Technical Publication SJ2003-2

Regional Characterization and Assessment of the Potential for Saltwater Intrusion in Northeast Florida and Camden County, Georgia, Using the Sharp-Interface Approach

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REGIONAL CHARACTERIZATION AND ASSESSMENT OF THE POTENTIAL FOR SALTWATER INTRUSION IN NORTHEAST FLORIDA AND CAMDEN COUNTY, GEORGIA, USING THE SHARP-INTERFACE APPROACH

by

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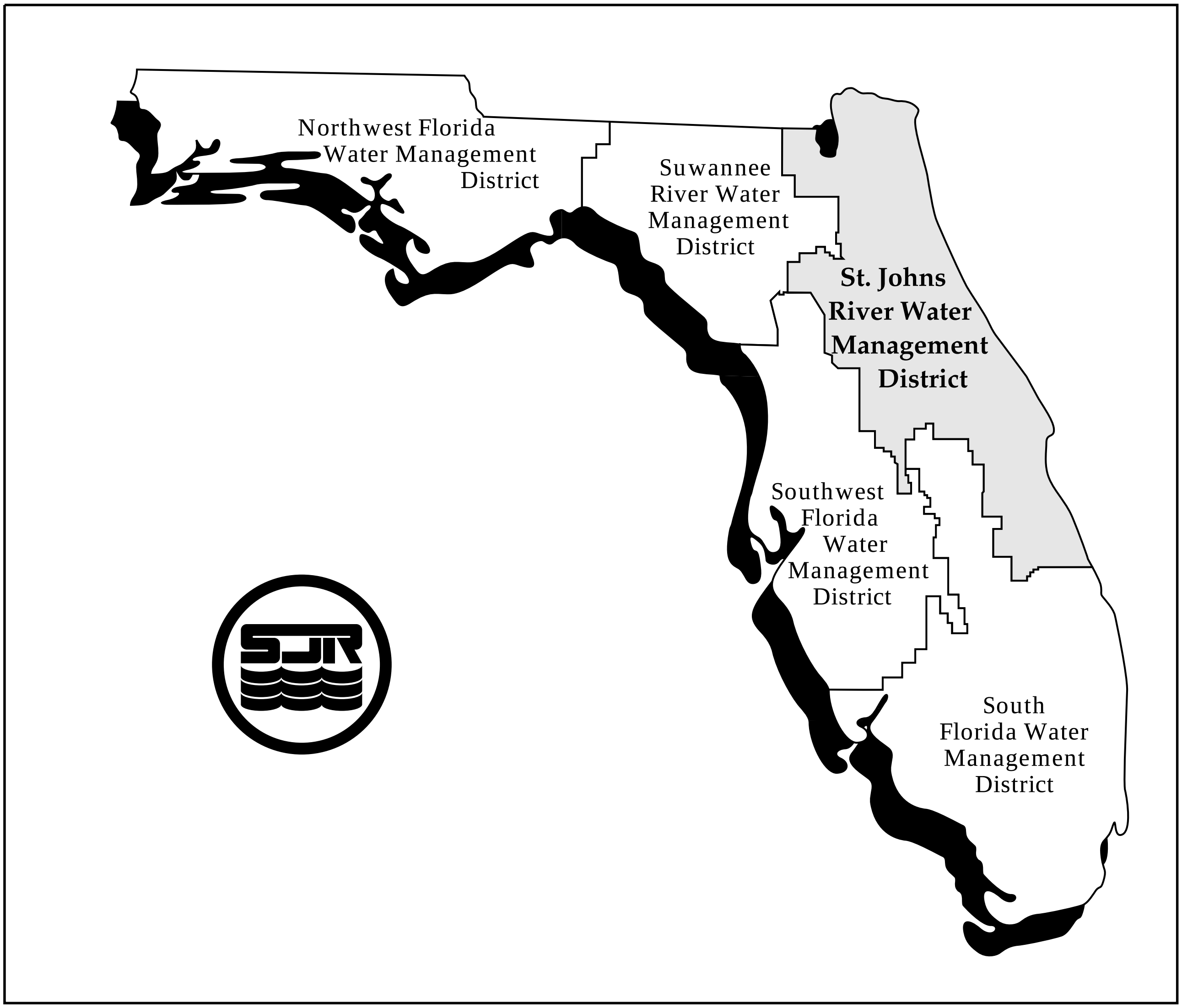

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EXECUTIVE SUMMARY

The primary objective of the present study was to construct a regional model to investigate saltwater intrusion into the freshwater zone of the Floridan aquifer system of northeast Florida in response to groundwater withdrawals. Another objective was to evaluate strategies for reducing the potential for saltwater intrusion within the Floridan aquifer system of the study area. A third objective was to ascertain relative levels of stress on the freshwater/saltwater interface at various well locations.

The study methodology consisted primarily of the development and use of a finite-element, multi-aquifer, sharp-interface groundwater flow model. The model code used was SIMLAS (Saltwater-Intrusion Model for Layered Aquifer Systems). The SIMLAS code was used to enable simulation of the movement of the boundary between the fresh- and saltwater portions of the Floridan aquifer system. This boundary is represented in SIMLAS as a sharp interface.

Development of the sharp-interface model began with the conversion of the transmissivity and leakance estimates of the MODFLOW groundwater flow model of Durden (1997) to corresponding values of intrinsic permeability and vertical leakage factor, respectively, which are utilized by the SIMLAS code.

Calibration of the models consisted of matching simulated values of the elevation of the interface and simulated values of hydraulic head of the freshwater zone of the model domain to corresponding estimated or observed values. Estimated elevations of the interface were determined based primarily on well observations and geophysical measurements. Hydraulic-head values were either observed in wells or interpolated from available maps of the potentiometric surface of the Upper Floridan aquifer. The model calibration was performed to conditions present prior to groundwater withdrawals (predevelopment conditions) and to conditions present in 1985 (postdevelopment conditions).

Upon completion of the model calibration, an uncertainty analysis was performed to test further the results of the calibration and the assumptions on which the sharp interface division between freshwater and salt water was based. The uncertainty analysis consisted primarily of varying key model parameters within a range based on values observed typically in the Floridan aquifer system. The key model parameters used in the uncertainty analyses included horizontal intrinsic permeability values in various model layers, vertical leakage factors, water table elevations, freshwater and saltwater general-head boundary assignments, volume compressibility, porosity, and water withdrawal rates from the aquifer. The results of the uncertainty analyses indicate that the changes in the permeability parameters in model layers 2 and 3, vertical leakage in layer 3, and the freshwater and saltwater general-head boundary have the most significant impact on the overall rise and rate of change of the interface elevation.

Evaluations of potential strategies for reducing saltwater intrusion were based primarily on two different “what if” simulations. In one of the simulations, projected rates of well withdrawals were maintained at 1985 rates (base case). This simulation was intended to provide insight into the potential for additional saltwater intrusion due to projected increases in rates of well withdrawals. In the other simulation, production wells penetrating into the Lower Floridan aquifer were “backplugged” into the Upper Floridan aquifer. This simulation was intended to indicate whether or not backplugging such wells into the Upper Floridan aquifer could be expected to reduce the stress placed on the interface by well withdrawals.

The relative amount of stress exerted on the interface by production wells that tap the Floridan aquifer system was inferred based on a comparison of percent-rise of the interface with respect to the well bottoms of various wells over a specified period of time. In this analysis, the stress on the interface due to well withdrawals is assumed to be greater at locations at which the percent-rise is greater.

The results of the model simulations indicate that significant movement of the interface within the Floridan aquifer system due to the effects of groundwater withdrawals will require between 1,000 and 4,500 years at most locations within the study area. Thus, regional-scale encroachment of salt water into the freshwater zones of the Floridan aquifer system should not be a practical concern for the foreseeable future within the study area.

The results of the first “what if” simulation indicate that reductions in projected increases in rates of groundwater withdrawals between 1985 and 2010 would result in small to moderate reductions in the potential for water quality degradation due to saltwater transport via structural anomalies. This interpretation is based on a comparison of the amount of simulated interface movement in the test simulation representing a reduction of withdrawal rates to the 1995 base case.

The results of the second “what if” simulation indicate that the amount of stress on the interface due to groundwater withdrawals would not be changed substantially by the backplugging of multi-aquifer wells to the Upper Floridan aquifer. Again, this interpretation was based on a comparison of the amount of simulated interface movement in the test simulation to that of the base case. Based on the results, backplugging appears to be generally neutral with regard to the amount of stress on the interface.

A comparison of the distribution of the percent-rise levels to the distribution of above-background chloride concentrations showed that areas of higher percent-rise and above-background chloride concentration generally coincide. Hence, the results appeared to indicate that percent-rise is a good general indicator of the relative risk for saltwater degradation in the wells of the study area.

The areas of highest percent-rise were the area of Duval County east and south of the St. Johns River, the area of northeast St. Johns County along the Atlantic coast, and the area of northeast Nassau County near Fernandina Beach. The areas of lowest percent-rise are generally those to the west and north of the St. Johns River.

The application of the SIMLAS model to evaluate the impacts of water use on the location of freshwater and saltwater interface was limited by several model assumptions which include immiscible liquids, the sharp interface change between freshwater and salt water without a mixing zone, and the limited availability of the discrete vertical trends in water quality data over the regional model domain. Therefore, the model simulation results can only be qualitatively interpolated for application purposes.

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INTRODUCTION

The Floridan aquifer system is the primary source of potable water in northeast Florida and Camden County, Georgia. Development of the Floridan aquifer system in northeast Florida and Camden County, Georgia, began in the 1880s. At present, within the region, hundreds of wells of varying depths tap the Floridan aquifer system, discharging water from it at rates that vary spatially and temporally. These groundwater withdrawals have resulted in substantial drawdowns in the water levels of the Floridan aquifer system within the region. Given sufficient time, these drawdowns will result in substantial upward and landward movement of the salt water that occurs naturally within the coastal and offshore Floridan aquifer system of northeast Florida and Camden County, Georgia.

OBJECTIVES

The primary objective of the study was to construct a regional model to investigate saltwater intrusion into the freshwater zone of the Floridan aquifer system of the study area in response to groundwater withdrawals. A second objective was to determine a relative potential for water quality degradation in various wells that tap the Floridan aquifer system due to the dispersal of salt water via large-scale solution features or faults in the rock matrix of the Floridan aquifer system. A third objective was to evaluate strategies for reducing the potential for saltwater intrusion within the Floridan aquifer system.

PREVIOUS STUDIES

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

Publications that focus on the potential for saltwater intrusion within the study area include those by Frazee and McClaugherty (1979), Munch et al. (1979), Brown (1984), Spechler (1994), Motz and Strazimiri (1996), and Phelps and Spechler (1997).

Publications that focus on the offshore Floridan aquifer system include those by Bunce et al. (1965), Emery and Zarudski (1967), Manheim (1967), Hathaway et al. (1970), Schlee (1977), Paull and Dillon (1979), Scholle (1979), Johnston, Bush et al. (1980), and Spechler (1997).

Publications that present data from deep observation wells in the Floridan aquifer system of northeast Florida or southeast Georgia include those by Leve and Goolsby (1966), Brown (1980), Brown et al. (1984), Brown et al. (1985), Brown et al. (1986), and Jones and Maslia (1994).

Publications that describe groundwater flow models with domains corresponding to areas within the present study area include those by Bush (1982), Krause (1982), Krause and Randolph (1989), Durden and Motz (1991), and Durden (1997).

METHODOLOGY

The study methodology consisted primarily of the development and use of a finite-element, multi-aquifer, sharp-interface groundwater flow model. The model code used was SIMLAS (Saltwater-Intrusion Model for Layered Aquifer Systems), developed by Huyakorn et al. (1992). The SIMLAS code was used to enable simulation of the movement of the boundary between the fresh- and saltwater portions of the Floridan aquifer system. This boundary is represented in SIMLAS as a sharp interface.

The models of the present study were based largely on the results of the study by Durden (1997) in which a MODFLOW (McDonald and Harbaugh 1988) groundwater flow model of the freshwater zone of the Floridan aquifer system of the study area was developed. Development of the sharp-interface model began with the conversion of the transmissivity and leakance estimates of the Durden (1997) model to corresponding values of intrinsic permeability and the vertical leakage factor, respectively, which are utilized by the SIMLAS code (Huyakorn et al. 1992).

Calibration of the models consisted of matching simulated values of the elevation of the interface and simulated values of hydraulic head of the freshwater zone of the model domain to corresponding estimated or observed values. Estimated elevations of the interface were determined based primarily on well observations and geophysical measurements. Hydraulic-head values were either observed in wells or interpolated from available maps of the potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980; Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987). The model calibration was performed to conditions present prior to groundwater withdrawals (predevelopment conditions) and to conditions present in 1985 (postdevelopment conditions).

Upon completion of the model calibration, an uncertainty analysis was performed to test further the results of the calibration and the assumptions on which the sharp interface division between freshwater and salt water was based. The uncertainty analysis consisted primarily of varying key model parameters within a range based on values observed typically in the Floridan aquifer system. The uncertainty analysis was used to determine a general range in the predictions of the extent and rate of movement of salt water into the freshwater zone of the Floridan aquifer system.

Evaluations of potential strategies for reducing saltwater intrusion were based primarily on two different “what if” simulations performed using the calibrated study models. In the first simulation, projected rates of well discharges were maintained at 1985 discharge rates. This simulation was intended to provide an inference regarding the potential impacts of present rates of well withdrawals versus the 2010 projected rates of well withdrawals. In the second simulation, production wells penetrating into the Lower Floridan aquifer were “backplugged” into the Upper Floridan aquifer. This simulation was intended to indicate whether or not backplugging such wells into the Upper Floridan aquifer could be expected to reduce the stress placed on the interface by well withdrawals.

The relative amount of stress exerted on the interface by production wells that tap the Floridan aquifer system was inferred by comparing the percent-rise of the interface with respect to the well bottoms of various wells over a specified period of time. In this analysis, the stress on the interface due to well withdrawals is assumed to be greater at locations at which the percent-rise is greater.

DESCRIPTION OF THE STUDY AREA

LOCATION AND EXTENT

The study area includes parts of Duval, St. Johns, Clay, and Nassau counties, Florida; Camden County, Georgia; and a sizable offshore area in the Atlantic Ocean (Figure 1). The study area ranges approximately from latitude 29°51' to 31°2' north and from longitude 81°7' to 81°52' west. The boundaries of the study area encompass approximately 3,660 square miles. The study area is approximately the same as that of Durden 1997.

CLIMATE

The climate of the study area is humid subtropical (Bermes et al. 1963). About 60% of the average yearly rainfall occurs in the months of June through October (Rao et al. 1989). Between 1941 and 1970, average annual rainfall ranged from approximately 52 inches in the northeast corner of the study area to 56 inches in the southwest corner (Krause and Randolph 1989). The average annual temperature at Jacksonville (Figure 1) during the period 1951–80 was 68°F (NOAA 1985).

INDUSTRY AND POPULATION

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

Population centers within the study area include Jacksonville, Jacksonville Beach, Mayport, St. Augustine, Fernandina Beach, Green Cove Springs, and Orange Park, Florida, and St. Marys and Kingsland, Georgia (Figure 1). In 1990, the total population of the five counties of the study area was approximately 936,894 (Hoffman 1992), of which 71.8% was concentrated in Duval County (Table 1).

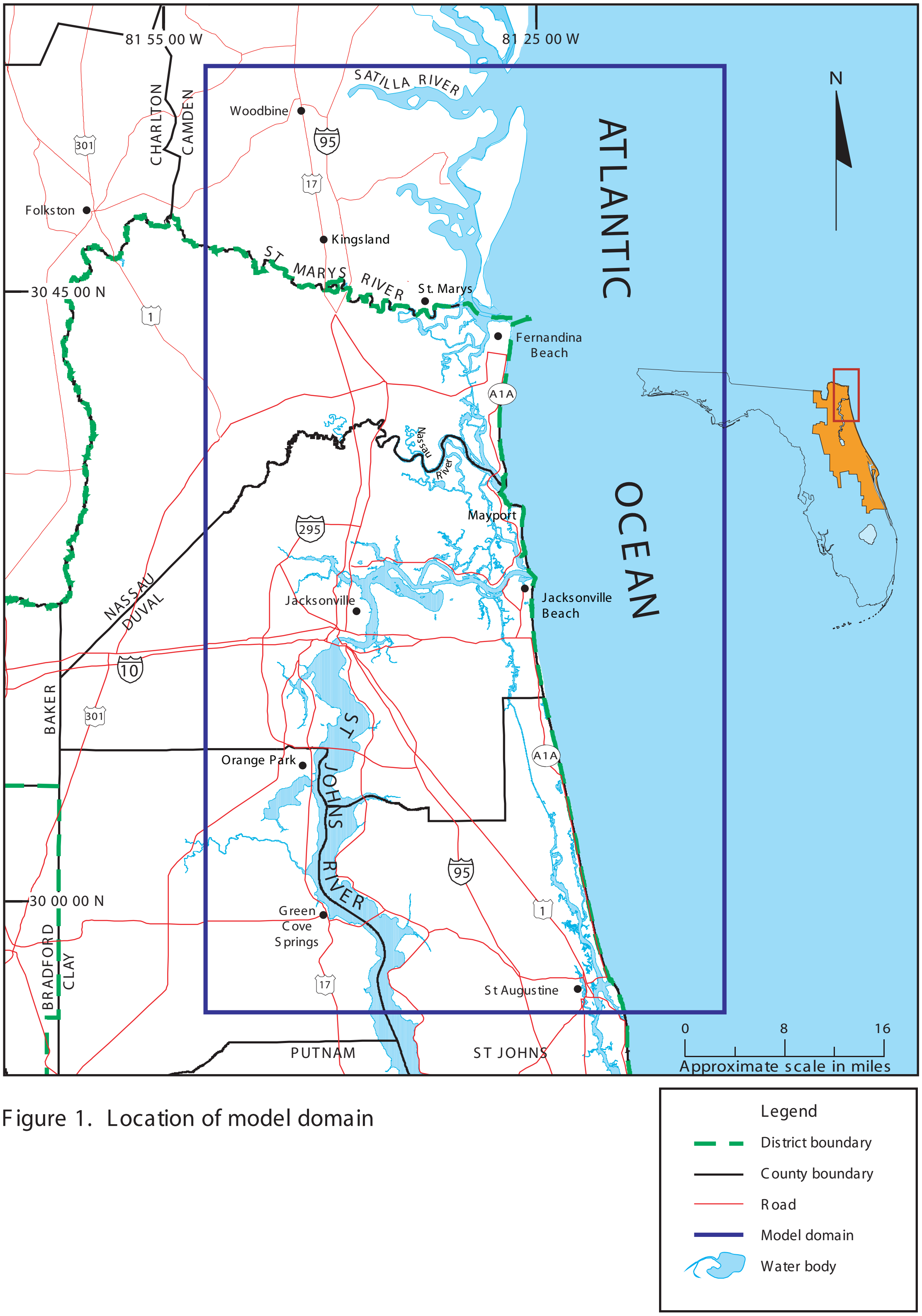


Figure 1. Location of model domain

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

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

Source: Hoffman 1992

SURFACE WATER FEATURES

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

DESCRIPTION OF THE STUDY AREA GROUNDWATER HYDROLOGIC SYSTEM

ONSHORE HYDROGEOLOGIC FRAMEWORK OF THE FLORIDAN AQUIFER SYSTEM

A more detailed description of the hydrogeologic framework of the onshore Floridan aquifer system may be found in Durden 1997. Briefly, the hydrogeologic framework of the onshore portion of the study area consists of the surficial aquifer system, the upper confining unit/intermediate aquifer system, and the Floridan aquifer system.

Surficial Aquifer System

The surficial aquifer system within the study area consists primarily of sand, clayey sand, shell, and thin carbonate beds of Pliocene, Pleistocene, and Holocene deposits (Bermes et al. 1963; Clark et al. 1964; Krause and Randolph 1989). In much of the study area, the surficial aquifer system is divided by a semiconfining unit into upper and lower permeable zones, called the water table zone and the shallow-rock zone, respectively (Causey and Phelps 1978; Franks 1980; Hayes 1981; Spechler and Stone 1983; Brown 1984; Spechler and Hampson 1984; Clarke 1990).

Hydraulically, the surficial aquifer system acts as a source or sink of water for the underlying Floridan aquifer system, recharging the Floridan aquifer system where the water table is above the potentiometric surface of the Upper Floridan aquifer and being recharged by the Floridan aquifer system where the water table is below the potentiometric surface of the Upper Floridan aquifer (Krause and Randolph 1989). Measurements of water table elevations in Duval and Clay counties generally confirm that the water table is a “subdued replica of the configuration of the land surface” within the region (Miller 1986, p. B41; Durden and Motz 1991; Caprara 1993).

Upper Confining Unit/Intermediate Aquifer System

The onshore upper confining unit of the Floridan aquifer system consists of deposits of clay, sand, sandy clay, clayey sand, marl, limestone, and dolomite of the middle Miocene Hawthorn Group and the Pliocene deposits above the Hawthorn Group (Leve 1966). The intermediate aquifer system consists principally of the carbonate, shell, and sand beds in the Hawthorn Group and overlying Pliocene deposits that are sufficiently transmissive to be considered aquifers.

Floridan Aquifer System

The onshore Floridan aquifer system consists of the Ocala Limestone of late Eocene age, the Avon Park Formation of middle Eocene age, the Oldsmar Formation of early Eocene age, and the Cedar Keys Formation of Paleocene age (Miller 1986). The interbedded layers of limestone, dolomite, and other rock types that make up these units can be grouped together to delineate areally extensive zones of high and low permeability. The zones of high permeability function as aquifers, while the zones of low permeability function as semiconfining units that retard vertical movement of water between the high-permeability zones (Leve 1966).

The Floridan aquifer system within the study area has been differentiated into three aquifers separated by two semiconfining units (Brown 1984; Krause and Randolph 1989; Toth 1990). In descending order, these units are the Upper Floridan aquifer, the middle semiconfining unit, the Lower Floridan aquifer, the lower semiconfining unit, and the Fernandina permeable zone (Krause and Randolph 1989). At its base, the Floridan aquifer system is bounded by extensive beds of low-permeability anhydrite (Miller 1986).

OFFSHORE HYDROGEOLOGIC FRAMEWORK OF THE FLORIDAN AQUIFER SYSTEM

Data concerning the hydrogeologic framework of the offshore Floridan aquifer system within and near the study area have been collected at the sites of an offshore sinkhole called Red Snapper Sink (Spechler 1997), along the paths of numerous offshore seismic surveys (Emery and Zarudski 1967; Paull and Dillon 1979; Popenoe et al. 1984), and at the sites of six offshore wells (Figure 2). The six wells include the JOIDES (Joint Oceanographic Institutions' Deep Earth Sampling) Program J-1, J-2, and J-5 wells, geologic research wells drilled in 1965 (Bunce et al. 1965; Emery and Zarudski 1967; Manheim 1967; Hathaway et al. 1970; Schlee 1977); the AMCOR (Atlantic Margin Coring) 6002 well, a geologic research well drilled in 1976 (Hathaway et al. 1979); the COST GE-1 (Continental Offshore Stratigraphic Test, Georgia Embayment Number 1) well, an oil-exploration well drilled in 1977 (Scholle 1979); and the Tenneco LB (Lease-Block) 427 well, another oil-exploration well drilled in 1979 (Johnston et al. 1980).

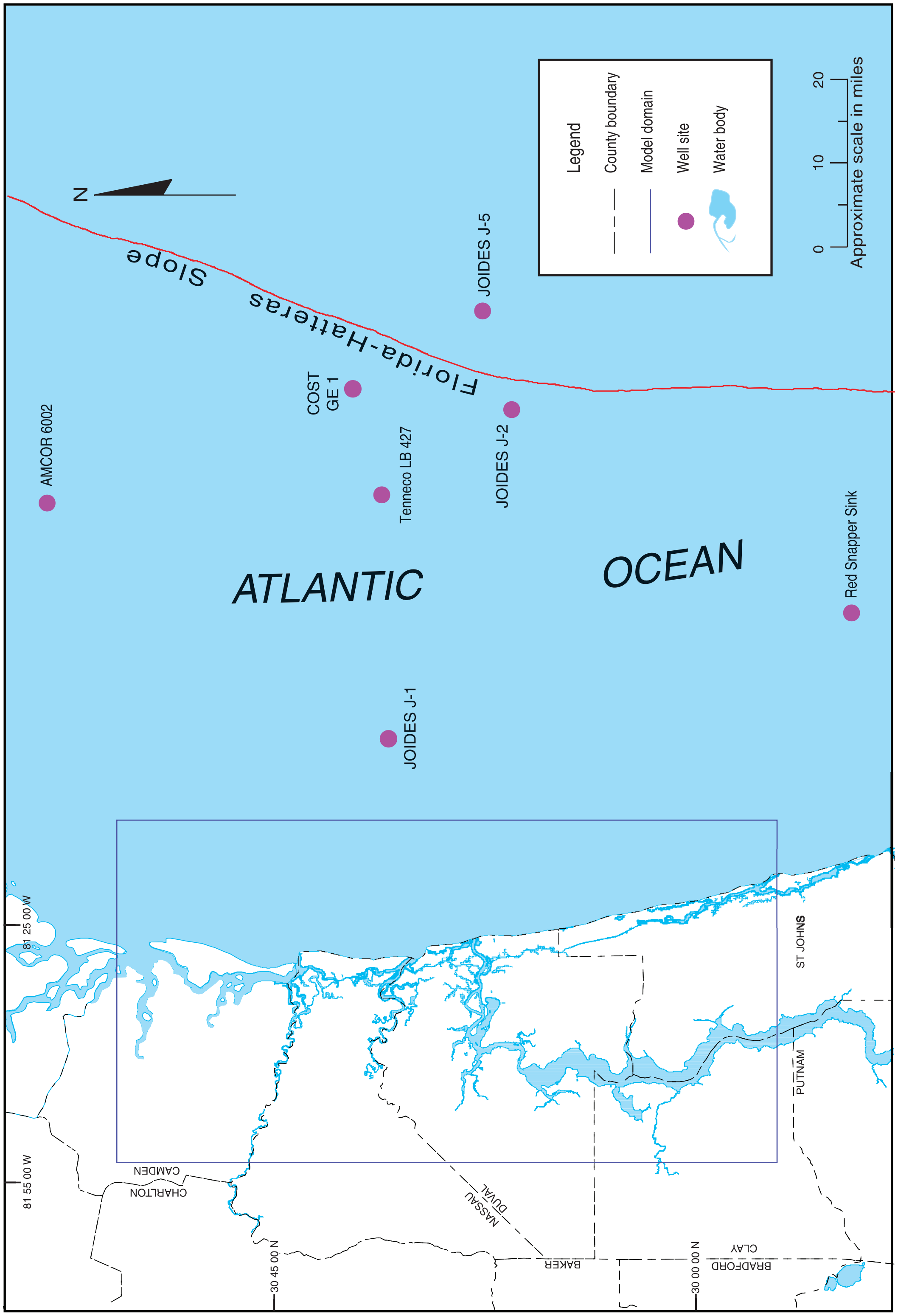


Figure 2. Location of offshore test well sites and Red Snapper Sink

The data collected at these sites show that the Floridan aquifer system offshore of northeast Florida and southeast Georgia consists of Eocene-age carbonates (Emery and Zarudski 1967; Schlee 1977; Paull and Dillon 1979; Johnston et al. 1980; Popenoe et al. 1984; Spechler 1997). As on land, the offshore Eocene carbonates can be delineated into upper, middle, and lower units (Scholle 1979). A carbonate Oligocene unit, which is not present in the onshore portion of the study area, lies atop the Eocene units at the sites of all six offshore wells, thickening towards the Florida-Hatteras Slope (Figure 2).

The upper Eocene unit corresponds apparently to the Ocala Limestone of the onshore Floridan aquifer system (Bunce et al. 1965; Schlee 1977; Johnston et al. 1980). The top of the offshore Floridan aquifer system at the sites of the Tenneco LB 427 and COST GE-1 wells coincides with the top of the Ocala Limestone (Johnston et al. 1980). The base of the Floridan aquifer system at the Tenneco LB 427 well site is a calcilutite formation of early Eocene age (Johnston et al. 1980). The Oligocene unit and overlying units of Miocene-to-Holocene age appear to function as the upper confining unit of the offshore Floridan aquifer system at the sites of the Tenneco LB 427 and COST GE-1 wells (Johnston et al. 1980).

