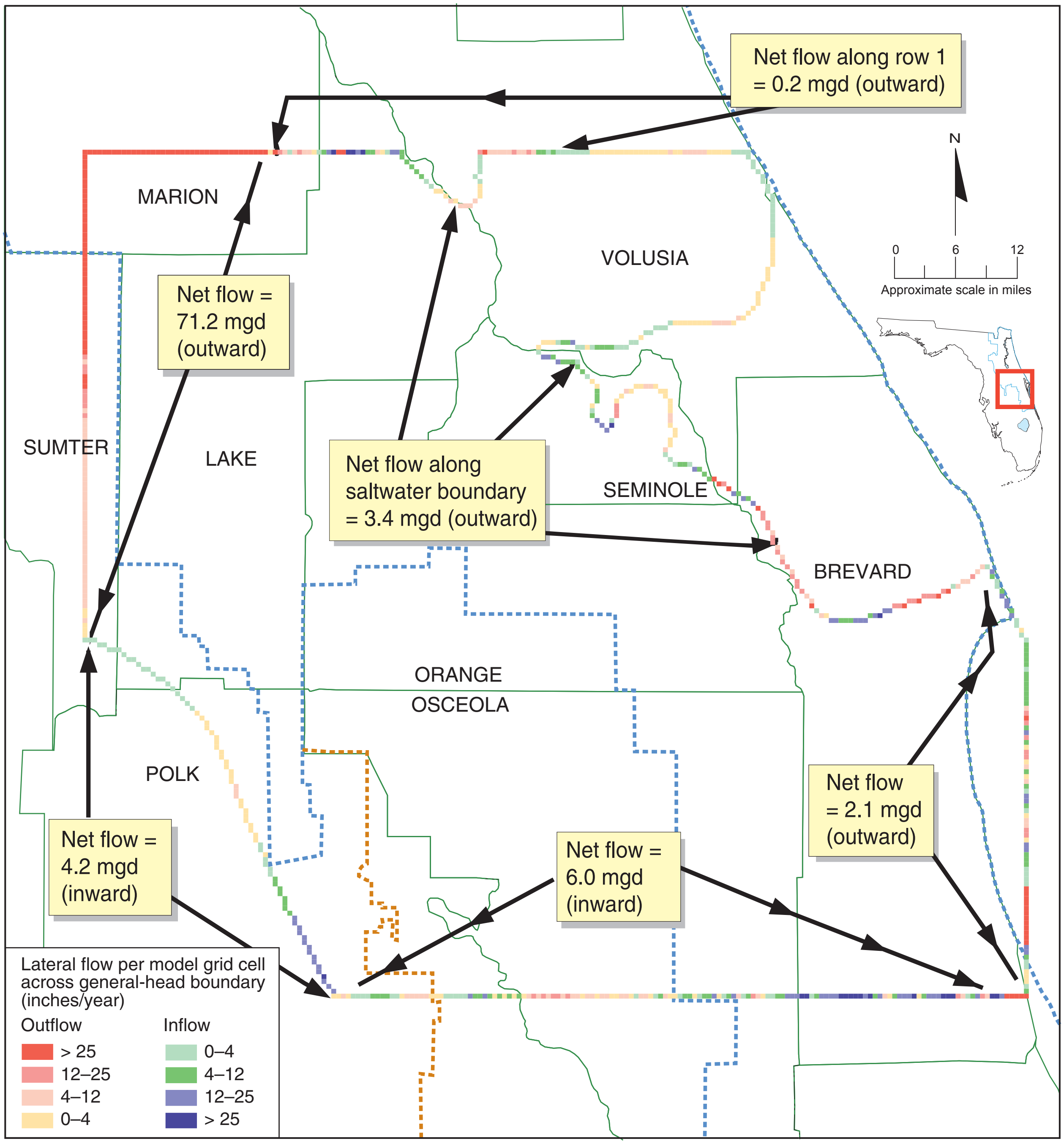


Figure 60. Simulated layer 3 (Upper Floridan aquifer—lower zone) lateral boundary flows, predevelopment conditions

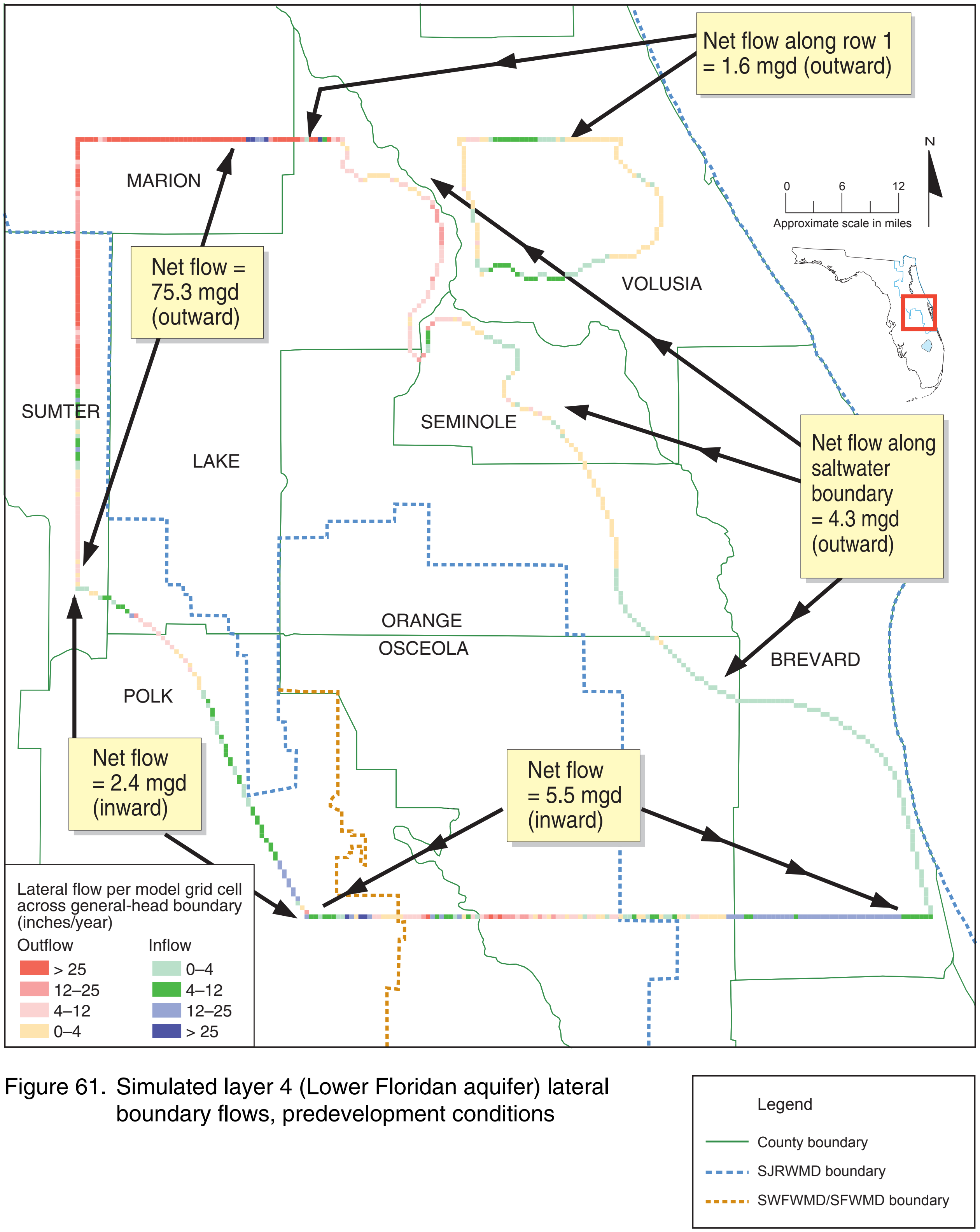


Figure 61. Simulated layer 4 (Lower Floridan aquifer) lateral boundary flows, predevelopment conditions

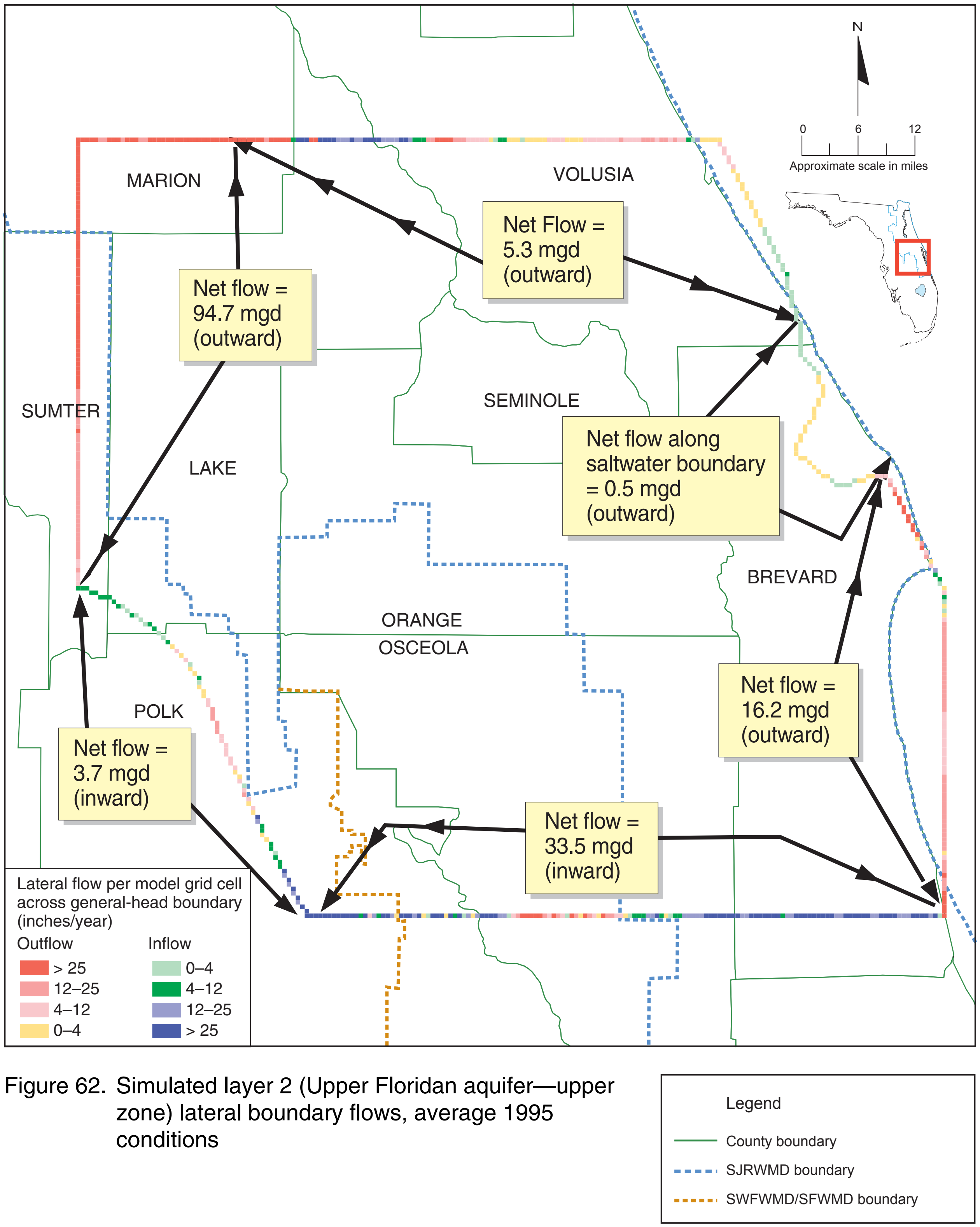


Figure 62. Simulated layer 2 (Upper Floridan aquifer—upper zone) lateral boundary flows, average 1995 conditions

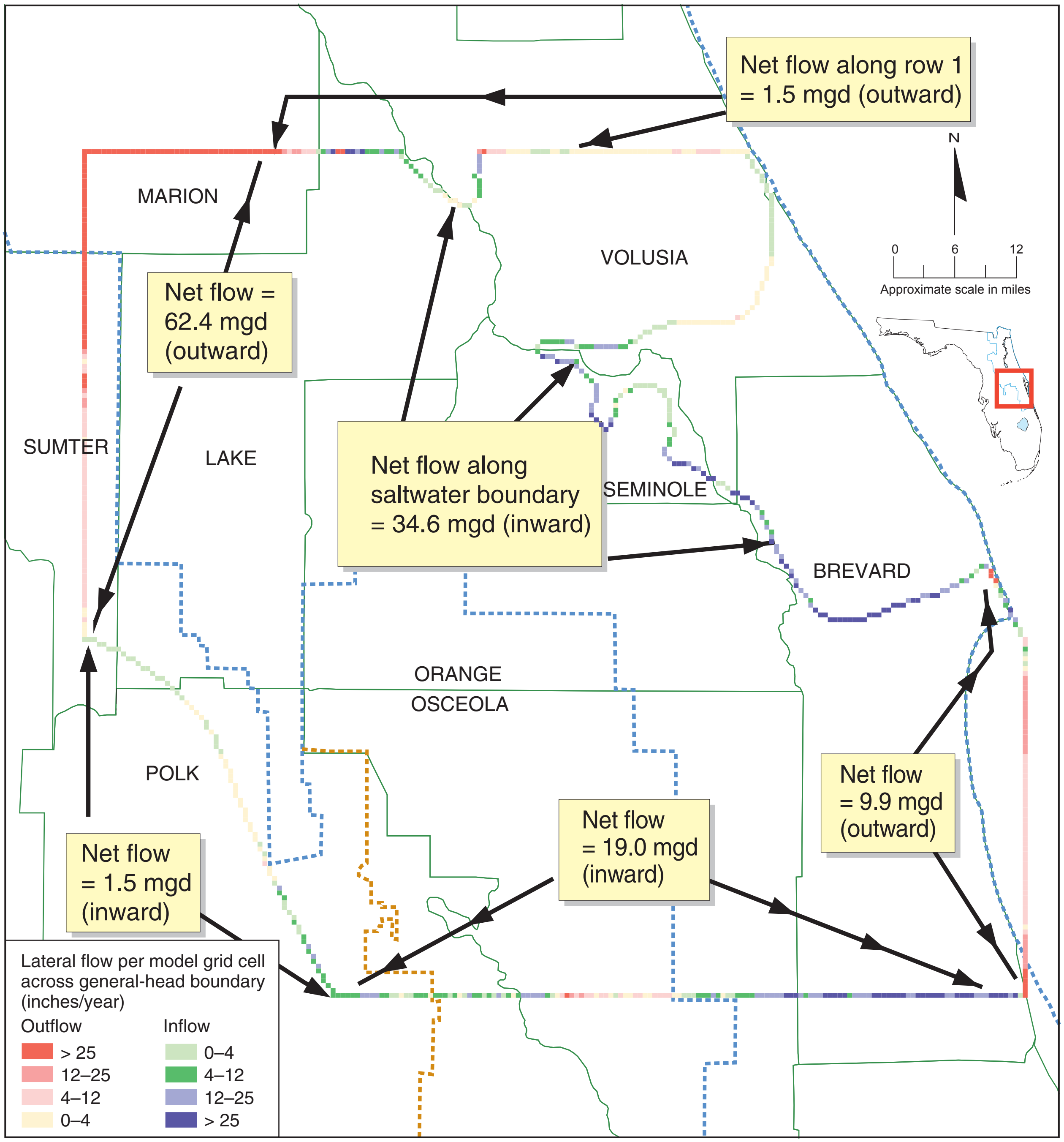
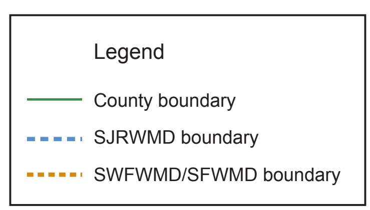


Figure 63. Simulated layer 3 (Upper Floridan aquifer—lower zone) lateral boundary flows, average 1995 conditions



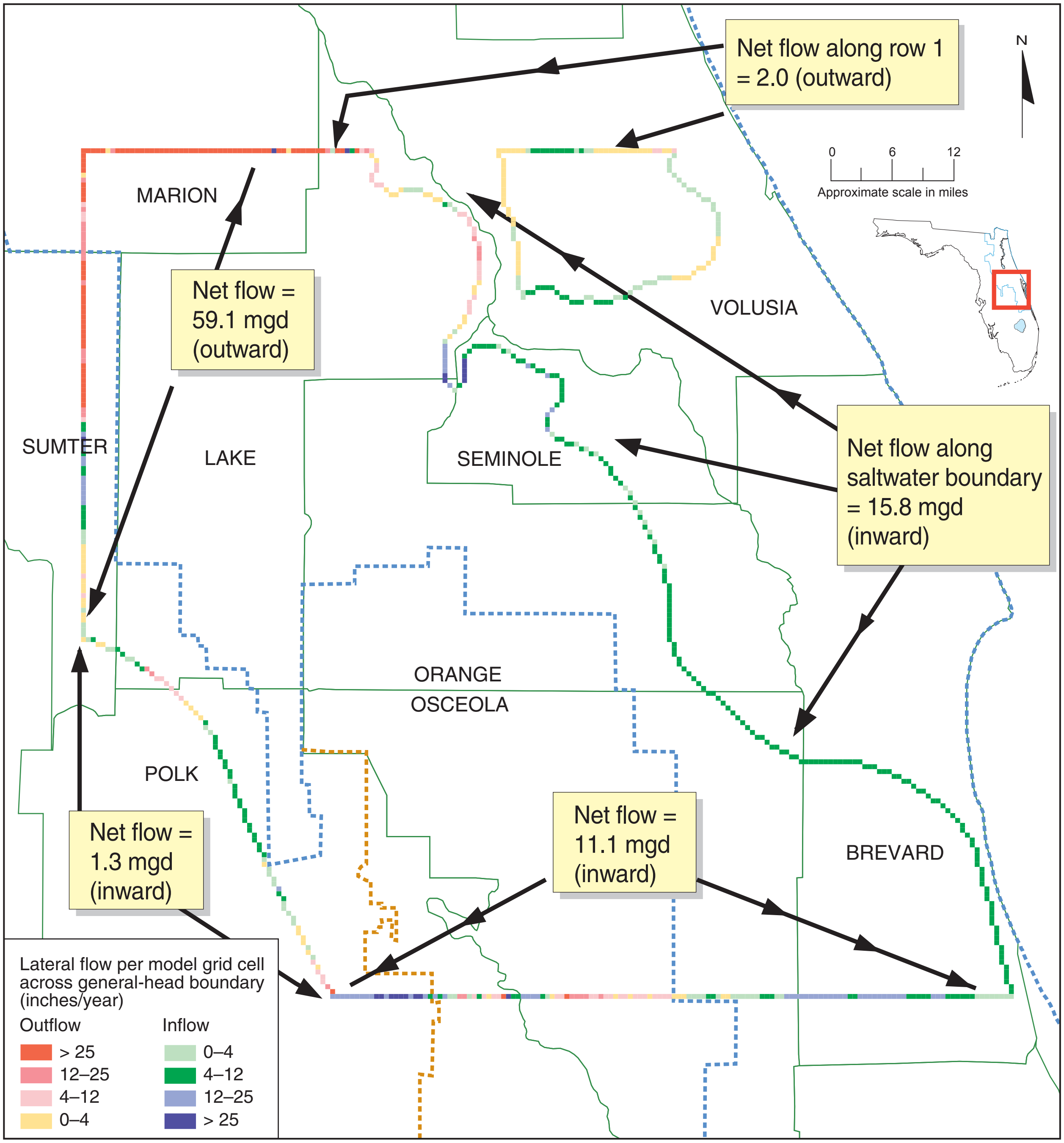


Figure 64. Simulated layer 4 (Lower Floridan aquifer) lateral boundary flows, average 1995 conditions

Legend

County boundary

SJRWMD boundary

SWFWMD/SFWMD boundary

Table 8. Calculated overland runoff and modeled baseflow by stream basin, and comparison with reported mean annual stream flows

A—Summary of calculated overland runoff and model-simulated baseflow within selected surface water basins

Gauging Station	Number of Model Cells in Basin	Calculated Average Annual Overland Runoff for Model Cells in Surface Water Basin (inches)	Calculated Average Daily Flow Due to Overland Runoff (cfs)	(A) Layer 1 River Flow (cfs)	(B) Layer 2 River Flow (cfs)	(C) Flow Into Constant-Head Cells From Layer 2 (cfs)	(D) Flow Into Constant-Head Cells From Layer 1 (cfs)	(E) Upper Floridan Spring Flow (cfs)	(F) Free-Flowing Wells (cfs)	Total Simulated Base Flow (A+B+C+D+E+F) [cfs]	Total Modeled Surface Water Flow (column 4 + column 11) [cfs]	Model-Estimated Total Runoff (inches per year)
St. Johns River near Melbourne	1,866	13.73	423	25	0	0	1	0	0	26	449	14.57
St. Johns River near Cocoa	3,379	14.74	823	46	0	1	2	0	1	50	872	15.63
St. Johns River near Christmas	4,478	14.41	1,066	63	11	1	3	0	1	79	1,144	15.47
Econlockhatchee River near Chuluota	1,071	11.73	207	45	0	0	0	0	0	45	253	14.29
St. Johns River above Lake Harney	6,844	13.62	1,539	132	45	5	7	0	1	190	1,729	15.30
St. Johns River near Sanford	9,413	13.50	2,099	206	106	44	28	12	2	398	2,496	16.06
Wekiva River near Sanford	830	5.26	72	18	7	0	1	188	0	214	286	20.86
St. Johns River near De Land	11,599	12.38	2,372	308	138	46	30	421	2	945	3,317	17.31
Ocklawaha River below Moss Bluff dam	3,902	13.25	854	23	0	9	31	54	0	117	971	15.07
Reedy Creek at SR 531	1,067	9.97	176	15	0	0	3	0	0	18	194	10.99
Kissimmee River at S-65	5,537	15.40	1,408	75	0	12	34	0	0	121	1,529	16.72

B—Comparison between reported annual mean flows and modeled flows

Gauging Station	Flow Measurement Rating	Reported 1995 Annual Mean (cfs)	Annual Mean Flow, Low End of Range (cfs)	Annual Mean Flow, High End of Range (cfs)	Total Modeled Surface Water Flow [runoff + simulated base flow] (cfs)	Reported Annual Runoff (inches/year)	Model-Estimated Total Runoff (inches/year)	Total Modeled Surface Water Flow as Percentage of Reported 1995 Annual Mean Flow
St. Johns River near Melbourne	Poor	1,273	1,018	1,528	449	N/A	14.57	35
St. Johns River near Cocoa	Fair	1,847	1,570	2,124	872	18.84	15.63	47
St. Johns River near Christmas	Fair	2,286	1,943	2,629	1,144	20.17	15.47	50
Econlockhatchee River near Chuluota	Fair	416	354	478	253	23.44	14.29	61
St. Johns River above Lake Harney	Fair	3,077	2,615	3,539	1,729	20.45	15.30	56
St. Johns River near Sanford	Fair	3,945	3,353	4,537	2,496	N/A	16.06	63
Wekiva River near Sanford	Fair	337	286	388	286	N/A	20.86	85
St. Johns River near De Land	Fair	4,704	3,998	5,410	3,317	20.81	17.31	71
Ocklawaha River below Moss Bluff dam	Fair	286	243	329	971	N/A	15.07	339
Reedy Creek at SR 531	Fair	163	138	187	194	N/A	10.99	119
Kissimmee River at S-65	N/A	2,016	1,714	2,318	1,529	N/A	16.72	76

Note: cfs = cubic feet per second
N/A = not available
SR = state road

grid cell. This rate was then multiplied by the number of cells located within the basin, resulting in an average daily flow due to overland runoff. Total groundwater discharge (base flow) was then estimated by summing the simulated outflows to rivers from layers 1 and 2, the simulated flow to constant-head cells from layers 1 and 2, the simulated spring discharge from layer 2, and the prescribed free-flowing well discharge. The total modeled surface water flow equals the sum of the calculated overland runoff plus base flow. Modeled surface water flow is generally lower than reported, especially at surface water stations in the Upper St. Johns River Basin where simulated base flow to streams is low. The comparison between model-estimated and reported surface flow improves along the St. Johns River in a downstream direction. Approximately 138 cfs (89 mgd) of river cell discharge from layer 2 was simulated along the middle reaches of the St. Johns River (Table 8), and the calibration to spring flows in the St. Johns River basin is very good (Table 5). The reported mean annual 1995 flows along the river are substantially higher than the corresponding long-term average flows (USGS 1997), probably because of significantly higher than normal rainfall in parts of the basin (see Figure 33). Because the calculated overland runoff in the upper reaches of the basin is also relatively high (see Figure 40), the deficiency in model-estimated surface water flow is probably due to an underestimation of base flow from the surficial aquifer system (layer 1).