Delineation of the top and bottom elevations of the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone in the offshore portion of the study area, based primarily on offshore data, is not possible due to the scarcity of data. In the present study, elevation maps of these horizons in the offshore portion of the study area were constructed primarily by extrapolating equal-elevation lines of the onshore portions of these horizons obtained from maps in Miller (1986) or based on data obtained from Miller (pers. com. 1991) (Figures 3–8). The top of the Upper Floridan aquifer was assumed to coincide with the top of the upper Eocene unit in the offshore portion of the study area, consistent with Johnston et al. (1980). Equal-elevation lines of the top of the upper Eocene unit in the offshore portion of the study area were obtained from a map by Schlee (1977), which was based partly on geologic data obtained from the JOIDES J-1 and J-2 wells.

Transition Zone Between Freshwater and Salt Water and Its Approximation as a Sharp Interface

Coastal aquifer systems such as the Floridan aquifer system of the study area generally contain separate freshwater and saltwater flow zones. Groundwater in the freshwater zone generally flows seawardly, while groundwater in the saltwater zone generally flows landwardly. Because it is less dense, the

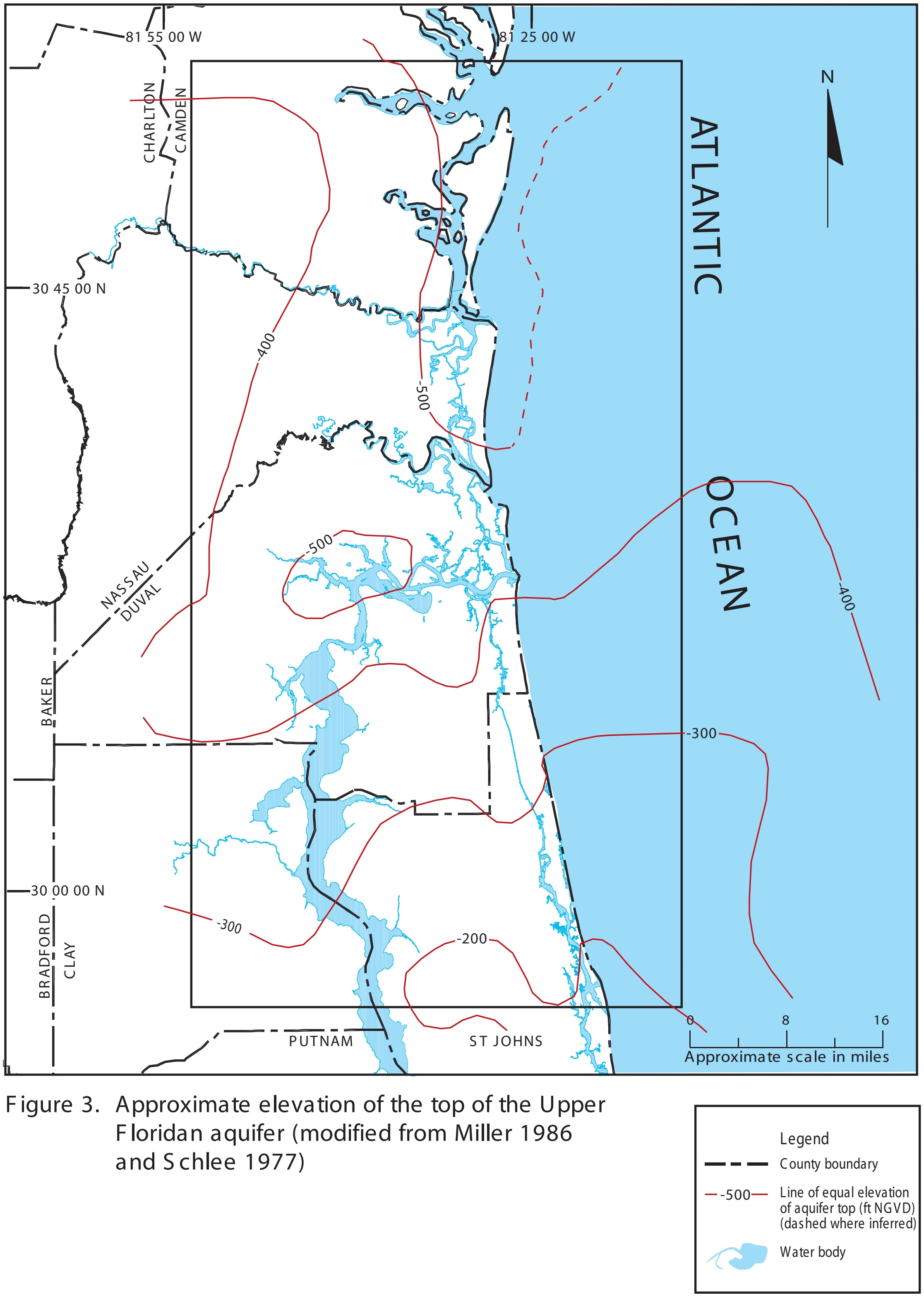


Figure 3. Approximate elevation of the top of the Upper Floridan aquifer (modified from Miller 1986 and Schlee 1977)

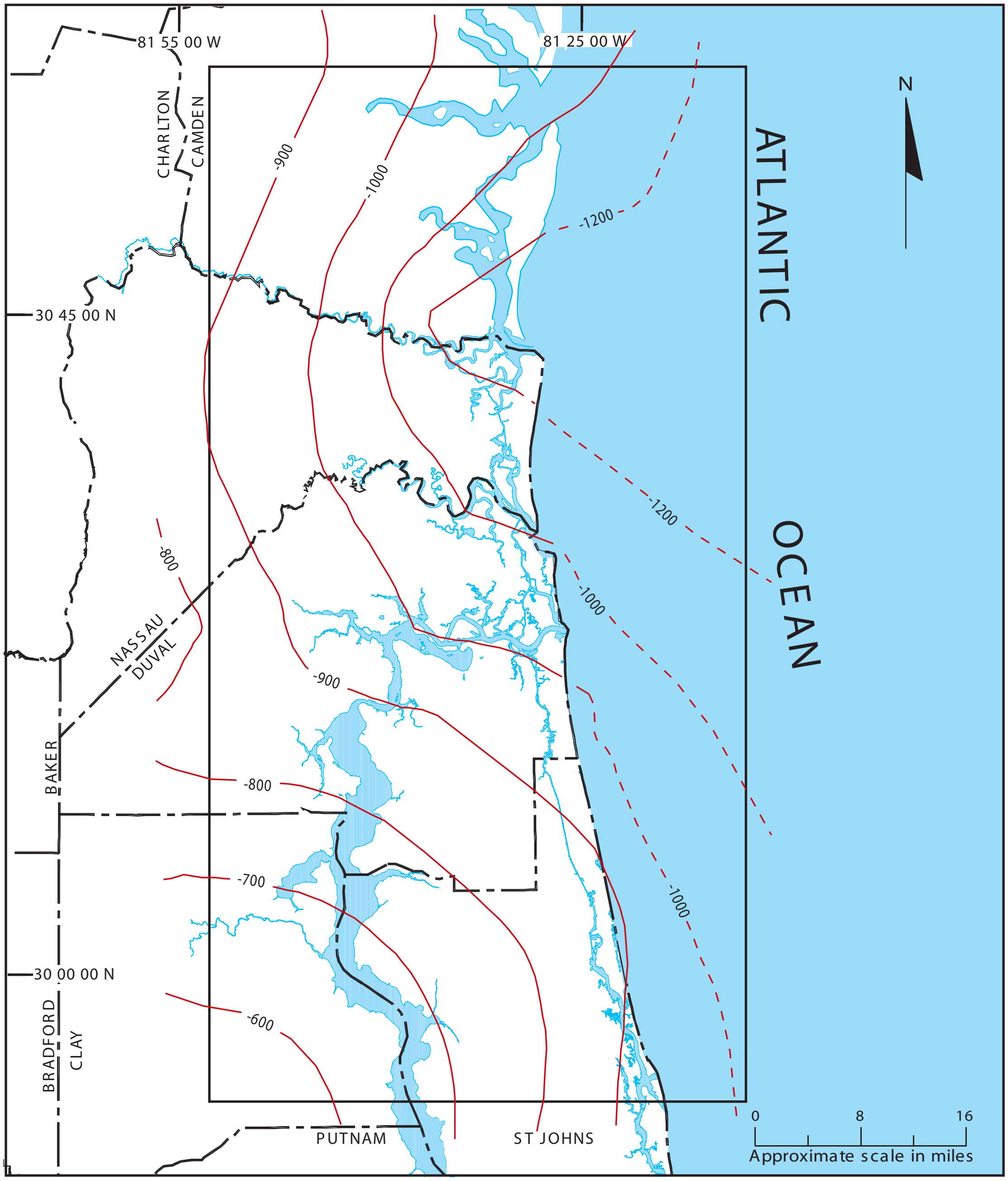
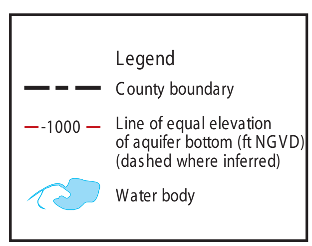


Figure 4. Approximate elevation of the bottom of the Upper Floridan aquifer (modified from Miller 1986)



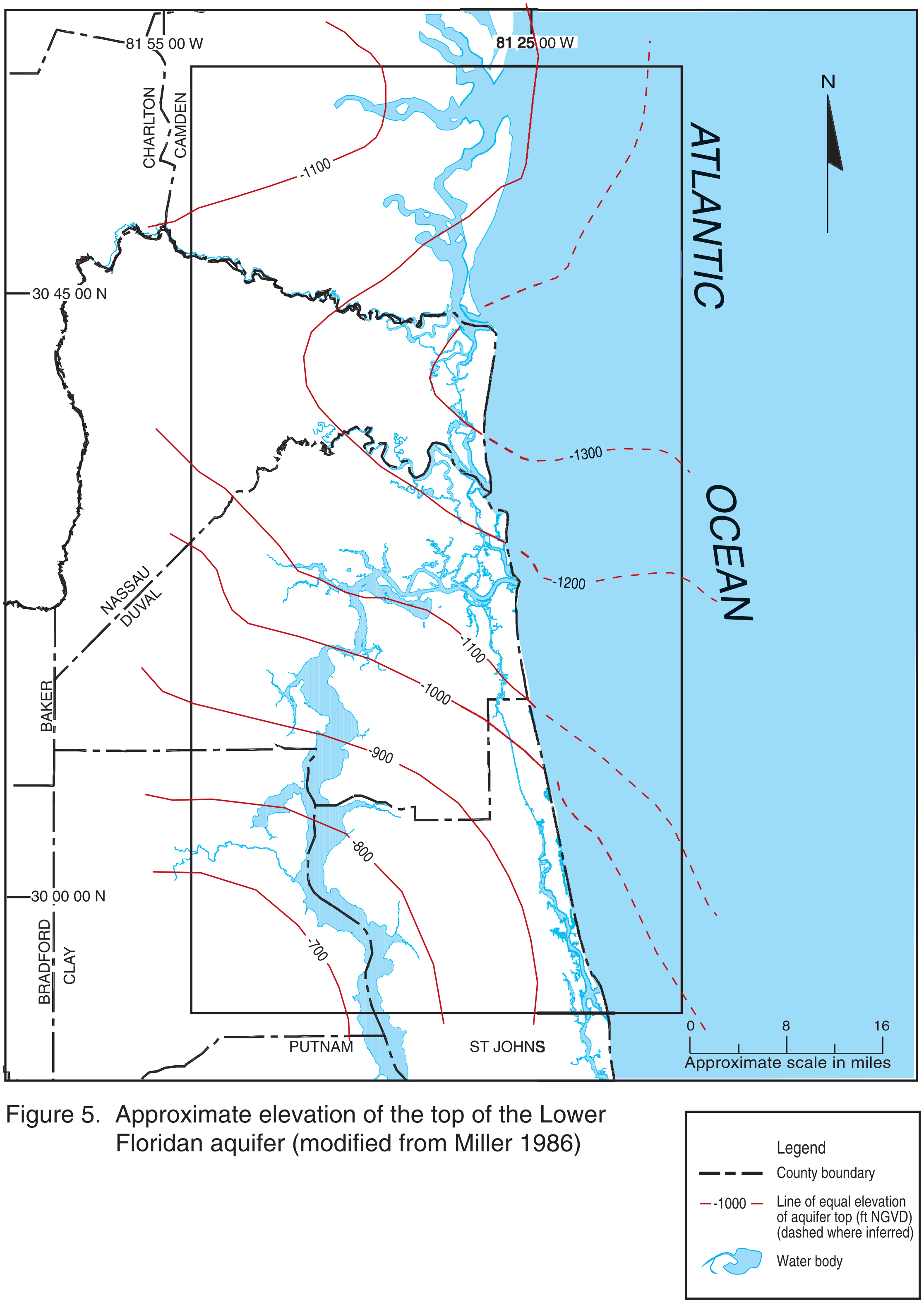


Figure 5. Approximate elevation of the top of the Lower Floridan aquifer (modified from Miller 1986)

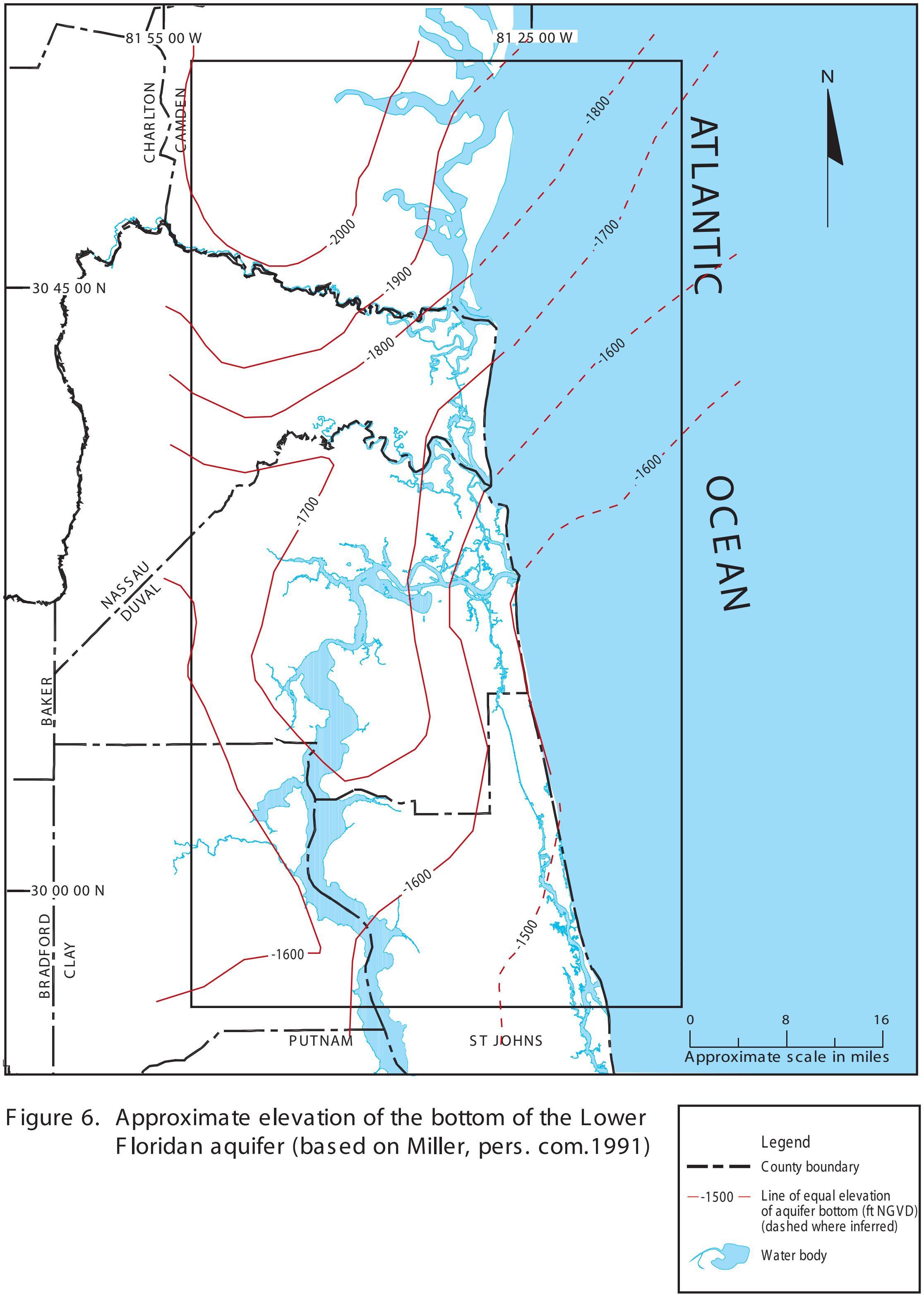


Figure 6. Approximate elevation of the bottom of the Lower Floridan aquifer (based on Miller, pers. com.1991)

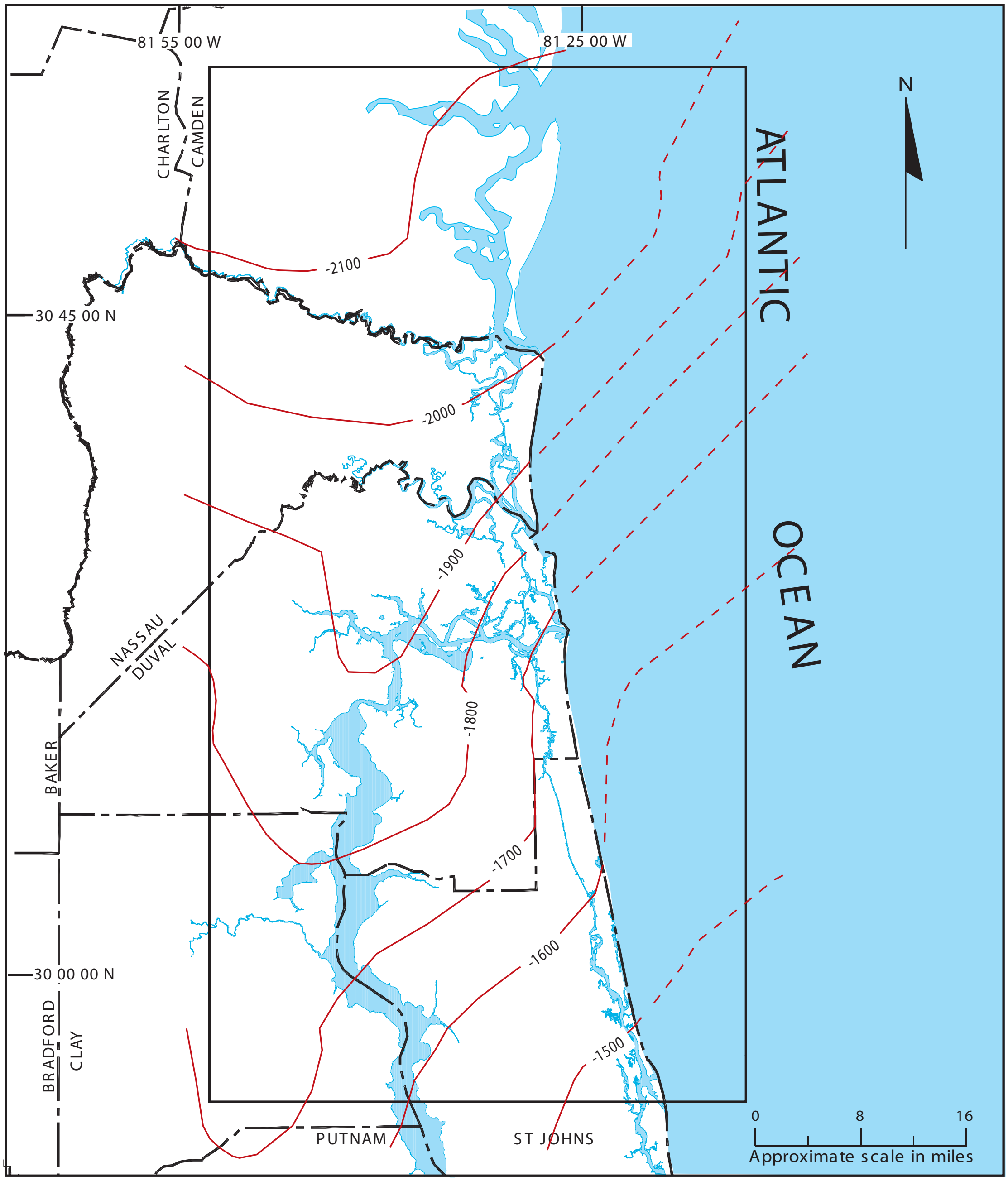


Figure 7. Approximate elevation of the top of the Fernandina permeable zone (modified from Miller 1986)

Legend
County boundary
-1500 Line of equal elevation of aquifer top (ft NGVD) (dashed where inferred)
Water body

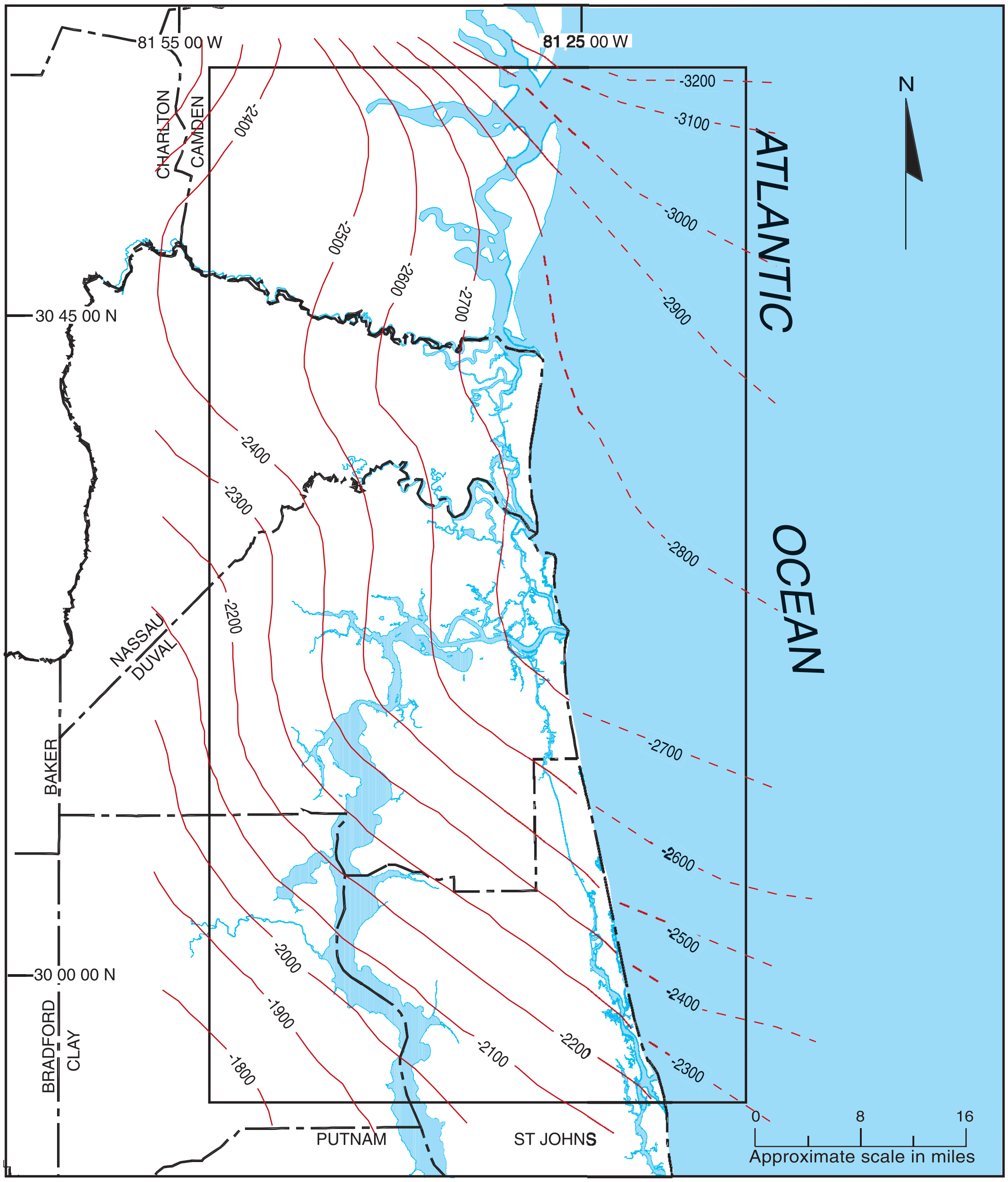
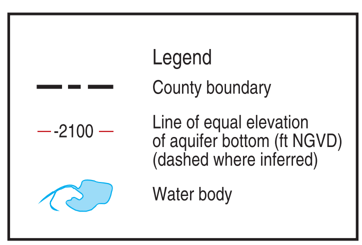


Figure 8. Approximate elevation of the bottom of the Fernandina permeable zone (modified from Miller 1986)



groundwater of the freshwater zone flows on top of that of the saltwater zone. Flows from the two zones meet and intermingle in a zone of dispersion of finite thickness called the transition zone (Figure 9). In the transition zone, groundwater salinity levels (and, accordingly, groundwater densities) increase seawardly from that of the freshwater zone to that of the saltwater zone (Cooper et al. 1964; Bear 1979).

In many cases, the width of the transition zone is small in comparison to the aquifer thickness. In such cases, the transition zone can be represented accurately as an abrupt (or sharp) interface between the freshwater and saltwater flow zones. In the sharp-interface concept, the relatively complex hydraulics of the variable density flow in the transition zone are not addressed. Therefore, use of the sharp-interface concept can result in a considerable simplification of the overall conceptualization of a coastal aquifer system (Bear 1979).

Analyses of water samples obtained from five deep-observation wells within the study area showed relatively sharp increases in chloride concentration at depths ranging from approximately 1,900 to 2,300 feet below land surface (ft bls) (Leve and Goolsby 1966; Brown et al. 1980; Brown et al. 1984; Brown et al. 1985; Brown et al. 1986). At the sites of these wells, therefore, the transition zone appears to be thin compared to the thickness of the Floridan aquifer system (Figures 10–14). The wide distribution of these wells throughout the study area suggests that the transition zone may be approximated accurately as a sharp interface in most of the study area. A possible exception, however, is the area of central St. Johns County, in the southeast corner of the study area. In that area, the transition zone may be somewhat wider than in other parts of the study area, based on chloride concentrations observed in wells that penetrate the Upper Floridan aquifer (Munch et al. 1979).

For areas in which the transition zone is perhaps relatively wide, such as central St. Johns County, the approximate location of the sharp interface may be thought of as corresponding to the location of a surface of constant chloride concentration halfway between that of freshwater and salt water (i.e., the 50% isochlor) (Cooper et al. 1964; Schmorak and Mercado 1969; Reilly and Goodman 1985). This concentration is approximately 9,750 milligrams per liter (mg/L), assuming the chloride concentration of salt water to be 19,500 mg/L (the approximate chloride concentration of seawater). In the present study, the transition zone was approximated throughout the study area as a sharp interface. Given the regional scope of the study, this approximation was felt to be adequate.

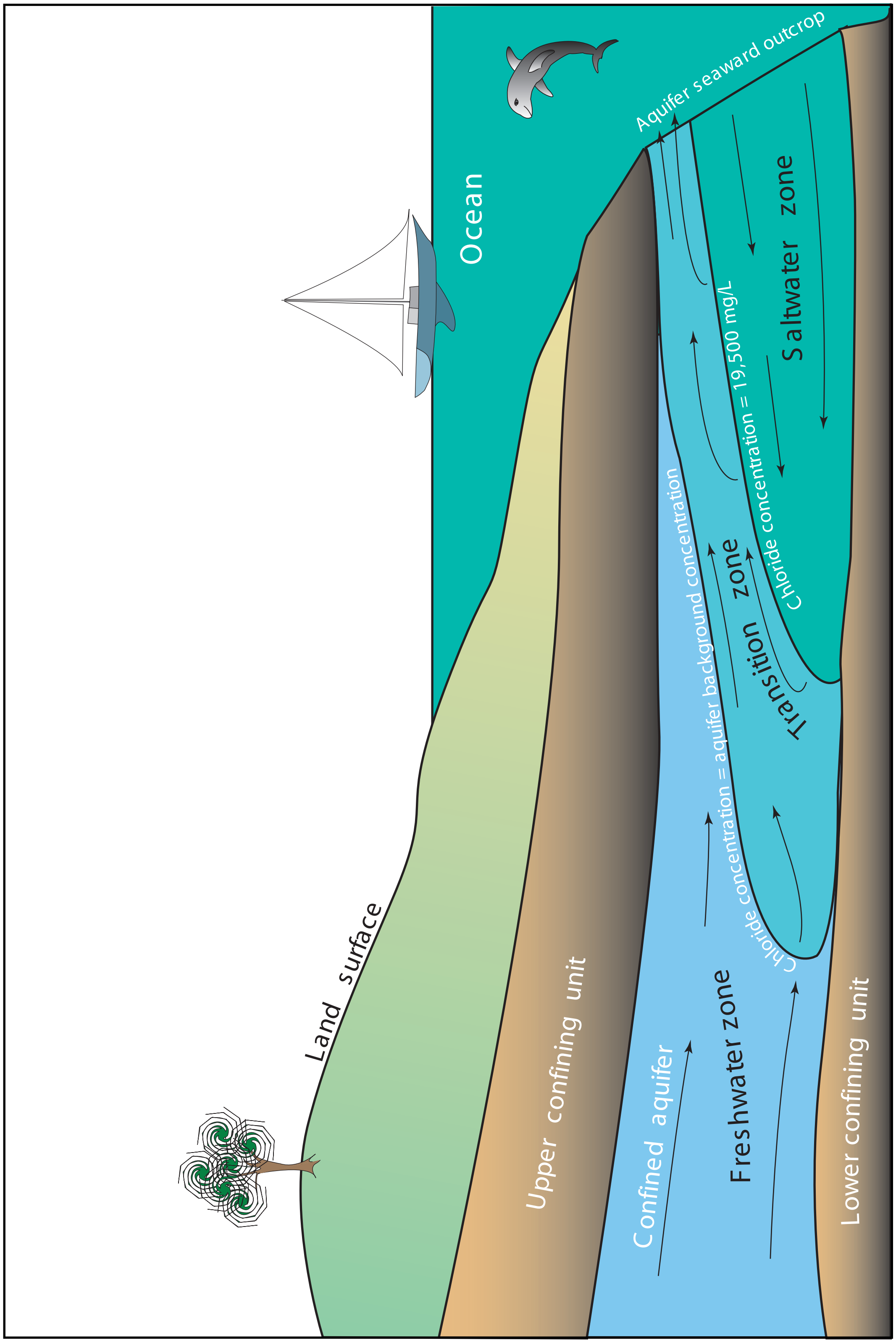


Figure 9. Hypothetical coastal aquifer system

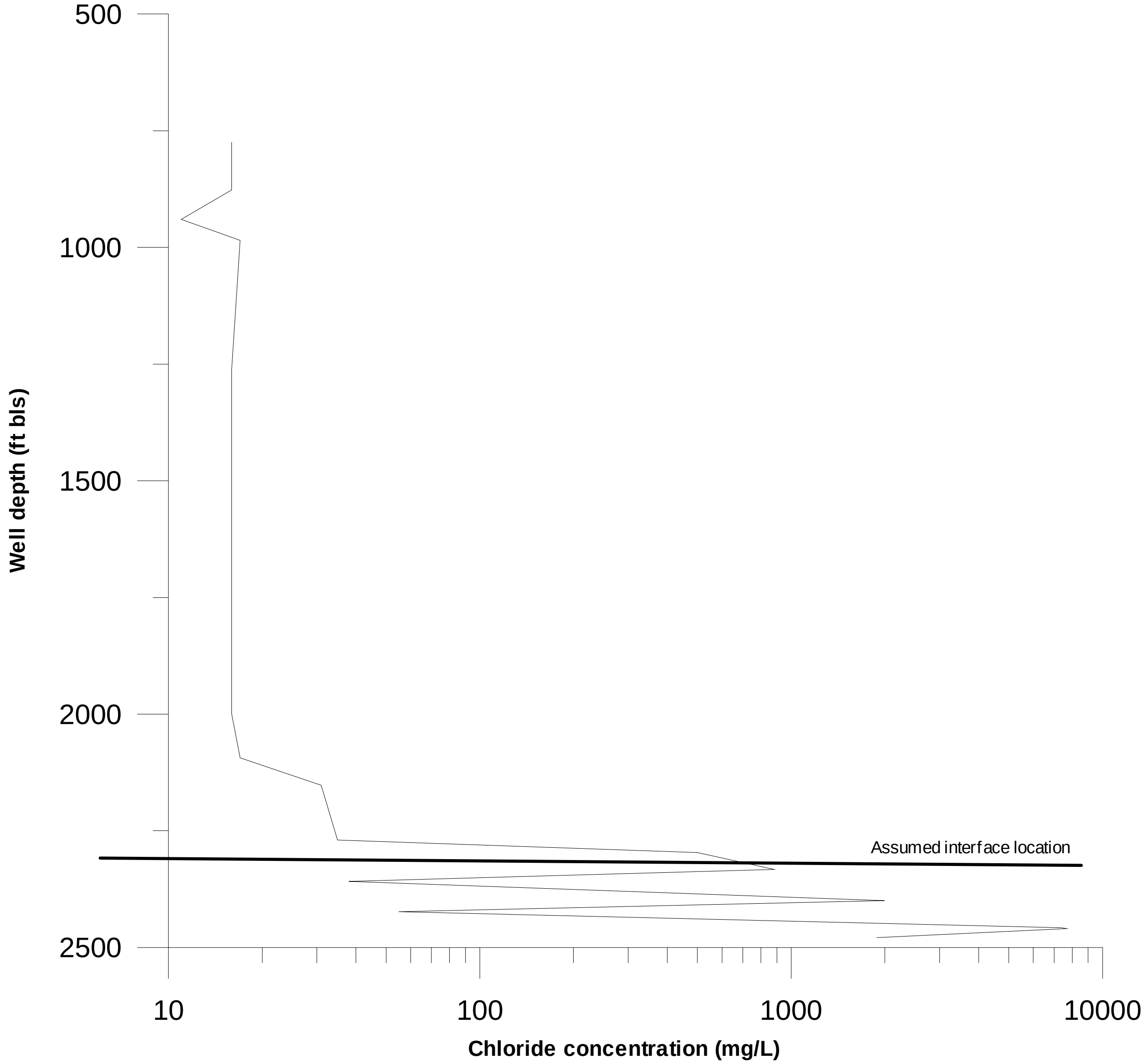


Figure 10. Chloride concentration versus depth and assumed interface location in well D425B (Jacksonville) (modified from Leve and Goolsby 1966)

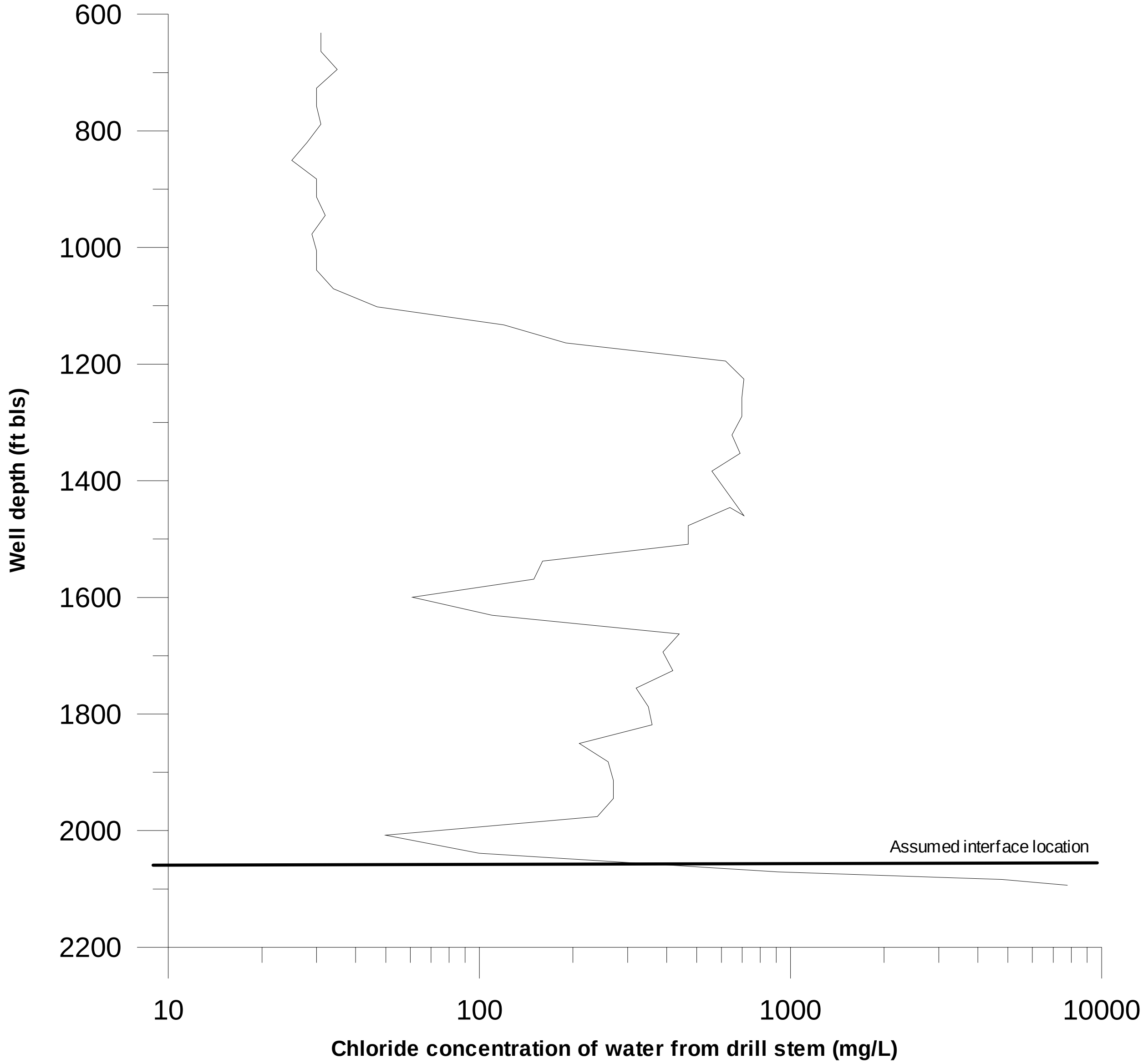


Figure 11. Chloride concentration versus depth and assumed interface location in well N-0117 (Fernandina Beach) (modified from Brown 1980)

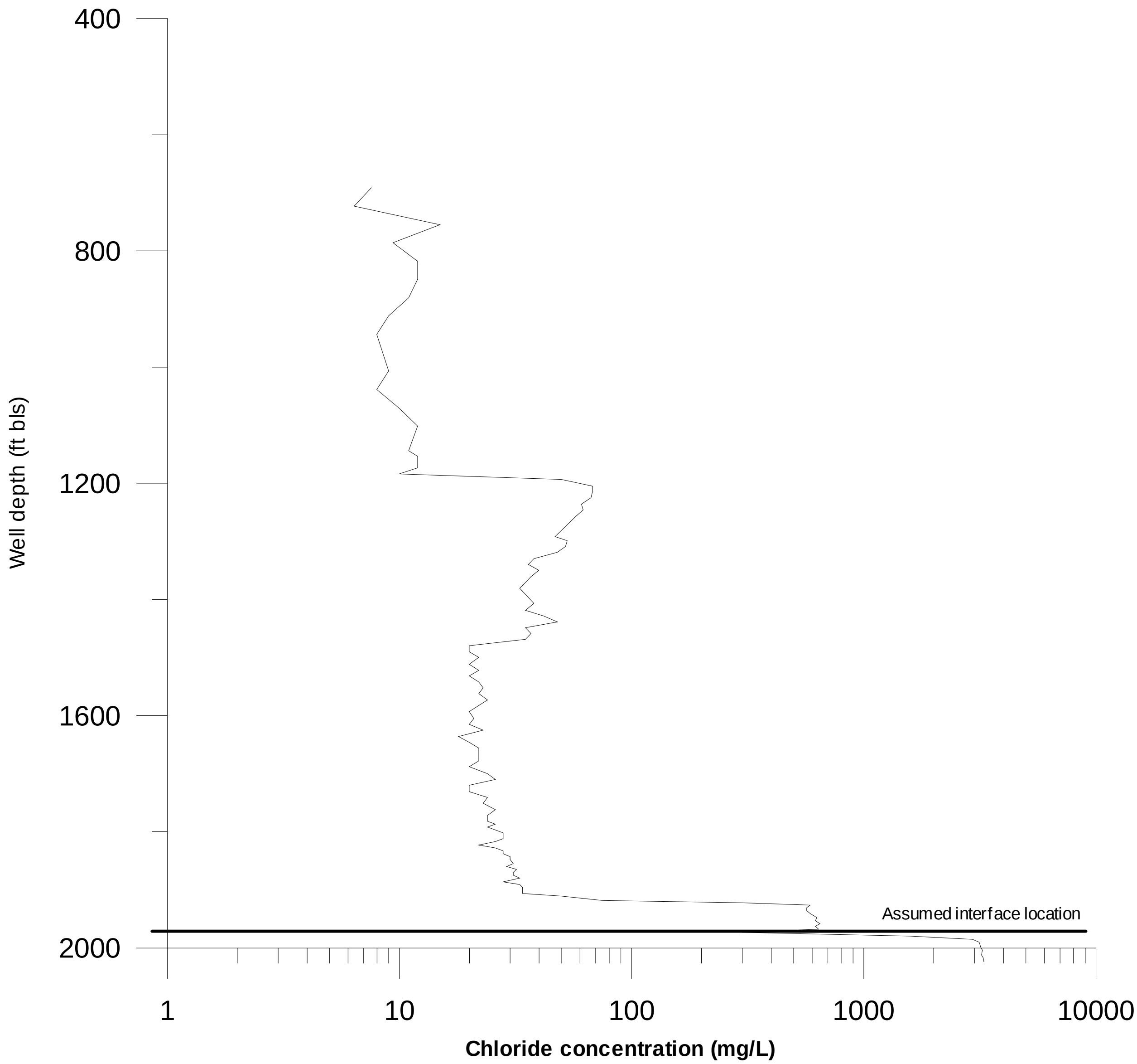


Figure 12. Chloride concentration versus depth and assumed interface location in well D-2386 (Hanna Park) (modified from Brown et al. 1984)

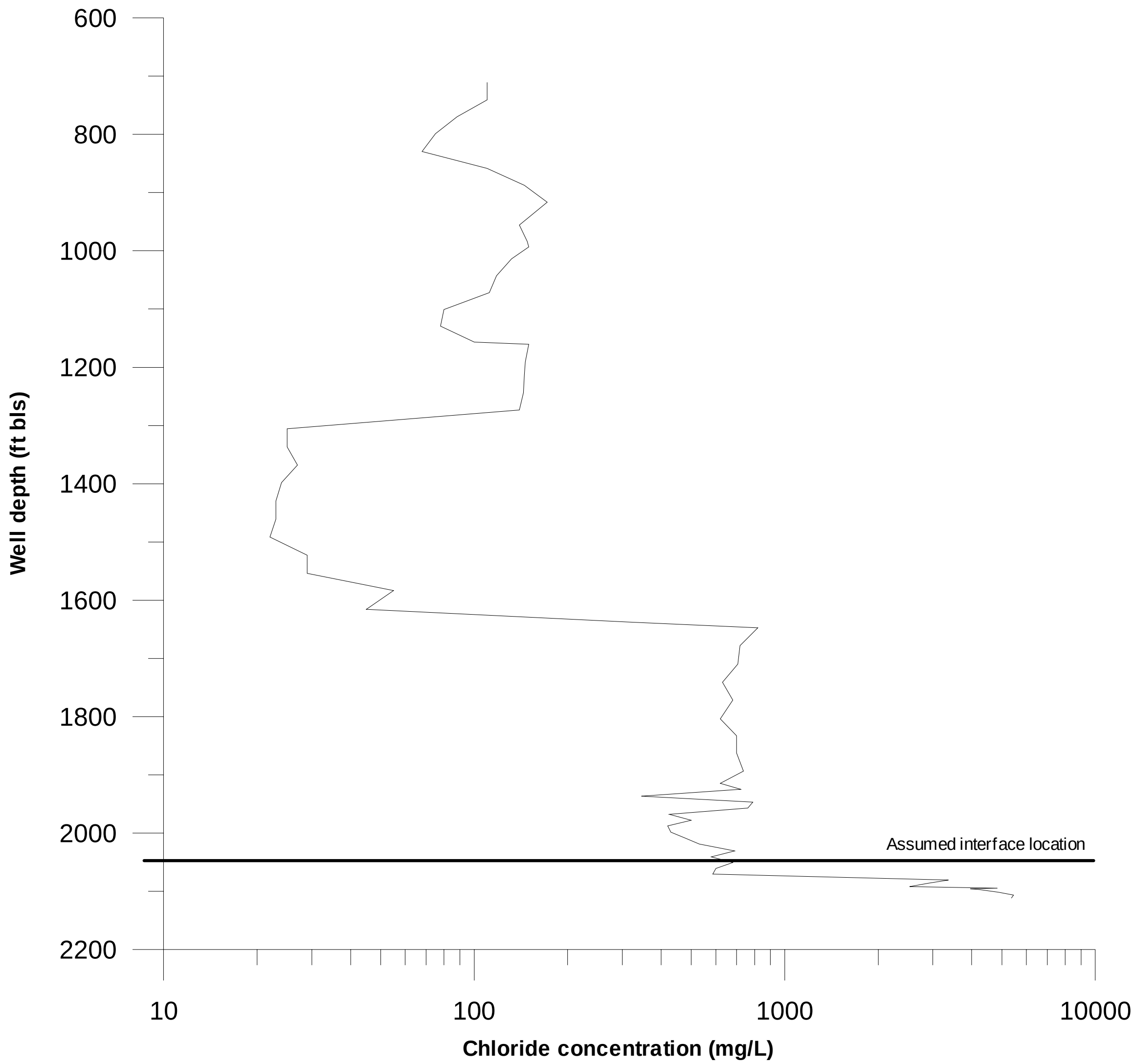


Figure 13. Chloride concentration versus depth and assumed interface location in well D-3060 (Arlington East) (modified from Brown et al. 1985)

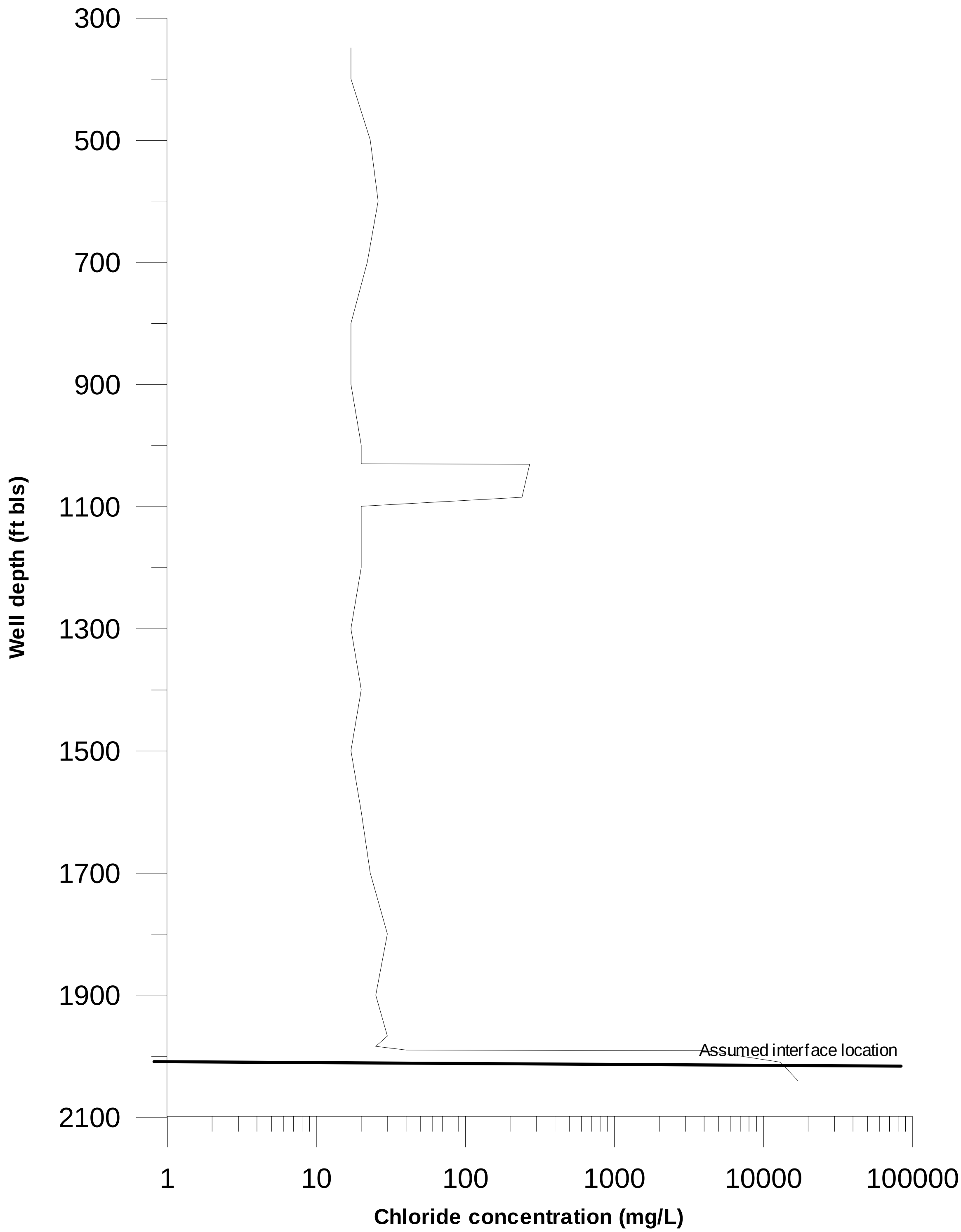


Figure 14. Chloride concentration versus depth and assumed interface location in well SJ-0025 (Ponte Vedra Beach) (modified from Brown et al. 1986)

ESTIMATION OF ELEVATIONS OF THE ONSET OF SALT WATER IN THE FLORIDAN AQUIFER SYSTEM WITHIN AND NEAR THE STUDY AREA

Elevations of the onset of salt water within the present study area were estimated at various onshore sites and at the above-referenced offshore sites (Figure 15). A map of equal-elevation lines of the onset of salt water within and near the study area was created using these data (Figure 16). The map is a contour plot created using the ARC/INFO TIN contouring package.

In many cases, the available data indicated only that fresh or salt water is present or is likely to be present throughout the thickness of the Floridan aquifer system. Where freshwater was deemed to be present throughout the thickness of the Floridan aquifer system, the elevation of the onset of salt water was equated to an estimate of the bottom elevation of the Floridan aquifer system. Where salt water was deemed to be present throughout the thickness of the Floridan aquifer system, the elevation of the onset of salt water was equated to an estimate of the top elevation of the Floridan aquifer system.

The “interface,” as conceptualized in the present study, is the boundary between the fresh- and saltwater zones of an aquifer. Strictly speaking, therefore, the interface exists only where both freshwater and saltwater zones are present within an aquifer. Thus, the inclusion in the analysis of data points that represent locations in which only a single zone is present means that the resulting map (Figure 16) is more accurately described as a map of the elevation of the onset of salt water rather than as a map of the elevation of the interface. The line along which the interface intersects the bottom of an aquifer is referred to as the toe of the interface. The line

along which the interface intersects the top of an aquifer is referred to as the tip of the interface. Comparison of the estimated elevations of the onset of salt water (Figure 16) to the top and bottom elevations of the Upper and Lower Floridan aquifers and the Fernandina permeable zone (Figures 3–8) enabled the determination of the approximate locations of the toes and tips of the interface within these aquifers.