Calibrated Aquifer and Confining Unit Hydraulic Characteristics

The calibrated distributions of vertical hydraulic conductivity and leakance of the intermediate confining unit are shown by Figures 65 and 66, respectively. Calibrated values of vertical conductivity ranged from less than 0.001 ft/day to approximately 0.1 ft/day. The highest values occurred where clays are relatively thin or absent from the intermediate confining unit, particularly in the karstic upland areas of Lake, Marion, northern Polk, western Orange, western and northwestern Seminole, and southwestern Volusia counties. The values were lowest where the intermediate confining unit is dominated by relatively thick clay beds of the Hawthorn Group sediments in southeastern Orange, eastern Osceola, and southern Brevard counties. Intermediate confining unit leakance values ranged from approximately 1 x 10^{-6} ft/day/ft to 0.008 ft/day/ft. The highest leakances occurred where vertical hydraulic conductivity is high and where the intermediate confining unit is thin (see Figure 9). These areas include the Green Swamp area of northern Polk and southern Lake and Sumter counties, southwestern Volusia County, and other scattered areas within Lake, Orange, and Seminole counties.

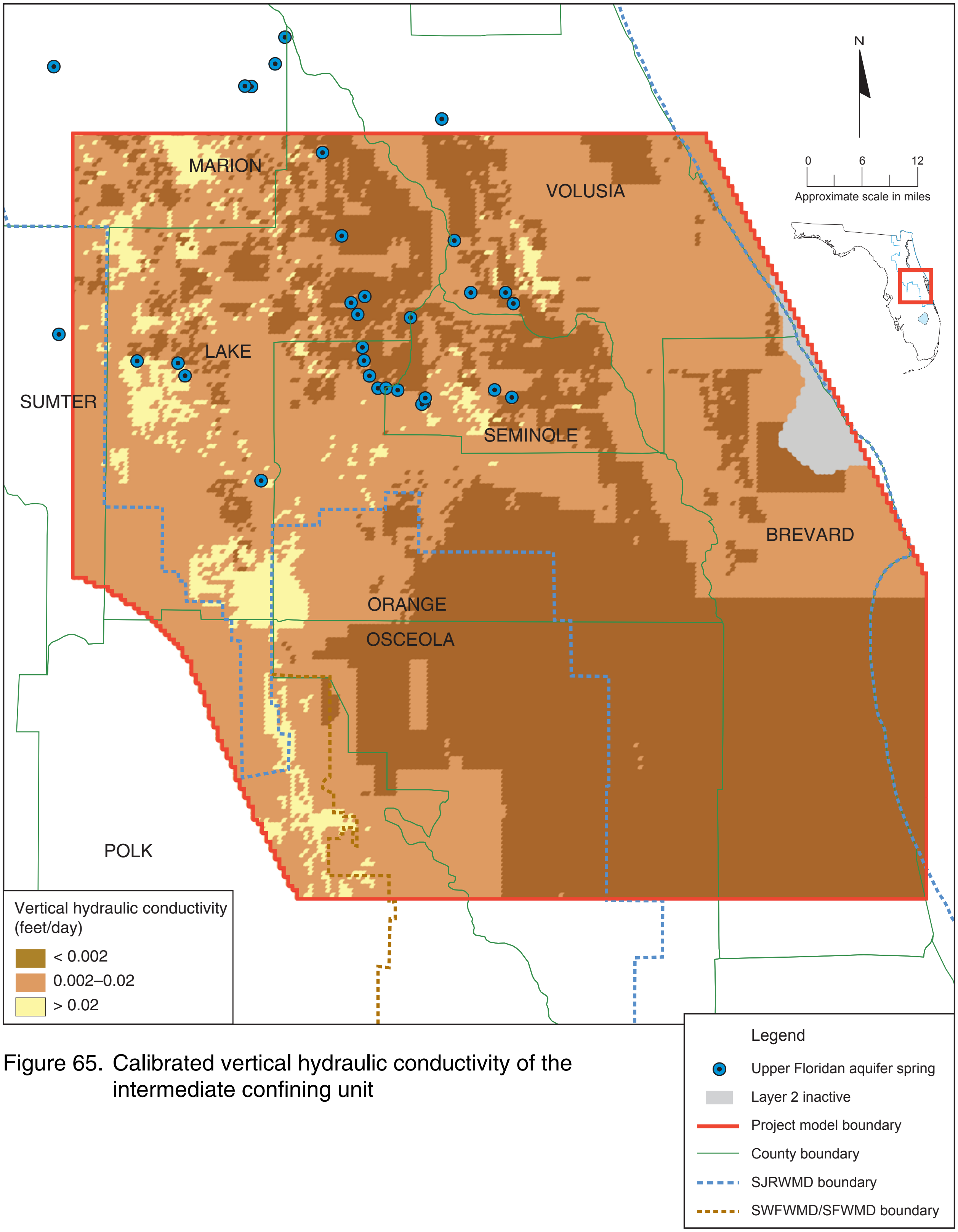


Figure 65. Calibrated vertical hydraulic conductivity of the intermediate confining unit

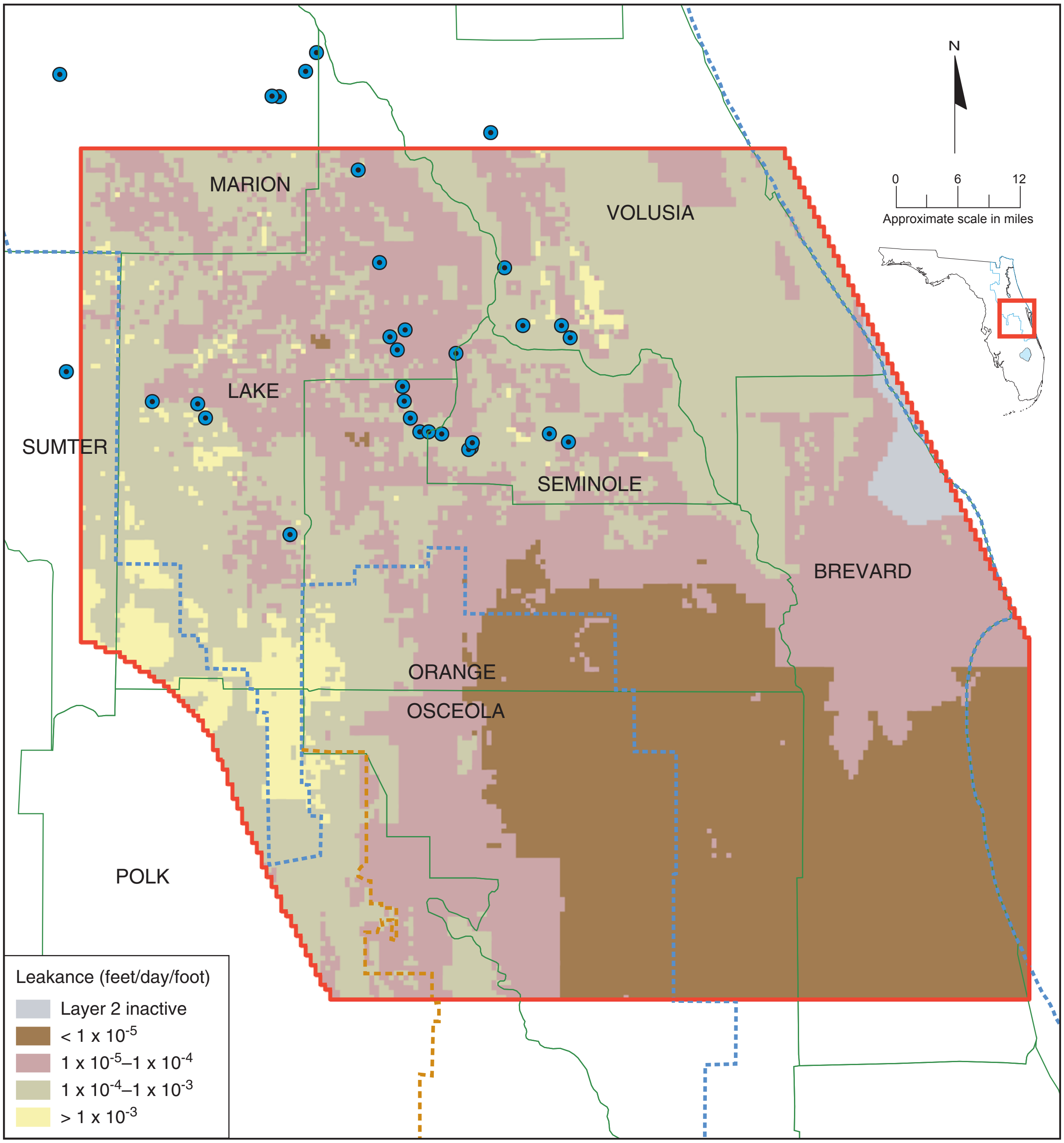


Figure 66. Calibrated leakance of the intermediate confining unit

Calibrated layer 1 (surficial aquifer system) horizontal hydraulic conductivity (K_h) equaled 20 ft / day throughout the model domain. A constant, modelwide value was used primarily because of the scarcity of large-scale hydraulic conductivity estimates for the surficial aquifer system.

Calibrated horizontal hydraulic conductivity values for Upper Floridan aquifer layers 2 (Figure 67) and 3 (Figure 68) ranged from less than 50 ft / day to greater than 5,000 ft / day. Values were highest around Blue Spring in southwestern Volusia County. Significantly high values (1,000–5,000 ft / day) occurred in layer 2 around other first- and second-magnitude springs, in southwestern Volusia County near Blue Spring, and in the Silver Springs basin in the northwestern corner of the model. Layer 3 K_h values exceeded 1,500 ft / day in roughly the southeastern one-half of the model. K_h values of both Upper Floridan aquifer layers were relatively low in southwestern Orange County, in central and eastern Volusia County, and along the southwestern border of the ECF region. The lowest values occurred in the Green Swamp and in central Volusia County where potentiometric levels are relatively high (see Figures 17 and 18). An equivalent Upper Floridan aquifer K_h was calculated at each grid cell using the calibrated layer 2 and layer 3 K_h values and the corresponding layer thicknesses. The resulting thickness-weighted Upper Floridan aquifer K_h was then multiplied by the sum of the layer 2 and layer 3 thicknesses to obtain a transmissivity value. Over most of the model domain, transmissivity values (Figure 69) were generally high where K_h values were high and low where K_h values were low. The decrease in Upper Floridan aquifer thickness due to the saline boundary is apparent, however, in northern Brevard County and along the St. Johns River valley. Upper Floridan aquifer transmissivity ranged from less than 20,000 ft^2 / day in parts of Volusia County to greater than 1,000,000 ft^2 / day in southwestern Volusia County. Transmissivities approaching the latter value occur in relatively small areas near first- and second-magnitude springs. Model-calculated transmissivity values are generally higher than those estimated by aquifer-test analyses. However, areas of high model-calculated transmissivities correspond to areas of high analytically derived transmissivities, and areas of low model-calculated transmissivities correspond to areas of low analytically derived transmissivities.

The calibrated values of Upper Floridan aquifer layer 2 and layer 3 vertical hydraulic conductivity (K_z) (Figures 70 and 71) ranged from 0.25 to 50 ft / day. These values resulted from the assumption made prior to calibration that the vertical anisotropy (K_h:K_z ratio) within layers 2 and 3 should generally range between approximately 100:1 and 1000:1. These vertical anisotropy ratios

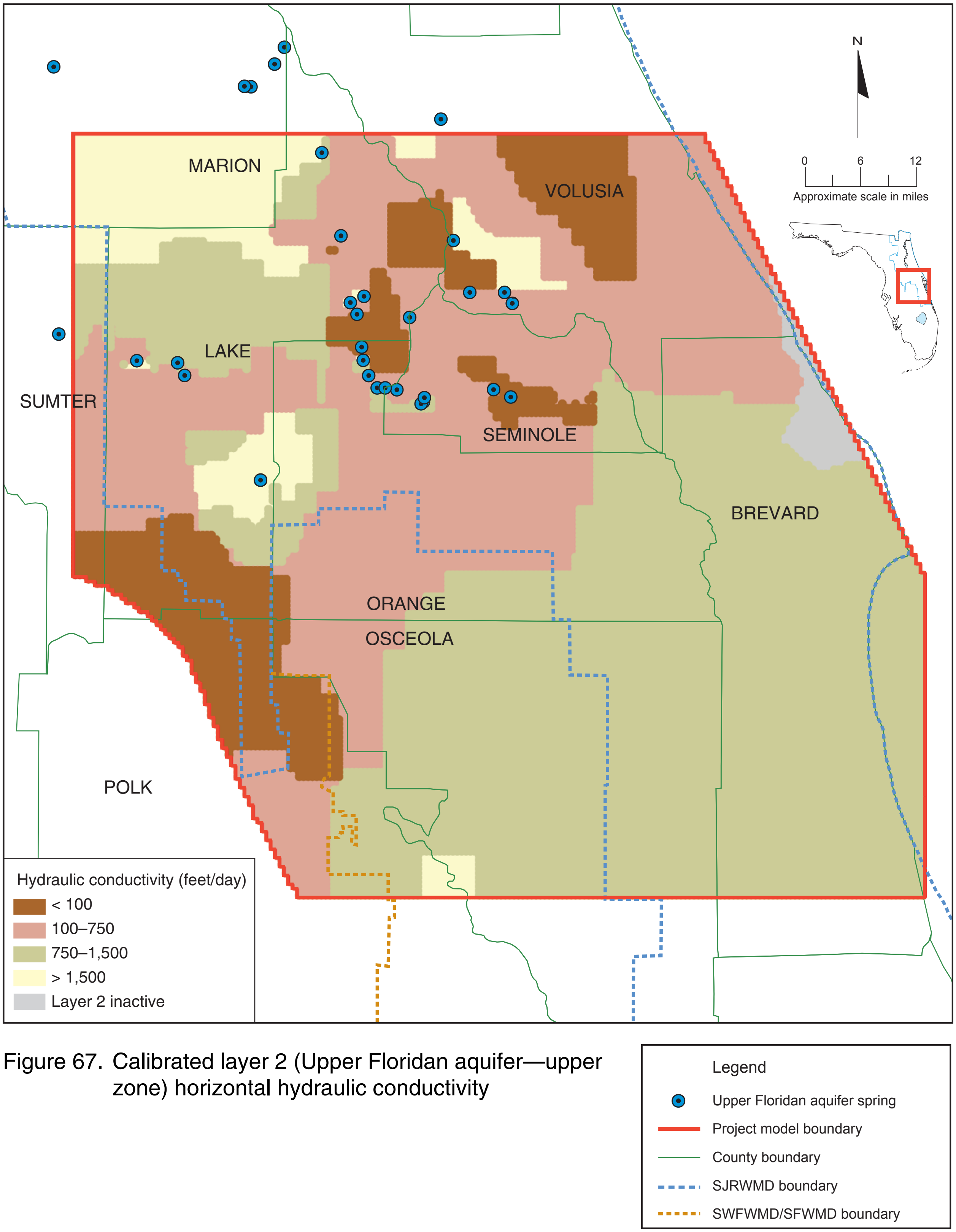


Figure 67. Calibrated layer 2 (Upper Floridan aquifer—upper zone) horizontal hydraulic conductivity

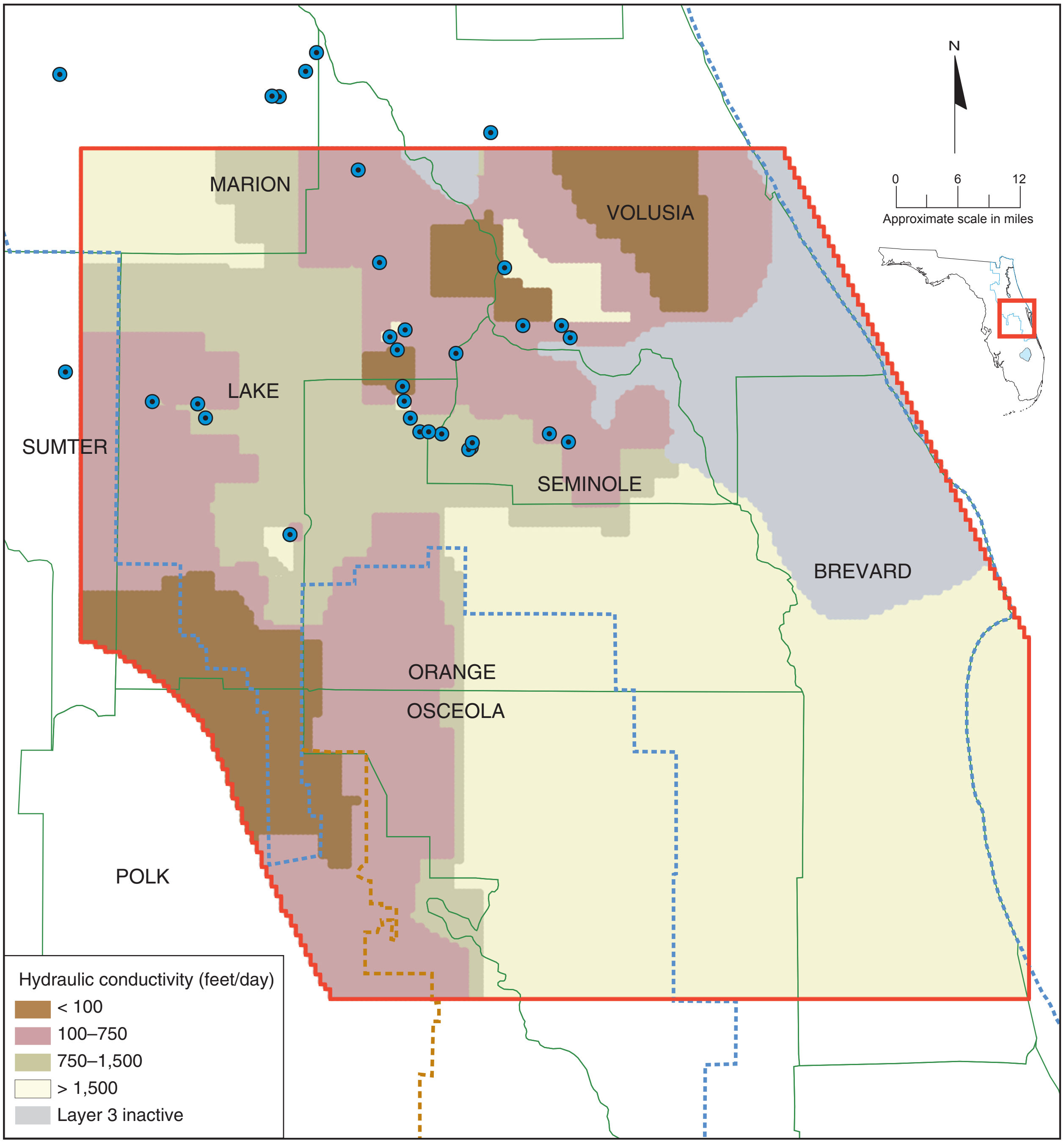


Figure 68. Calibrated layer 3 (Upper Floridan aquifer—lower zone) horizontal hydraulic conductivity

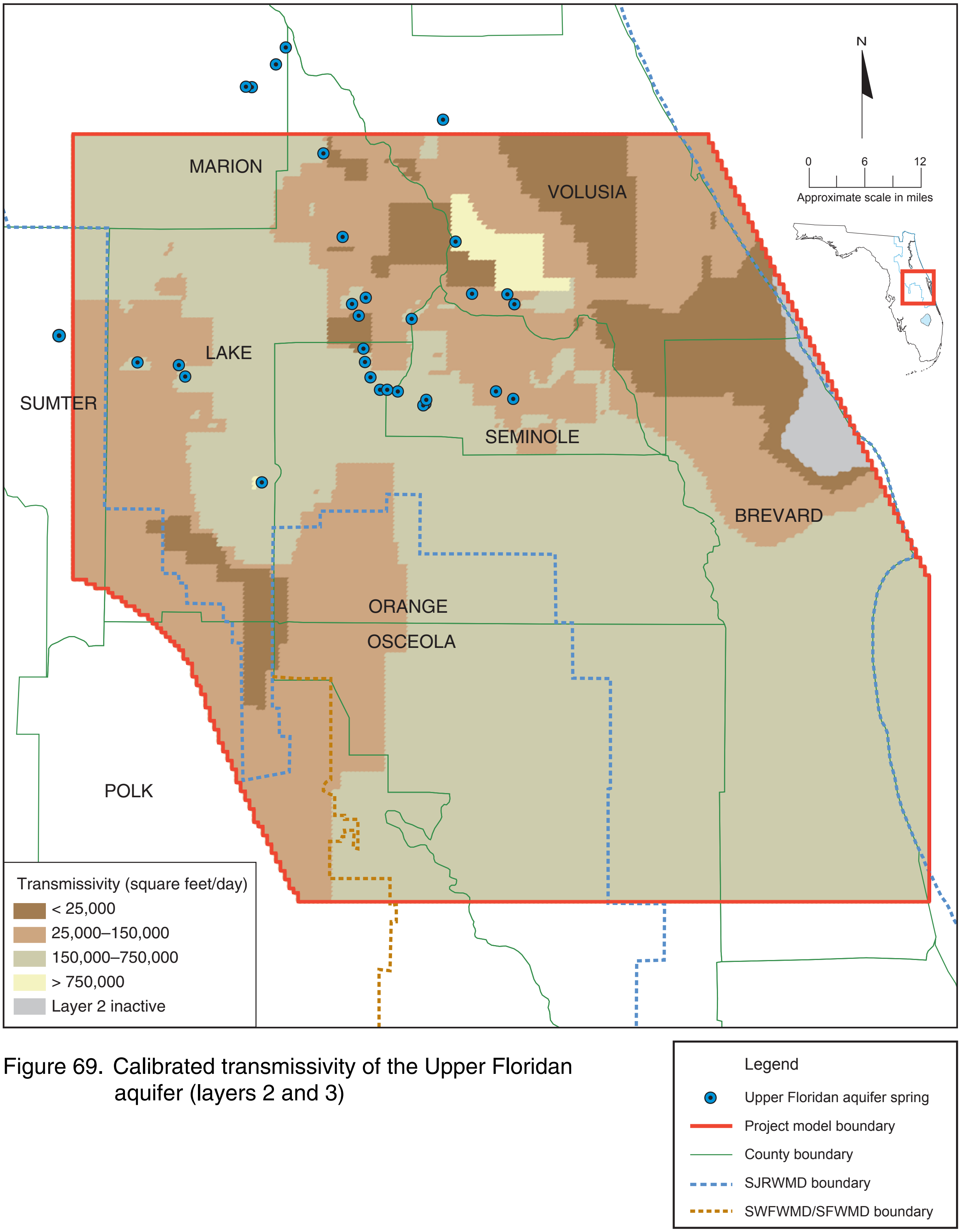


Figure 69. Calibrated transmissivity of the Upper Floridan aquifer (layers 2 and 3)

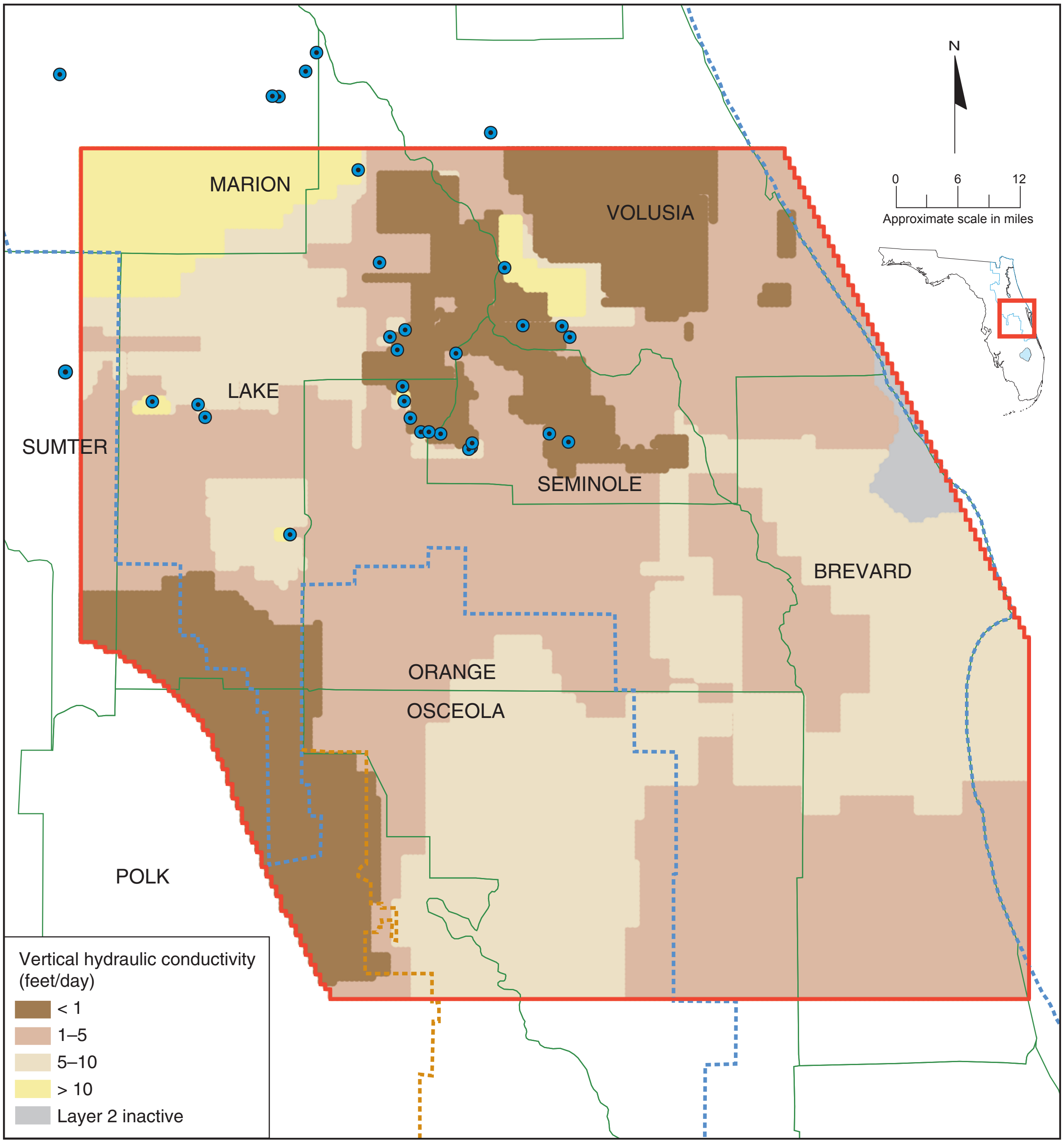
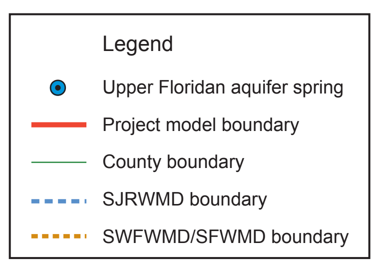