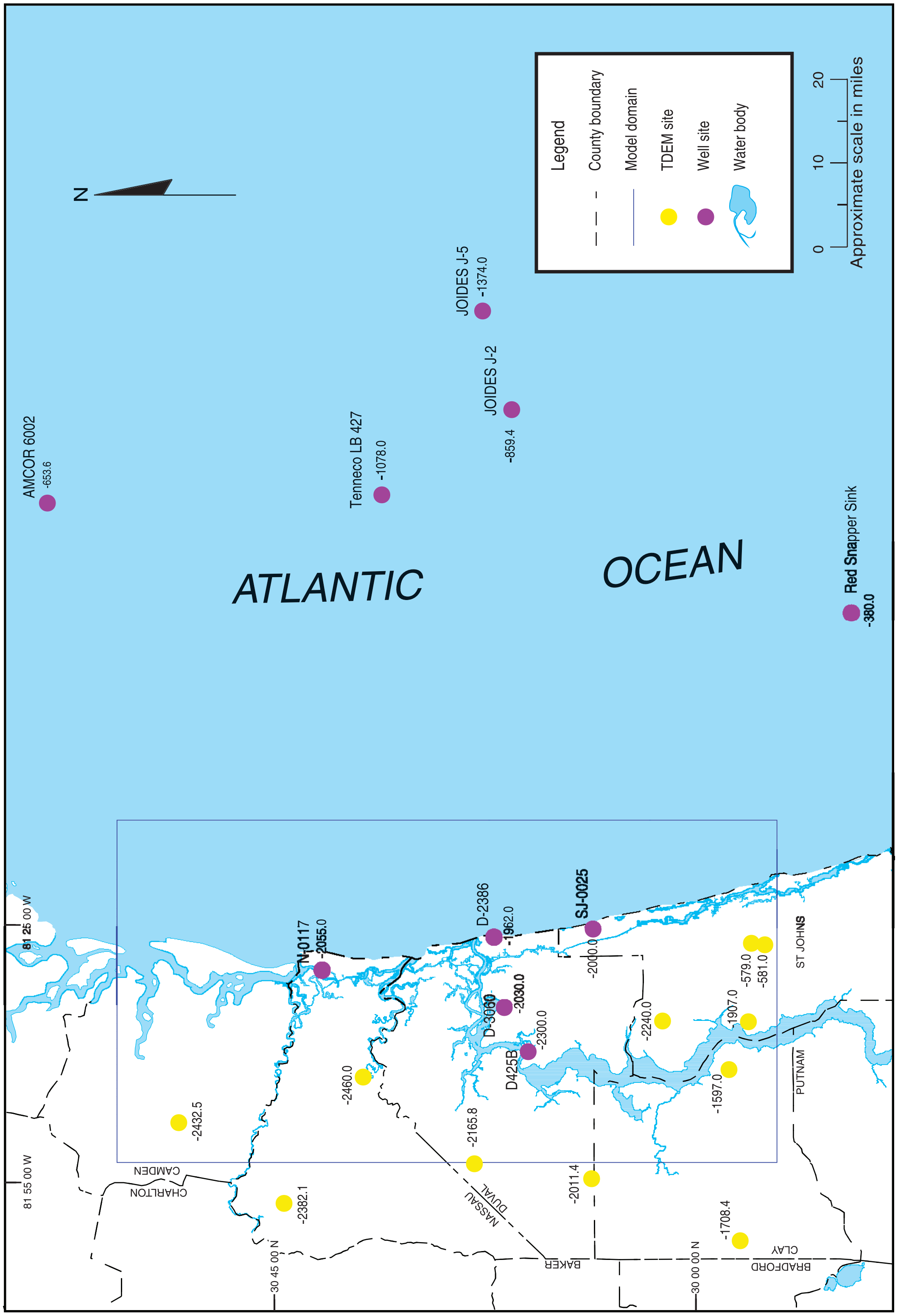


Figure 15. Approximate elevation (feet NGVD) of the onset of salt water in the Floridan aquifer system at selected onshore and offshore sites

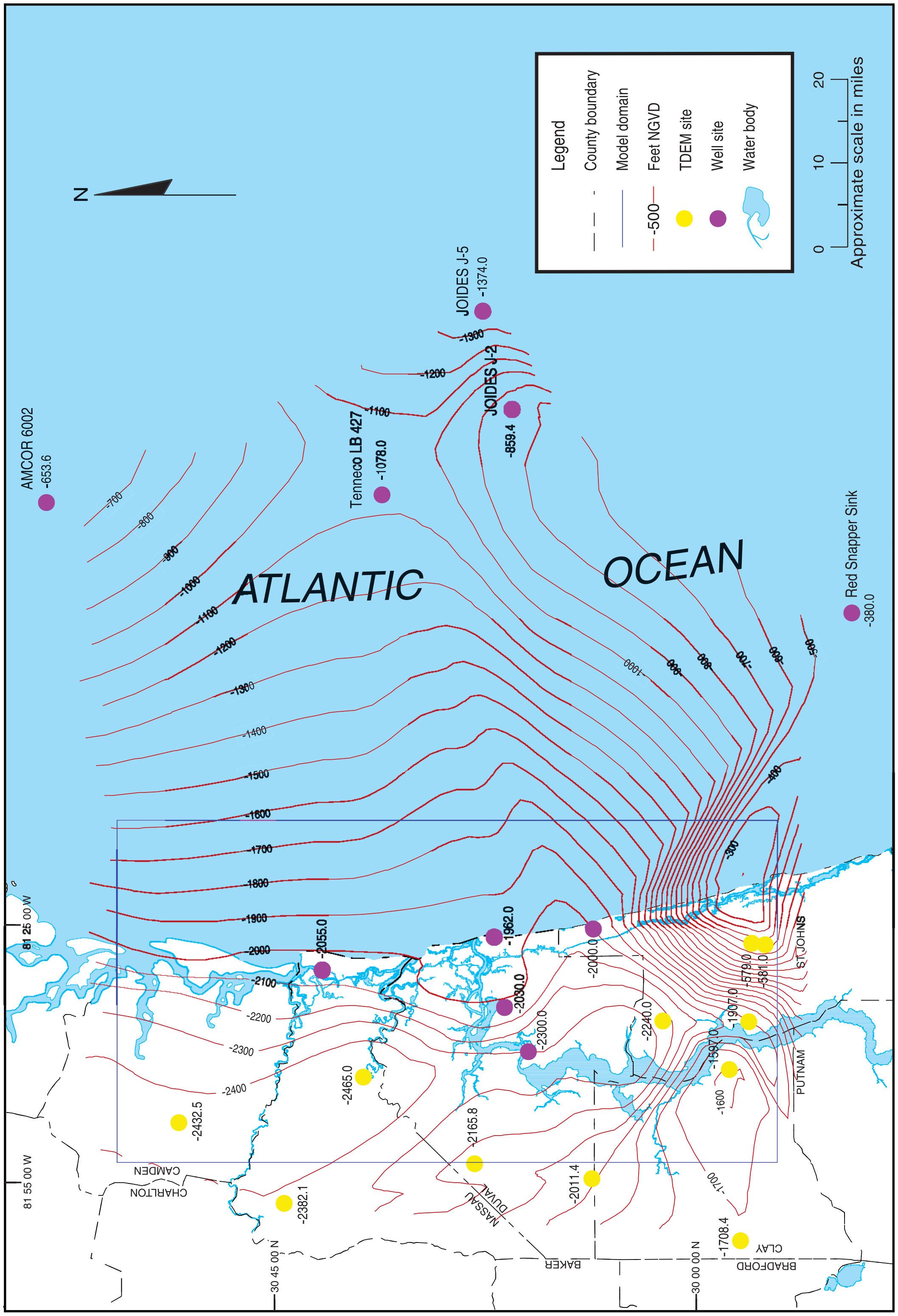


Figure 16. Approximate elevation of the onset of salt water in the Floridan aquifer system

DATA AND APPROXIMATIONS USED TO CREATE THE MAP OF THE ELEVATIONS OF THE ONSET OF SALT WATER

The onshore data on which the map of the elevations of the onset of salt water is based (hereafter referred to as the saltwater onset map) include measurements of chloride concentrations in water obtained from drill stems used in the construction of the five deep-observation wells in the Floridan aquifer system of the study area (Figure 15). Water samples in these five wells were obtained at periodic depths during drilling, which was continued until zones of elevated chloride concentration were penetrated (Leve and Goolsby 1966; Brown et al. 1980; Brown et al. 1984; Brown et al. 1985; Brown et al. 1986). Relatively large, abrupt increases in chloride concentrations with respect to depth below land surface were observed in each of these wells, at depths ranging from approximately 1,900 to 2,300 ft. The location of the interface in each of these wells was assumed to be near the onset of the abrupt increase in chloride concentration with respect to depth.

In addition to data obtained from the five deep-observation wells, the onshore data include measurements of spatial variations in electrical resistivity within the Floridan aquifer system using the time-domain electromagnetic (TDEM) geophysical technique (Blackhawk Geosciences 1990; CEES-Blackhawk Geosciences Division 1992; Subsurface Detection Investigations 1993). TDEM measurements are attained by projecting an electromagnetic field into an underground geologic formation to determine depths at which significant changes in formation resistivity occur. Significant changes in resistivity can be attributed to changes in the ionic content of formation water, assuming approximately constant formation lithology and porosity (D. Toth, SJRWMD, pers. comm. 1993). TDEM was used at several sites within and near the present study area to determine approximate depths below land surface to the 5,000-mg/L isochlor surface (Figure 15). The elevation of this surface was assumed in the present study to approximate adequately the elevation of the onset of salt water.

At several sites within the study area, TDEM measurements indicated that the 5,000-mg/L isochlor surface was lower than the estimated base elevation of the Floridan aquifer system (Blackhawk Geosciences 1990; CEES-Blackhawk Geosciences Division 1992). The base of the Floridan aquifer system within the study area is marked by the onset of an evaporite zone (Miller 1986), which contains highly mineralized groundwater (D. Toth, SJRWMD, pers. comm. 1993). In cases in which the Floridan aquifer system is fresh throughout its vertical extent, therefore, TDEM measurements would be expected to indicate that the onset of salt water occurs at the base of the Floridan aquifer system, providing the assumptions of constant formation lithology and porosity are adequately approximated (D. Toth, SJRWMD, pers. comm. 1993). Hence, these TDEM measurements were interpreted in the present study as indicating that the Floridan aquifer system is fresh throughout its vertical extent at the respective measurement sites. The elevations of the onset of salt water at these sites were set equal to the respective base elevations of the Floridan aquifer system, which were estimated from Miller (1986).

In the offshore portion of the study area, chloride concentrations have been observed in water samples obtained from five of the referenced offshore wells, including the JOIDES J-1, J-2, and J-5, Tenneco LB 427, and AMCOR 6002 wells. Data collected at these sites were used directly or indirectly in the present study to estimate elevations of the onset of salt water within the Floridan aquifer system in the offshore area near the study area. Observations made by scuba divers at Red Snapper Sink (Spechler 1997) provided the basis of an additional estimate of the elevation of the onset of salt water within the Floridan aquifer system in the offshore area near the study area.

The elevations of the onset of salt water at the sites of the JOIDES J-2 and Tenneco LB 427 wells were scaled from a vertical cross-section diagram in Johnston et al. (1980). The elevations of the onset of salt water as indicated on the diagram were estimated based on chloride concentrations observed in the JOIDES J-1 and J-2, Tenneco LB 427, and N-0117 wells and water levels observed in the JOIDES J-1 and Tenneco LB 427 wells (Johnston et al. 1980) (Figure 16).

The elevation of the onset of salt water at the site of the JOIDES J-5 well was based on the chloride concentration observed in a water sample from the well when it penetrated the top of the Floridan aquifer system. The observed concentration was approximately 12,000 mg/L (Manheim 1967). Based on an assumption of a thin transition zone at this site, the elevation of the onset of salt water was estimated as being the same as that of the top of the Floridan aquifer system.

The elevation of the onset of salt water at the site of the AMCOR 6002 well was estimated from a plot of well salinity versus depth shown in Hathaway et al. (1979). Salinity levels in water samples obtained from the AMCOR 6002 well were at or somewhat above the salinity levels observed in seawater throughout the interval of the Floridan aquifer system penetrated by the well

(Hathaway et al. 1979). Thus, the elevation of the onset of salt water at the site of the AMCOR 6002 well was estimated as being the same as that of the top of the Floridan aquifer system.

In addition to the data obtained from the five offshore wells, data were obtained in the form of sight observations at Red Snapper Sink, which is located approximately 25 miles east of Crescent Beach (Spechler 1997). The top of the Ocala Limestone was observed at approximately 380 ft below the water surface at this site. The bottom of Red Snapper Sink was observed between 434 and 495 ft below the water surface. At a depth of approximately 482 ft, seawater was observed entering caverns in a wall of the sink (Spechler 1997), thus the sink is a point of entry of seawater into the Floridan aquifer system. Discharge from the Floridan aquifer system, of either fresh or brackish water, was not observed at Red Snapper Sink. Based on the observed entry of seawater and the apparent absence of discharge from the Floridan aquifer system, the Floridan aquifer system was assumed to be occupied completely with seawater at Red Snapper Sink. The elevation of the onset of salt water was assumed to be the same as that of the top of the Floridan aquifer system.

NORMALIZED SALTWATER ONSET MAPS OF THE FLORIDAN AQUIFER SYSTEM IN THE STUDY AREA

The saltwater onset map (Figure 16) was used in conjunction with the maps of the tops and bottoms of the Upper Floridan aquifer, Lower Floridan aquifer, and Fernandina permeable zone (Figures 3–8) to create “normalized saltwater onset” maps of these three aquifers. A normalized saltwater onset contour map is defined as the portion of the vertical extent of an aquifer that is occupied with salt water. Each contour line represents a ratio of the vertical saltwater extent in the aquifer to the total aquifer thickness. These maps are useful for illustrating the lateral and vertical distribution of freshwater and salt water within aquifers.

The normalized saltwater onset map (Figure 17) of the Upper Floridan aquifer shows that freshwater exists throughout the vertical extent of the Upper Floridan aquifer everywhere except in the southeast corner of the study area. Nowhere within the study area is the full vertical extent of the Upper Floridan aquifer occupied with salt water, though it nearly is in the extreme southeast corner.

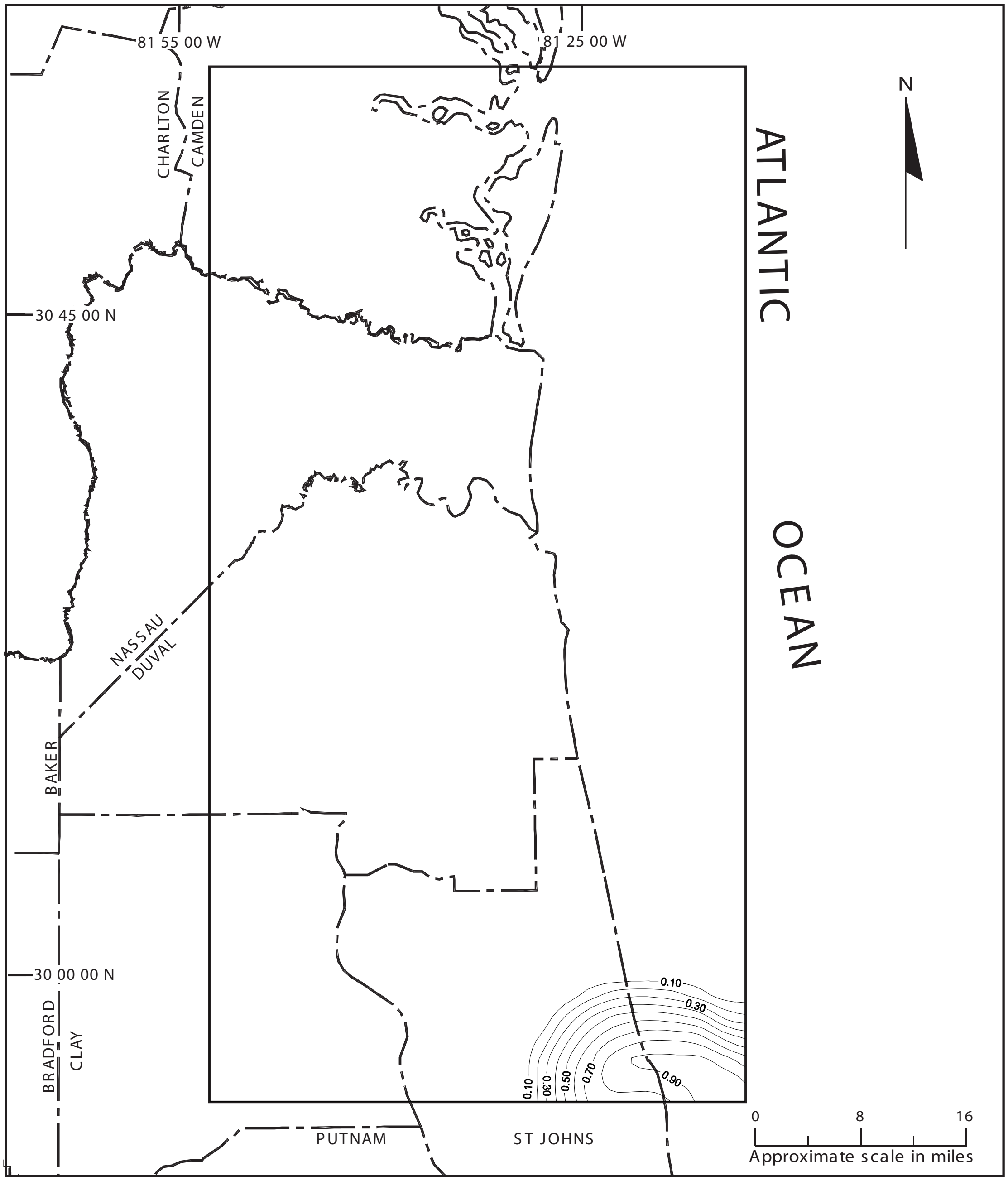


Figure 17. Estimated percentage of occupation of the Upper Floridan aquifer by salt water in the model domain

Legend	
— — —	County boundary
—0.90—	Line of equal percentage of occupation (decimal percent)

The location of the 0.1 contour line approximates the position of the interface toe in the Upper Floridan aquifer of the study area. The location of the 0.9 contour line, if present, would approximate the position of the interface tip. Its absence, however, indicates that the interface tip in the Upper Floridan aquifer lies outside the study area.

The normalized saltwater onset contour map (Figure 18) of the Lower Floridan aquifer shows that freshwater occupies the entire vertical extent of the Lower Floridan aquifer everywhere except in the southeast and northeast corners of the study area. In parts of the southeast corner of the study area, salt water occupies the entire vertical extent of the Lower Floridan aquifer. In the northeast corner, salt water occupies a small portion of the vertical extent of the Lower Floridan aquifer.

The location of the 0.1 contour line approximates the position of the interface toe in the Lower Floridan aquifer of the study area. The location of the 0.9 contour line approximates the position of the interface tip. The locations of these lines indicate that only a relatively small portion of the lower Floridan aquifer is occupied by the saltwater wedge.

The normalized saltwater onset contour map (Figure 19) of the Fernandina permeable zone shows that salt water partially occupies the vertical extent of the Fernandina permeable zone throughout most of the study area. In the southeast and northeast corners of the study area, salt water occupies the whole vertical extent of the Fernandina permeable zone.

In the southwest corner of the study area, salt water occupies the entire vertical extent of the Fernandina permeable zone (Figure 19). The configuration of this saltwater body was based primarily on a single TDEM measurement made near Green Cove Springs (CEES-Blackhawk Geosciences 1992). This TDEM measurement indicated an anomalously high elevation of the interface in the area of Green Cove Springs.

In areas south of the present study area, salt water within the Floridan aquifer system has been observed at higher elevations beneath the St. Johns River than in surrounding areas (Tibbals 1990). This phenomenon may be due to the lowering of hydraulic head caused by the discharges from springs located adjacent to or within the river. Thus, an anomalously high elevation of the onset of salt water in the area of Green Cove Springs is plausible. However, the extension of the body of salt water to the western boundary and to the western half of the southern boundary of the study area as shown on the

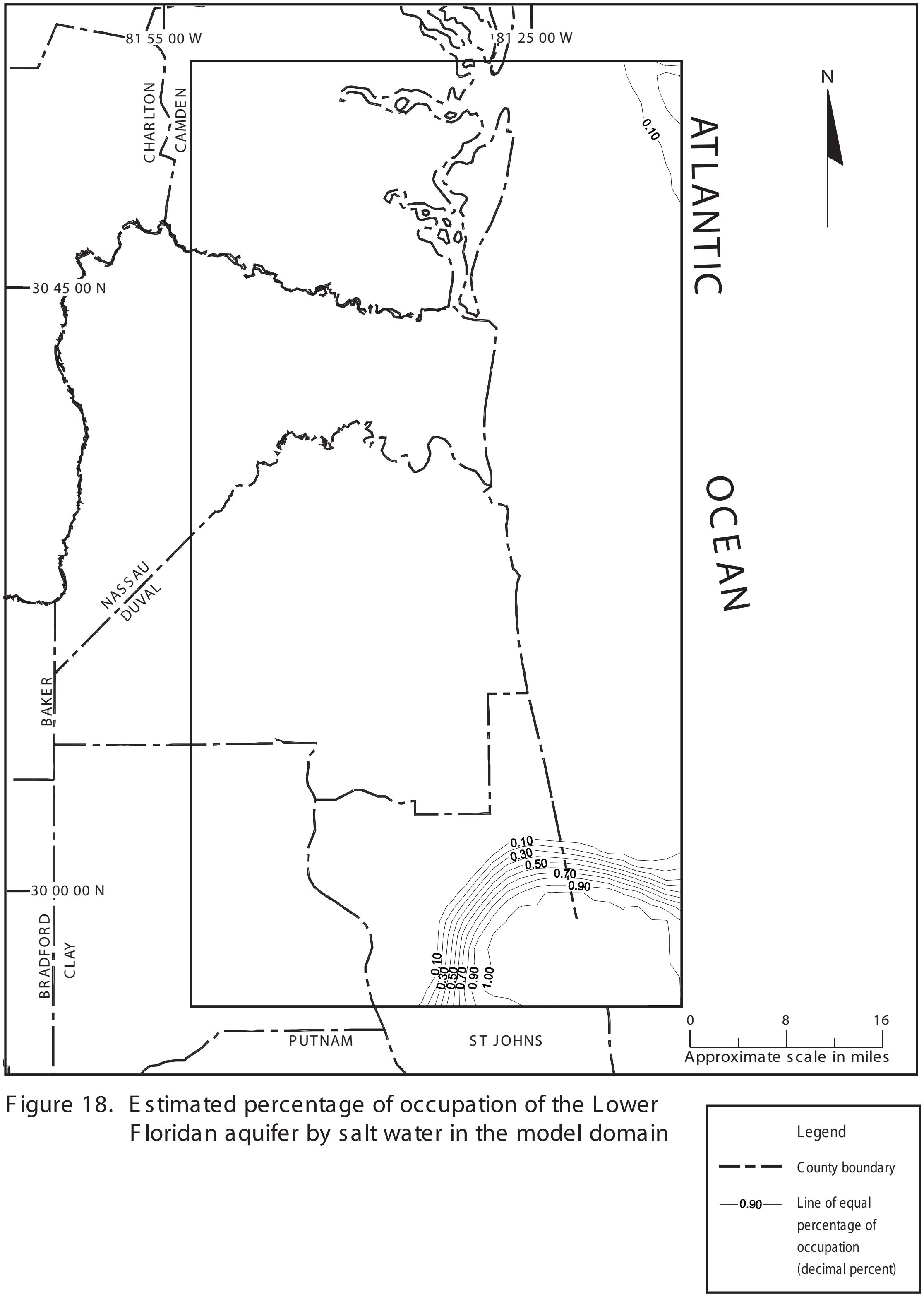


Figure 18. Estimated percentage of occupation of the Lower Floridan aquifer by salt water in the model domain

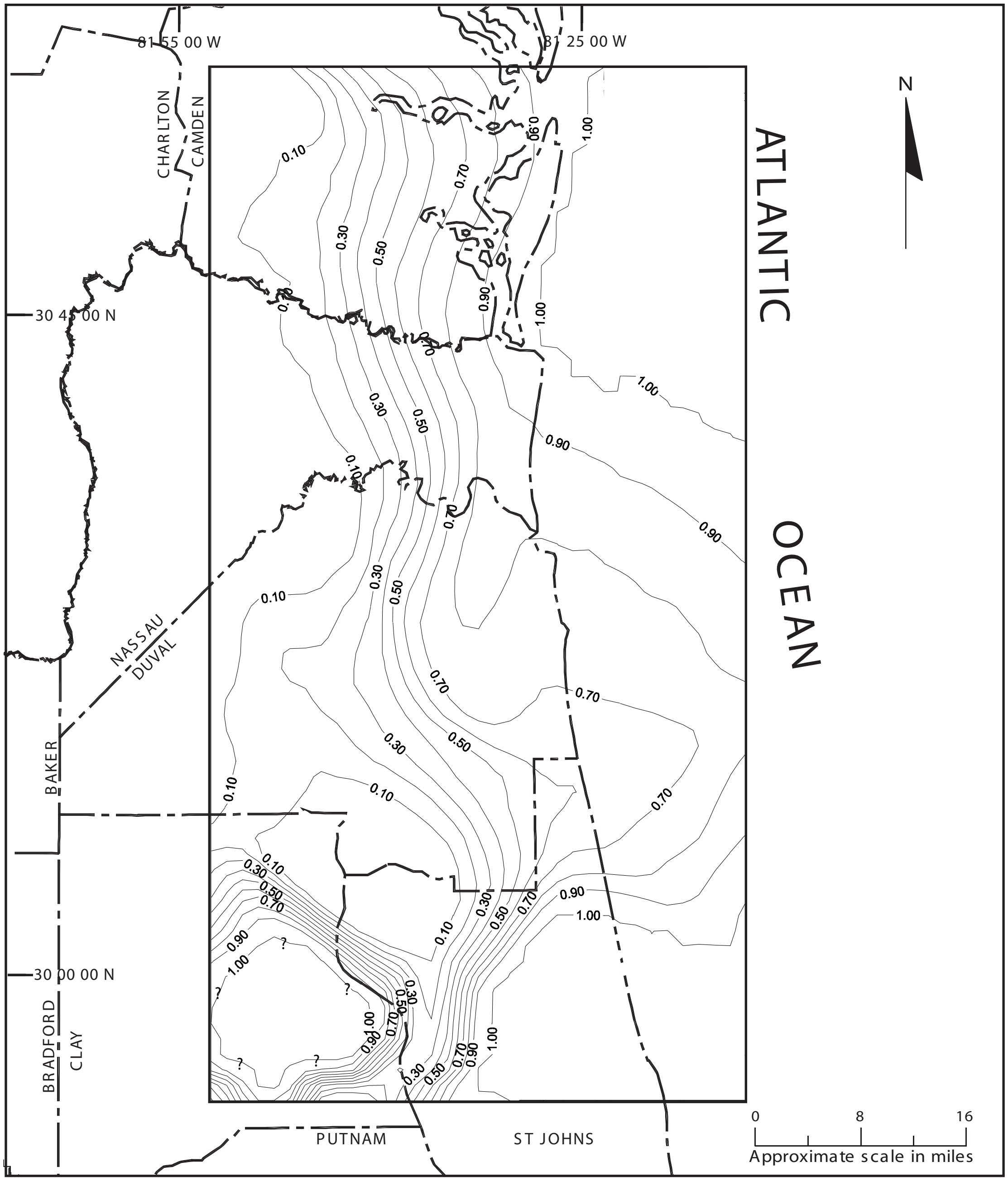


Figure 19. Estimated percentage of occupation of the Fernandina permeable zone by salt water in the model domain

Legend

County boundary

0.90 Line of equal percentage of occupation (decimal percent)

normalized saltwater onset map (Figure 19) is felt to be unlikely for the following reasons:

1. The southwest corner of the study area is an area of relatively high recharge of freshwater to the Floridan aquifer system (Boniol et al. 1993).
2. Salt water was not indicated to be present in the Fernandina permeable zone by TDEM measurements made at other near locations of comparable distance from the Atlantic coast (e.g., the Garden Street site discussed in Blackhawk Geosciences 1990).

Overestimation of the size of the area could be due to a combination of factors. One factor is the rather extreme variation from the mean of the single control point available for representation of the interface elevation in the area. This deviation might have resulted in the overestimation of the elevation of the onset of salt water. The overestimation may also be attributable to the inability of the computer algorithm to make a subjective determination of the reasonable limits of influence of the TDEM measurement made at Green Cove Springs. The relative thinness of the Fernandina permeable zone in the southwest portion of the study area is another possible factor because a given amount of error in the elevation of the onset of salt water represents a higher percentage of the total thickness of a thinner portion of the aquifer.

The location of the 0.1 contour line approximates the position of the interface toe in the Fernandina permeable zone of the study area. The location of the 0.9 contour line approximates the position of the interface tip. The toe of the interface within the Fernandina permeable zone of the study area runs primarily from north to south. The tip of the interface within the Fernandina permeable zone bounds areas of the Fernandina permeable zone that are occupied completely by salt water in the northeast and southeast corners of the study area (Figure 19).

In general, the interface slopes upwardly in the seaward direction, as expected. The saltwater onset map (Figure 16) and normalized saltwater onset maps (Figures 17–19) suggest the existence of areas beneath the continental shelf to the northeast and southeast of the study area in which the vertical extent of the Floridan aquifer system is occupied completely with salt water, with the area to the southeast extending inland more than the area to the northeast. Furthermore, the maps suggest that a broad tongue of freshwater within the Floridan aquifer system flows seawardly between these areas, extending perhaps as much as 50 miles to the east of Jacksonville Beach.

MODEL CODE AND CONFIGURATION

BRIEF DESCRIPTION OF SIMLAS

SIMLAS (Saltwater Intrusion Model for Layered Aquifer Systems) (Huyakorn et al. 1992) is a finite-element code that enables simulations of the interaction between freshwater and salt water in multi-aquifer groundwater flow systems. The transition zone between freshwater and salt water in SIMLAS is approximated as a sharp interface. Groundwater flow in SIMLAS is represented by three governing equations: the groundwater flow equation representing the freshwater zone of the flow system, the groundwater flow equation representing the saltwater zone of the flow system, and an equation derived by Hubbert (1940) that enables determination of the elevation of the interface as a function of fresh- and saltwater hydraulic heads and assigned density values (see appendix). These equations are solved simultaneously in the SIMLAS model for each time-step of simulation.

Fundamental assumptions incorporated into the SIMLAS code include the following (Huyakorn et al. 1992):

- Freshwater and salt water are immiscible fluids.
- Groundwater flow obeys Darcy's law.
- The densities and dynamic viscosities of the freshwater and salt water can be represented adequately by constant values.
- The direction of groundwater flow through aquifers is represented as being horizontal (i.e., the Dupuit assumption applies).
- The direction of groundwater flow through semiconfining units is represented as being vertical.
- The storage effects of semiconfining units are neglected.

Representation of aquifer material properties in SIMLAS requires specification of aquifer horizontal intrinsic permeability, volume compressibility, effective porosity, aquifer bottom elevation, and aquifer thickness. Representation of semiconfining-unit material properties requires specification of semiconfining-unit vertical leakage factor and semiconfining unit thickness (of uppermost semiconfining units only). Representation of fluid properties requires specification of fresh- and saltwater density and dynamic viscosity. Representation of wells requires specification of well location, screen length, bottom elevation, and mass flow rate (Huyakorn et al. 1992).

Lateral boundary conditions in the SIMLAS code are specified for both the fresh- and saltwater portions of the model domain. Available boundary-condition types include the no-flow boundary condition, the head-dependent flux boundary condition, the specified-head boundary condition, and the specified-flux boundary condition (Huyakorn et al. 1992).

MODEL CONFIGURATION

Three versions of the model were developed in the course of the study: a version representing conditions during the predevelopment period, a version representing conditions in 1985, and a version representing projected conditions in 2010. The essential configuration of all the versions is the same. Each consists of three confined aquifer layers, three semiconfining unit layers, an implied confining unit layer, and a source/sink surficial aquifer layer (Figure 20). In ascending order, the layers represent the lower confining unit (the confining unit layer), the Fernandina permeable zone (aquifer layer 1), the lower semiconfining unit (semiconfining unit layer 1), the Lower Floridan aquifer (aquifer layer 2), the middle semiconfining unit (semiconfining unit layer 2), the Upper Floridan aquifer (aquifer layer 3), the upper confining unit (semiconfining unit layer 3), and the surficial aquifer system (the source/sink layer). As the lowermost layer of the model, the confining-unit layer is not represented explicitly in the model input file. Rather, the vertical leakage factors of this layer are assumed within the SIMLAS code to be uniformly zero. The source/sink layer consists entirely of specified values of hydraulic head that represent estimated elevations of the water table of the surficial aquifer system, the level of the ocean, or some other body of surface water, such as the St. Johns River.

The model mesh consists of 2,278 elements and 2,380 (35×68) nodes per aquifer layer (Figure 21). The total number of elements and nodes is 6,834 and 7,140, respectively. The elements are rectangular and arranged in rows and columns. Element rows (68 rows) are oriented approximately from west to east, while element columns (35 columns) are oriented approximately from south to north. The nodes are located at the corners of the elements. Distances

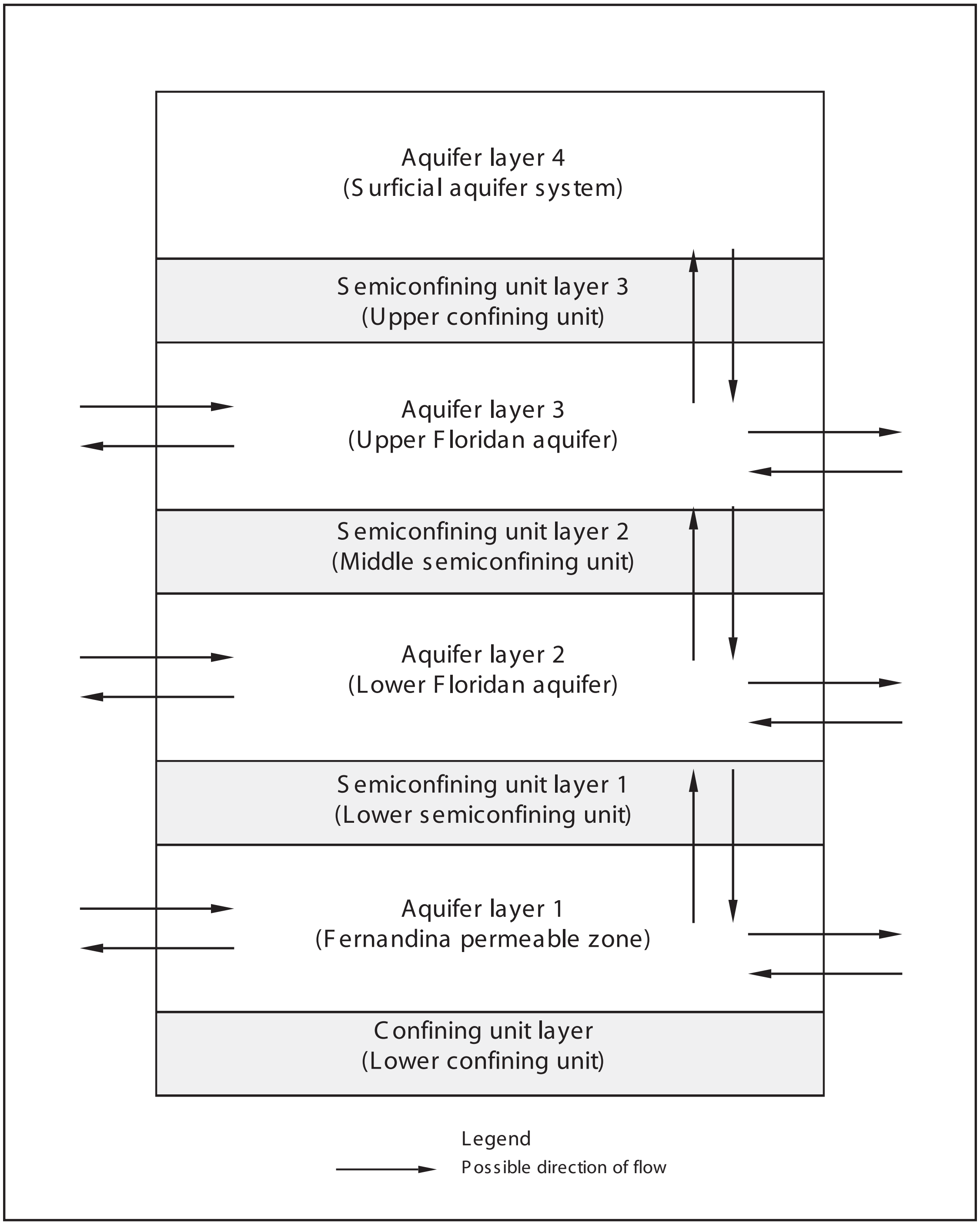


Figure 20. General configuration of the models of the study area

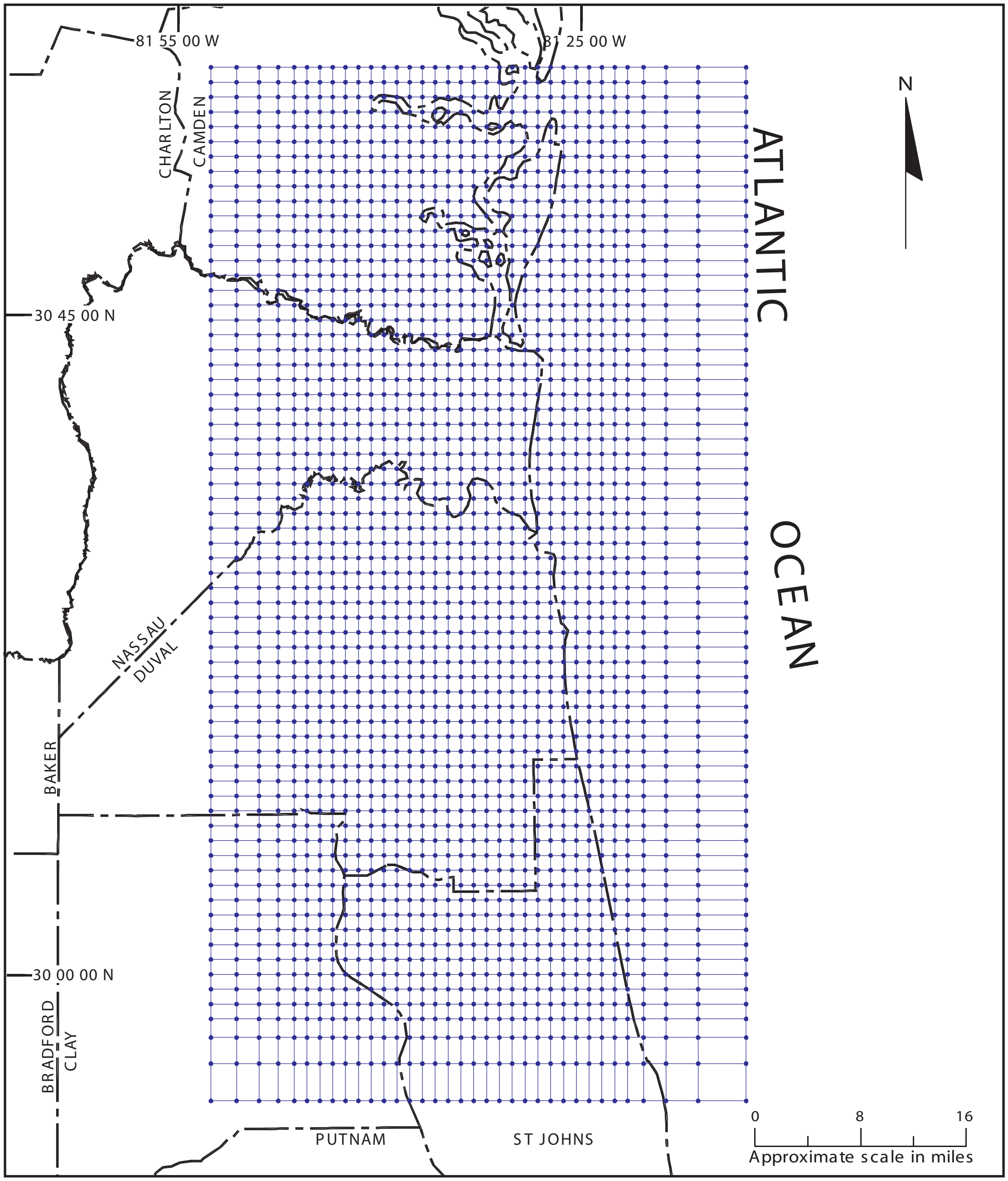
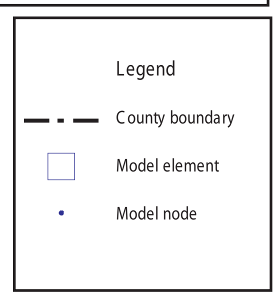


Figure 21. Finite-element SIMLAS model domain



between nodal rows range from approximately 6,060 ft to 15,200 ft, while distances between nodal columns range from approximately 5,220 ft to 19,600 ft. The nodes of the present model correspond in location to those of the MODFLOW groundwater flow model of Durden (1997), but they do not in every case represent the same areas, due to differences in the model code formulations.

The lateral boundary conditions of the model are specified as either head-dependent flux—referred to hereafter as GHFB (general head-dependent flux boundary) conditions—or no-flow boundary conditions. The lateral boundary conditions of the model were assigned only to the nodes of the outermost nodal rows and columns.

Hundreds of wells are represented in the model. Each well represented in the model was assigned a location that coincides with that of a nearby node. The nodal location to which each well was assigned in the present model is the same as that to which it was assigned in the MODFLOW model of Durden (1997). Many wells in the study area are open to both the Upper and Lower Floridan aquifers. Such wells were represented in the model as well pairs, with one of the pair assigned to aquifer layer 3 (the Upper Floridan aquifer) and the other assigned to aquifer layer 2 (the Lower Floridan aquifer). The distribution of the total discharge from such wells was proportioned between aquifer layers 2 and 3 based on the ratio of the respective assigned value of intrinsic permeability to the sum of the intrinsic permeabilities of both layers 2 and 3.

PREDEVELOPMENT VERSION OF THE MODEL

The predevelopment version of the model represents conditions in the Floridan aquifer system prior to aquifer development (i.e., the onset of groundwater withdrawals). The primary purpose of the predevelopment version of the model was to generate steady-state initial conditions for the 1985 version of the model. Steady-state initial conditions were needed to represent the starting point of postdevelopment conditions in the 1985 model simulations.

LATERAL BOUNDARY CONDITIONS

In the SIMLAS code, the groundwater flow in the fresh- and saltwater zones of an aquifer system is represented by fresh- and saltwater groundwater flow equations, respectively (see appendix). Therefore, two sets of lateral boundary conditions must be specified along the lateral boundaries of a SIMLAS model, one set for the freshwater flow equation and the other for the saltwater flow equation (Huyakorn et al. 1992).

Freshwater Lateral Boundary Conditions

The procedure for specifying freshwater lateral boundary conditions in the predevelopment version of the model was essentially the same as that used in the predevelopment and revised predevelopment versions of the MODFLOW model of Durden (1997) (Figures 22 and 23). As with the MODFLOW model, the specification of freshwater lateral boundary conditions was based primarily on the direction of groundwater flow relative to the orientation of the model lateral boundaries. The direction of groundwater flow in the freshwater portion of the Upper Floridan aquifer was inferred according to the orientation of lines of equal hydraulic head shown on a map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 24). The direction of groundwater flow in the freshwater portion of the Lower Floridan aquifer at a given location was assumed to be generally the same as in the Upper Floridan aquifer at the same location. The direction of groundwater flow in the freshwater portion of the Fernandina permeable zone was assumed to be generally eastward.

In cases in which the direction of groundwater flow was determined to be perpendicular to a lateral boundary of the model, GHFB conditions were specified. In cases in which the direction of groundwater flow was

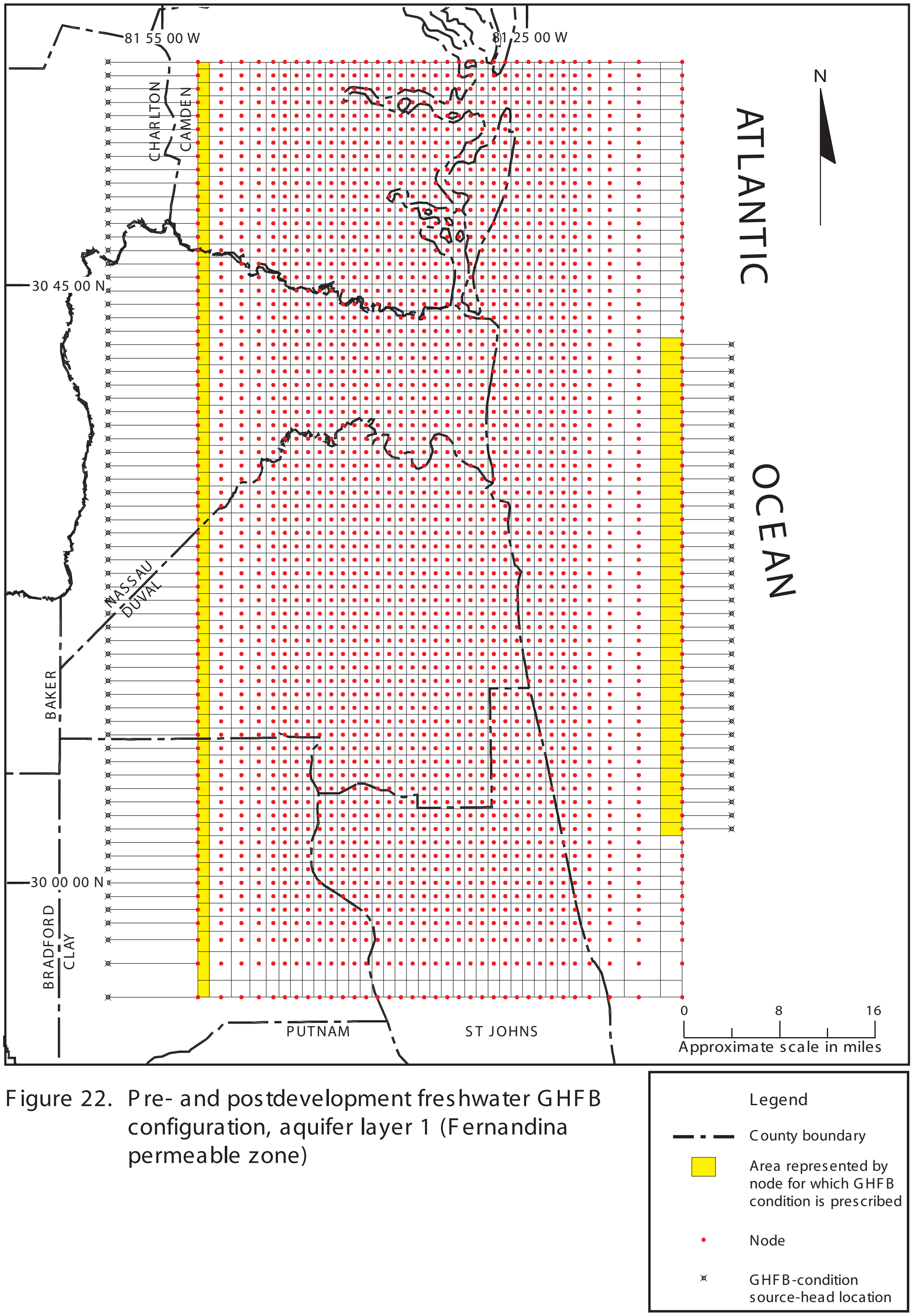


Figure 22. Pre- and postdevelopment freshwater GHFB configuration, aquifer layer 1 (Fernandina permeable zone)

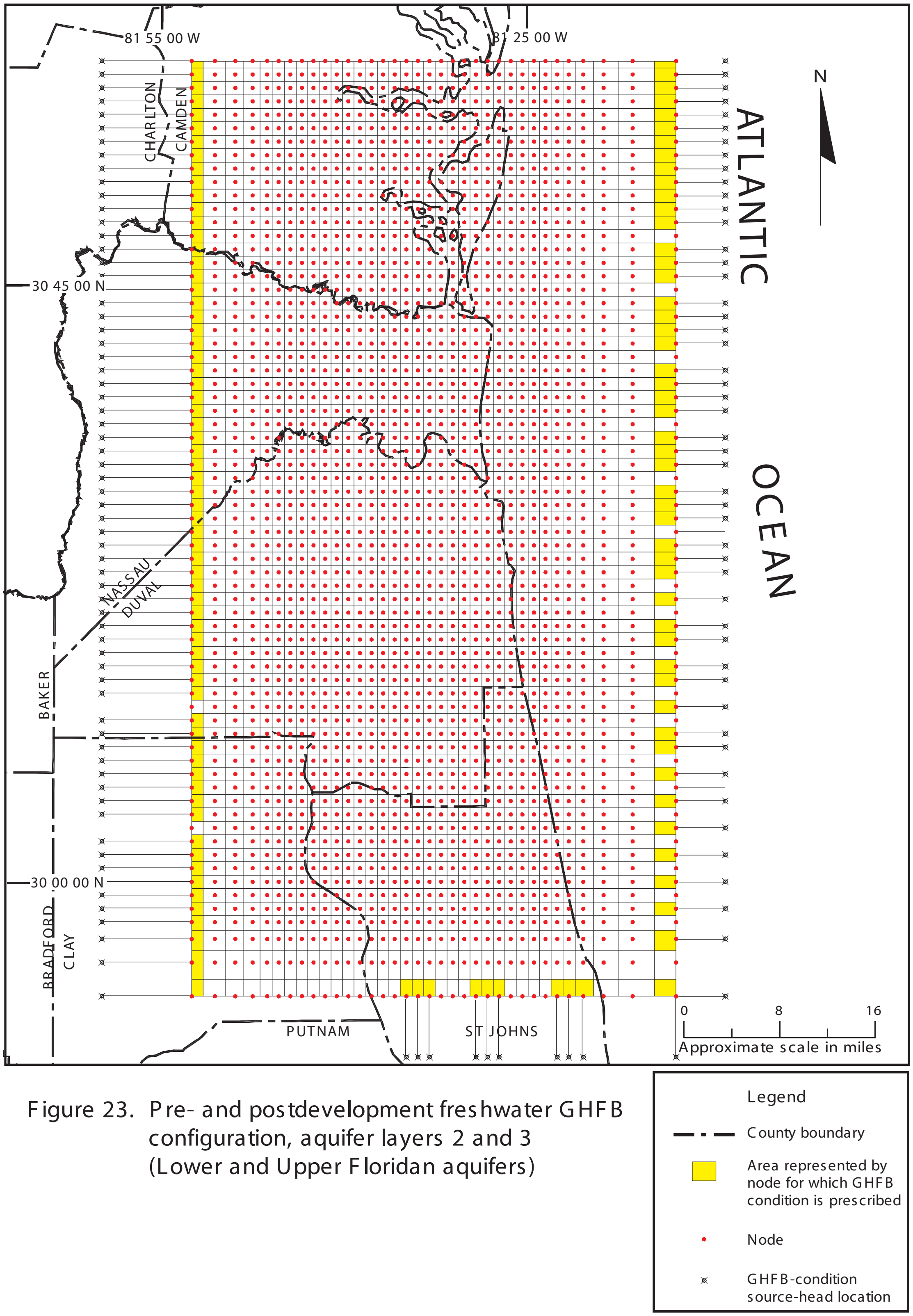


Figure 23. Pre- and postdevelopment freshwater GHFB configuration, aquifer layers 2 and 3 (Lower and Upper Floridan aquifers)

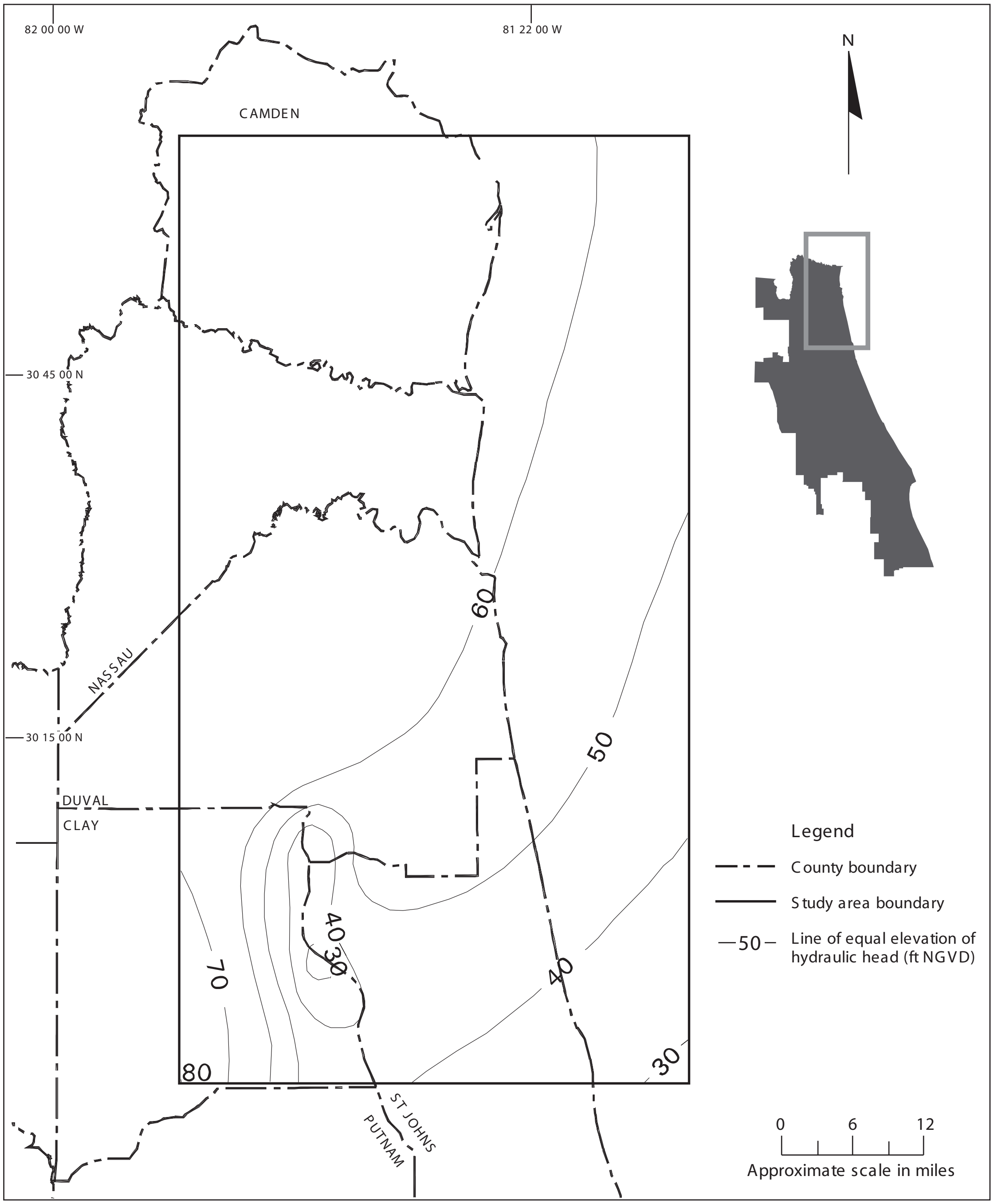


Figure 24. Estimated predevelopment potentiometric surface of the Upper Floridan aquifer (modified from Johnston, Krause et al.1980)

determined to be parallel to a lateral boundary of the model, no-flow boundary conditions were specified. In cases in which the direction of groundwater flow was determined to be neither predominantly parallel nor perpendicular to a lateral boundary of the model, a combination of GHFB and no-flow boundary conditions was specified to represent, in approximate fashion, both the parallel and perpendicular components of the groundwater flow. No-flow boundary conditions were also specified for nodes of aquifer layers corresponding to locations where salt water was present according to the normalized-interface maps (Figures 17–19).

The specification of a GHFB condition for a given node requires the specification of a source head at some distance from the node. The distance between the node and the GHFB-condition source head, however, is not specified explicitly in either the SIMLAS or MODFLOW codes. This distance is implied in the specification of the GHFB-condition source head and in the calculation of the GHFB-condition conductance (McDonald and Harbaugh 1988; Huyakorn et al. 1992).

In the present model, the same distance was specified for all the nodes of a given lateral boundary of an aquifer layer, just as in the MODFLOW model of Durden (1997). Along the eastern and southern boundaries of all three aquifer layers, the specified distances are 4.2 and 5.2 miles, respectively. Along the western boundary of aquifer layers 2 and 3, the specified distance is 5.4 miles, and along the western boundary of aquifer layer 1, the specified distance is 7.6 miles (Figures 22 and 23).

The values of the GHFB-condition source heads assigned to the Upper Floridan aquifer (aquifer layer 3) were interpolated from the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 24). The values of the GHFB-condition source heads assigned to the aquifer layers representing the Lower Floridan aquifer and the Fernandina permeable zone (aquifer layers 2 and 1) were determined based on assumed differences in hydraulic head between the Upper and Lower Floridan aquifers and the Fernandina permeable zone and an assumed direction of the vertical hydraulic gradient.

The difference in hydraulic head was assumed to be 1 ft between the Upper Floridan aquifer and the Lower Floridan aquifer and 2 ft between the Upper Floridan aquifer and the Fernandina permeable zone. The direction of the vertical hydraulic gradient between the Upper and Lower Floridan aquifers and the Fernandina permeable zone was assumed to be the same as that between the Upper Floridan aquifer and the surficial aquifer system. The direction of the vertical hydraulic gradient between the Upper Floridan aquifer and the surficial aquifer system was determined based on estimated water levels in the Upper Floridan aquifer and the surficial aquifer system.

For cases in which the vertical hydraulic gradient was determined to be upward, the source-head values of the Lower Floridan aquifer were determined by adding the 1-ft difference in hydraulic head to the corresponding estimates of the hydraulic head in the Upper Floridan aquifer. For cases in which the vertical hydraulic gradient was downward, the source-head values of the Lower Floridan aquifer were determined by subtracting the assumed 1-ft difference in hydraulic head. Source-head values of the Fernandina permeable zone were determined in the same fashion using the assumed 2-ft difference in hydraulic head between the Upper Floridan aquifer and the Fernandina permeable zone.

Saltwater Lateral Boundary Conditions

General Description. The specification of saltwater lateral boundary conditions was based on the assumed direction of groundwater flow within the saltwater zone of the Floridan aquifer system and on the configuration of the saltwater zone according to the normalized saltwater onset maps (Figures 17–19). The direction of groundwater flow in the saltwater zone of the Floridan aquifer system was assumed to be generally opposite to that of the freshwater zone, in accordance with the generalized conceptualization of coastal aquifer systems as described in Cooper et al. (1964) and Bear (1979) and depicted in Figure 9.

GHFB conditions were specified for boundary nodes in cases in which the direction of groundwater flow was assumed to be perpendicular to a model lateral boundary. Along a given lateral boundary, the distance specified between boundary nodes and corresponding GHFB-condition source heads was the same as for freshwater GHFB conditions along the same lateral boundary. Along the eastern lateral boundary of all three aquifer layers, this distance is 4.2 miles, and along the southern lateral boundary, it is 5.2 miles (Figures 25–27).