Figure 70. Calibrated vertical hydraulic conductivity of model layer 2 (Upper Floridan aquifer—upper zone)



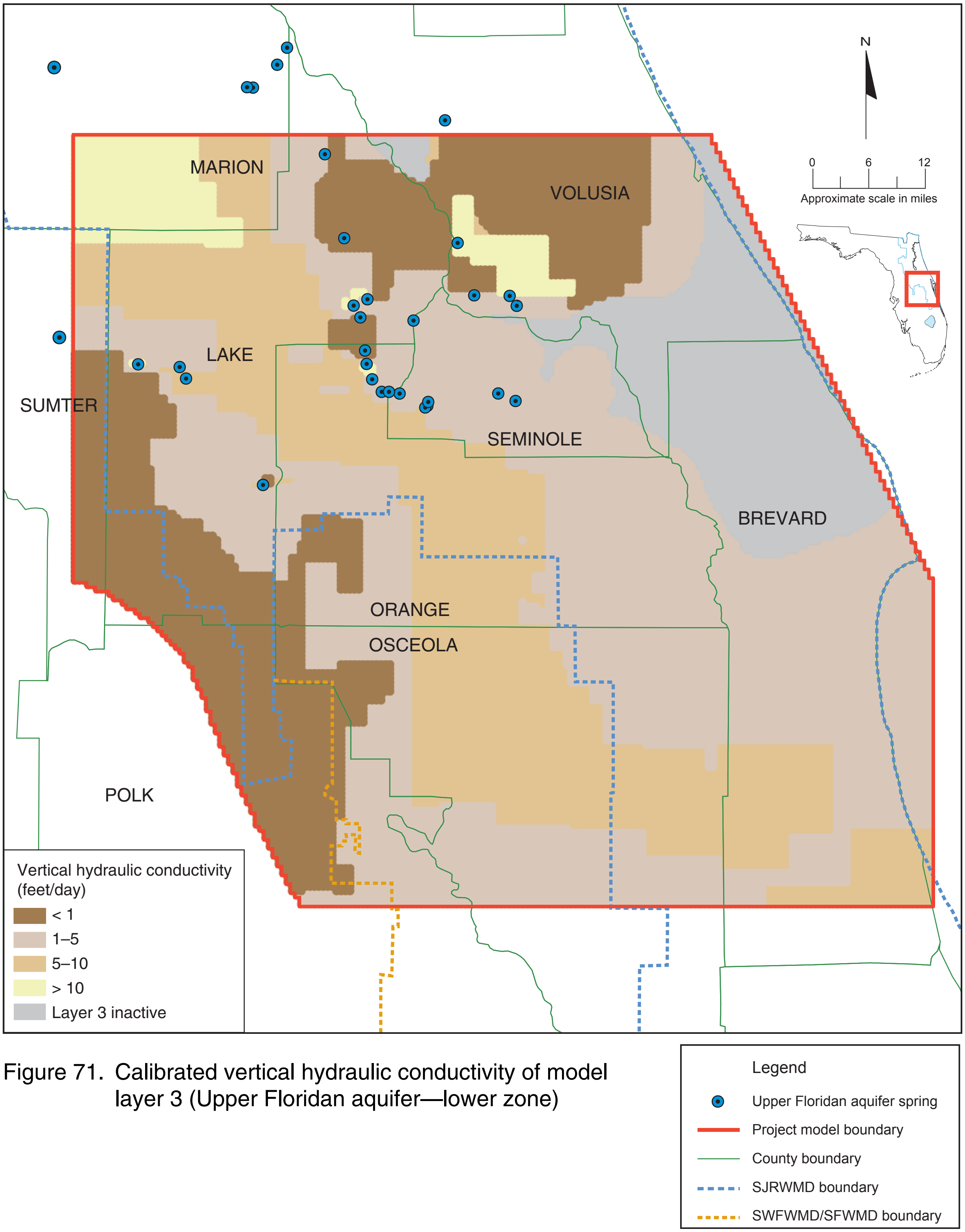


Figure 71. Calibrated vertical hydraulic conductivity of model layer 3 (Upper Floridan aquifer—lower zone)

were within the ranges generally considered valid for regional groundwater flow systems (Anderson and Woessner 1992; Freeze and Cherry 1979). Leakance between layers 2 and 3 calculated using these K_z values (see Equation 13 above) ranged from approximately 0.001 ft / day / ft to approximately 0.2 ft / day / ft (Figure 72). These leakances were highest where the K_h of both Upper Floridan aquifer layers was high and were lowest where the K_h values of both Upper Floridan aquifer layers was lowest.

Calibrated vertical hydraulic conductivity (K_z) values of the middle semiconfining unit (Figure 73) ranged from less than 0.01 ft / day to approximately 1.5 ft / day. Leakance of the middle semiconfining unit (derived by dividing each cell's K_z value by its corresponding middle semiconfining unit thickness) ranged from approximately 1.0 x 10^{-5} ft / day / ft to 3.8 x 10^{-3} ft / day / ft (Figure 74). The highest values of both middle semiconfining unit K_z and leakance were near Blue Spring (Volusia County). The lowest values occurred along the southwestern model boundary, where available data suggest that the base of the fresh groundwater flow system lies at or not far below the base of the Upper Floridan aquifer (Ryder 1985).

Middle semiconfining unit leakance was relatively high in central Orange County, where there is little vertical gradient between the Upper Floridan aquifer and the Lower Floridan aquifer. Calibrated middle semiconfining unit leakance was significantly higher than values reported by previous modeling studies in the ECF region within much of the northwest-southeast band stretching from Marion County to southern Brevard County. The higher values resulted primarily from the application of lateral boundaries within the Lower Floridan aquifer, where the elevation of the 5,000-mg / L chloride isosurface has been mapped higher than the elevation of the top of the Lower Floridan aquifer. Previous models did not consider water quality within the Lower Floridan aquifer as a boundary condition, allowing simulated flow in the Lower Floridan aquifer to flow laterally toward the coastline (Blandford and Birdie 1992; Murray and Halford 1996; Tibbals 1990). In the ECF model simulations, most of the water in the Lower Floridan aquifer discharged vertically upward into the Upper Floridan aquifer layers along this boundary (see Table 7).

Calibrated horizontal hydraulic conductivity (K_h) of layer 4 (Figure 75) ranged from 15 ft / day to 500 ft / day. Layer 4 transmissivity, calculated by multiplying the K_h values times the modeled (freshwater) thickness, ranged from 2,550 ft^2 / day to approximately 685,000 ft^2 / day (Figure 76). The highest K_h and transmissivity values were in central and northwestern Orange and

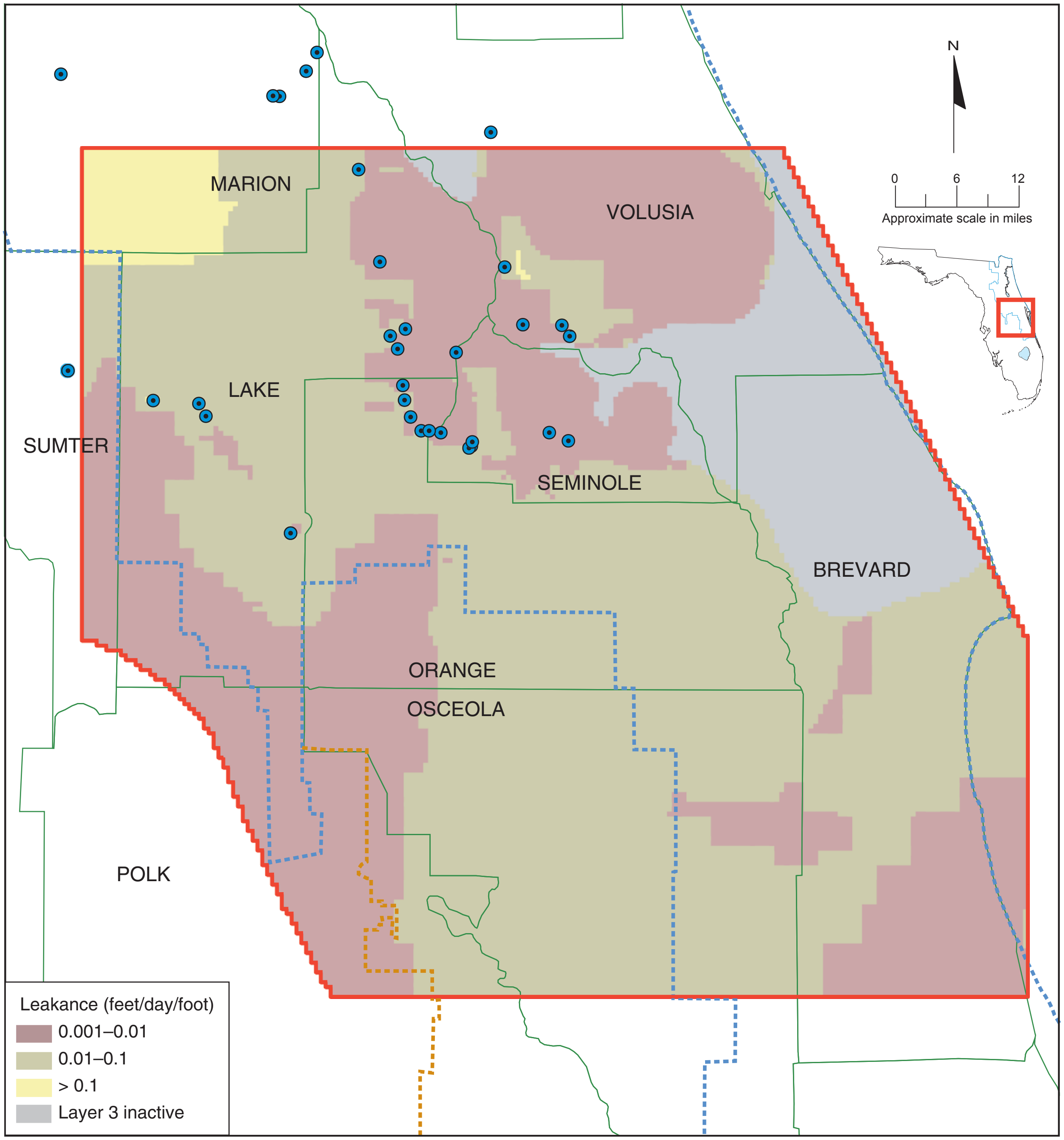
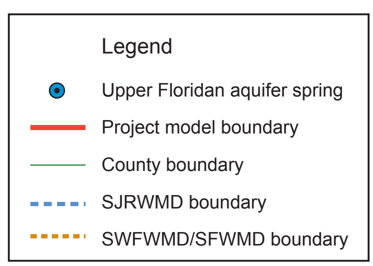


Figure 72. Calibrated leakance between Upper Floridan aquifer layers 2 and 3



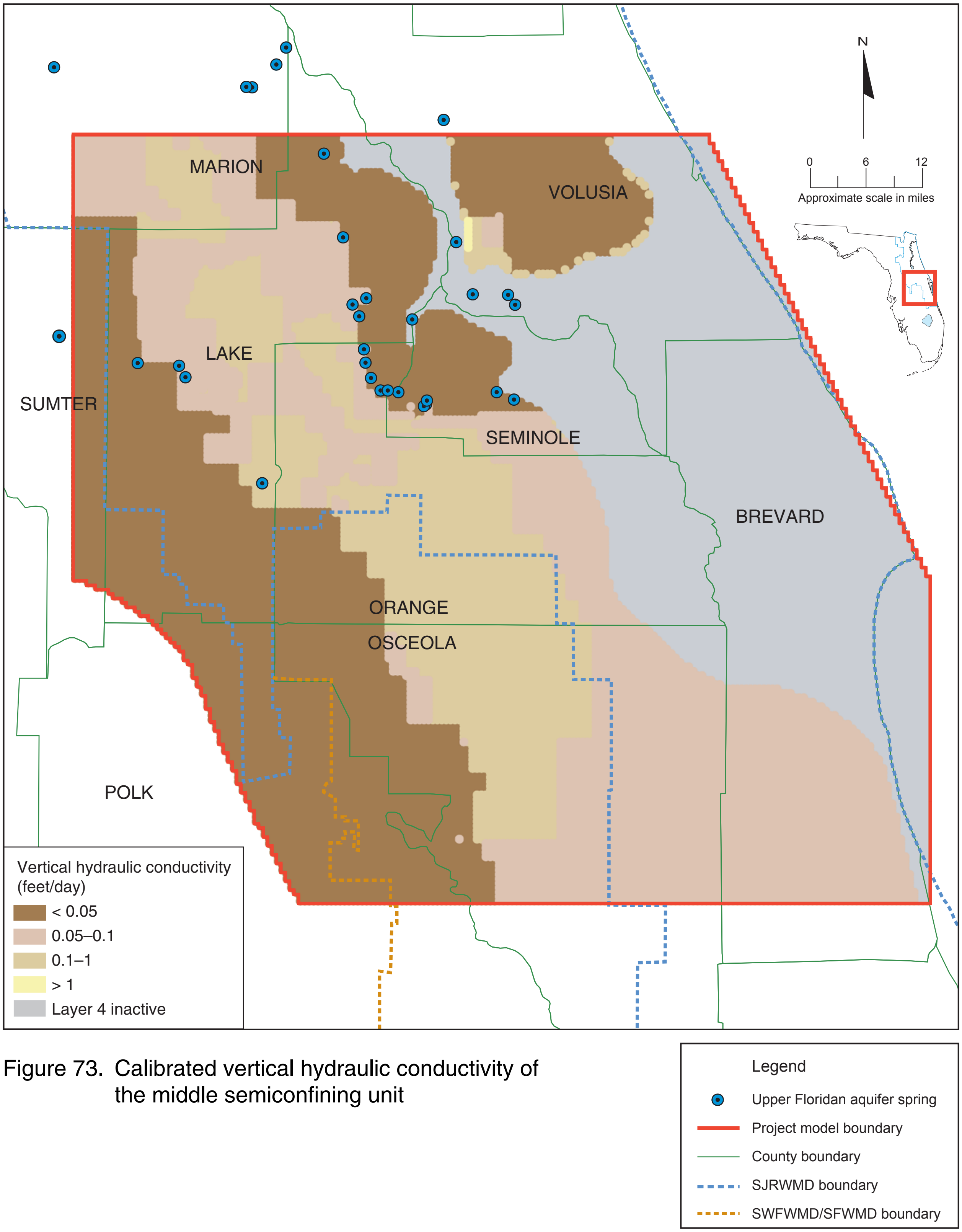


Figure 73. Calibrated vertical hydraulic conductivity of the middle semiconfining unit

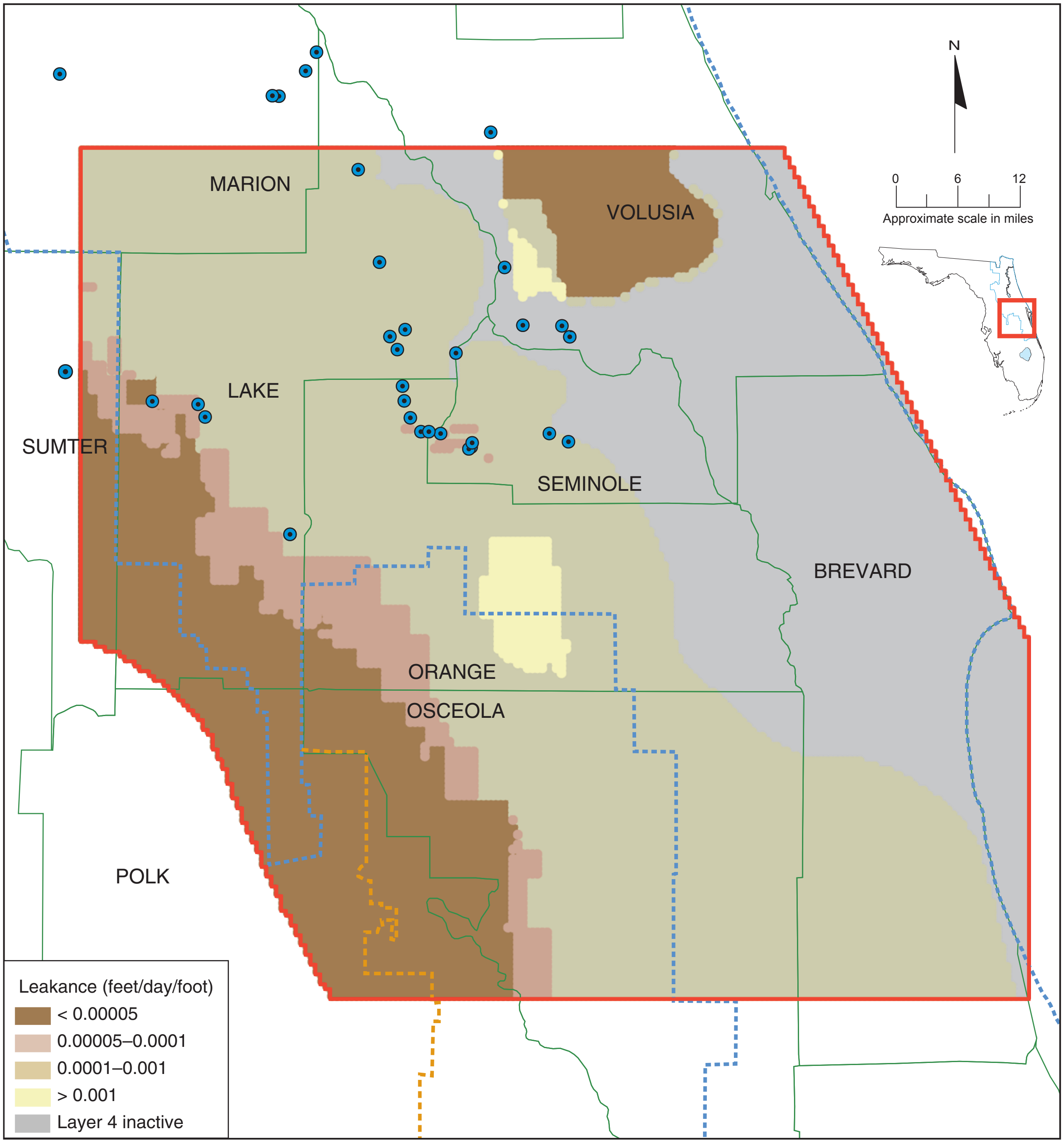


Figure 74. Calibrated leakance of the middle semiconfining unit

Legend
Upper Floridan aquifer spring
Project model boundary
County boundary
SJRWMD boundary
SWFWMD/SFWMD boundary

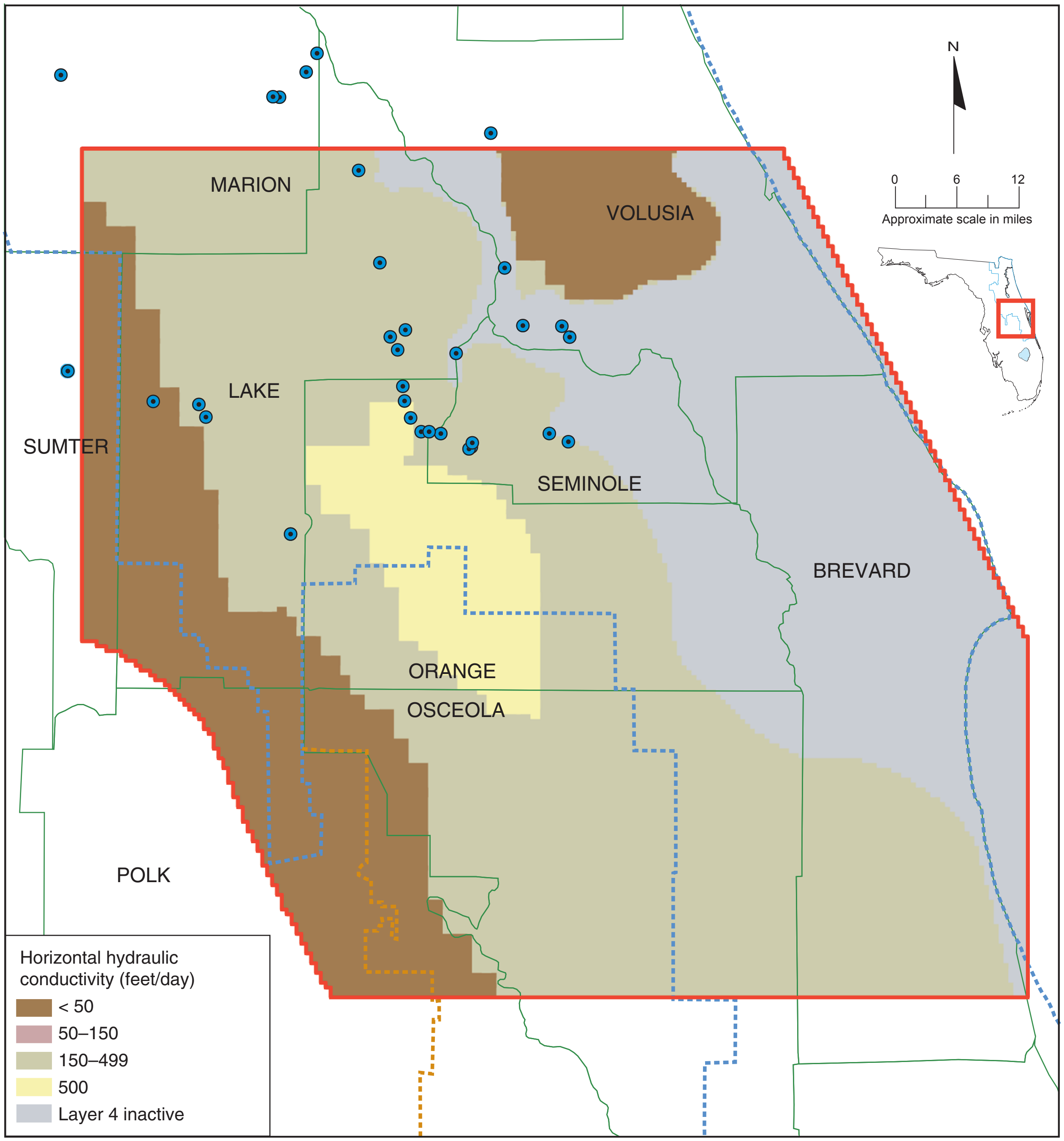


Figure 75. Calibrated layer 4 (Lower Floridan aquifer) horizontal hydraulic conductivity

Legend
Upper Floridan aquifer spring
Project model boundary
County boundary
SJRWMD boundary
SWFWMD/SRFWMD boundary

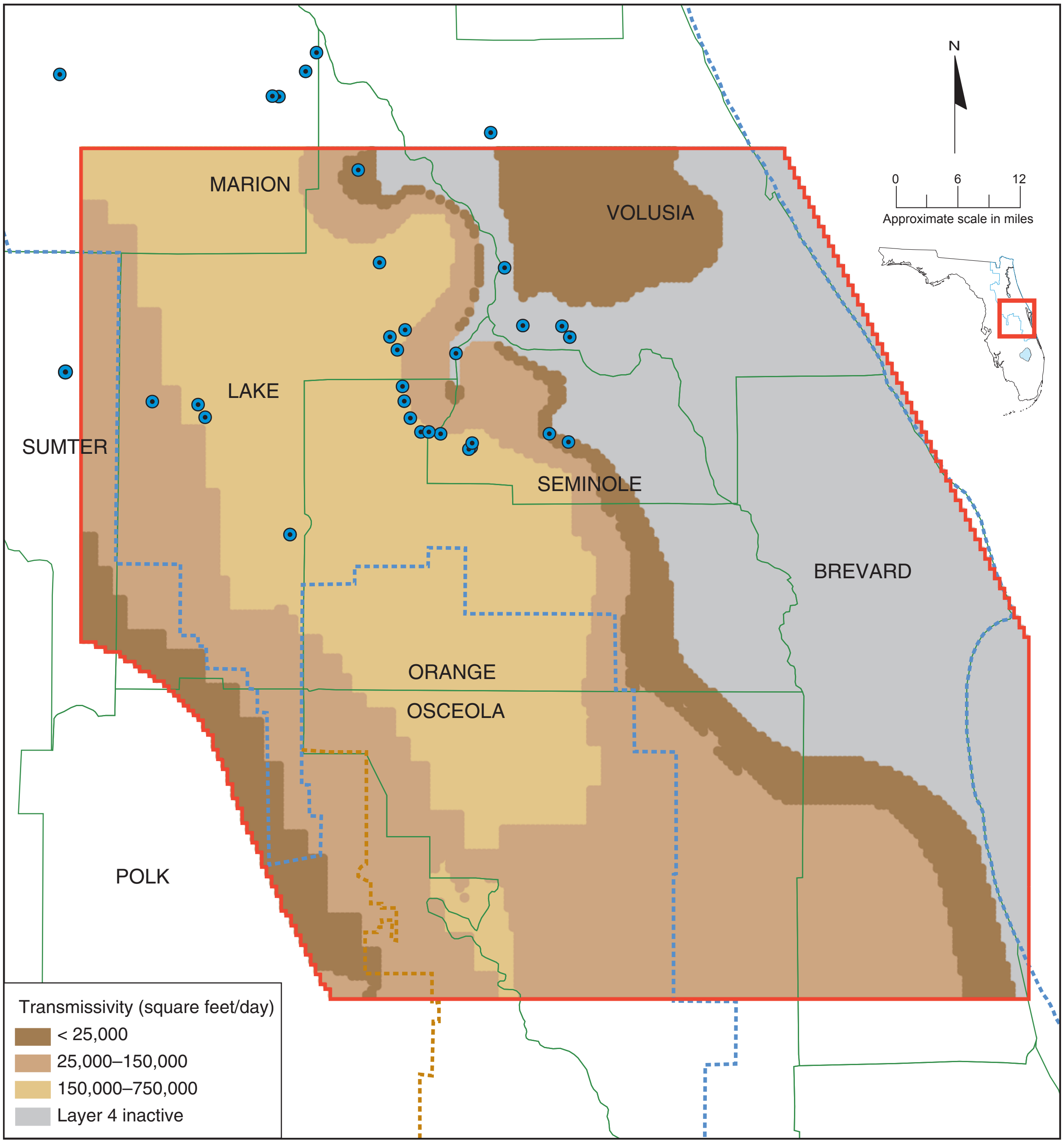


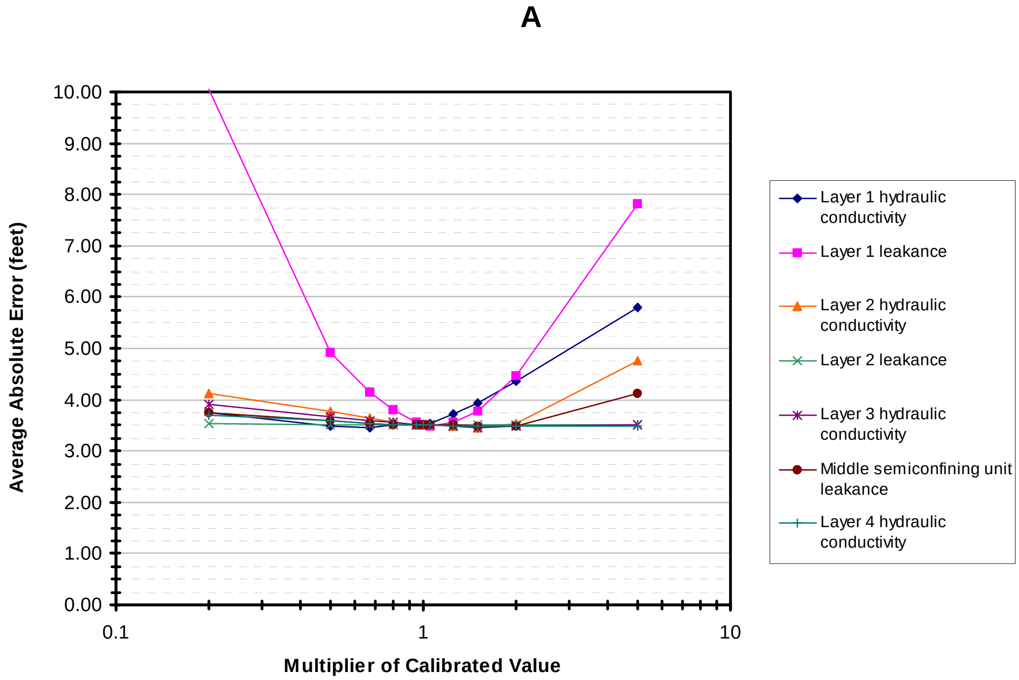
Figure 76. Calibrated transmissivity of the Lower Floridan aquifer (layer 4)

astern Lake counties, where aquifer test results also indicate high transmissivities. The lowest K_h values were along the southwestern model boundary where available data suggest that the base of the fresh groundwater flow system lies at or not far below the base of the Upper Floridan aquifer (Ryder 1985). The lowest layer 4 transmissivity values, however, occurred along the saline boundary where freshwater thickness (in terms of salinity) is least.

SENSITIVITY ANALYSES

A sensitivity analysis can quantify the relationships between model results and the input hydraulic properties and boundary conditions used in a model (ASTM 1999). The sensitivity analysis was performed by systematically changing the values of the calibrated model parameters and boundary conditions within a pre-established reasonable range. The amount of change in model results from that of the calibrated model provides an estimate of how sensitive the solution is to the input values of each parameter. The sensitized model parameters included the hydraulic conductivity of the aquifer layers, leakance of the semiconfining units, and leakance between layers 2 and 3. Boundary conditions included applied recharge, ET_{max}, ET_{min}, ET extinction depth, conductance values for river, drain, and GHB cells, the irrigation component of the recharge algorithm (R_{app}), and both freshwater and saltwater lateral boundary heads. Each parameter or stress was varied modelwide, one at a time, over a range that is equal to or greater than the estimated error in that parameter or stress. The resulting values of surficial aquifer system and Upper Floridan aquifer (model layer 2) mean absolute error were plotted against the change in each parameter or stress. Also plotted were the resulting total simulated spring flows from drain cells against the change in each parameter or stress.

Simulated surficial aquifer system heads were most sensitive to changes in intermediate confining unit leakance, recharge, ET_{max}, ET_{min}, and Floridan aquifer system freshwater heads along lateral boundaries (Figure 77). Simulated surficial aquifer system heads were moderately sensitive to changes in layer 1 and layer 2 hydraulic conductivity and relatively insensitive to changes in layer 3 and layer 4 hydraulic conductivity, middle semiconfining unit and leakance between layers 2 and 3, and conductance values applied to river, drain, and GHB cells. Simulated surficial aquifer system heads were also relatively insensitive to changes in irrigation, ET extinction depth, and lateral boundary saltwater heads except when those boundary conditions were multiplied by a factor of two or greater.



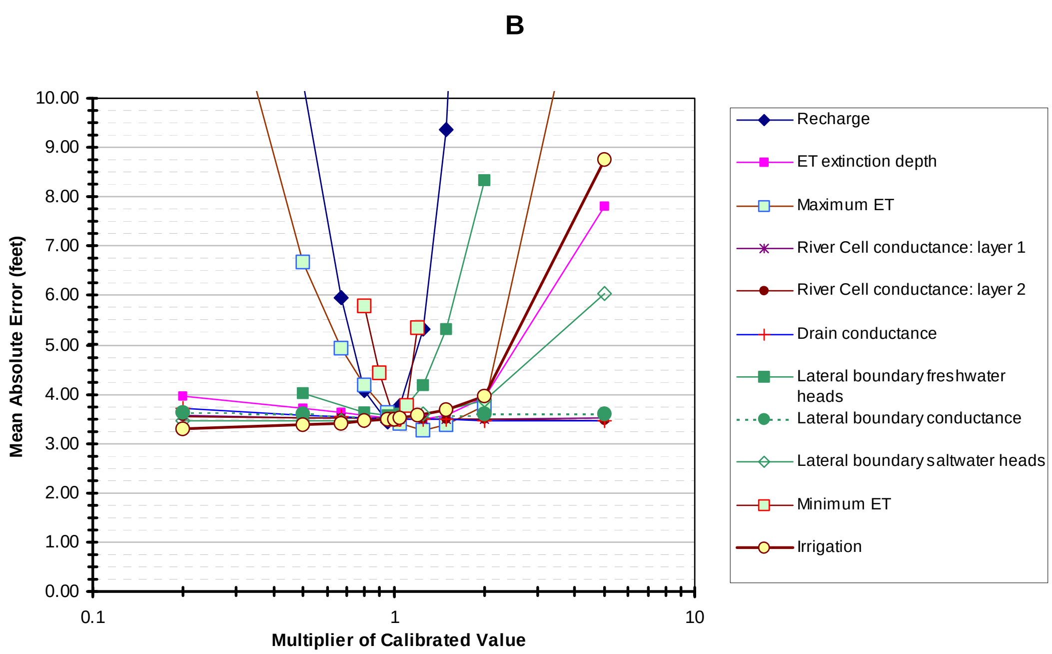


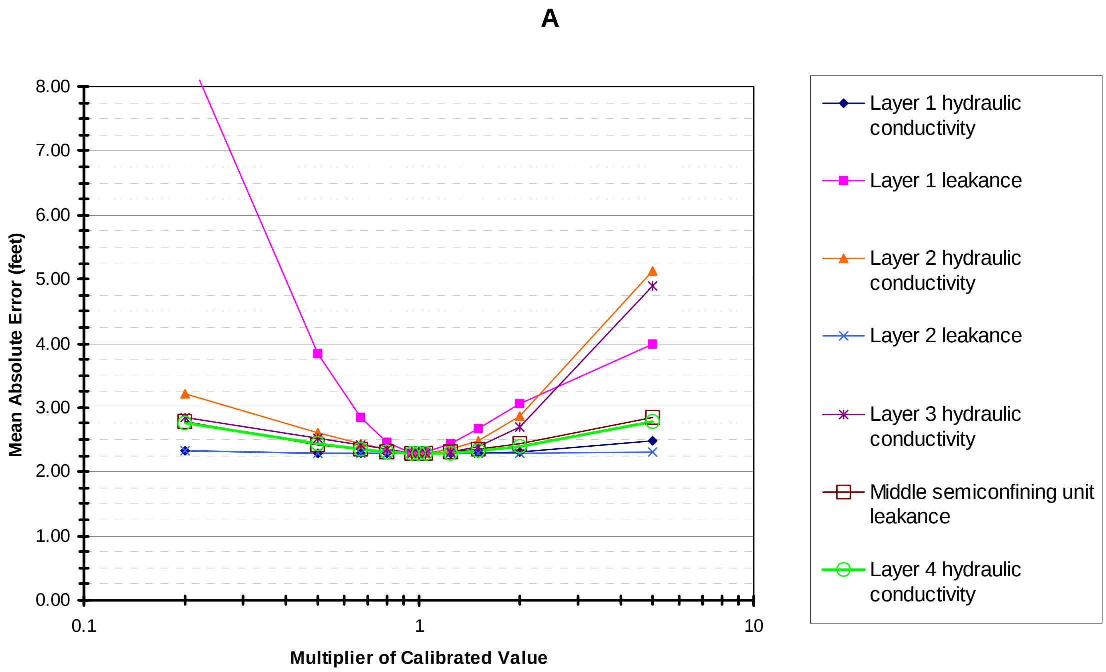
Figure 77. Sensitivity of surficial aquifer system (layer 1) simulated heads to changes in (A) aquifer and confining unit parameters and (B) selected boundary conditions

Simulated Upper Floridan aquifer (layer 2) heads were most sensitive to changes in intermediate confining unit leakance, recharge, ET_{min}, and Floridan aquifer system freshwater heads along lateral boundaries (Figure 78). Simulated Upper Floridan aquifer heads were moderately sensitive to changes in layer 2 and layer 3 hydraulic conductivity, ET_{max}, and lateral boundary saltwater heads and relatively insensitive to changes in layer 1 and layer 4 hydraulic conductivity, middle semiconfining unit and layer 2 leakance, and conductance values applied to river, drain, and GHB cells. Simulated Upper Floridan aquifer heads were also relatively insensitive to changes in irrigation and ET extinction depth, except when those boundary conditions were multiplied by a factor of five.

Total simulated spring flow was most sensitive to changes in intermediate confining unit leakance, layer 2 hydraulic conductivity, recharge, ET_{min}, and Floridan aquifer system freshwater heads along lateral boundaries (Figure 79). Total simulated spring flow was moderately sensitive to changes in drain conductance, layer 3 hydraulic conductivity, ET_{max}, and lateral boundary saltwater heads and relatively insensitive to changes in layer 1 and layer 4 hydraulic conductivity, middle semiconfining unit and layer 2 leakance, and conductance values applied to river cells. As with Upper Floridan aquifer heads, total spring flow was insensitive to changes in irrigation and ET extinction depth unless those boundary conditions were multiplied by a factor of five.

The sensitivity of model results to changes in ET_{min} was very similar but inversely proportional to that for changes in recharge. This is because recharge is a function of ET_{min} (see Equations 8 and 9). For the majority of model grid cells, a decrease of 1 inch in ET_{min} resulted in a 1-inch increase in recharge (N) and a 1-inch increase in ET_{min} resulted in a 1-inch decrease in recharge.

Although model results were sensitive to the head values used in the GHB package to represent lateral boundary freshwater heads, the error in the specified heads used for the 1995 calibration was probably less than or equal to approximately 5%–10%. This is because of the relatively detailed Upper Floridan aquifer potentiometric surface maps for the region that are available for 1995 (Knowles et al. 1995; O'Reilly et al. 1996). This error range is approximately equal to the ranges shown by the recharge sensitivity plots in Figures 77b and 78b below which the mean absolute error was below the calibration targets of 4.00 ft and 2.50 ft, respectively, for the surficial aquifer system and the Upper Floridan aquifer. This sensitivity suggests that the



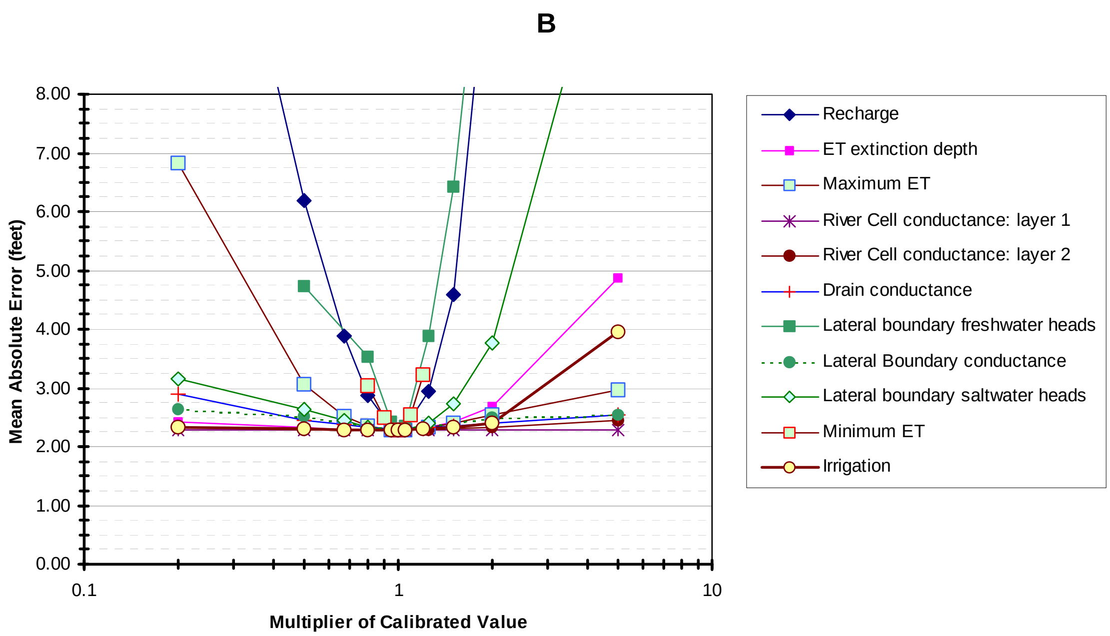
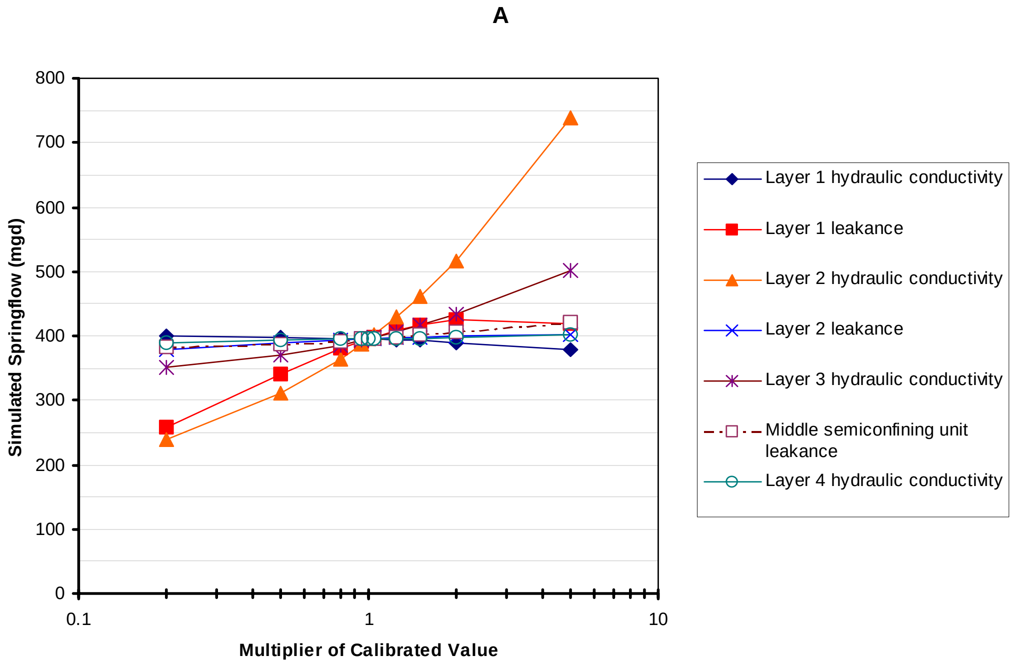


Figure 78. Sensitivity of Upper Floridan aquifer (layer 2) simulated heads to changes in (A) aquifer confining unit parameters and (B) selected boundary conditions



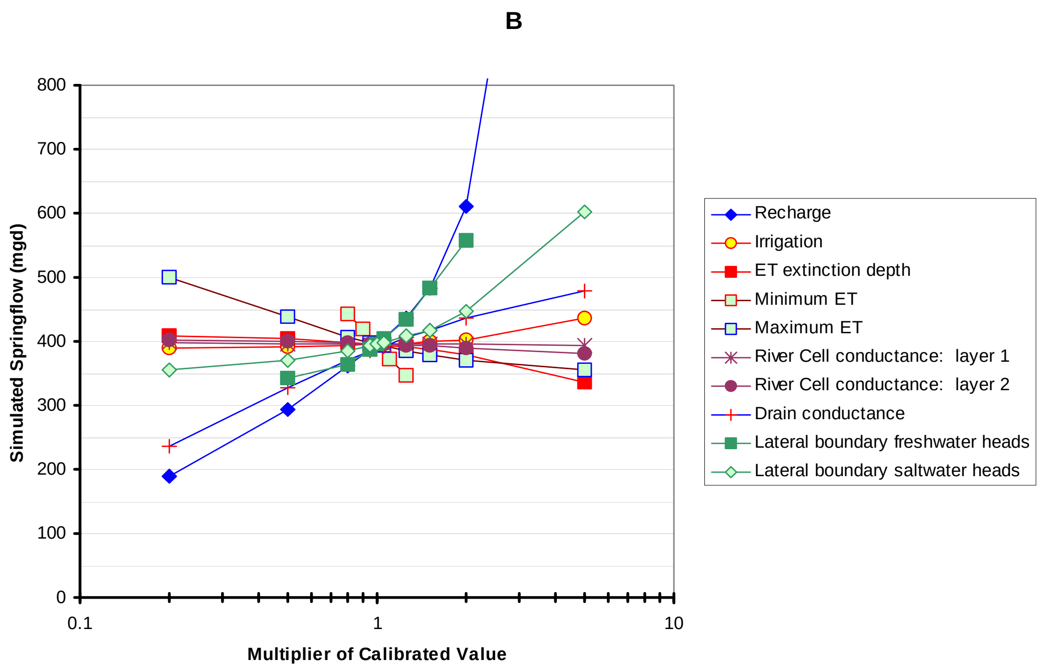


Figure 79. Sensitivity of simulated spring flow to changes in (A) aquifer and confining unit parameters and (B) selected boundary conditions

Results of predictive simulations would be affected by whether or not changes in boundary heads due to future Floridan aquifer system withdrawals just outside of the model domain were incorporated. Much less is known, however, about the error range regarding lateral boundary saltwater heads. Although model results are less sensitive to changes in saltwater boundary heads than other parameters and boundary conditions, the potential error in estimating these heads may also affect predictive simulations.

PREDICTIVE SIMULATIONS

The calibrated steady-state model was used to evaluate the potential changes to the groundwater flow system due to projected average Floridan aquifer system withdrawals for the year 2020. Most boundary conditions for the 2020 simulation were kept the same as those used for 1995. The only differences in model input between the 1995 calibration and the 2020 simulation were groundwater withdrawals and the irrigation component of recharge. In addition, a predictive sensitivity analysis was conducted that included four additional 2020 predictive simulations. For those simulations, selected input parameters and boundary conditions were changed in order to provide a range of potential future changes to the groundwater flow system due to projected 2020 withdrawals.

Projected 2020 Withdrawals

Projected 2020 water use data were obtained from the SJRWMD Division of Water Supply Management (Vergara 1998). Water use for each public water supplier was distributed to each well based upon the capacity of the well, if available, or the water use was distributed evenly among all the wells if no capacity data were available. The same process was applied to the commercial/industrial wells to assign withdrawal rates at each well location.

Projected public supply and commercial/industrial water use data for SFWMD and SWFWMD wells were obtained from each respective district. The SFWMD data were applied in a similar fashion to the SJRWMD data. The SWFWMD public-supply and commercial/industrial withdrawal rates were initially calculated by adjusting the 1995 withdrawal rate by the percentage of increase reported by county in SWFWMD (1998, draft).

SJRWMD projected 2020 water use withdrawal rates for each agricultural well were calculated based upon the average annual 1995 water use and the projected percentage of increase in each crop by county as reported in Vergara (1998). Projected 2020 agricultural water use data for SFWMD and SWFWMD were calculated using the average annual 1995 water use and adjusting the values by the projected percentage change in agricultural water use by county indicated in SWFWMD (1998) and SFWMD (1998).

At some locations, initial 2020 withdrawal projections were updated where site-specific water use permit data became available. Also, projected withdrawals at some SFWMD and SWFWMD locations were further updated after review by staff of those districts.

Across the model domain, public supply water use was projected to increase to approximately 651 mgd by 2020, or by 103% from 1995. Commercial/industrial water use was projected to remain approximately unchanged at 302 mgd. Agricultural, golf course, and recreational irrigation withdrawals were projected to increase to 198 mgd by 2020, or by 12% from 1995. Although self-supplied domestic withdrawals were projected to decrease slightly by 2020 (Table 3), there is no information describing the spatial distribution of future withdrawals of this type. Therefore, self-supplied domestic pumpage was not changed for the 2020 simulation. A significant number of the abandoned free-flowing wells that were believed to be flowing in 1995 have since been valved, repaired, or plugged. Therefore, it was assumed that discharge due to free-flowing wells would be zero by 2020. The total projected 2020 groundwater withdrawal in the ECF model was 915 mgd. The public supply increases in withdrawal were projected to occur both at existing wellfields and at new wellfield locations. The agricultural increases were disbursed across the model area; however, there were significant projected increases in greenhouse and nursery irrigation in Lake County.

The distribution of projected average 2020 withdrawals by model layer is similar to that of the average 1995 withdrawals (compare Figures 30–32 with Figures 80–82).