Values of the GHFB-condition source heads were determined by one of two methods, depending on whether salt water alone or both freshwater and salt water were believed to occupy the portion of an aquifer volume represented by a given boundary node. In cases in which salt water alone was believed to

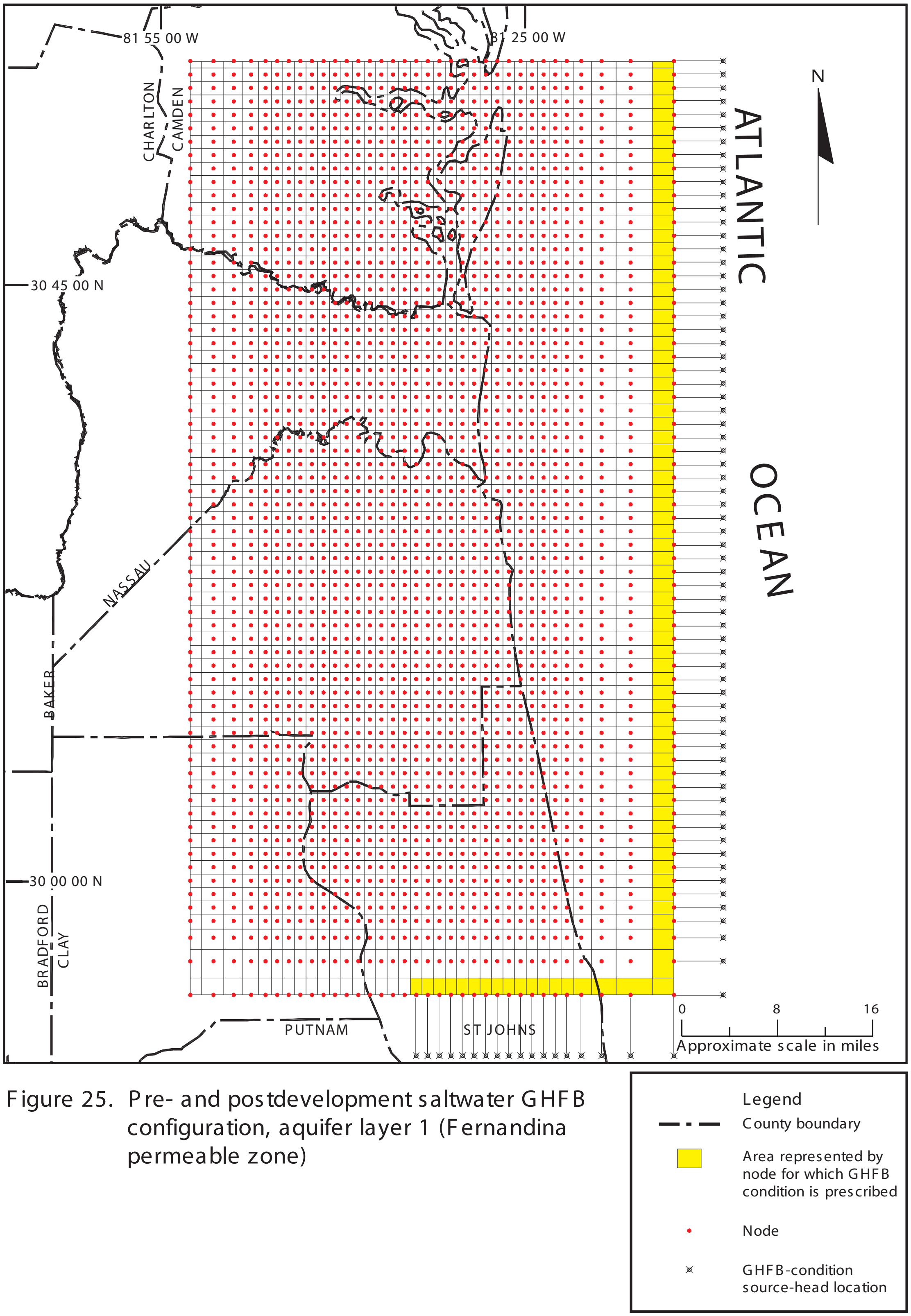


Figure 25. Pre- and postdevelopment saltwater GHFB configuration, aquifer layer 1 (Fernandina permeable zone)

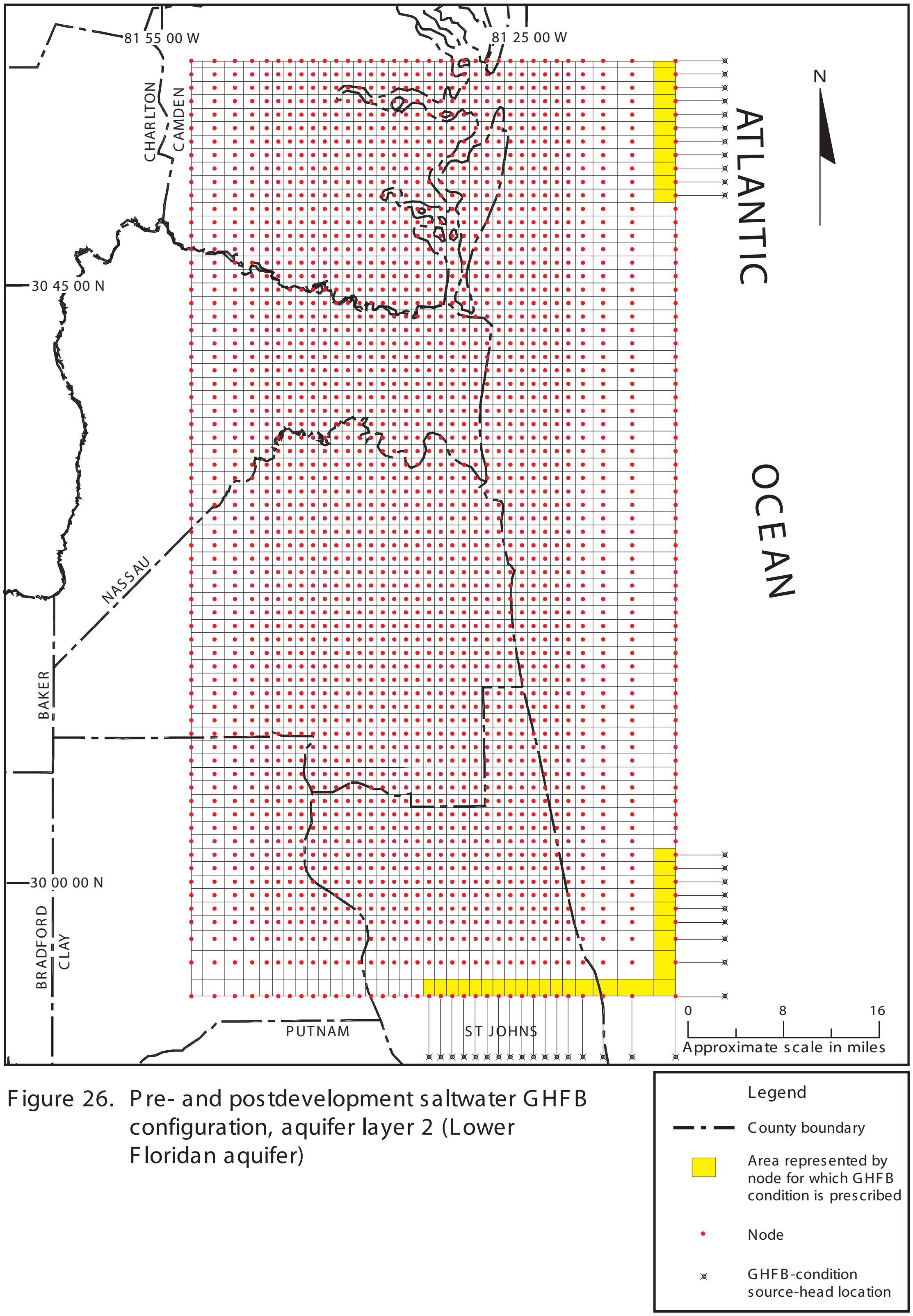


Figure 26. Pre- and postdevelopment saltwater GHFB configuration, aquifer layer 2 (Lower Floridan aquifer)

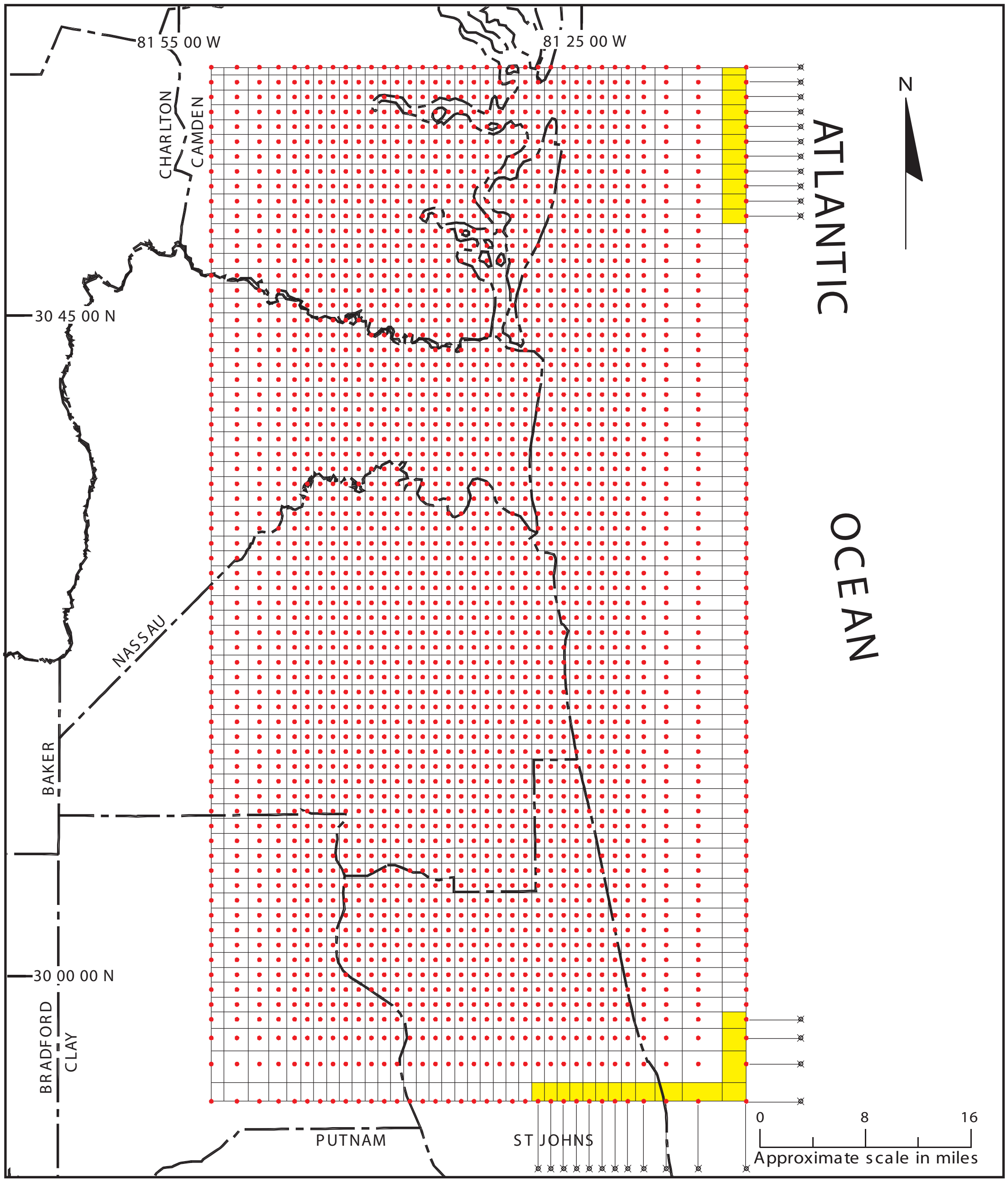


Figure 27. Pre- and postdevelopment saltwater GHFB configuration, aquifer layer 3 (Upper Floridan aquifer)

occupy the volume, the GHFB-condition source heads were assumed to be 0 ft NGVD. The assumption of the saltwater hydraulic head was necessary in these cases because observations of hydraulic head in the saltwater zone of the Floridan aquifer system of the area are not available. The value of 0 ft NGVD was chosen as the upper bound of possible values based on the assumption that the saltwater zone is connected hydraulically to the ocean, the hydraulic head of which is 0 ft NGVD. The actual values of saltwater hydraulic head are less than 0 ft NGVD due to friction losses incurred as the water moves from the seaward outcrop of the Floridan aquifer system towards the transition zone.

In cases in which both freshwater and salt water were believed to occupy the volume, the saltwater hydraulic head was estimated using the Hubbert (1940) equation (see appendix). The Hubbert equation enables determination of the saltwater hydraulic head at the interface as a function of the estimated freshwater hydraulic head at the interface, the elevation of the interface, and the densities of the freshwater and salt water.

In many cases, the Hubbert (1940) equation yielded estimates of saltwater hydraulic head in excess of 0 ft NGVD. The overestimation of the saltwater hydraulic head in these cases is attributable to inaccuracies in estimates of the freshwater hydraulic head, the interface elevation, or both. No-flow boundary conditions were assigned to boundary nodes in cases in which the direction of groundwater flow was assumed to be parallel to a model lateral boundary. No-flow boundary conditions were specified also for nodes corresponding to portions of model boundaries where freshwater is present.

Specific Description. Inspection of the normalized saltwater onset maps suggests that salt water occupies a large portion of the Floridan aquifer system in the southeast corner of the study area (Figures 17–19). This body of salt water extends farther inland to the south of the study area, as indicated by analyses of water samples and by TDEM readings (Sprinkle 1989; Blackhawk Geosciences 1990; CEES-Blackhawk Geosciences Division 1992). Based on the inferred southeastward direction of groundwater flow in the freshwater zone of the Upper Floridan aquifer in this area, north-south components of groundwater flow in the saltwater zone of the Floridan aquifer system were deemed to be likely in this area. Accordingly, GHFB conditions were specified for nodes along the eastern portions of the southern lateral boundaries of all three aquifer layers.

Salt water is present along the entire length of the eastern boundary of the study area in the Fernandina permeable zone and along portions of the eastern lateral boundary in the Upper and Lower Floridan aquifers (Figures 17–19). The direction of groundwater flow in the saltwater zone of the Floridan aquifer system along the eastern boundary was assumed to be westward to northwestward, since the direction of groundwater flow in the freshwater zone of the Upper Floridan aquifer was inferred as eastward to southeastward. Accordingly, saltwater GHFB conditions were specified along the entire length of the eastern lateral boundary of aquifer layer 1 and along portions of the eastern lateral boundaries of aquifer layers 2 and 3.

Along the northern boundary of the study area, the direction of groundwater flow in the saltwater zone of the Floridan aquifer system was assumed to be generally westward, since the direction of groundwater flow in the freshwater zone of the Floridan aquifer system was inferred as generally eastward. Accordingly, no-flow boundary conditions were specified for nodes along the northern lateral boundaries of aquifer layers 1 and 2, despite the presence of salt water according to the normalized saltwater onset maps of the Lower Floridan aquifer and the Fernandina permeable zone.

Because the presence of salt water in the Fernandina permeable zone along the western boundary of the study area was deemed unlikely, even in areas where it is present according to the normalized saltwater onset map (Figure 19), no-flow boundary conditions were specified for all nodes along the western lateral boundary of aquifer layer 1. Likewise, no-flow boundary conditions were specified for nodes along the western portion of the southern lateral boundary of aquifer layer 1. No-flow boundary conditions were specified due to the absence of salt water for nodes along portions of other lateral boundaries as well. Included were nodes along the westernmost portion of the northern lateral boundary of aquifer layer 1, nodes along the northern and western lateral boundaries of aquifer layers 2 and 3, and nodes along portions of the eastern lateral boundaries of aquifer layers 2 and 3.

REQUIRED INPUT DATA

Water Table and Surface Water Elevations

Elevations of the water table of the surficial aquifer system are specified as constant values of hydraulic head in the source / sink layer (aquifer layer 4). Elevations of the surfaces of surface water bodies, such as the Atlantic Ocean and the St. Johns River, are specified as constant values of hydraulic head in the source/sink layer also. The hydraulic head gradients between the source/sink layer with the Upper Floridan aquifer (layer 3) and the leakance of the upper confining layer were used to calculate the steady-state rates of leakage across the upper confining unit.

Estimates of the elevation of the water table were determined according to the linear correlation between the elevation of the water table and the land surface within the study area derived by Durden (1997). In most cases, the estimate of the water table or the surface water elevation assigned to a given node is identical to the value assigned to the corresponding node in the MODFLOW model of Durden (1997).

The hydraulic-head values assigned to the nodes of the source/sink layer were specified as either fresh or salty, in accordance with the requirements of the SIMLAS code (Huyakorn et al. 1992). Hydraulic-head values assigned to nodes that correspond in location to the surficial aquifer system or to generally fresh surface water bodies, such as the St. Johns River, were specified as fresh. Hydraulic-head values assigned to nodes that correspond in location to generally salty surface water bodies, such as the Atlantic Ocean, were specified as salty.

For nodes that correspond in location to the Atlantic Ocean, a hydraulic-head value of 0 ft NGVD was assigned. For nodes that correspond in location to the St. Johns River, hydraulic-head values slightly in excess of sea level, usually less than or equal to 1 ft NGVD, were assigned. For nodes that correspond in location to smaller surface water bodies, such as the numerous meandering streams in the coastal areas of Duval, Nassau, and Camden counties, hydraulic-head values that were estimated based on nearby land-surface elevations were assigned. Land-surface elevations were estimated using U.S. Geological Survey 1:24,000-scale and 1:100,000-scale topographic maps.

Freshwater and Saltwater Density

The density of water in the Floridan aquifer system was estimated in accordance with its approximate temperature and salinity. The average temperature of water in the Floridan aquifer system of the study area was estimated to be 80°F (based on Brown 1980 and Brown et al. 1986). The density of freshwater at 80°F is approximately 1.934 slug ft^{-3} (Fischer et al. 1979). The density of the salt water was assumed to be the same as that of seawater at a temperature of 80°F and a salinity of 35,000 parts per million.

The density of seawater at this temperature and salinity is approximately 1.985 slug ft^{-3} (Fischer et al. 1979).

Dynamic Viscosity

The dynamic viscosity of freshwater at 80°F is approximately 1.56 slug ft^{-1} day^{-1} (Streeter and Wylie 1985). The dynamic viscosity of salt water was assumed to be the same as that of freshwater (based on Roberson and Crowe 1975).

Effective Porosity

Porosity tends to vary widely within the Floridan aquifer system, and estimates of effective porosity are generally not available. Therefore, an average effective porosity of 0.25 was assumed, based on the results of porosity tests performed on core samples obtained from the Floridan aquifer system (Navoy 1986; Toth 1985). This value was assigned uniformly to all nodes of the model.

Volume Compressibility

The volume compressibility of the Floridan aquifer system was estimated based on its relationship to the storage coefficient, freshwater density, porosity, and bulk compressibility of water, as stated in the following equation (Freeze and Cherry 1979):

$$\alpha = S_f \left(\rho_f g\right)^{-1} - \theta\beta_w \qquad \textbf{(1)}$$

where

α = the volume compressibility $[LT^2M^{-1}]$
S_f = the storage coefficient $[L^{-1}]$
ρ_f = the density of freshwater $[ML^{-3}]$
g = the acceleration due to gravity $[LT^{-2}]$
θ = the porosity
β_w = the bulk compressibility of water $[LT^2M^{-1}]$

The storage coefficient was estimated to be 1.0 x 10^{-6} ft^{-1} based on the results of aquifer pump tests conducted in the area of Fernandina Beach (Brown 1984). The resulting estimate of α was 0.145 x 10^{-17} ft-day^2 $slug^{-1}$. This value was assigned uniformly to all nodes of the model.

Horizontal Intrinsic Permeability

Initial estimates of horizontal intrinsic permeability were based primarily on estimates of transmissivity obtained from the postdevelopment version of the MODFLOW model of Durden (1997). Other data used in estimating the horizontal intrinsic permeability included estimates of the top and bottom elevations of the Upper and Lower Floridan aquifers and the Fernandina permeable zone obtained from Miller (1986 and pers. com. 1991); estimates of the interface elevation were obtained from the map of the interface developed as part of the present study (Figure 16) and estimates of the dynamic viscosity and density of the groundwater in the fresh- and saltwater portions of the Floridan aquifer system. The transmissivity estimates obtained from the MODFLOW model were assumed to represent the freshwater zone of the Floridan aquifer system only, because MODFLOW is not designed to represent dual-phase or density-dependent groundwater flow (McDonald and Harbaugh 1988). Using the transmissivity estimates, the horizontal intrinsic permeability was calculated as

$$k = T\mu\left(\rho_f g b_f\right)^{-1} \tag{2}$$

where

k = the horizontal intrinsic permeability [L^2]
T = the transmissivity [L^2T^{-1}]
μ = the dynamic viscosity of water [$ML^{-1}\,T^{-1}$]
ρ_f = the density of freshwater [ML^{-3}]
g = the acceleration due to gravity [LT^{-2}]
b_f = the thickness of the freshwater flow system within an aquifer [L]

For the parts of the model domain where the estimated location of the interface toe exists within an aquifer, the thickness of the freshwater flow system, b_f, was calculated as the difference in the estimated elevation of the top of the aquifer and that of the interface. For the parts of the model domain where the estimated location of the interface toe is not present, the thickness of the freshwater flow system, b_f, was calculated as the difference in the estimated elevations of the top and bottom of the aquifer.

To obtain transmissivity estimates for the saltwater portion of the Floridan aquifer system, transmissivity estimates from the model of Durden (1997) were extrapolated to areas that are seaward of the interface tip (Figures 17–19). Using these estimates of transmissivity, the horizontal intrinsic permeability was calculated as

$$k_s = T\mu\left(\rho_s g b_s\right)^{-1} \tag{3}$$

where

- k_s = the horizontal intrinsic permeability [L^2]
- T = the transmissivity [L^2T^{-1}]
- μ = the dynamic viscosity of water [$ML^{-1}T^{-1}$)]
- ρ_s = the density of seawater [ML^{-3}]
- g = the acceleration due to gravity [LT^{-2}]
- b_s = the thickness of the saltwater flow system within an aquifer [L]

The thickness of the saltwater flow system, b_s, was calculated as the difference in estimated elevations of the top and bottom of the aquifer. This approach yielded estimates of horizontal intrinsic permeability that were in many cases 1 to 2 orders of magnitude lower than values calculated for near nodes using Equation 2. This abrupt change in horizontal intrinsic permeability is due to the fact that the extrapolated transmissivity values were not adjusted for the relatively large differences in values of b_f and b_s that exist near the tip of the interface. In the model calibration, the horizontal intrinsic permeability values of this part of the model domain were adjusted for greater consistency with the values that were calculated using Equation 2.

Vertical Leakage Factor

The vertical leakage factor is defined as the ratio of the vertical intrinsic permeability of a semiconfining unit to its thickness (Huyakorn et al. 1992). The vertical leakage factors of semiconfining-unit layers 1, 2, and 3 (Figure 20) were estimated initially based on the estimated leakance values of the lower semiconfining unit, middle semiconfining unit, and upper confining unit, respectively, of the MODFLOW model of Durden (1997). Using the leakance estimates from the MODFLOW model, the vertical leakage factors were calculated as

$$k'/b' = \lambda\mu\left(\rho_f g\right)^{-1} \tag{4}$$

where

- k' = the vertical intrinsic permeability [L^2]
- b' = the thickness of the semiconfining unit [L]
- λ = the leakance of the semiconfining unit [T^{-1}]
- μ = the dynamic viscosity of water [$ML^{-1}T^{-1}$]
- ρ_f = the density of freshwater [ML^{-3}]
- g = the acceleration due to gravity [LT^{-2}]

MODEL CALIBRATION

Ultimately, the calibration of the predevelopment version of the model was conducted in concert with that of the 1985 version of the model. To start the process, however, the predevelopment version of the model was at first calibrated independently to an acceptable level of agreement with available estimates of predevelopment hydraulic head and interface elevation. The resulting estimates of aquifer intrinsic permeability and semiconfining-unit vertical leakage factor were looked upon as interim values, however. These values were then transferred to the 1985 version of the model, and the calibration process was continued, with the two versions of the model being calibrated simultaneously from that point on.

The predevelopment version of the model was needed to simulate the steady-state initial conditions used in the runs of the 1985 version of the model. In effect, the predevelopment and 1985 versions of the model were linked as a result of this requirement. Thus, adequate simulation of both predevelopment and 1985 conditions using identical estimates of aquifer intrinsic permeability and the semiconfining-unit vertical leakage factor was a necessity in the present study. The estimates of hydraulic head and interface elevation used in the calibration of the predevelopment version of the model and the ability of the predevelopment version of the model to simulate the estimates are discussed in the present chapter. A similar discussion with respect to the 1985 version of the model may be found in the next chapter of this report.

Comparison of Estimated and Simulated Hydraulic-Head and Interface-Elevation Values

The model was calibrated partly by comparing values of hydraulic head that were estimated from the map of the predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980) (Figure 24) to values simulated at model nodes. The residual of hydraulic head, defined as the difference in the estimated and simulated values of hydraulic head at the location of a given model node, was determined for each node of the Upper Floridan aquifer (layer 3).

As a quantitative measure of the level of agreement between the estimated and simulated values of hydraulic head, the following items related to estimated and simulated head residuals were determined: the mean, standard deviation, and mean of the absolute values of the residuals, and the percentage of the residuals less than or equal to 5 ft. The final mean of the residuals was -1.1 ft. The final standard deviation of the residuals was 2.2 ft. The final mean of the absolute values of the residuals was 2.0 ft. The final percentage of the residuals less than or equal to 5 ft was 94.3.

As a qualitative measure of the level of agreement, maps of the estimated and simulated predevelopment potentiometric surface of the Upper Floridan aquifer maps are presented in Figures 28a and 28b. In addition, a map of the residuals of hydraulic head was created to illustrate the spatial distribution of the residuals (Figure 29).

The model was calibrated also by comparing visually the normalized-interface maps of the Upper and Lower Floridan aquifers and Fernandina permeable zone (Figures 30a, 31a, and 32a) to corresponding maps that were based on the simulated elevations of the interface (Figures 30b, 31b, and 32b). The general features of the estimated interface were simulated successfully, as inspection of the referenced figures makes apparent. Because the interface map (Figure 16) was based primarily on data collected over the past 30 years or so, an implicit assumption in the calibration of the predevelopment version of the model was that the interface did not move substantially between the end of the predevelopment period and 1985, a time span of approximately 100 years.

Resultant Hydraulic Parameters

Horizontal Intrinsic Permeability. The final range of horizontal intrinsic permeability in the Upper Floridan aquifer was 9.71×10^{-12} to 2.28×10^{-8} ft^2 (Figure 33). The final range of horizontal intrinsic permeability in the Lower Floridan aquifer was 2.77×10^{-11} to 7.43×10^{-9} ft^2 (Figure 34). The final range of horizontal intrinsic permeability in the Fernandina permeable zone was 2.54×10^{-12} to 8.46×10^{-10} ft^2 (Figure 35).

Vertical Leakage Factor. The final range of the vertical leakage factor in the upper confining unit was 1.68×10^{-19} to 6.72×10^{-15} ft. The final range of the vertical leakage factor in the middle semiconfining unit was 3.36×10^{-22} to 1.68×10^{-13} ft. The final range of the vertical leakage factor in the lower semiconfining unit was 1.45×10^{-17} to 3.23×10^{-16} ft.