Boundary Conditions and Applied Recharge

The 2020 predictive simulation was run on the assumption that the same climatic conditions would exist that existed in 1995. Therefore, lateral (GHB) boundaries, ET extinction depth and surface elevation, and drainage well inflow, as well as river and drain (spring) boundary conditions were

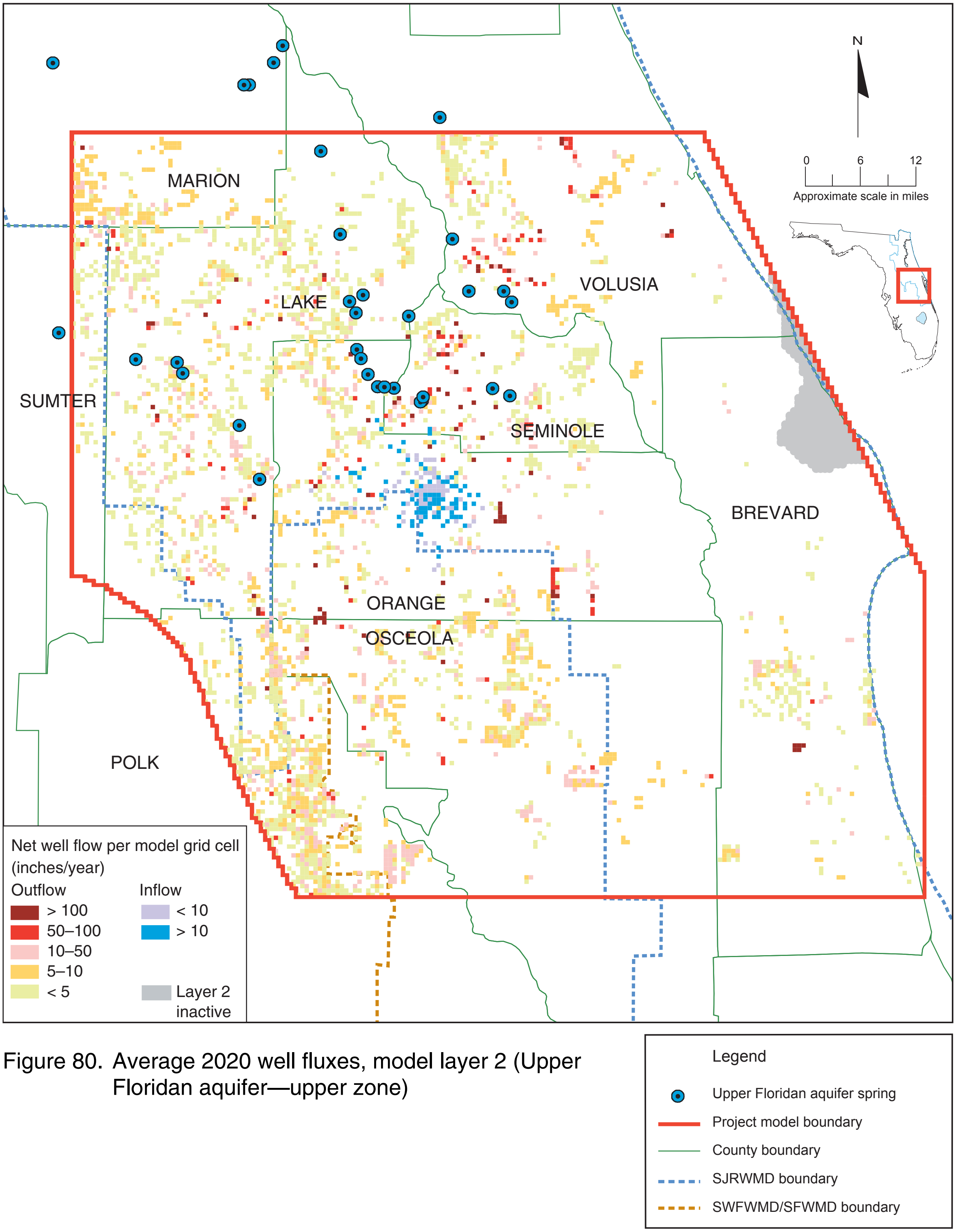


Figure 80. Average 2020 well fluxes, model layer 2 (Upper Floridan aquifer—upper zone)

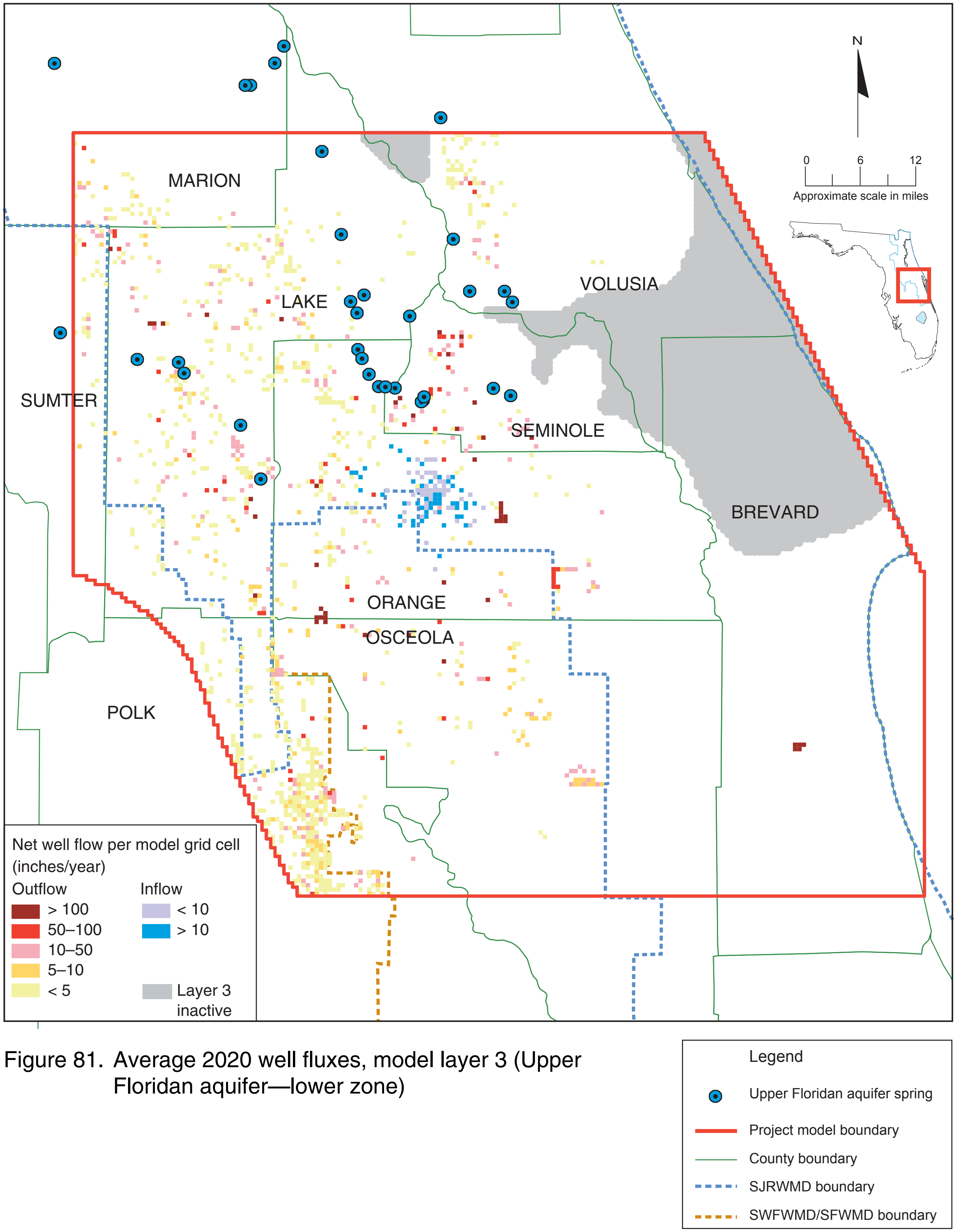


Figure 81. Average 2020 well fluxes, model layer 3 (Upper Floridan aquifer—lower zone)

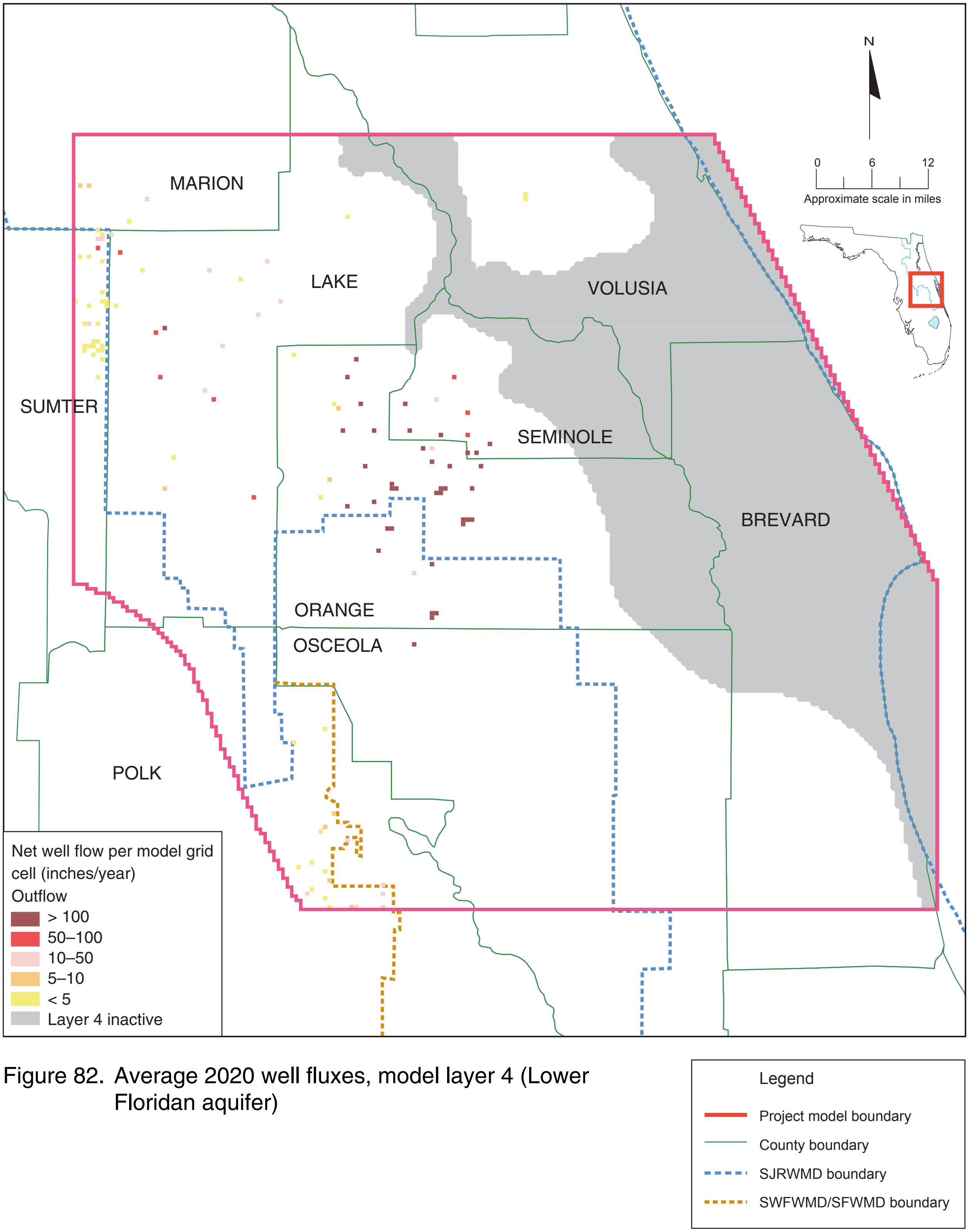


Figure 82. Average 2020 well fluxes, model layer 4 (Lower Floridan aquifer)

unchanged for the 2020 predictive simulation. (Another assumption that pertains to the lateral GHB boundaries is that adjacent withdrawals outside the model domain would not change the assigned boundary heads.) Also unchanged were the main components of the recharge algorithm used in Equations 8–10 (R_{mr}, ET_{min}, and ET_{max}). However, several of the components of irrigation (R_{app}) that comprise Equation 7 were increased to correspond with the projected increase in irrigation use of Floridan aquifer system withdrawals. Agricultural and golf course irrigation (R_{ag}) and public-supply lawn irrigation (R_{psli}) were recomputed in the same manner as before, using the appropriate 2020 withdrawals. R_{psli} was distributed over a larger portion of some public water supply service areas than for 1995 because of projected future increases in residential land uses. Projections of 2020 flow rates of reclaimed water to rapid infiltration basins (R_{rib}) and for irrigation (R_{spray}) are not available for many municipalities. However, because public-water supply withdrawals are projected to approximately double between 1995 and 2020, it was assumed that reclaimed water use would approximately increase by the same amount. Therefore, R_{rib} and R_{spray} flow rates were doubled over those estimated for 1995 for those municipalities for which detailed projections were not available. Projected 2020 R_{rib} and R_{spray} flow rates were applied at the same model grid cells where they were applied for 1995 unless detailed information on new locations was available.

Self-supplied domestic lawn irrigation (R_{ssdli}) and septic tank effluent (R_{septic}) were not changed from the 1995 values because of the lack of information describing future changes in their spatial distribution. Using the revised values for R_{ag}, R_{psli}, R_{rib}, and R_{spray}, net recharge (N) was recalculated for average 2020 conditions using Equations 11–13. The spatial distributions of average 2020 R_{rib}, R_{spray}, R_{psli}, R_{ag}, and recharge (Figures 83–86, respectively) were similar to those applied for average 1995 conditions.

Predicted Average 2020 Water Levels and Spring Flows

The simulated average 2020 Upper Floridan aquifer potentiometric surface (Figure 87) is similar in shape and appearance to the simulated average 1995 Upper Floridan aquifer potentiometric surface (see Figure 52); however, it has a lower elevation in certain areas. The average 2020 surface is most different from the average 1995 surface in central and southwestern Orange County and western Seminole County, where projected increases in Floridan aquifer system withdrawals are the greatest. Simulated heads were also noticeably lower in parts of southeastern Lake County, northwestern Osceola County, and southwestern Volusia County. Drawdowns (drop in average water level

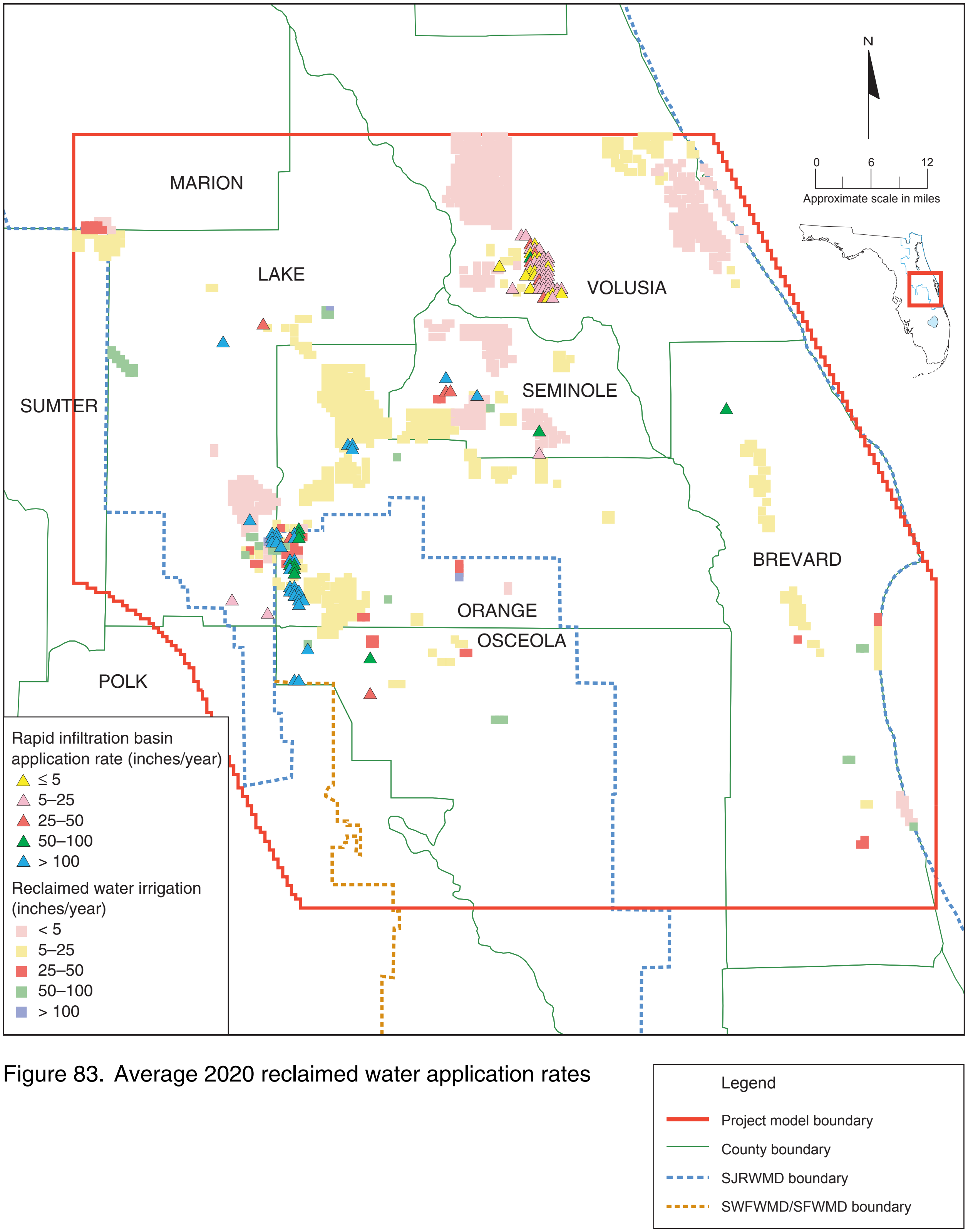


Figure 83. Average 2020 reclaimed water application rates

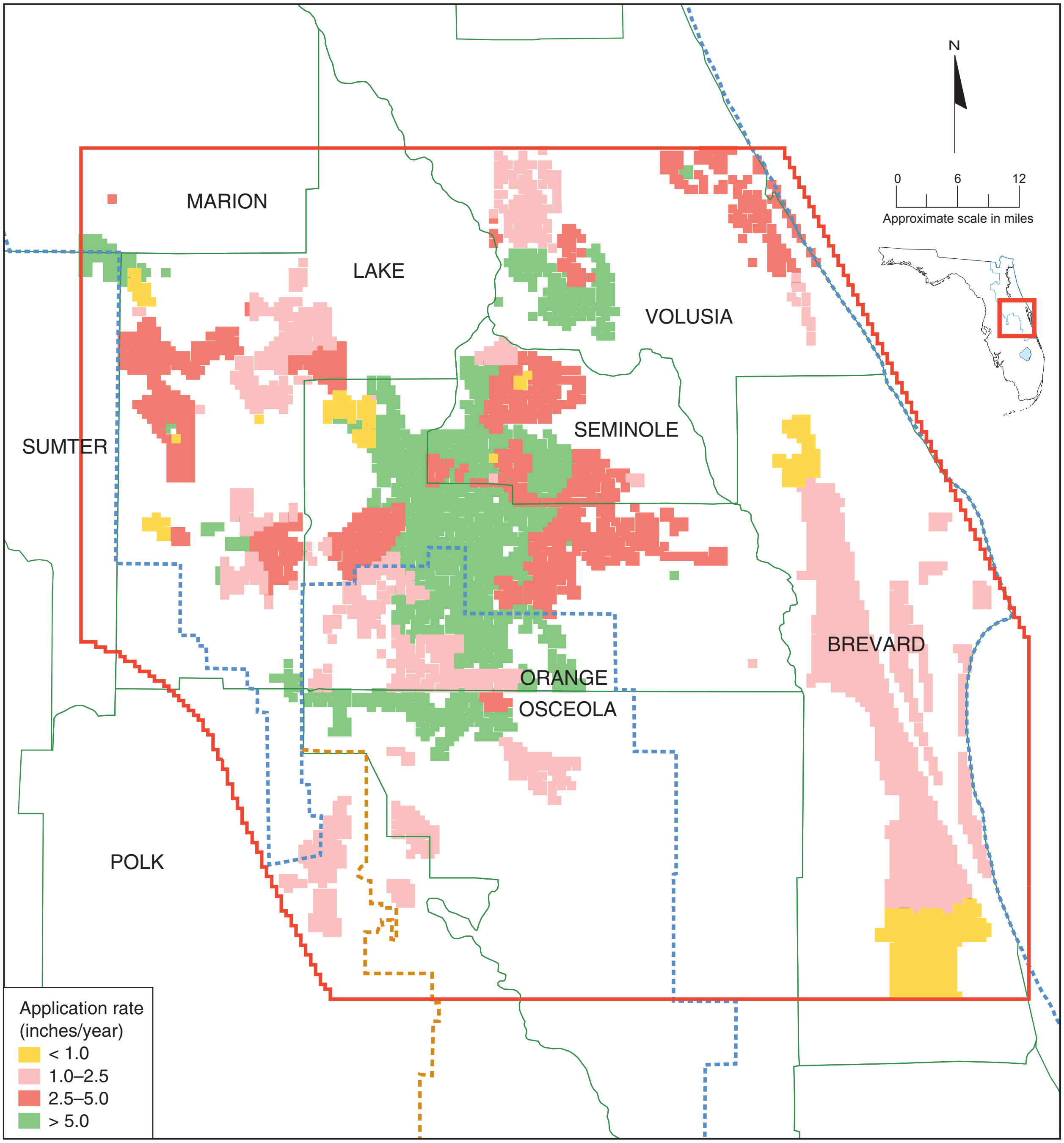


Figure 84. Average 2020 public-water supply landscape irrigation rates

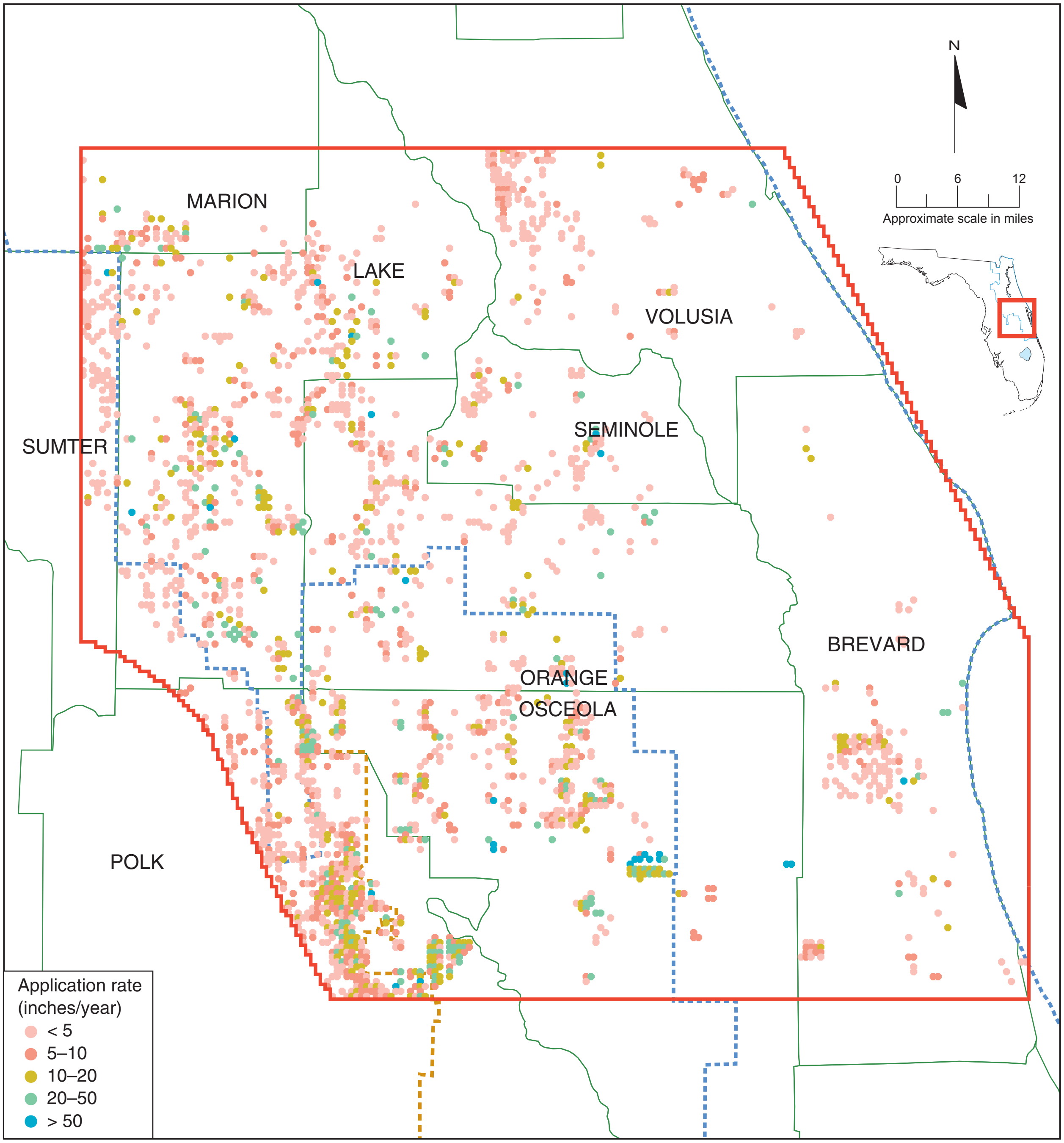


Figure 85. Average 2020 agricultural and golf course irrigation rates (derived from Floridan aquifer system withdrawals)

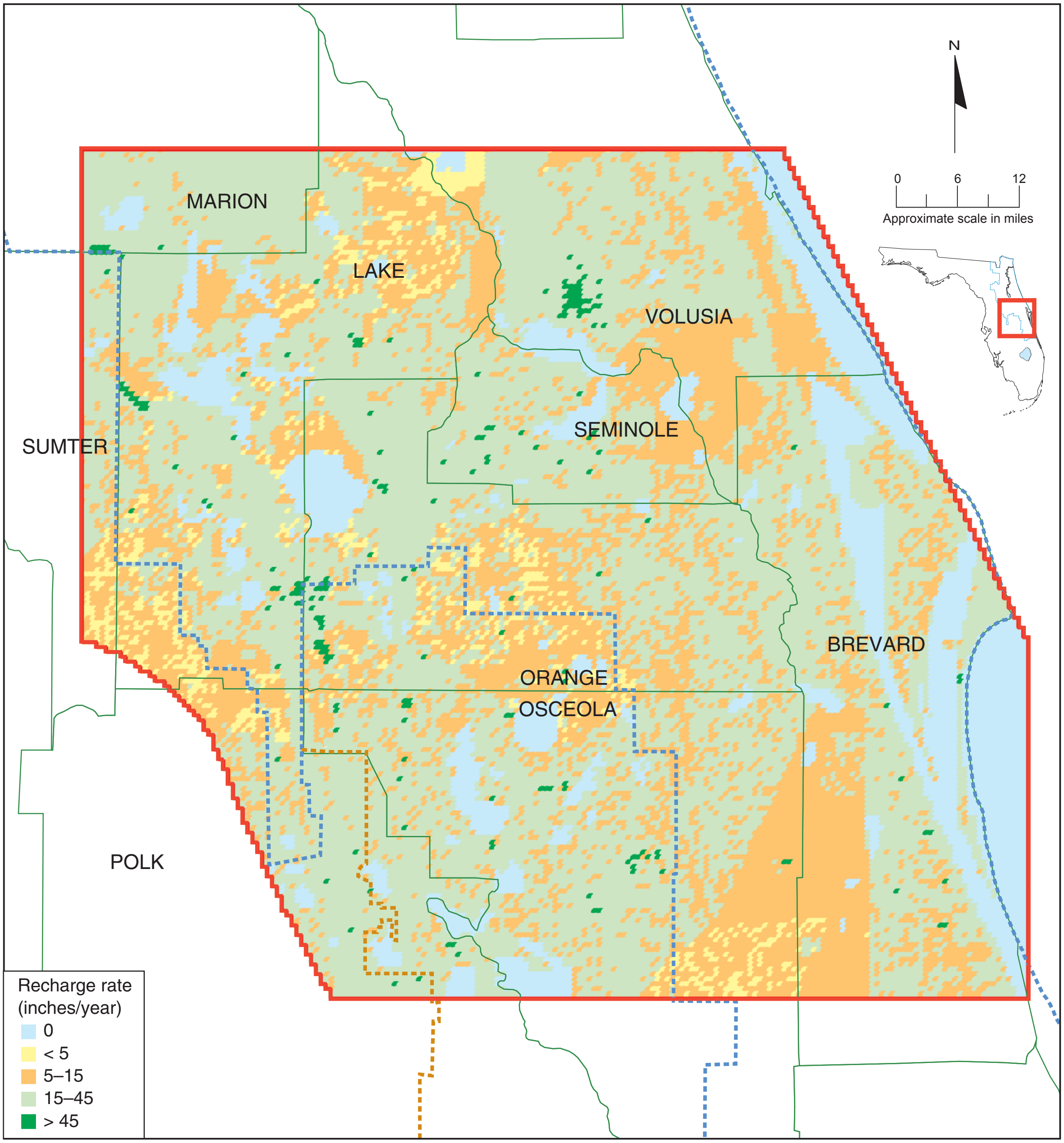


Figure 86. Recharge applied to the surficial aquifer system for average 2020 conditions

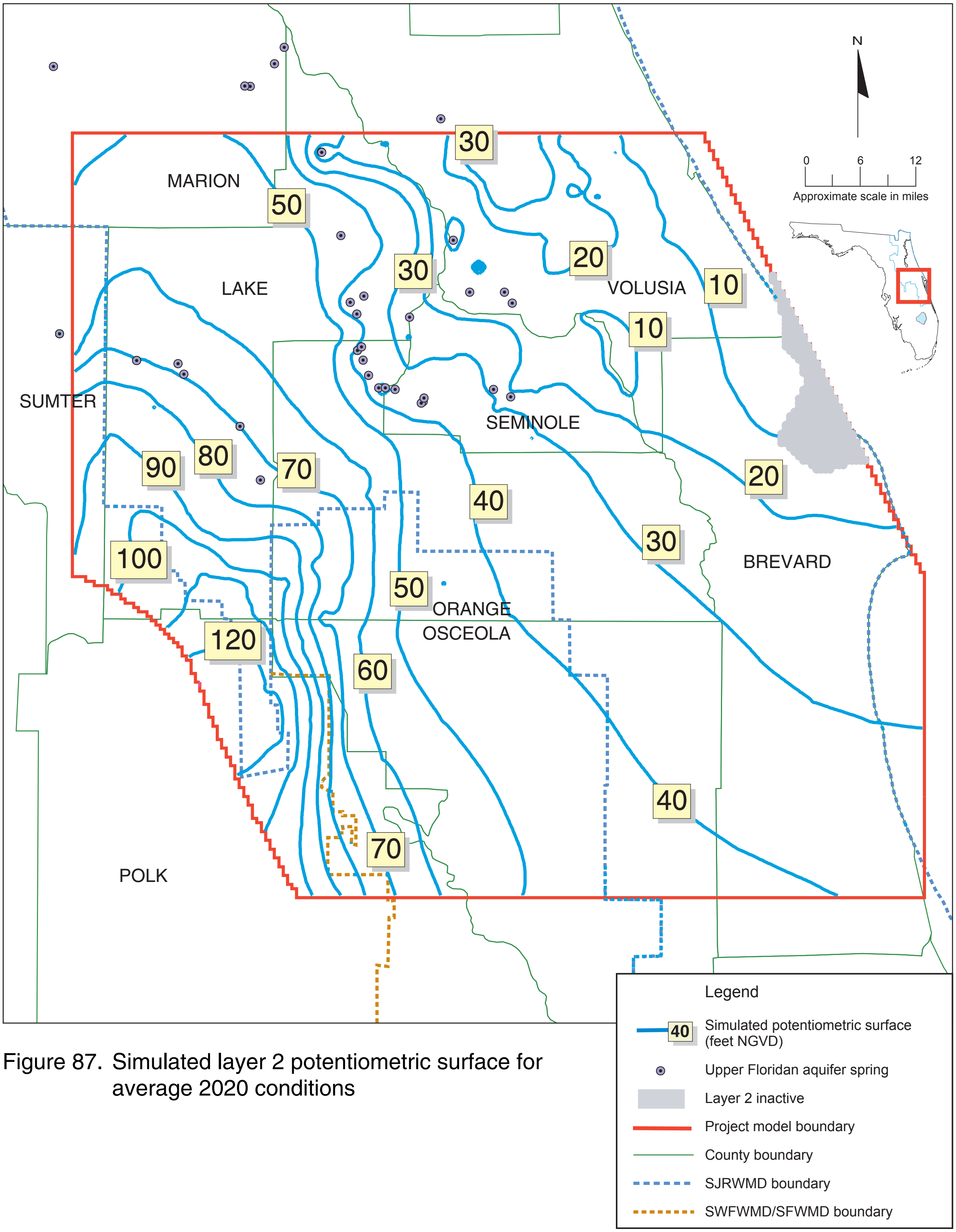


Figure 87. Simulated layer 2 potentiometric surface for average 2020 conditions

relative to average 1995 conditions) in these areas exceeded 2 ft in the surficial aquifer system (Figure 88) and 5 ft in the Upper Floridan aquifer (Figure 89).

The Upper Floridan aquifer drawdown exceeded 10 ft around the locations of the greatest increases in pumping. In an area extending from northwestern Orange County into central and northwestern Lake County, Upper Floridan aquifer drawdown ranged from 2 to 5 ft and surficial aquifer system drawdown was greater than 2 ft in scattered areas where the intermediate confining unit is leakiest (compare Figure 66 with Figure 88). Drawdown in the Lower Floridan aquifer (Figure 90) was greatest in western and central Orange County and southwestern Seminole County. Lower Floridan aquifer drawdown exceeded 2 ft throughout most of the active layer 4 area. The spatial pattern of drawdowns in the Upper Floridan aquifer and the Lower Floridan aquifer is primarily affected by the centrally located withdrawal increases. However, the imposed boundary conditions in the northwestern and southeastern corners of the model domain may have had some effect upon the magnitude of the predicted drawdowns. Aquifer transmissivities and, therefore, boundary conductances, in these areas are very high. Consequently, the high boundary conductance values may have limited water-level changes in these areas.

Three small areas of projected Upper Floridan aquifer water-level increase are located in western Lake County, southwestern Orange County, and northwestern Osceola County near the Polk County boundary. All of these areas encompass large-scale reclaimed water application projects, and all are located where the intermediate confining unit is leaky. The predicted increases in average surficial aquifer system water levels resulted from the increase in prescribed recharge due to either reclaimed water application, lawn irrigation in public-water supply service areas, or agricultural/golf course irrigation. Areas of predicted surficial aquifer system water level increase (Figure 88) are more extensive in the southeastern third of the ECF model where the intermediate confining unit is thick and non-leaky, and they are less extensive throughout the rest of the model domain where the intermediate confining unit is relatively thin.

The predicted 2020 total spring flow was approximately 64 ft^3/second (11%) less than the simulated 1995 total spring flow (see columns labeled “base case” in Table 9). Among the first- and second-order springs, the greatest predicted decrease in flow occurred at Palm/Sanlando Springs (27%), while significant decreases were also predicted at Apopka Spring (24%) and

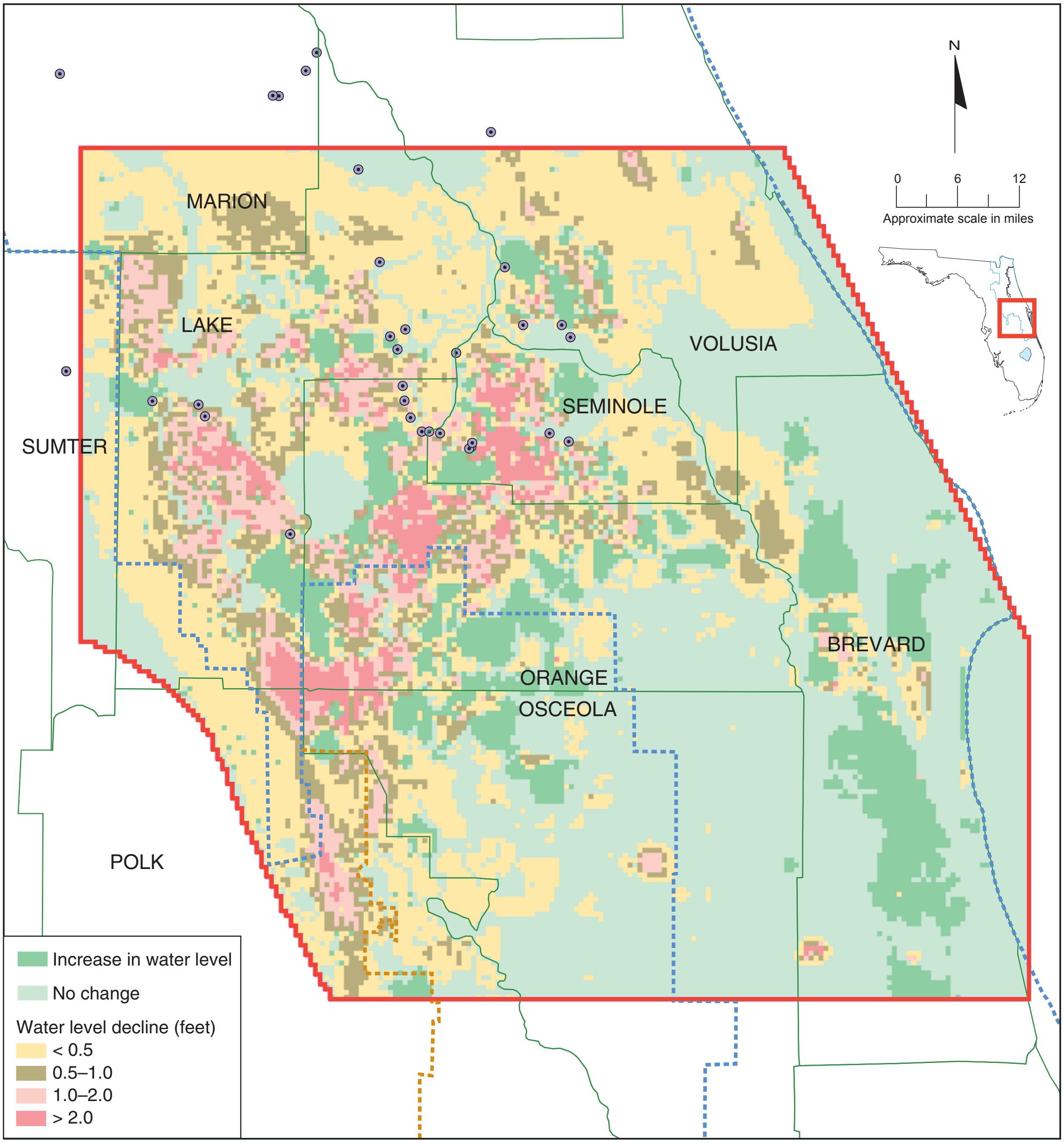


Figure 88. Predicted change in average surficial aquifer system water levels, 1995–2020

Legend

Upper Floridan aquifer spring
Project model boundary
County boundary
SJRWMD boundary
SWFWMD/SFWMD boundary

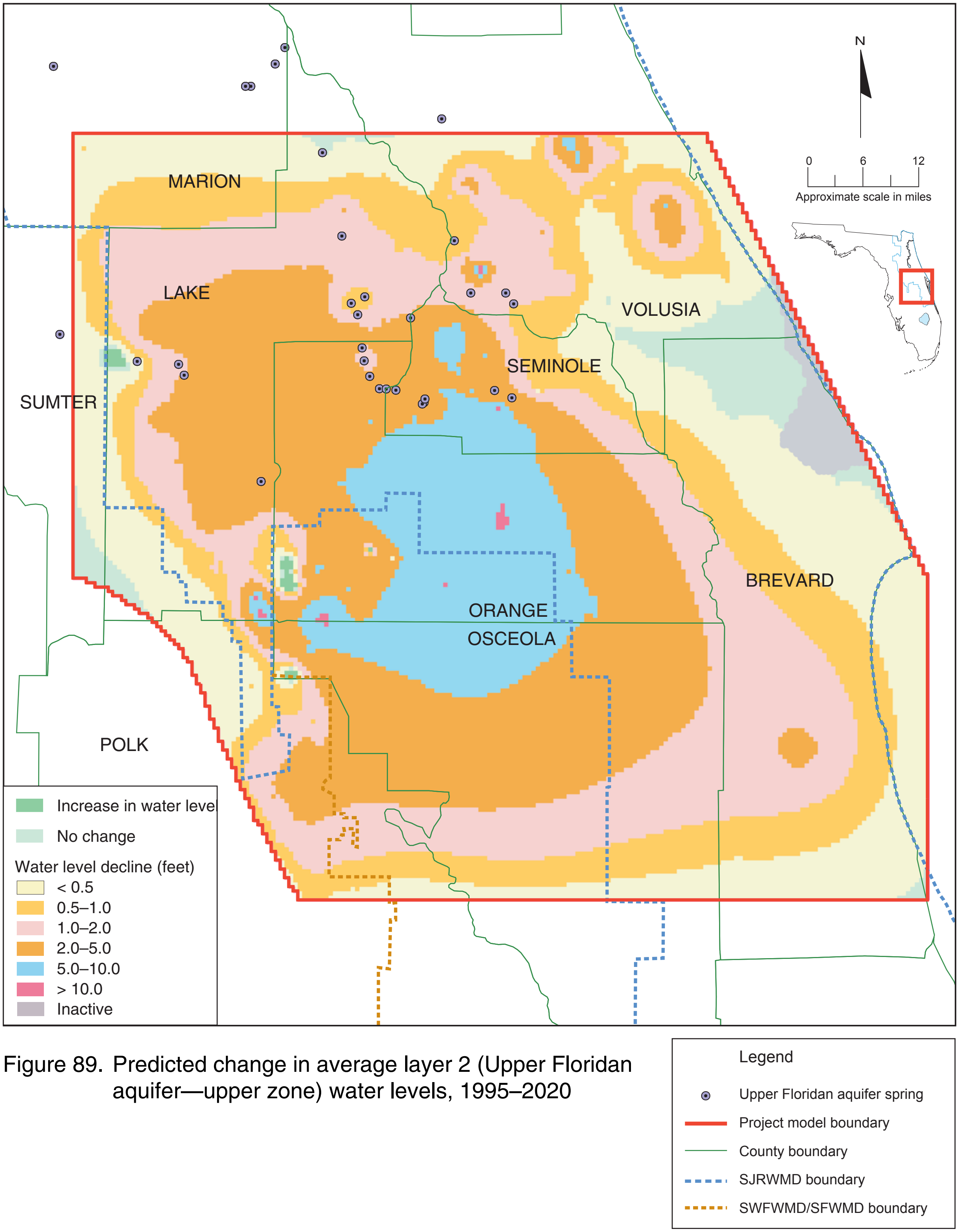


Figure 89. Predicted change in average layer 2 (Upper Floridan aquifer—upper zone) water levels, 1995–2020

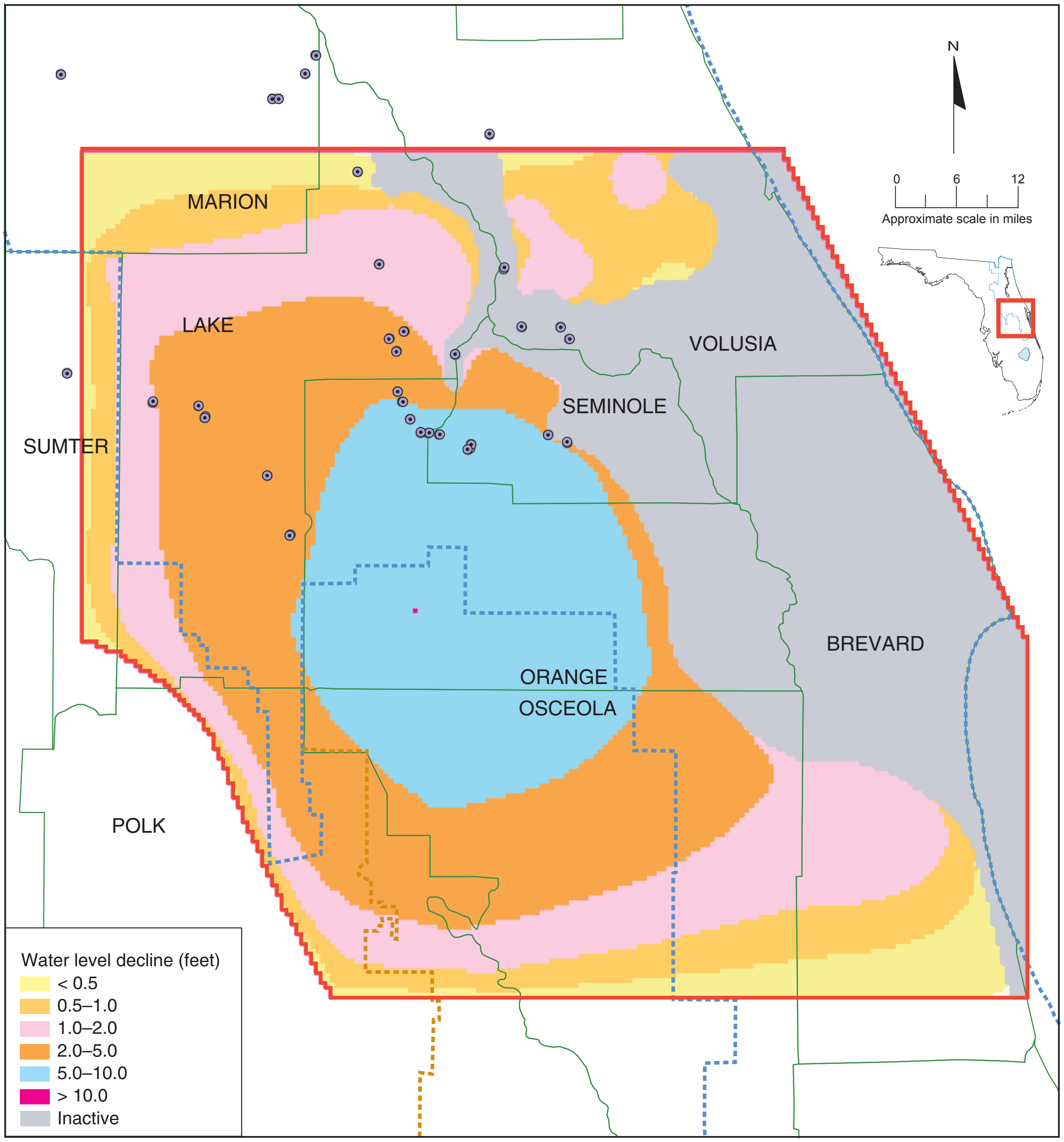


Figure 90. Predicted change in average layer 4 (Lower Floridan aquifer) water levels, 1995–2020

Table 9. Predicted changes in average spring flows, 1995–2020

Spring	Average Measured 1995 Flow (cfs)*	Predicted Percent Change, Base Case	Predicted Percent Change, Maximum Estimate	Predicted Percent Change, Minimum Estimate	Predicted 2020 Average Flow, Base Case (cfs)	Predicted 2020 Average Flow, Maximum Estimate (cfs)	Predicted 2020 Average Flow, Minimum Estimate (cfs)	Minimum Flow or Screening Flow (cfs)†
Blue (Volusia County)	150	8.0	4.9	10.9	138	143	134	134
Alexander	104	0.7	0	0	103	104	104	85
Wekiva	73	10.7	7.5	13.7	65	68	63	**62**
Rock	61	15.3	9.7	19.6	52	55	49	**53**
Seminole	39	13.9	9.5	15.8	34	35	33	**34**
Alexander Creek	33	0.7	0	0	33	33	33	28
Apopka	32	24.2	16.7	25.6	24	27	24	27
Palm and Sanlando	29	26.8	16.1	41.7	21	24	17	**22**
Messant	16	8.5	5.9	12.5	15	15	14	**12**
Starbuck	15	22.4	12.5	38.5	12	13	9	**13**
Bugg	11	6.5	0	16.7	10	11	9	8
Gemini	8	9.2	0	14.3	7	8	7	9
Island	6	10.5	12.5	14.3	5	5	5	5
Miami	6	13.9	14.3	16.7	5	5	5	**4**
Blue (Lake County)	3	41.9	33.3	50.0	2	2	2	3
Holiday	4	62.4	100.0	50.0	2	0	2	3
Witherington	4	15.5	0	0	3	4	4	3
Green	2	8.3	0	50.0	2	2	1	2
Clifton	1	13.8	0	0	1	1	1	1
Camp La-No-Che	1	13.3	0	0	1	1	1	nd

Table 9—*Continued*

Spring	Average Measured 1995 Flow (cfs)*	Predicted Percent Change, Base Case	Predicted Percent Change, Maximum Estimate	Predicted Percent Change, Minimum Estimate	Predicted 2020 Average Flow, Base Case (cfs)	Predicted 2020 Average Flow, Maximum Estimate (cfs)	Predicted 2020 Average Flow, Minimum Estimate (cfs)	Minimum Flow or Screening Flow (cfs)†
Lake Jesup	1	13.8	0	0	1	1	1	nd
Sulphur	1	15.1	0	0	1	1	1	nd
Droty	1	6.9	0	0	1	1	1	nd
Total, modelwide	601	10.7	6.7	13.6	537	559	519	
Total, Wekiva River above State Road 46	189	15.6	10.1	21.1	159	170	148	158‡

Note: cfs = cubic feet per second
nd = screening flow not determined

Shaded numbers refer to values less than the minimum or screening flow.