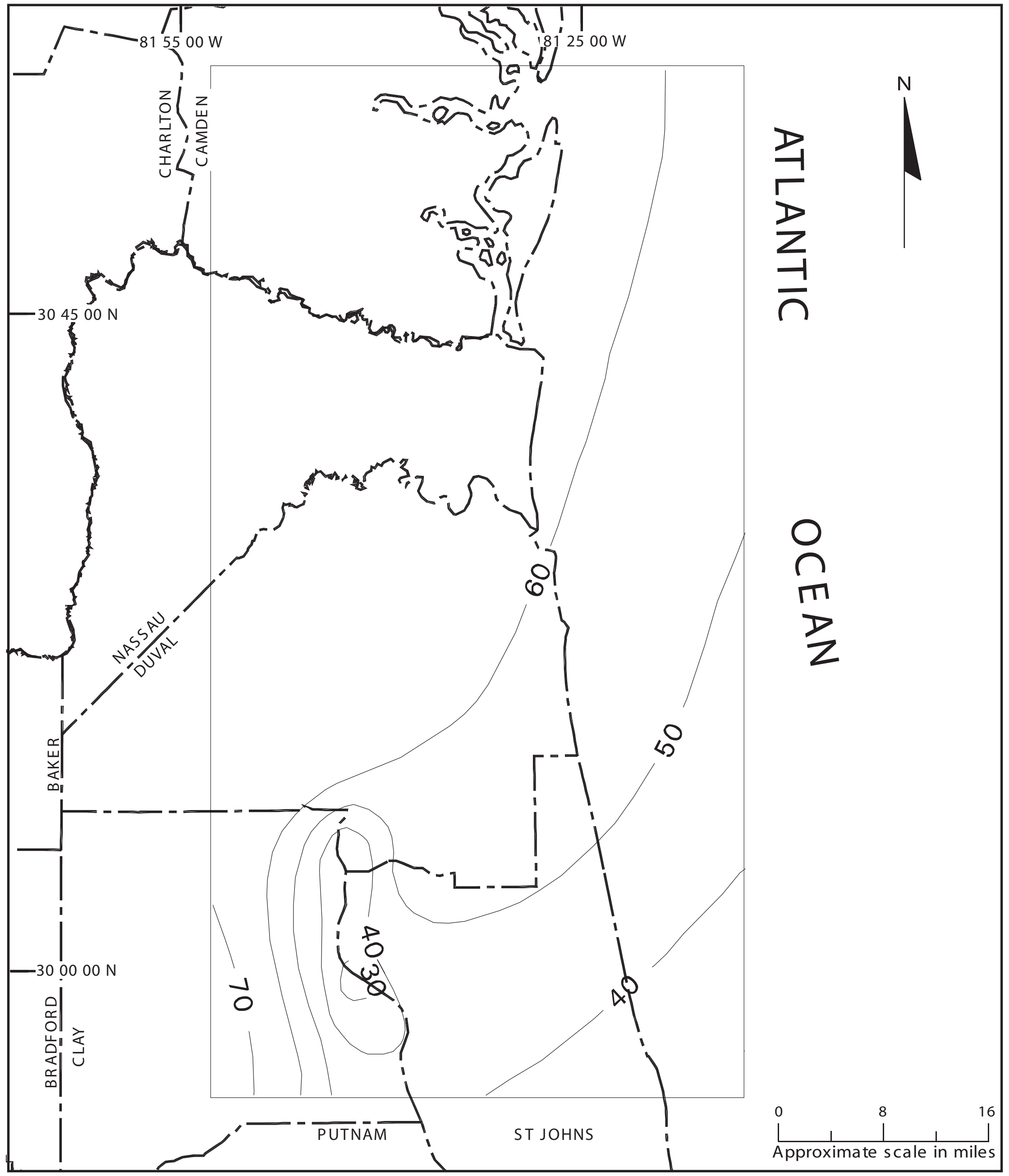


Figure 28a. Estimated predevelopment potentiometric surface of the Upper Floridan aquifer (Johnston, Krause et al. 1980)

Legend

County boundary

50 Line of equal elevation of hydraulic head (ft NGVD)

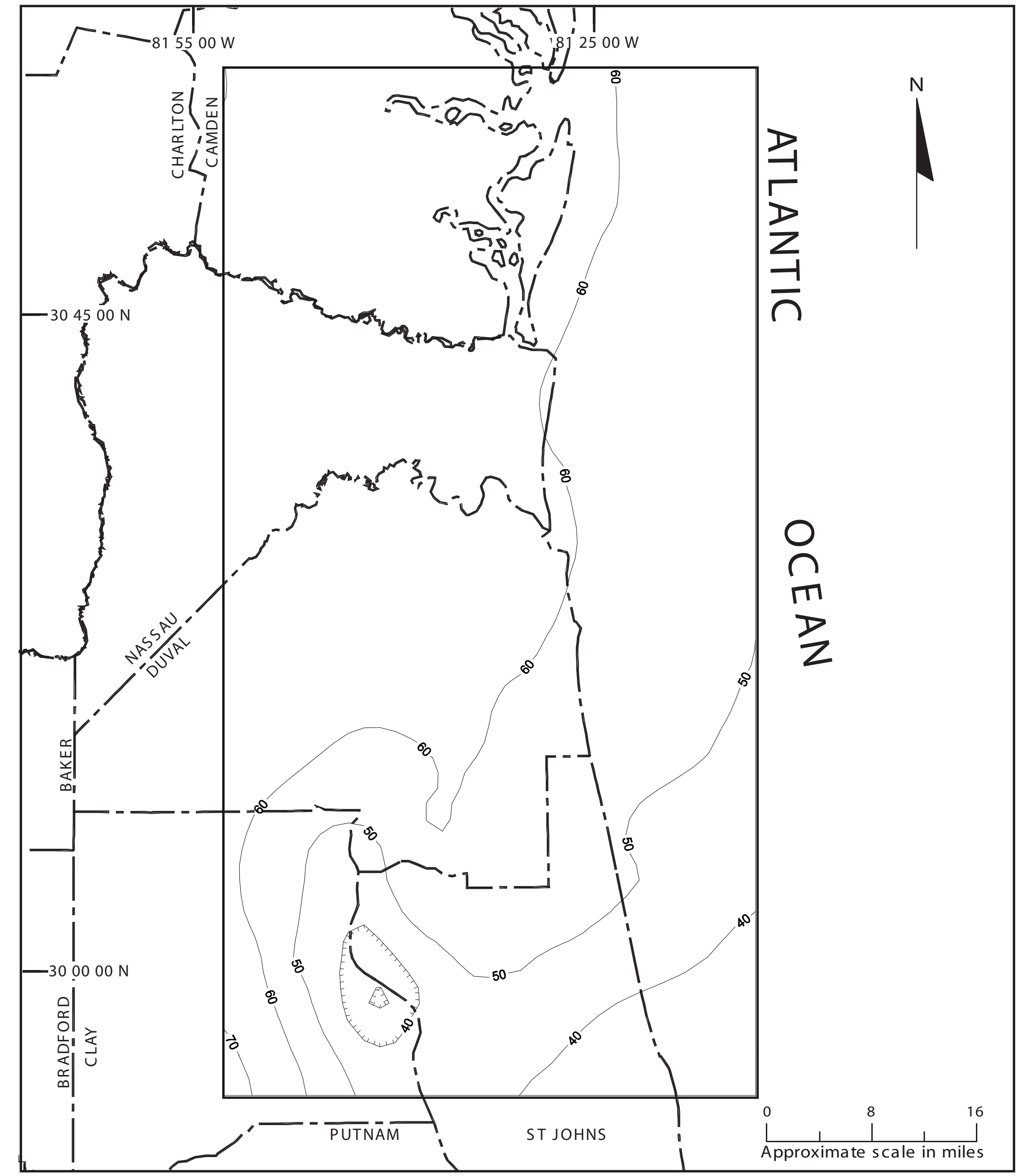


Figure 28b. Simulated predevelopment potentiometric surface of the Upper Floridan aquifer

Legend

County boundary

0.90 Line of equal elevation of hydraulic head (ft NGVD)

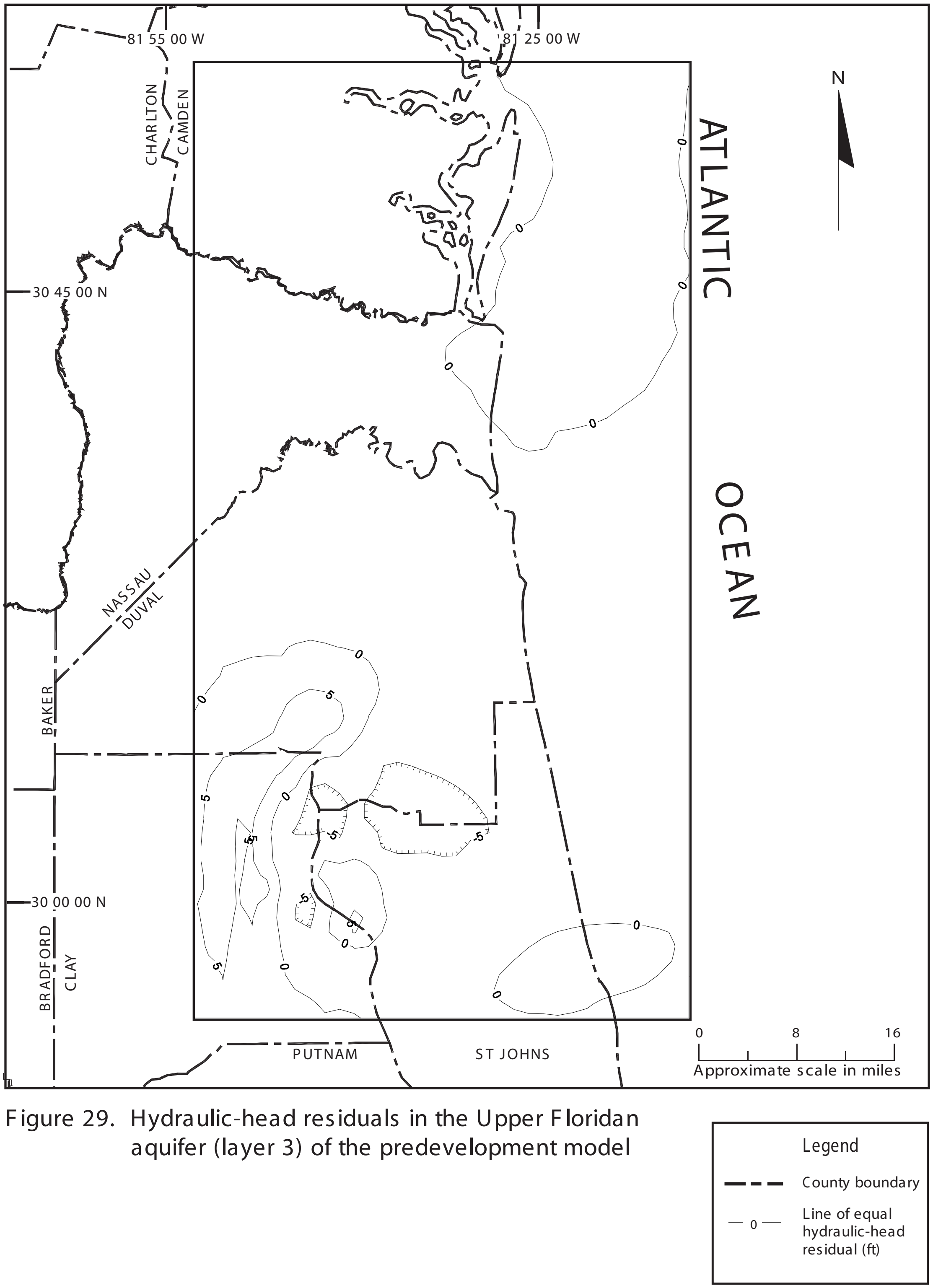


Figure 29. Hydraulic-head residuals in the Upper Floridan aquifer (layer 3) of the predevelopment model

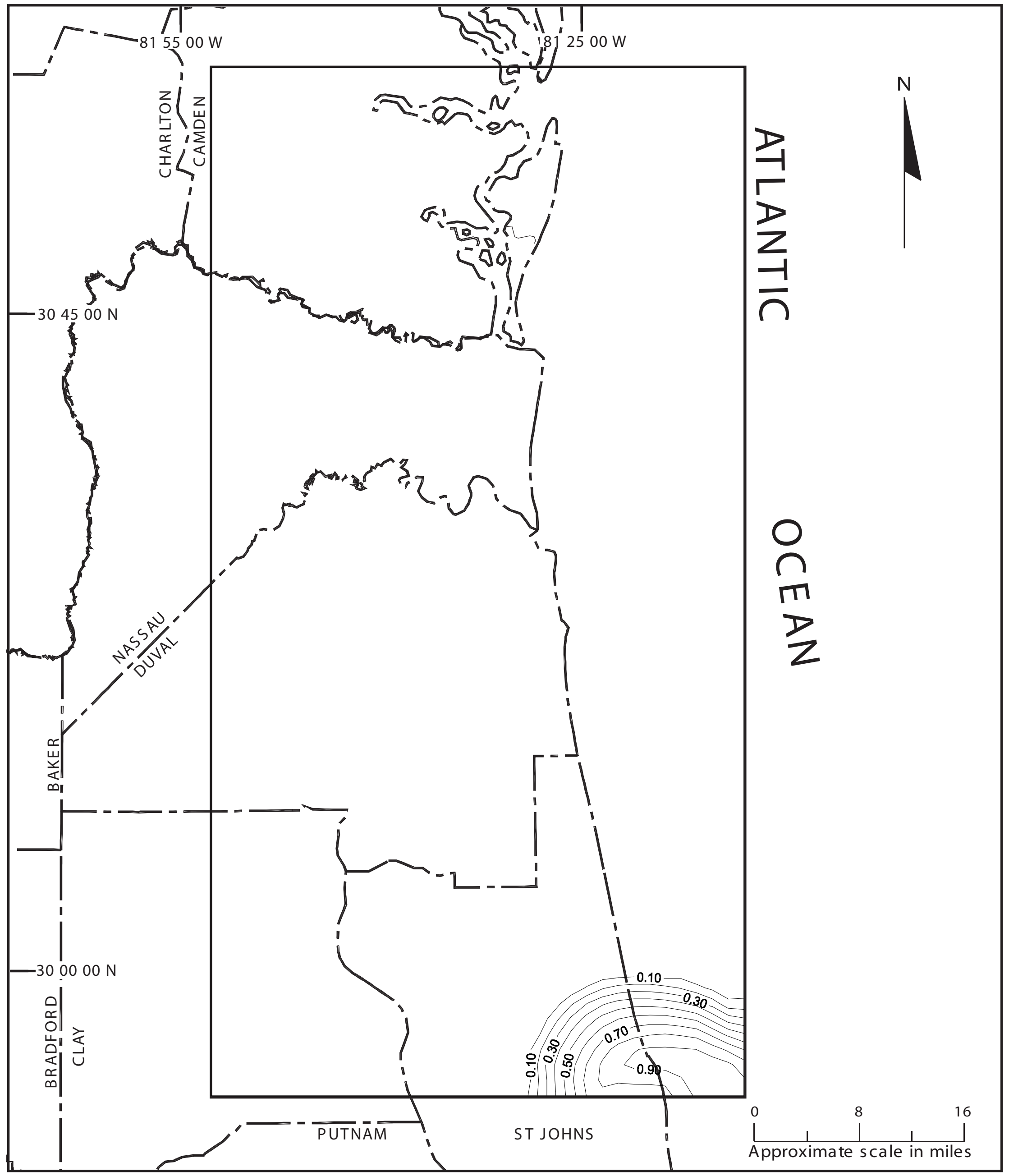
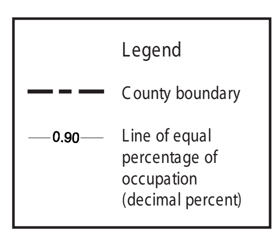


Figure 30a. Estimated percentage of occupation of the Upper Floridan aquifer by salt water



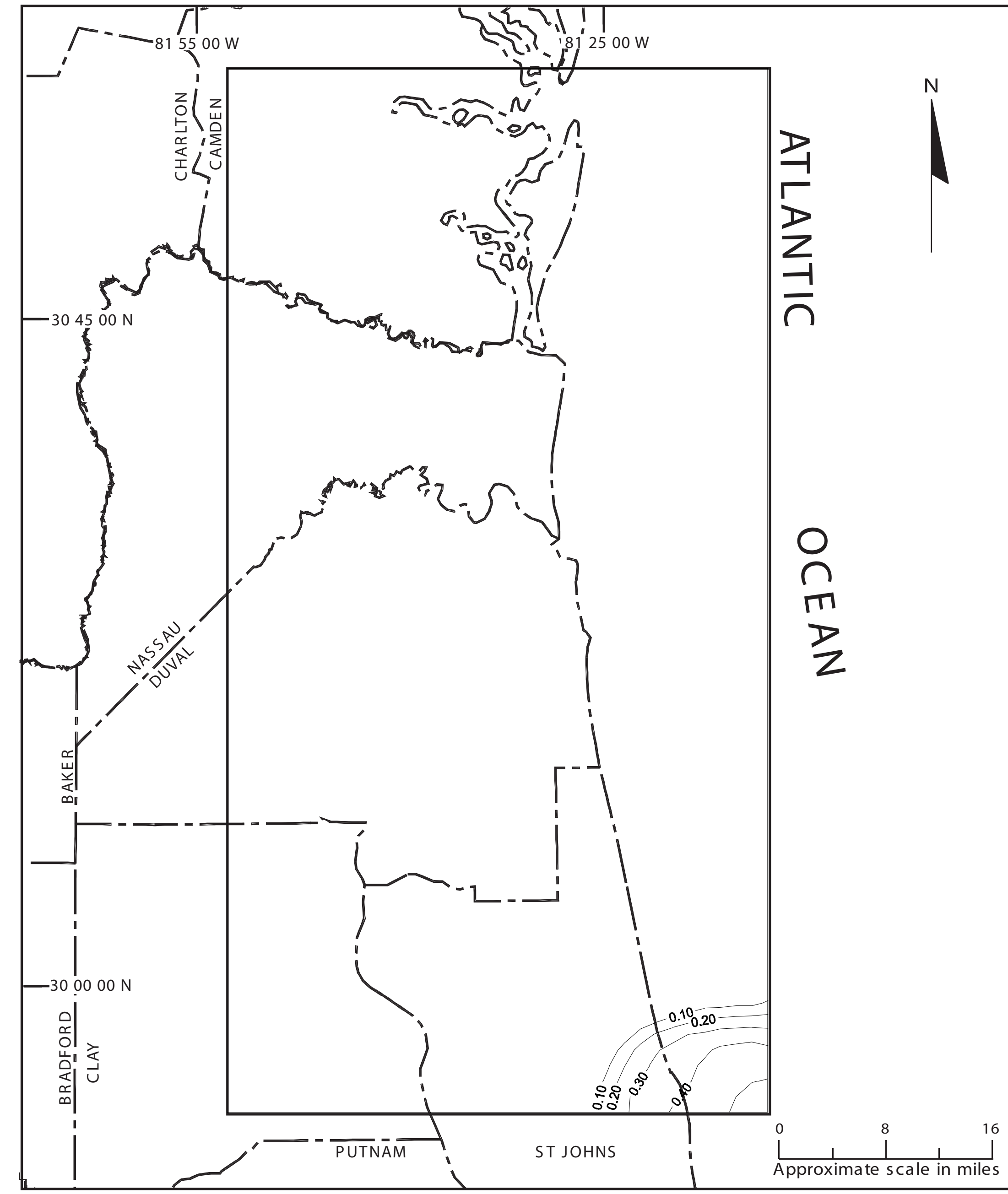
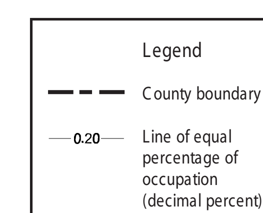


Figure 30b. Simulated percentage of occupation of the Upper Floridan aquifer by salt water, predevelopment model



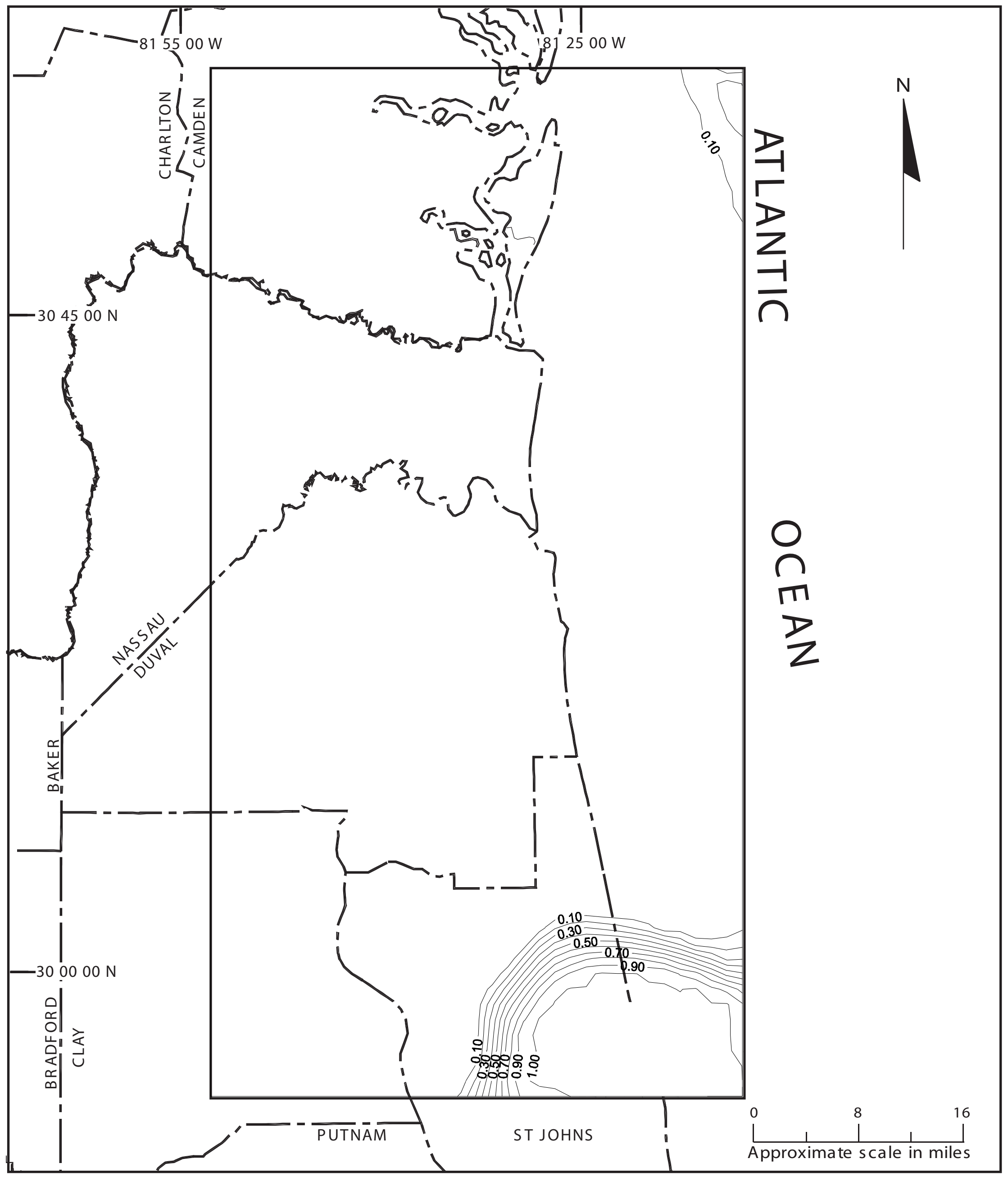


Figure 31a. Estimated percentage of occupation of the Lower Floridan aquifer by salt water

Legend

County boundary

0.90 Line of equal percentage of occupation (decimal percent)

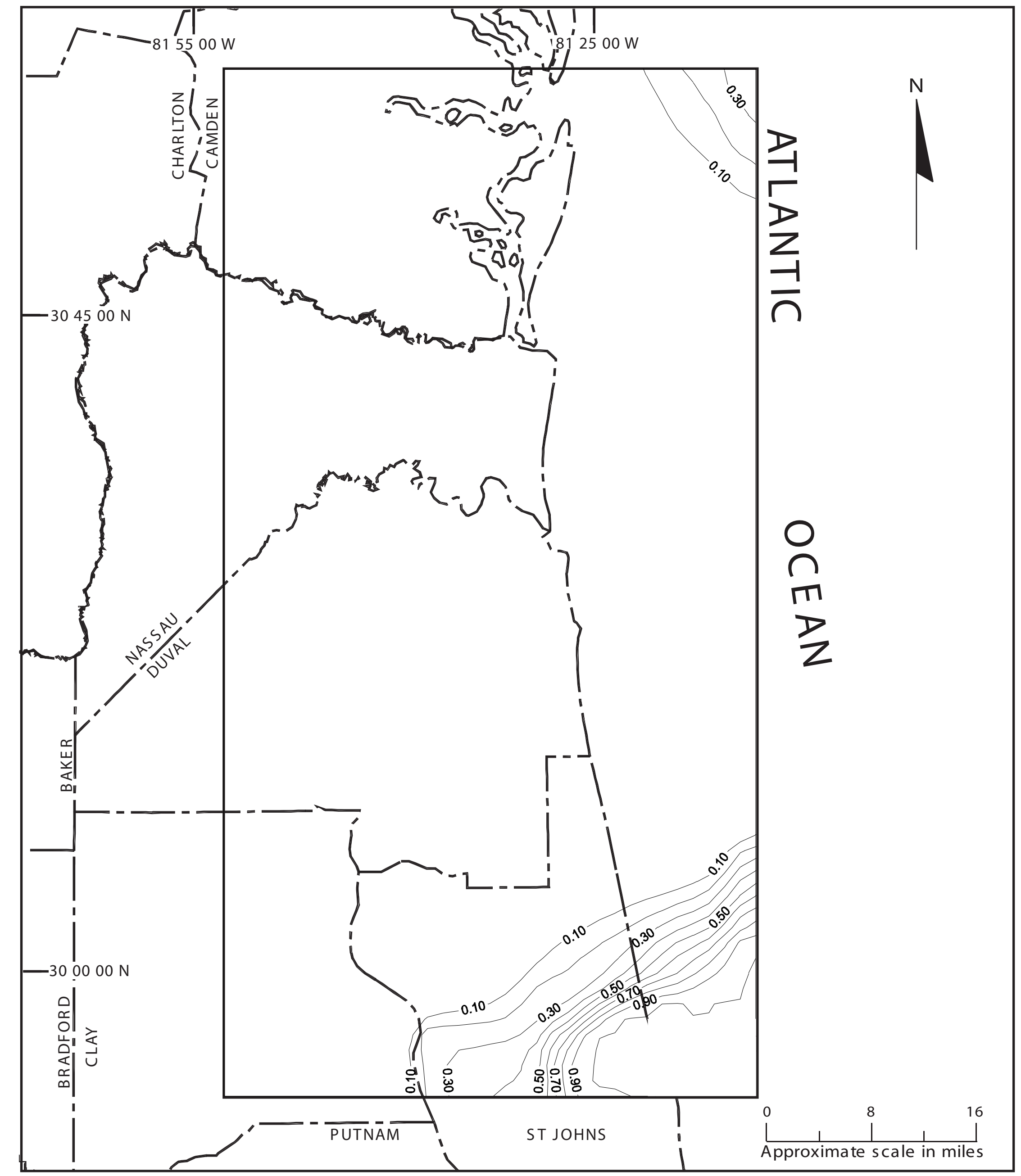


Figure 31b. Simulated percentage of occupation of the Lower Floridan aquifer by salt water, predevelopment model