*Data from Rao and Clapp 1996; USGS 1996, 1997, 1998; and SJRWMD unpublished data files.

†Minimum flow rates adopted by rule are in bold; screening flows = historic median flow minus 15% (from data through 1999).

‡Sum of screening flows for corresponding springs.

Starbuck Spring (22%). All of these springs are located just downgradient from relatively large proposed increases in Upper Floridan aquifer withdrawals. Springs in the Wekiva River Basin upstream of State Road 46 were predicted to experience a 15% cumulative decline in flow. In fact, the predicted average 2020 flow (base case) for three of the springs in this part of the Wekiva River Basin (Rock, Palm / Sanlando, and Starbuck) was less than or equal to the corresponding adopted minimum average flow. Predicted flow rates at several other springs were less than or equal to their adopted minimum average or screening flow rate.

In addition to declines in spring discharges, the projected 2020 Floridan aquifer system well withdrawals resulted in reduced discharge to rivers and large surface water bodies (listed as constant heads in Table 10), ET from groundwater, and lateral outflow at the model boundaries. The simulated 2020 water budget (Table 10) also included a relatively significant increase in lateral inflow compared to the 1995 budget. The comparatively small modelwide decrease in ET was a net change caused by the balance between surficial aquifer system drawdown in some areas and a rise in surficial aquifer system water levels in other areas. Areas of increased simulated ET between 1995 and 2020 (negative values on Figure 91) correspond to areas of increased irrigation (compare Figures 83–85 with Figures 34, 36, and 37). Areas of zero change in simulated ET on Figure 91 correspond to large surface water bodies that were designated as constant-head cells in layer 1 and to areas where the simulated layer 1 water level was below the ET extinction depth for both 1995 and 2020 conditions. Areas of decreased simulated ET between 1995 and 2020 are areas of “ET capture,” where surficial aquifer system drawdown was predicted above the extinction depth.

The Lower Floridan aquifer (layer 4) was projected to experience the largest percentage increase in well withdrawals relative to 1995 (Table 11). Lower Floridan aquifer pumping was projected to increase approximately 104%, from 109 mgd to 222 mgd. This increased pumpage was compensated by increases in downward leakage from Upper Floridan aquifer layer 3 (67 mgd), freshwater lateral boundary inflow (7 mgd), and saltwater boundary inflow (11 mgd), plus decreased freshwater lateral boundary outflow (10 mgd) and upward leakage to Upper Floridan aquifer layer 3 (17 mgd). Layers 2 and 3 exhibited similar increases and decreases in vertical and lateral flow rates; however, the changes amounted to lesser percentages of the total inflow and outflow per layer.

Table 10. Simulated modelwide volumetric water budgets for average 1995 and 2020 conditions

	1995	2020	Increase	Decrease
Totals by Source and Sink Type (in million gallons per day)				
Inflow				
Constant heads*	27	37	10	
Wells	33	33	0	
Lateral boundaries	174	228	54	
Recharge	4,458	4,591	133	
Total inflow	4,692	4,889	197	0
Outflow				
Constant heads*	201	190		11
Wells	565	915	350	
Springs	385	343		42
Rivers	400	388		12
Evapotranspiration	2,838	2,789		50
Lateral boundaries	303	264		39
Total outflow	4,692	4,889	350	153
Linearized Over Model Domain (in inches per year)				
Inflow				
Constant heads*	0.1	0.1		
Wells	0.1	0.1		
Lateral boundaries	0.6	0.7	0.2	
Recharge†	14.5	14.9	0.4	
Total inflow	15.2	15.9	0.6	0.0
Outflow				
Constant heads*	0.7	0.6		0.0
Wells	1.8	3.0	1.0	
Springs	1.3	1.1		0.2
Rivers	1.3	1.3		0.1
Evapotranspiration†	9.2	9.1		0.1
Lateral boundaries	1.0	0.9		0.0
Total outflow	15.2	15.9	1.0	0.4

Note: Individual numbers may not match totals.

*Includes vertical and horizontal flow to/from constant-head cells in layer 1 representing large surface water bodies.
†Recharge evapotranspiration not simulated at layer 1 constant-head cells.

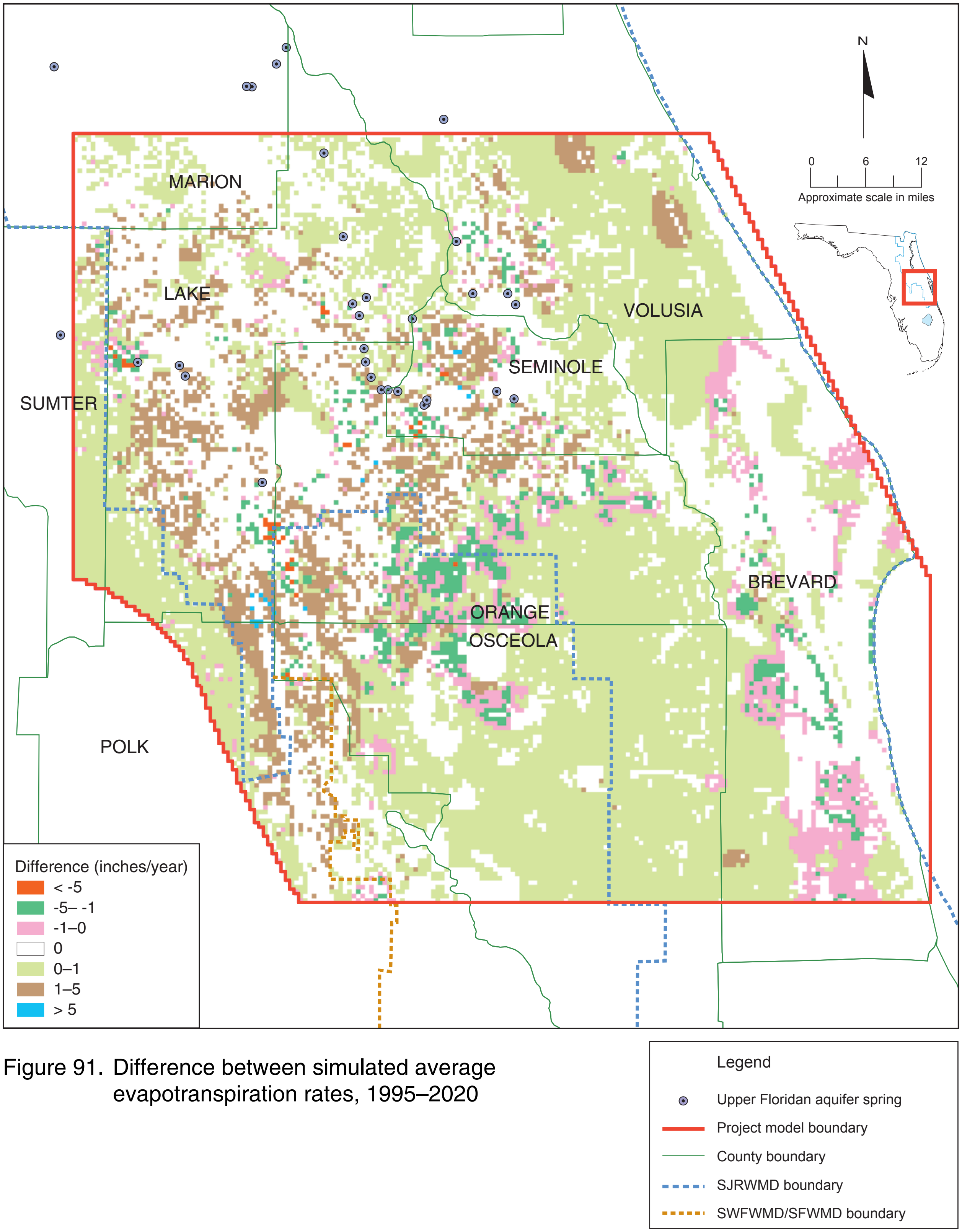


Figure 91. Difference between simulated average evapotranspiration rates, 1995–2020

Table 11. Simulated layer-by-layer volumetric water budgets for average 1995 and 2020 conditions (in million gallons per day)

Layer	Flux Type	Volumetric Flow Rates		Increase	Decrease	Net Change
		1995	2020			
1	**Inflow**					
	Recharge	4,458	4,591	133		
	Upward leakage from layer 2	169	148		21	
	Lateral flow from constant-head cells	6	6			
	Total	4,633	4,745			112
	Outflow					
	Evapotranspiration	2,838	2,789		49	
	Downward leakage to layer 2	1,379	1,549	170		
	River discharge	301	295		6	
	Lateral flow to constant-head cells	115	112		3	
	Total	4,633	4,745			112
2	**Inflow**					
	Downward leakage from layer 1	1,379	1,549	170		
	Upward leakage from layer 3	459	438		21	
	Downward leakage from constant-head cells	21	31	10		
	Lateral inflow along freshwater boundary	68	84	16		
	Lateral inflow along saltwater boundary	0	0			
	Drainage wells	23	23			
	Total	1,950	2,215			175
	Outflow					
	Downward leakage to layer 3	732	839	107		
	Wells	332	495	163		
	Springs	385	343		42	
	Upward leakage to layer 1	169	148		21	
	Upward leakage to constant-head cells	86	78		8	
	Lateral outflow along freshwater boundary	146	129		17	
	Lateral outflow along saltwater boundary	1	1			
	River discharge	99	92		7	
	Total	1,950	2,125			175

Table 11—*Continued*

Layer	Flux Type	Volumetric Flow Rates		Increase	Decrease	Net Change
		1995	2020			
3	Inflow					
	Downward leakage from layer 2	732	839	107		
	Upward leakage from layer 4	178	161		17	
	Lateral inflow along freshwater boundary	28	35	7		
	Lateral inflow along saltwater boundary	35	49	14		
	Drainage wells	10	10			
	Total inflow	983	1,094			111
	Outflow					
	Upward leakage to layer 2	459	438		21	
	Wells	123	198	75		
	Downward leakage to layer 4	320	387	67		
	Lateral outflow along freshwater boundary	80	70		10	
	Lateral outflow along saltwater boundary	1	1			
	Total outflow	983	1,094			111
4	Inflow					
	Downward leakage from layer 3	320	387	67		
	Lateral inflow along freshwater boundary	23	30	7		
	Lateral inflow along saltwater boundary	19	30	11		
	Total inflow	362	447			85
	Outflow					
	Wells	109	222	113		
	Upward leakage to layer 3	178	161		17	
	Lateral outflow along freshwater boundary	72	62		10	
	Lateral outflow along saltwater boundary	3	2		1	
	Total outflow	362	447			85

Note: 1 mgd equals approximately 1.55 cubic feet per second.

Predictive Sensitivity Analysis

The possible effects of projected Floridan aquifer system pumping upon lake and wetland stage elevations and upon Floridan aquifer system average springflow rates are of particular concern within the ECF region. Therefore, a sensitivity analysis was conducted to estimate the potential ranges in predicted values of (1) surficial aquifer system water level change and (2) springflow declines (relative to 1995) that might result from the projected 2020 pumping increases. The analysis was conducted in two stages. For the first stage, a series of average 1995 and average 2020 simulations was completed which parameters and / or boundary conditions were multiplied modelwide, one at a time, by values at either end of, but within, the calibration range that was illustrated by the detailed sensitivity analysis discussed previously. For example, a 1995 simulation was completed for which the recharge was calculated using 1995 applied irrigation (R_{app}) values that were multiplied by a factor of 0.2. Heads from this simulation were then used as starting heads for a 2020 simulation that used 2020 applied irrigation (R_{app}) values that were also multiplied by a factor of 0.2. The simulations were repeated using 1995 and 2020 R_{app} values that were multiplied by 1.5. This process was continued for 10 additional parameters and / or boundary conditions. The results were analyzed by comparing (1) the predicted surficial aquifer system water level changes between 1995 and 2020 and (2) the percentage decline in spring flow. Predicted surficial aquifer system water level changes were compared by computing the difference between each sensitivity run's predicted surficial aquifer system water level change to the base-case prediction surficial aquifer system water level change at each active model grid cell. (The base-case prediction is equal to the results described in the previous section using the calibrated model.) The mean difference (averaged over the model) computed for each sensitivity simulation is listed on Table 12. The percent decline in total (modelwide) spring flow, and the percent decline predicted for springs located within the Wekiva River Basin are also listed on Table 12.

A comparison of the mean differences indicates that the model's prediction of surficial aquifer system (layer 1) water level change was most sensitive to the top 4 parameters listed on Table 12 (R_{app}, intermediate confining unit leakance, layer 1 K_h, and ET_{max}). Their mean differences ranged from 0.25 ft to 0.06 ft, while the mean differences for all of the remaining parameters and boundary conditions were less than 0.06 ft. Note that, although the steady-state model calibration was not very sensitive to changes in R_{app}, predictions of surficial aquifer system water level change were somewhat sensitive to R_{app} values.

Table 12. Results of predictive sensitivity analysis

Parameter or Boundary Condition	Multiplier / Condition	Differences From Base-Case Predictive Simulation		
		Mean Difference in Layer 1 Water Level Change (feet)[1]	Percent Decline in Total Spring Flow[2]	Percent Decline in Flow From Wekiva River Basin Springs[3]
Applied irrigation (R_{app})	0.20	0.25	11.2	15.9
Applied irrigation (R_{app})	1.50	0.18	8.9	12.6
ICU leakance	0.67	0.12	13.4	
ICU leakance	1.50	0.15	9.0	
Layer 1 K_h	0.50	0.12	10.8	
Layer 1 K_h	1.50	0.06	10.8	
ET_{max}	0.80	0.09	10.6	
ET_{max}	1.25	0.07	11.0	
ET extinction depth	0.67	0.04	10.6	
ET extinction depth	1.50	0.05	11.1	
Layer 2 K_h	0.67	0.03	11.5	
Layer 2 K_h	1.50	0.03	10.0	
Layer 3 K_h	0.67	0.02	11.0	
Layer 3 K_h	1.50	0.02	10.5	
Layer 4 K_h	0.50	0.03	11.3	
Layer 4 K_h	2.00	0.03	10.1	
Saltwater boundaries—layers 3 and 4	No flow	0.02	14.6	
Saltwater boundaries—layers 3 and 4	Constant heads	0.03	9.5	
MSCU leakance	0.50	0.02	10.5	
MSCU leakance	2.00	0.02	11.0	
Drain conductance	0.50	0.02	10.1	
Drain conductance	2.00	0.01	11.4	

Note: ICU = intermediate confining unit
MSCU = middle semiconfining unit

[1]Mean difference = modelwide average of absolute value of (A), where (A) = [base-case water level change minus predictive sensitivity simulation water level change(feet).]
[2]Simulated base-case percent decline (1995–2020) in total spring flow = 10.7%.
[3]Simulated base-case percent decline (1995–2020) in Wekiva River Basin spring flow = 15.6%.

Spring flow declines predicted by the base-case predictive simulation were 10.7% for all springs and 15.6% for Wekiva River Basin springs. The sensitivity of predicted springflow declines to different parameter values can be assessed by comparing the ranges listed for each parameter in the rightmost two columns of Table 12. Predicted springflow declines were most sensitive to variability in intermediate confining unit leakance and the boundary condition prescribed for the saltwater boundaries.

For the second stage of the predictive sensitivity analysis, four additional 1995–2020 calibration-prediction simulation combinations were conducted based upon the results of the first stage. For each combination, the most sensitive parameters from Table 12 were varied together such that the 1995 dataset could still be considered calibrated. The first two of these combinations were aimed at gauging the potential range of surficial aquifer system (layer 1) water level change due to 2020 Floridan aquifer system withdrawals and were termed the minimum drawdown simulation and the maximum drawdown simulation, respectively. The minimum drawdown simulation was accomplished by performing the following modelwide changes to input:

- R_{app} multiplied by 1.2
- Intermediate confining unit leakance multiplied by 0.875
- Layer 1 K_h multiplied by 1.25
- ET_{max} multiplied by 1.1

These parameters were changed in order to minimize the potential for decline in surficial aquifer system (layer 1) water levels due to projected 2020 Floridan aquifer system withdrawals. As with the predictive sensitivity simulations, a 1995 simulation was first conducted, followed by a 2020 simulation using the 1995 heads as starting heads. The multiplication factors used were not exactly the same as those listed on Table 12 because changing all four parameters by those factors resulted in a 1995 simulation that didn't meet the calibration criteria. The factors were adjusted iteratively until the simulated 1995 heads and spring flows were as close as possible to the calibration criteria.

The maximum drawdown estimate was conducted in the same fashion using the following multiplication factors:

- R_{app} x 0.2
- Intermediate confining unit leakance x 1.25
- Layer 1 K_h x 0.67

- ET_{max} x 0.8

The same iterative adjustment of parameter adjustment factors was carried out that was done for the minimum drawdown simulation. The spatial distributions of surficial aquifer system water level changes resulting from the minimum drawdown simulation and from the maximum drawdown simulation are shown by Figures 92 and 93, respectively. The minimum drawdown simulation resulted in a larger area of predicted increase in surficial aquifer system water level and a smaller area of predicted surficial aquifer system drawdown relative to the base case (see Figure 88). The maximum drawdown simulation resulted in a smaller area of predicted increase in surficial aquifer system water level and a larger area of predicted surficial aquifer system drawdown relative to the base case. Both maps depict relatively widespread areas of surficial aquifer system drawdown of greater than 1 ft throughout the northwestern half of the model domain.

The spatial distribution of the potential range of predicted change in average surficial aquifer system water levels due to 2020 Floridan aquifer system withdrawals is illustrated by Figure 94. This range was computed using the absolute value of the differences between the water level change resulting from the minimum drawdown simulation (Figure 92) and the water level change resulting from the maximum drawdown simulation (Figure 93). The range is greatest in southeastern Lake County, western Orange County, western Seminole County, and southern Brevard County. A comparison of Figures 66, 83, 84, and 85 with Figure 88 indicates that in Brevard County, the range of predicted surficial aquifer system water level change is due primarily to the sensitivity of layer 1 heads to variations in the irrigation component of recharge. In the other counties, the range is due to the sensitivity of layer 1 heads to variations in both intermediate confining unit leakance and the irrigation component of recharge.

Figure 94 illustrates significant uncertainty in the magnitude of predicted surficial aquifer system water level changes but much less uncertainty in the location of where these changes might occur. Outside of Brevard and Osceola counties, decreases in the irrigation component of recharge between 1995 and 2020 were insignificant. In Lake, Orange, Seminole, and Volusia counties, the irrigation component was increased significantly in many areas for average 2020 simulations relative to average 1995 simulations. Despite these increases, widespread surficial aquifer system drawdown was still predicted due to projected increases in Floridan aquifer system pumping.

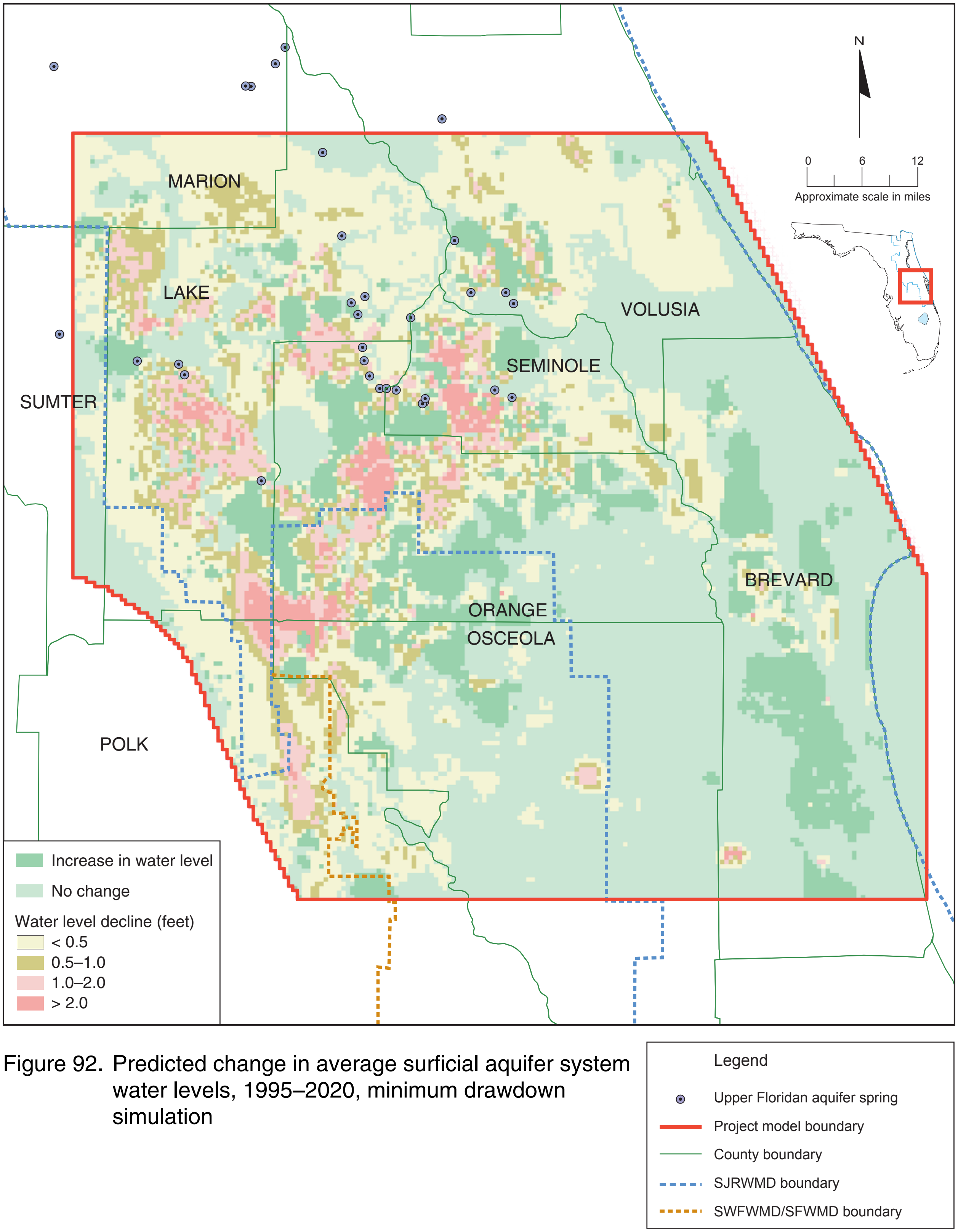


Figure 92. Predicted change in average surficial aquifer system water levels, 1995–2020, minimum drawdown simulation

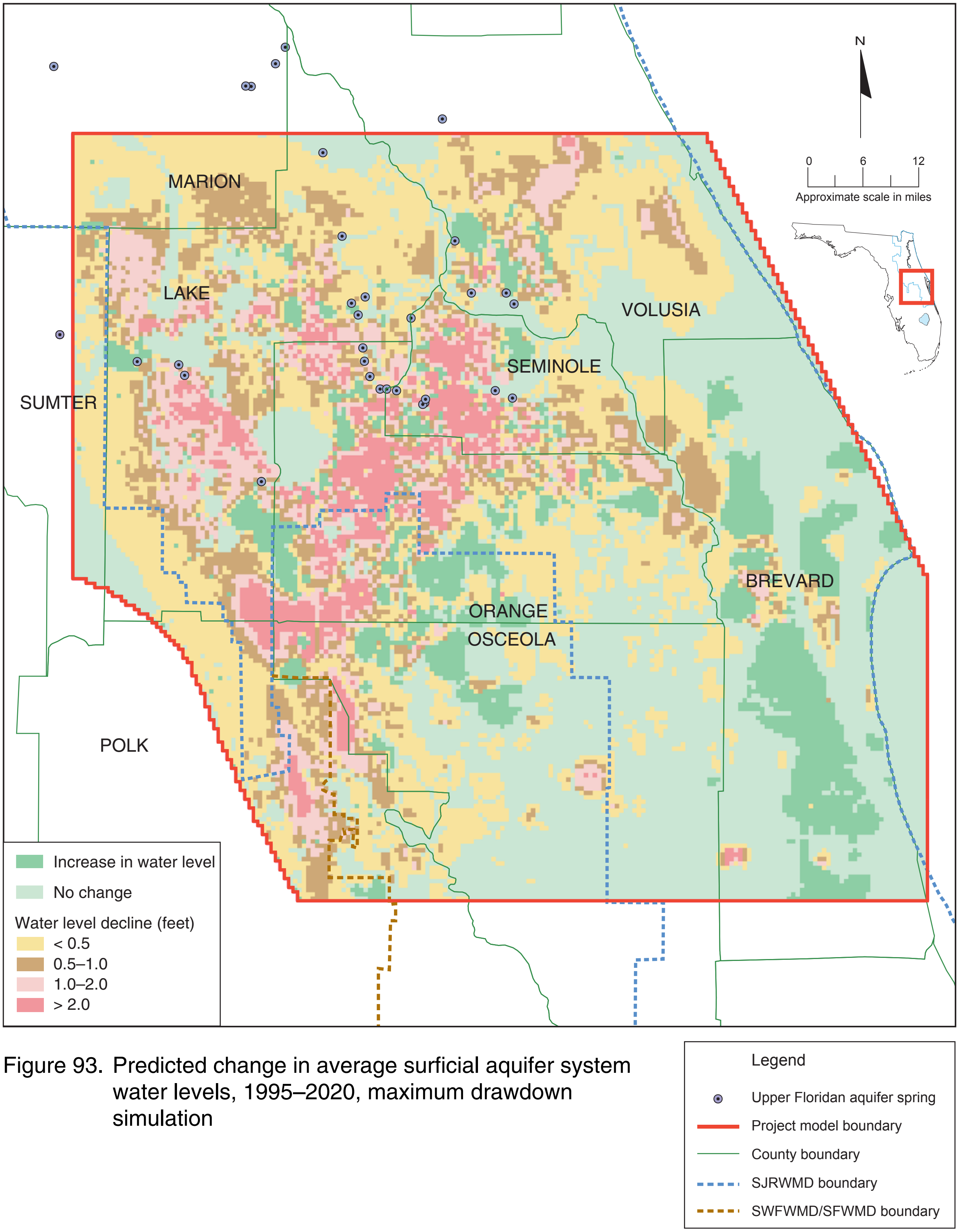


Figure 93. Predicted change in average surficial aquifer system water levels, 1995–2020, maximum drawdown simulation

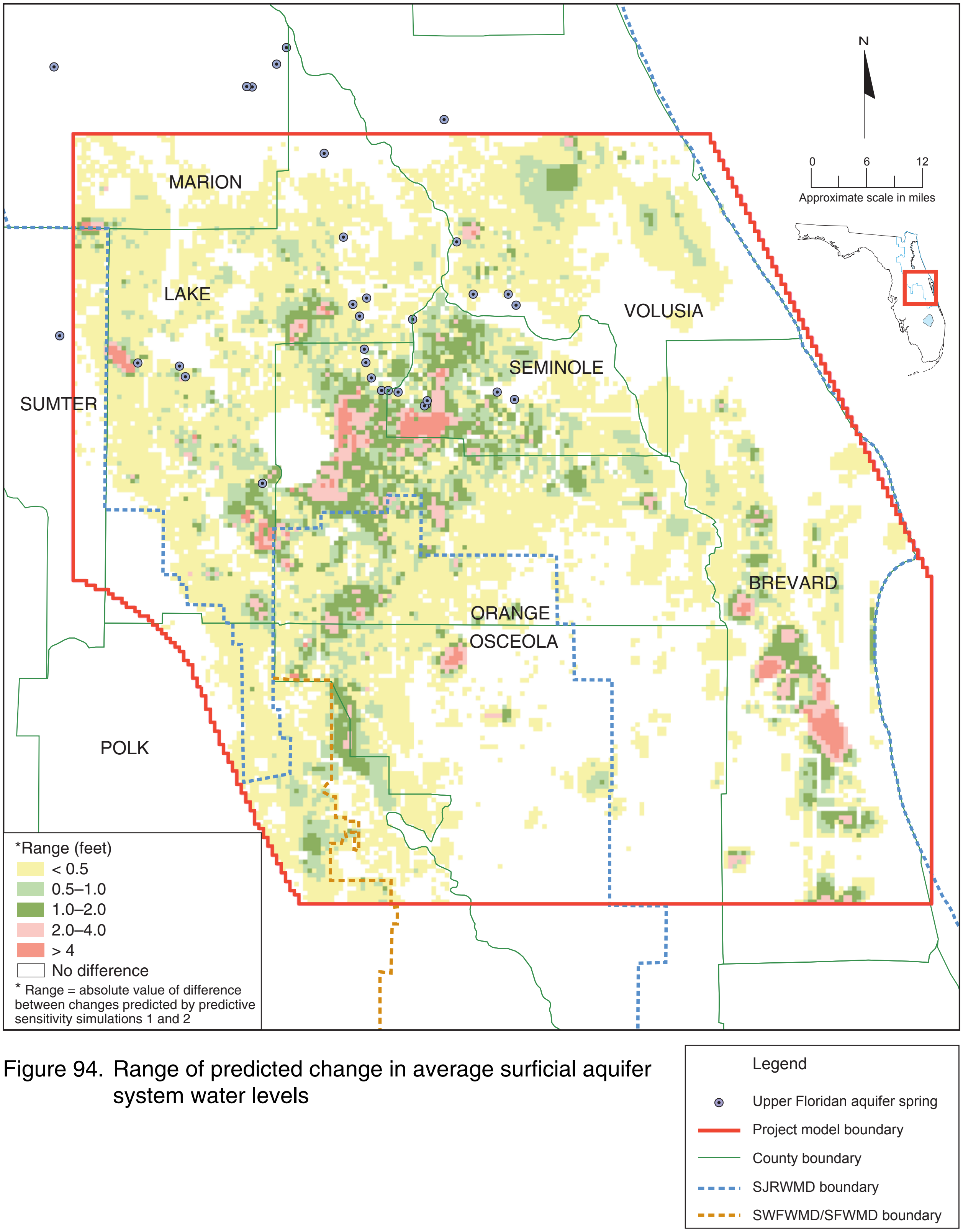


Figure 94. Range of predicted change in average surficial aquifer system water levels

Two predictive simulations were completed to estimate the potential range in springflow reductions due to projected 2020 withdrawals. The same procedure to determine the appropriate multiplication factors that was used for the surficial aquifer system minimum and maximum drawdown was applied. To estimate maximum average 2020 spring flows, the following input changes were made:

- R_{app} x 1.2
- Intermediate confining unit leakance x 1.25
- Layer 4 K_h x 2.0
- Layer 3 and layer 4 saltwater boundaries were converted to constant heads

To estimate minimum average 2020 spring flows, the following input changes were made:

- R_{app} x 0.2
- Intermediate confining unit leakance x 0.95
- Layer 3 and layer 4 saltwater boundaries were converted to no-flow boundaries
- Layer 4 K_h x 0.5

The maximum and minimum predictions of average 2020 spring flows are listed on Table 9. The resulting range in modelwide average 2020 spring flow was 40 cfs, or approximately 7% of the average 2020 flow predicted by the base case. The ranges in predicted percent flow reduction among the first- and second-magnitude springs varied between 0% for Alexander Springs and 26% for Palm / Sanlando and Starbuck springs. The minimum springflow simulation predicted average 2020 flow rates at five second-magnitude springs and five third-magnitude springs that were less than or equal to their adopted minimum average or screening flow rates. The maximum springflow simulation predicted average 2020 flow rates at two second-magnitude springs and five third-magnitude springs that were less than or equal to their adopted minimum average or screening flow rates. Therefore, the predictive sensitivity analysis indicates that, within a range of parameters and boundary conditions that maintains model calibration, currently projected 2020 Floridan aquifer system withdrawals were predicted to cause significant reductions in spring flow at several locations.

A comparison of the results of the predictive sensitivity analysis with the results of the sensitivity analysis illustrated by Figures 77, 78, and 79 allows a categorizing of the model's inputs in terms of sensitivity. Sensitivity types (ASTM 1999) were assigned depending upon how the variations of the inputs affect the calibration and / or the conclusions drawn from predictions (Table 13). Inputs with sensitivity type I cause insignificant changes in both the measures of calibration and in the model's conclusions and are therefore of little concern. Those with sensitivity type II cause significant changes in the measures of calibration but cause no significant changes to the model's conclusions. Therefore, these inputs are also of little concern because regardless of the values used, the conclusions remain the same. Type III sensitivities cause significant changes to both calibration measures and model conclusions. These inputs are of interest because they affect both model calibration and prediction results. However, even though the model's conclusions can change as a result of variation of the input, the input values used in those simulations cause the model to become uncalibrated (ASTM 1999). Thus, unrealistic inputs that can affect conclusions are "weeded out" by the calibration process. Type IV sensitivities cause insignificant changes to calibration measures but do change the model's conclusions. This type is of greatest concern because model conclusions change over the range of inputs that can be considered calibrated.

Table 13 lists sensitivities for each measurement type. Sensitivity types were listed with reference to both surficial aquifer system water levels and spring flows because the predictive sensitivity analysis focused upon potential changes to these aspects of the flow system. The parameters and boundary conditions with type III sensitivities also had the largest modelwide mean differences in layer 1 water level change on Table 12. The modelwide differences from the base-case prediction do not necessarily reflect model conclusions, however. Multiplying the applied irrigation component of recharge by factors ranging from 0.2 to 2 resulted in both widespread surficial aquifer system drawdown and significant reductions in spring flow at several locations. The effect of changing applied irrigation has an important spatial component; increasing or decreasing its magnitude has an impact only in the vicinity of where irrigation occurs and not the entire model domain.

MODEL LIMITATIONS

A model is any device that represents an approximation of a field situation (Anderson and Woessner 1992). The model described in this report is a numerical groundwater flow model that uses a well-known computer code (MODFLOW) to approximate, on a regional scale, the fresh groundwater flow system in east-central Florida. The model simulates the system as being in one of a series of steady-state equilibrium conditions that differ depending

Table 13. Sensitivity types

A. Aquifer and confining unit parameters

Parameter	Sensitivity Type (surficial aquifer system water levels)	Sensitivity Type (spring flow)
Layer 1 horizontal hydraulic conductivity	III	I
Layer 2 horizontal hydraulic conductivity	II	II
Layer 3 horizontal hydraulic conductivity	II	II
Layer 4 horizontal hydraulic conductivity	I	I
Intermediate confining unit leakance	III	III
Middle semiconfining unit leakance	II	I

B. Boundary conditions

Boundary Condition Type	Sensitivity Type (surficial aquifer system water levels)	Sensitivity Type (spring flow)
Drain conductance	II	II
ET extinction depth	III	III
Irrigation component of recharge	III	III
Maximum ET	III	III
Saltwater GHB boundaries	II	II

Note: ET = evapotranspiration
GHB = general-head boundary

upon the magnitude of the stresses that are applied. The assumption of steady-state conditions is in itself a limitation because averaged stress values are assumed to be representative of actual stresses that vary throughout the time period simulated. Model results are also limited by the simplification of the conceptual model upon which the numerical model is based, grid-scale, the inaccuracies of measurement data, and incomplete knowledge of the spatial variability of input parameters.

The conceptual model used to construct the ECF model is a highly simplified representation of the true groundwater flow system. Due to its karstic nature, the Floridan aquifer system can be characterized as an extremely complex, anisotropic, and heterogeneous aquifer system. Because of these features, parts of the Floridan aquifer system represented by model layers 2, 3, and 4, and by the middle semiconfining unit may contain zones of preferential flow in which the model's assumptions of horizontal-only or vertical-only flow do not hold true. These preferential flow zones are caused in large part by secondary porosity features such as fractures and solution conduits. Flow in some of these fractures and conduits may be turbulent, which would violate the laminar-flow-only assumption of the MODFLOW code. Turbulent flow probably occurs in the immediate vicinity of large springs. However, secondary porosity within the Floridan aquifer system aquifer layers is believed to be so ubiquitous that the resulting preferential flow zones merge together, resulting in a regional-scale porous-media equivalent flow system.

Characterizing the surficial aquifer system as a single aquifer layer is probably a significant limitation. Portions of the model domain where the lithology of the surficial aquifer system is highly layered vertically, or where there is significant local topographic relief, are areas where the horizontal-only flow assumption for layer 1 is likely to be violated. In these areas, the true average surficial aquifer system head may not be the same as the water table elevation. The model's use of the River Package to simulate surface water-groundwater interaction resulted in an apparent underestimation of base flow to streams. Conversely, this conceptualization does not allow for input to the surficial aquifer system from upstream surface water inflow. This inflow is important in wetland areas that receive upstream flow in large surface water basins. Model predictions of surficial aquifer system head decline will be most equivalent to lake and wetland water-level decline at locations that do not receive upstream surface water flow and that exchange water with the surficial aquifer system.

Horizontal and vertical discretization into model grid cells requires the assumption of average values of hydrologic properties and stresses for each cell. The larger the range of the true values of a property or stress within a grid cell area, the greater the difference between average value and true value at any particular location within a cell. In areas of significant topographical relief, this difference is greatest for input parameters involved with stresses at the water table surface, such as ET extinction depth, ET surface, or soil/land use type. In flatter areas, the difference may be greatest for intermediate confining unit leakance, which can vary greatly due to local changes in thickness and vertical hydraulic conductivity. The location of stresses (e.g., well pumping or reclaimed water application) is somewhat distorted by grid-scale discretization because all stresses within each grid cell are accumulated. Therefore, significant variations in stresses on a scale finer than the regular horizontal grid discretization of 2,500 ft by 2,500 ft are not accounted for in the model.

Model results are limited by the inaccuracy of measurement data. These data include groundwater potentiometric levels, surface water stage elevations, borehole log interpretations of hydrologic unit contacts, land surface elevation, metered water use, land use and soil type polygons in GIS coverages, streamflow rates, and springflow estimates. Measurement errors for the first six of these data types are relatively small, especially with regard to their effect upon a regional-scale model. Streamflow measurements often have a significant error. Springflow measurements for 1995 have, at best, an error of approximately 10%. However, many of the smaller springs included as drains in the model, plus one second-magnitude spring (Apopka) were not measured during the 1995 calibration period. Also, no reduction in spring pool elevation was applied for the 2020 predictive simulations, even though at some springs it is possible that pool elevations could be lowered by reduced spring flow. Predicted springflow declines should be interpreted with these measurement errors in mind. That is, the predicted 2020 flow estimates listed on Table 9 should be interpreted in the context of an error range of at least 10%.

Model results are limited by incomplete knowledge of the true spatial variability of input parameters. Complete knowledge of the spatial variability of all input parameters is impossible; therefore, all models are non-unique. That is, acceptable calibrations could be achieved for the ECF model, or for another model of the same area, with different spatial arrays of input parameters and stresses. However, sensitivity analyses conducted on the input arrays of parameters and stresses used for this ECF model have indicated that the model's calibration and predictive results are sensitive to certain input parameters and stresses and insensitive to others. Both model calibration and predictions of changes in surficial aquifer system water levels are sensitive to the values used for intermediate confining unit leakance and maximum average annual ET (ET_{max}). Model calibration is also very sensitive to recharge, and predicted surficial aquifer system water level changes are sensitive to the applied irrigation (R_{app}) component of recharge. Model sensitivity is therefore related primarily to the uncertainty of these input parameters. Intermediate confining unit leakance is a function of intermediate confining unit vertical hydraulic conductivity and intermediate confining unit thickness. Field-scale values for intermediate confining unit vertical hydraulic conductivity are poorly known, but on a regional scale, intermediate confining unit thickness (see Figure 9) is known fairly well. Consequently, the uncertainty in intermediate confining unit leakance is greatest in those locations where the ratio of intermediate confining unit vertical hydraulic conductivity to intermediate confining unit leakance is greatest (i.e., where the intermediate confining unit is thin). Estimates of recharge and R_{app} are subject to errors in the estimates of the data items used to estimate them. Although a fairly detailed spatial array was used for the largest of these (rainfall, see Figure 32), significant errors could occur locally where Thiessen polygons join. Estimates of R_{app} are subject to significant grid-scale errors where the exact locations or extent of agricultural or reclaimed water irrigation were unknown. Overestimation or underestimation of R_{app} probably results in unrealistic predicted increases and / or decreases in surficial aquifer system water levels, especially in lowland agricultural areas of Brevard, Osceola, and Seminole counties (soil area 1) where R_{app} was applied using Equation 11 (compare Figures 36, 85, and 88). Similar errors occurred where 2020 RIB flows were unrealistically applied to the same grid cells that received relatively high 1995 application rates. Aside from these localized errors, however, areal distribution of R_{app} is probably fairly accurate on a regional scale. Maximum ET is a function of several factors, including annual rainfall, solar radiation, and temperature (Visher and Hughes 1975). The effect of spatial variability in these factors during 1995 upon ET_{max} is unknown.

The results of the predictive sensitivity analyses indicate a range of surficial aquifer system drawdown of up to several feet (Figure 94). The areas where this range is greatest extend primarily across uplands below which the intermediate confining unit is relatively thin and where the predicted drawdown in the Upper Floridan aquifer is greatest (see Figures 9 and 89). Thus, although there is significant uncertainty in the magnitude of potential surficial aquifer system drawdown due to future Floridan aquifer system withdrawals, there is much more certainty in the identification of locations where significant drawdown may occur. A comparison of Figures 92 and 94 reveals that many of the areas with a range of predicted surficial aquifer system drawdown of greater than 2 ft also have a predicted minimum surficial aquifer system drawdown of greater than 2 ft. These areas are of greatest concern for potential impacts to lake levels or wetlands.

Simulated Upper Floridan aquifer water levels and springflow rates, plus predicted declines in springflow rates, were sensitive to changes in boundary conditions along the saltwater boundaries in layer 3 (Upper Floridan aquifer—lower zone) and layer 4 (Lower Floridan aquifer). There was a significant amount of inflow simulated across these boundaries for both 1995 and 2020 conditions. Although the true spatial variability of saltwater heads is unknown, there is evidence that saltwater intrusion along these boundaries has historically occurred and is continuing to occur. Chloride and salinity concentrations have increased in these layers, along with pumping increases at the Cocoa wellfield in eastern Orange County (Tibbals and Frazee 1976; Phelps and Schiffer 1996; Orr and Locke 1996; Taylor 1999). Many of the abandoned free-flowing wells in northern Brevard County and in Seminole County were originally irrigation wells that became unusable due to water quality deterioration. Although chloride concentration in most of these wells is much less than 5,000 mg/L (the assumed concentration at the boundaries), these increases serve as indirect evidence that potentiometric head declines at the boundaries cause some inflow of very brackish water.

The ECF model's conceptualization and discretization were designed at a regional scale. The spatial variability of input data is also best described at a similar scale. Therefore, the ECF model should be used and its results interpreted only at a regional scale. All stresses input to the model represented average, steady-state conditions. Therefore, the model should be used to examine the potential long-term, steady-state impacts due to changes in average conditions.

SUMMARY AND CONCLUSIONS

The ECF region is centered upon Orange and Seminole counties but includes most of Brevard, Lake, and Osceola counties plus parts of Marion, Polk, Sumter, and Volusia counties. A numerical groundwater flow model was developed for the ECF region that is capable of estimating the characteristics of the freshwater part of the flow system and the potential changes due to projected changes in withdrawals from the Floridan aquifer system. The model can be considered a “third generation” model of the ECF region because it was based upon a series of “second generation” models that covered much of the ECF area. These models were based upon larger “first-generation” regional models completed by USGS as part of the RASA program. The ECF model was favorably calibrated to average, steady-state 1995 conditions by quantitatively comparing simulated surficial aquifer system and Floridan aquifer system water levels with observed values at corresponding locations. Simulated Floridan aquifer system springflow rates were also quantitatively compared with estimates of average 1995 springflow rates computed from available measurements. Other simulated fluxes, such as ET rates, recharge to the Floridan aquifer system, and discharge to surface water bodies were compared qualitatively to estimates of actual flux values. The model was also calibrated in a qualitative fashion to estimated predevelopment conditions by comparing simulated water levels and spring flows to available estimates.

The model was used to predict the potential changes to average 1995 surficial aquifer system and Floridan aquifer system water levels, and to average 1995 springflow rates as a result of projected 2020 magnitudes and locations of Floridan aquifer system pumping. Because all simulations represented estimated average conditions, climatic stresses and boundary conditions were kept the same as those used for the 1995 calibration. A “base-case” scenario was first conducted wherein all input parameters and boundary conditions other than Floridan aquifer system withdrawals and the irrigation and RIB components of recharge remained the same as those used for the 1995 calibration. Predicted drawdown (relative to 1995) in the Upper Floridan aquifer potentiometric surface ranged from 2 ft to 10 ft throughout much of Lake, Orange, and Seminole counties, northern Osceola County, and southwestern Volusia County. Subsequent predicted decline in average surficial aquifer system water levels exceeded 2 ft in several areas within these counties. The Upper Floridan aquifer potentiometric surface was predicted to increase in parts of western Orange and Osceola counties due to projected increases in reclaimed water application. Surficial aquifer system water levels were predicted to increase in other scattered locations due to projected increases in irrigation. Modelwide total springflow rates were predicted to decrease by approximately 11% relative to 1995. Predicted springflow declines exceeded 11% at 13 springs (see Table 9). The predicted base-case flow rate was less than the adopted minimum or screening flow rate at four second-magnitude springs and three third-magnitude springs.

The results of a predictive sensitivity analysis indicated that predicted surficial aquifer system water level changes were most sensitive to intermediate confining unit leakance, applied irrigation, surficial aquifer system horizontal hydraulic conductivity, and the maximum ET rate. Consequently, two predictive simulations were conducted for which these four inputs were varied modelwide in order to estimate the predicted range in both magnitude of surficial aquifer system water level decline and spatial distribution of surficial aquifer system water-level decline. The minimum surficial aquifer system drawdown simulation resulted in smaller areas of surficial aquifer system decline than the base-case scenario, but these areas were still somewhat widespread throughout central and southeastern Lake County, western Orange County, western Seminole County, and southwestern Volusia County. The predictive sensitivity analysis also indicated that model predictions of springflow decline were most sensitive to intermediate confining unit leakance, applied irrigation, and the saltwater boundary condition in model layers 3 and 4. Consequently, two additional predictive simulations were conducted for which these inputs were varied modelwide in order to estimate the potential range in predicted springflow rate declines. The maximum 2020 springflow simulation resulted in flow rates at one second-magnitude spring and three third-magnitude springs that were below their adopted minimum flow rate or estimated screening flow rate.

Conclusions drawn from the ECF regional modeling effort are as follows:

- The cumulative effect of projected Floridan aquifer system pumping upon the Floridan aquifer system potentiometric surface extends throughout most of the ECF area and crosses municipal, county, and water management district boundaries.

- The predicted Floridan aquifer system potentiometric surface decline has a direct effect upon Floridan aquifer system springflow rates. Although there is significant uncertainty in the magnitude of the predicted springflow declines, currently projected 2020 Floridan aquifer system withdrawals may cause average 2020 flow rates at several second-magnitude springs that supply base flow to the Wekiva River to be below their adopted minimum average flow rates.

- The predicted change to the Floridan aquifer system potentiometric surface due to projected 2020 Floridan aquifer system pumping would ultimately have a widespread effect upon average surficial aquifer system water levels. Declines in average surficial aquifer system water levels would be limited to areas where both the Upper Floridan aquifer potentiometric decline is significant and the intermediate confining unit is relatively thin or breached by sinkhole formation. Upland lakes and wetlands in these areas could experience long-term water level declines.

- The boundary between the freshwater and saltwater portions of the Floridan aquifer system within the lower, dolomitic zone of the Upper Floridan aquifer and within the Lower Floridan aquifer has been affected by a regional decline in Floridan aquifer system water levels resulting from Floridan aquifer system withdrawals. This boundary would also be affected by projected 2020 Floridan aquifer system withdrawals. This effect has been noticed in the form of increased salinity in water samples from both observation and production wells completed within and beneath the production zones of Upper Floridan aquifer wellfields located near and above the boundary.

Several suggestions for additional efforts and / or information that would improve the performance and reliability of the ECF model are listed below.

- Calibration to transient conditions that extend through at least one cycle of wet-to-dry seasons would improve the robustness of the calibration and provide the ability to predict system changes over time. Preparations for a transient calibration are currently under way at this time. During the transient calibration, efforts will be focused upon improving the pre-processing methodology used for estimating recharge to the surficial aquifer system.
- Additional information is needed to refine existing knowledge of the spatial variability of the factors affecting recharge to the surficial aquifer system. Such information would include data on minimum and maximum ET rates, ET extinction depth, current and projected land use patterns, locations of projected future reclaimed water application sites, Doppler-derived rainfall estimates, and refined estimates of the percentage of public supply withdrawals that are used for landscape irrigation.

- Additional water-level and salinity data from observation wells completed within the saltwater portion of the Floridan aquifer system would improve understanding of the freshwater / saltwater boundary.

- Springflow measurements from major springs are needed with at least a bimonthly or monthly frequency, especially for a transient calibration.

- Additional hydrogeologic data from beneath the Upper Floridan aquifer are needed. Aquifer layer and semiconfining unit thickness, permeability, and water quality characteristics for layers underlying the Upper Floridan aquifer in southern Lake County, western Osceola County, northern Polk County, and Sumter County are not as well defined as in other areas of the model domain.

- The predicted Floridan aquifer system potentiometric declines are limited along the model's lateral boundaries by the applied head-dependent flux boundary condition. This boundary condition should be adjusted to account for the effects of withdrawals outside of the model domain by including predictions from other overlapping regional models as they become available.

Finally, predictions made to date with the ECF model have roughly delineated areas within which significant long-term Floridan aquifer system potentiometric declines may cause significant long-term declines in lake and wetland water levels. Detailed prediction of the magnitude and spatial variability of these lake and wetland water-level declines can best be accomplished using local-scale or subregional-scale models. Such models would require monitoring of local-scale variations in the water table surface and in surficial aquifer system vertical hydraulic gradients for calibration.

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