Legend

County boundary

0.90 Line of equal percentage of occupation (decimal percent)

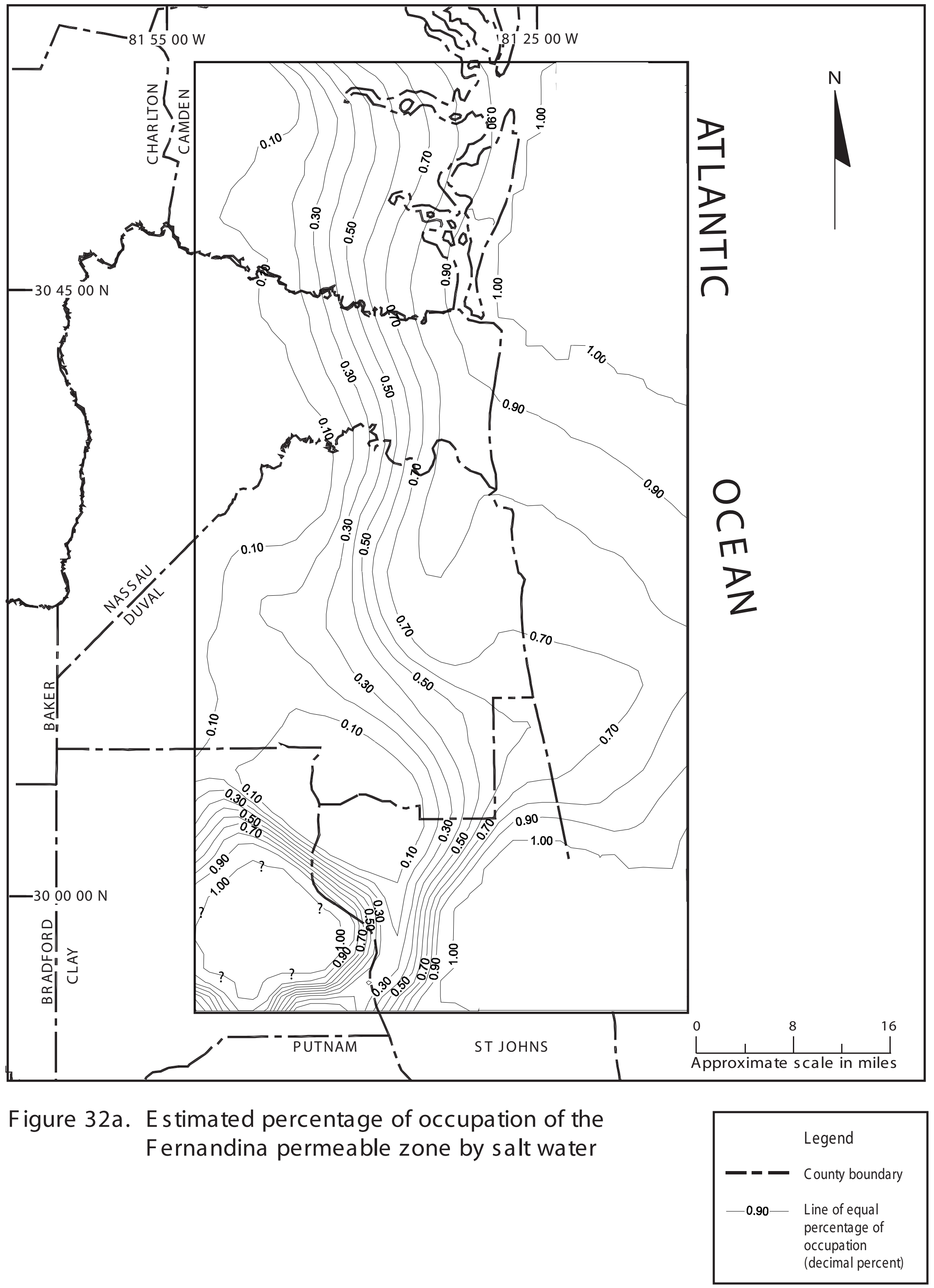


Figure 32a. Estimated percentage of occupation of the Fernandina permeable zone by salt water

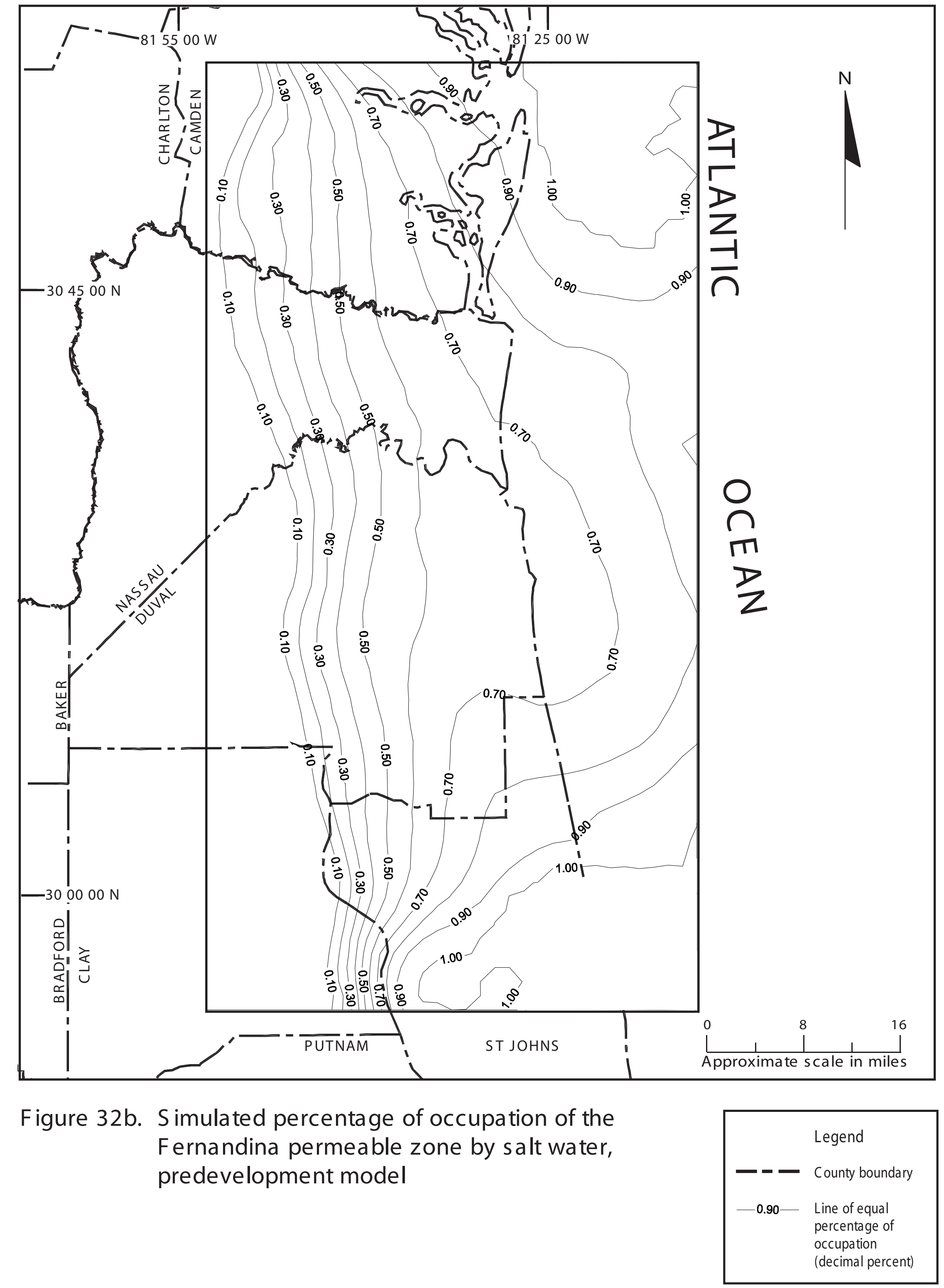


Figure 32b. Simulated percentage of occupation of the Fernandina permeable zone by salt water, predevelopment model

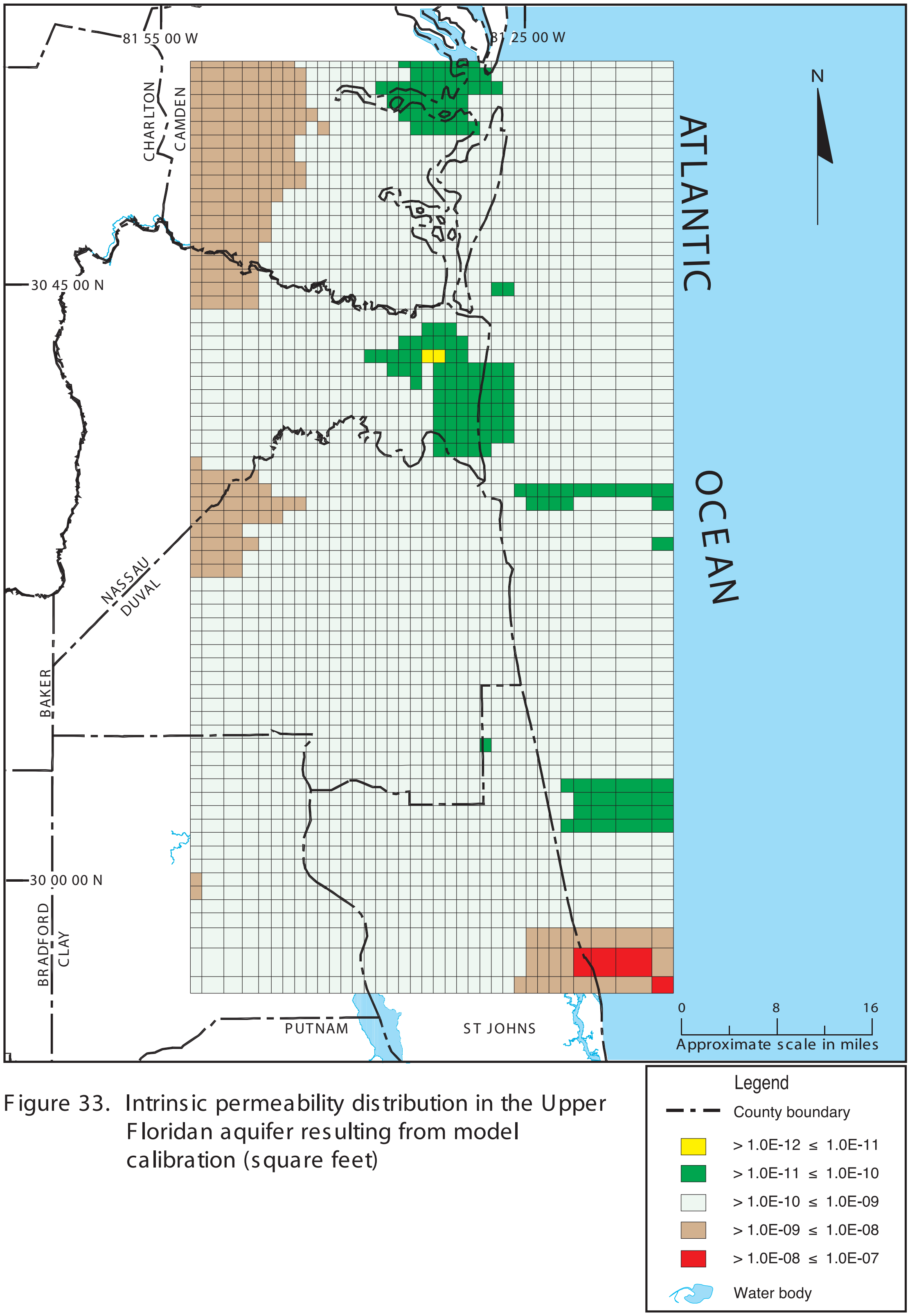


Figure 33. Intrinsic permeability distribution in the Upper Floridan aquifer resulting from model calibration (square feet)

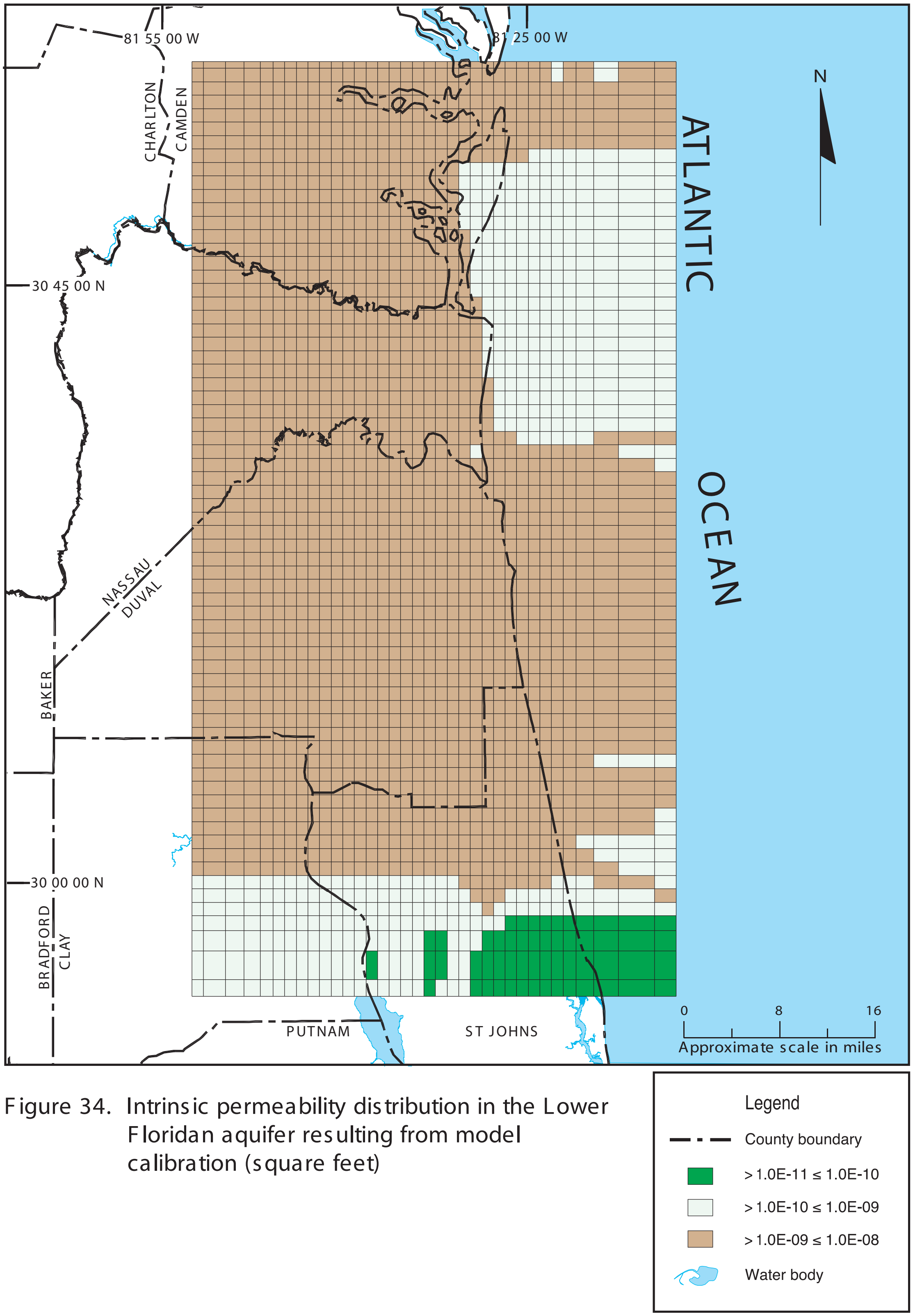


Figure 34. Intrinsic permeability distribution in the Lower Floridan aquifer resulting from model calibration (square feet)

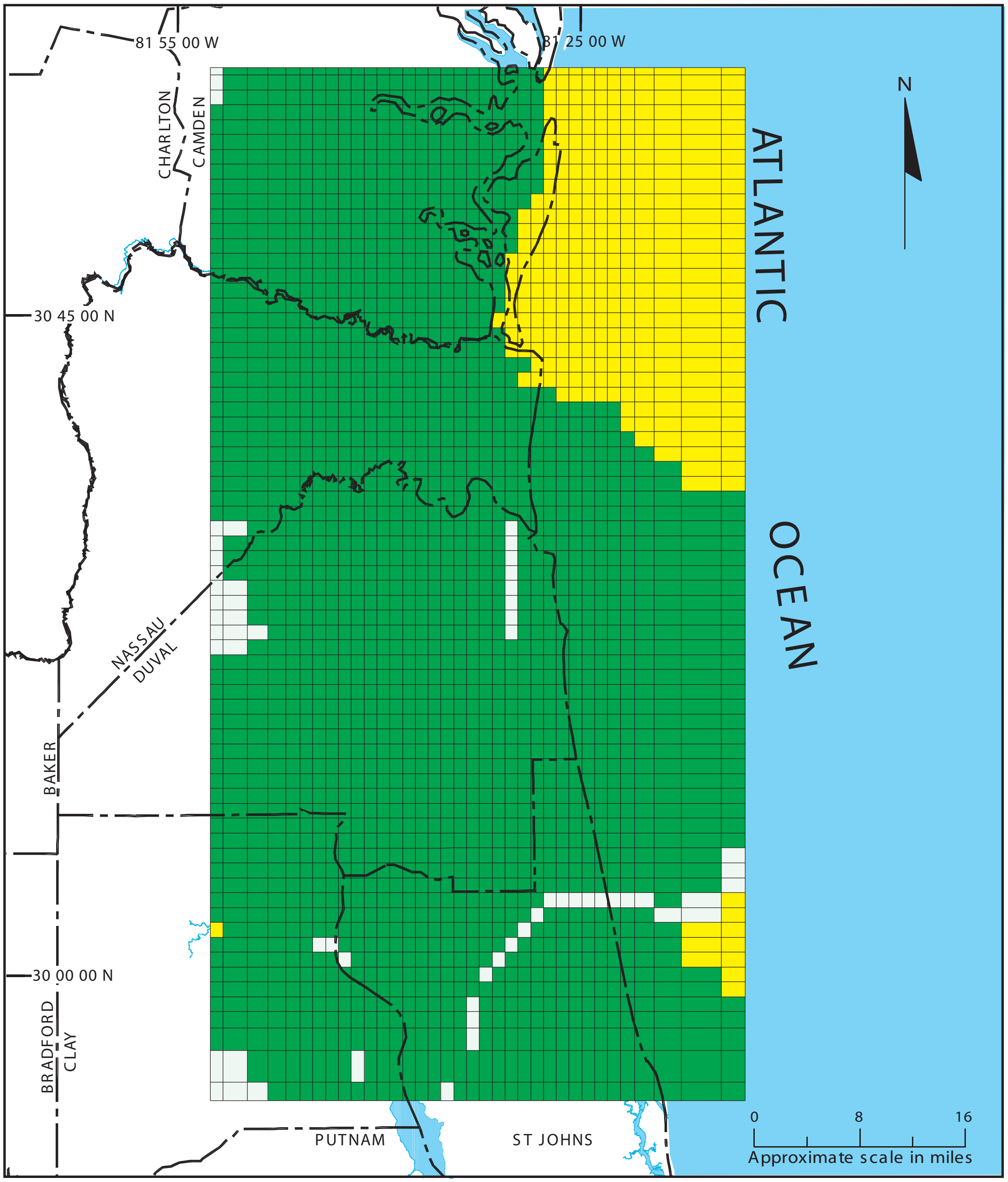


Figure 35. Intrinsic permeability distribution in the Fernandina permeable zone resulting from model calibration (square feet)

1985 AND 2010 VERSIONS OF THE MODEL

The 1985 version of the model represents present-day conditions in the Floridan aquifer system. The primary purpose of the 1985 version was to represent conditions in the Floridan aquifer system between the end of the predevelopment period and the present and to generate initial conditions for the 2010 version of the model. The 2010 version of the model was used to make predictions of the movement of the interface in response to projected 2010 rates of groundwater withdrawals.

LATERAL BOUNDARY CONDITIONS

Freshwater Lateral Boundary Conditions

The procedure for specifying freshwater lateral boundary conditions in the 1985 version of the model was essentially the same as that used in the predevelopment version of the SIMLAS model (Figures 22 and 23). As with the predevelopment version of the model, both GHFB and no-flow lateral boundary conditions were specified, depending on the direction of groundwater flow relative to the orientation of the model lateral boundaries. The direction of groundwater flow in the freshwater zone of the Upper Floridan aquifer was inferred according to the orientation of lines of equal hydraulic head shown on a map of the estimated potentiometric surface of the Upper Floridan aquifer in September 1985 (based on Johnston, Bush et al. 1980, Schiner and Hayes 1985, and Clarke 1987) (Figure 36). Also, as with the predevelopment version of the model, the direction of groundwater flow in the freshwater zone of the Lower Floridan aquifer at a given location was assumed to be generally the same as in the Upper Floridan aquifer at the same location. The direction of groundwater flow in the freshwater zone of the Fernandina permeable zone was, again, assumed to be generally eastward.

Distances between nodes and corresponding GHFB-condition source heads were the same for all the nodes of a given lateral boundary of an aquifer layer, just as in the predevelopment version of the model (Figures 22 and 23).

The values of the GHFB-condition source heads assigned to the Upper Floridan aquifer (layer 3) were determined by interpolating from the map of the September 1985 potentiometric surface of the Upper Floridan aquifer (Figure 36). The values of the GHFB-condition source heads assigned to the

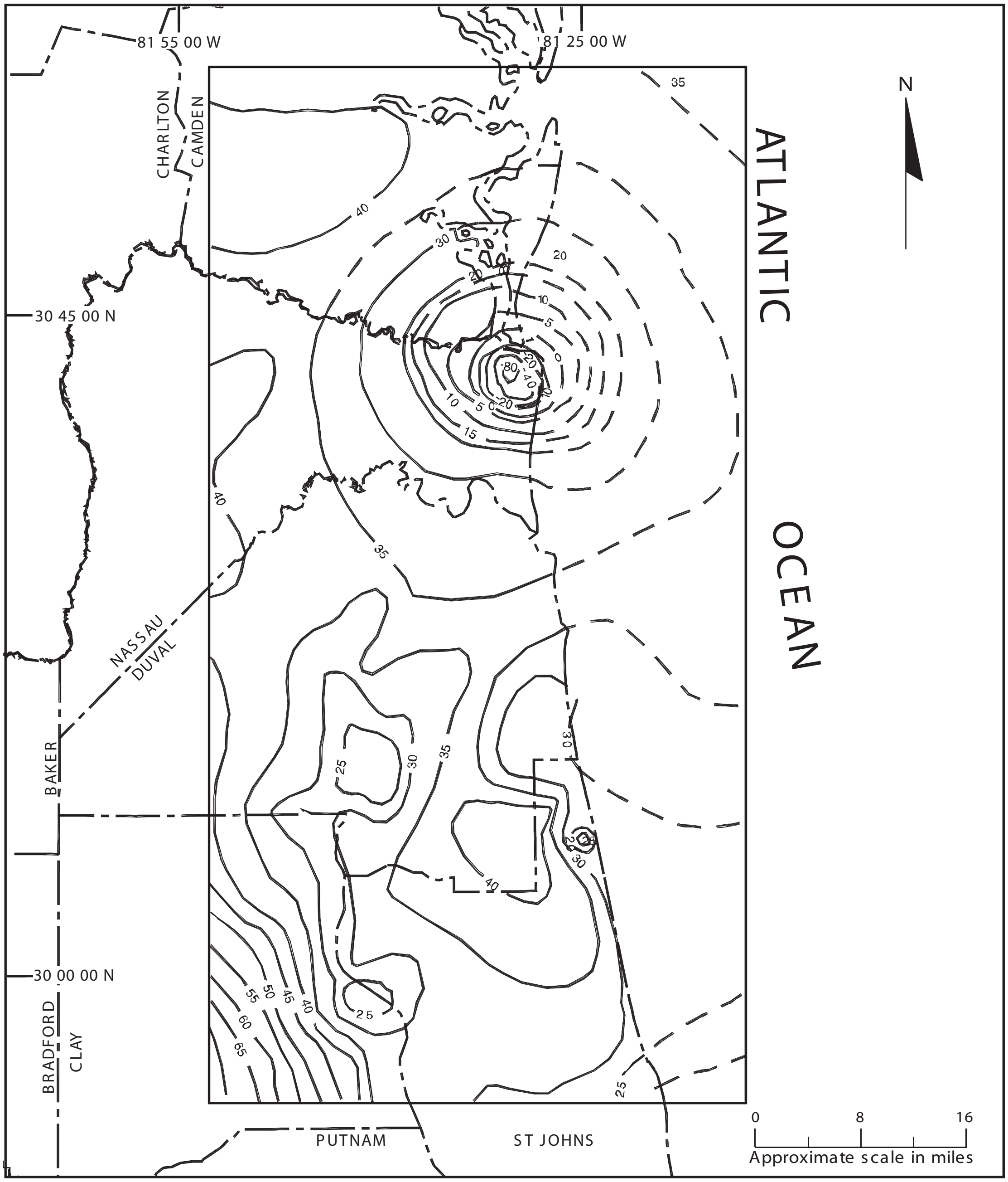


Figure 36. Estimated potentiometric surface of the Upper Floridan aquifer in September 1985 (derived from Johnston, Bush et al. 1980; Schiner and Hayes 1985; Clarke 1987)

Lower Floridan aquifer (layer 2) were determined by the same approach used with respect to the postdevelopment version of the MODFLOW model of Durden (1997). The decline in hydraulic head in the Lower Floridan aquifer at the location of a given GHFB-condition source head for the 1985 SIMLAS model was calculated by dividing the corresponding decline of hydraulic head in the Upper Floridan aquifer by the average ratio of decline in hydraulic head between the Upper and Lower Floridan aquifers. The average ratio was estimated as 1.02 (Durden 1997).

The decline in hydraulic head in the Upper Floridan aquifer was estimated by calculating the differences between the predevelopment (Figure 24) and the 1985 (Figure 36) potentiometric surfaces of the Upper Floridan aquifer. The 1985 value of hydraulic head in the Lower Floridan aquifer at the location was then estimated by subtracting the estimated decline in hydraulic head in the Lower Floridan aquifer from the estimate of the predevelopment hydraulic head in the Lower Floridan aquifer

The values of the GHFB-condition source heads assigned to the Fernandina permeable zone (layer 1) were estimated using the same approach as was used for aquifer layer 2. The average ratio of the decline in hydraulic head between the Upper Floridan aquifer and the Fernandina permeable zone was estimated as 1.07 (Durden 1997).

Saltwater Lateral Boundary Conditions

The general procedure for specifying the saltwater lateral boundary conditions for the 1985 version of the model was the same as that used in specifying the saltwater lateral boundary conditions of the predevelopment version of the model. The general configurations of the saltwater lateral boundaries are the same as in the predevelopment version of the model (Figures 25–27).

REQUIRED INPUT DATA

Water Table and Surface Water Elevations

The estimates of the elevations of the water table and surface water bodies in the 1985 version of the model are identical to those of the predevelopment version of the model. Thus, the water table and surface water bodies within the study area were assumed to have incurred negligible amounts of drawdown relative to their predevelopment levels. This assumption was based on the general lack of development of the surficial aquifer system within the study area and on the presumed ability of the upper confining unit to insulate the surficial aquifer system from the effects of groundwater withdrawals from the Floridan aquifer system. The insulative ability of the upper confining unit is attributable to its relative impermeability and thickness within the study area. The results of model simulations performed using a semi-analytical model called SURFDOWN (Huang and Williams 1996) appear to corroborate this ability (Vergara 1994).

Physical and Hydrologic Properties

The estimates of the freshwater and saltwater densities, the dynamic viscosity, the effective porosity, and the volume compressibility in the 1985 version of the model are identical to those of the predevelopment version of the model.

The initial estimates of the horizontal intrinsic permeability and the initial estimates of the vertical leakage factor were obtained from the predevelopment version of the model.

Well Discharge Rates, Locations, Open-Hole Lengths, and Bottom Elevations

Well data, including locations, open-hole lengths, bottom elevations, and estimated 1985 discharge rates, were specified for each well represented in the model. Approximately 30.6 million cubic feet per day of groundwater withdrawals from the Upper and Lower Floridan aquifers are represented in the 1985 version of the model (Figures 37a and 37b). A summary of these data and a discussion of their compilation are provided in Durden (1997).

MODEL CALIBRATION

As stated previously, the calibration of the 1985 version of the model was conducted in concert with that of the predevelopment version of the model. Therefore, the final values of aquifer intrinsic permeability and semiconfining-unit vertical leakage factor are identical to those resulting from the calibration of the predevelopment version of the model.

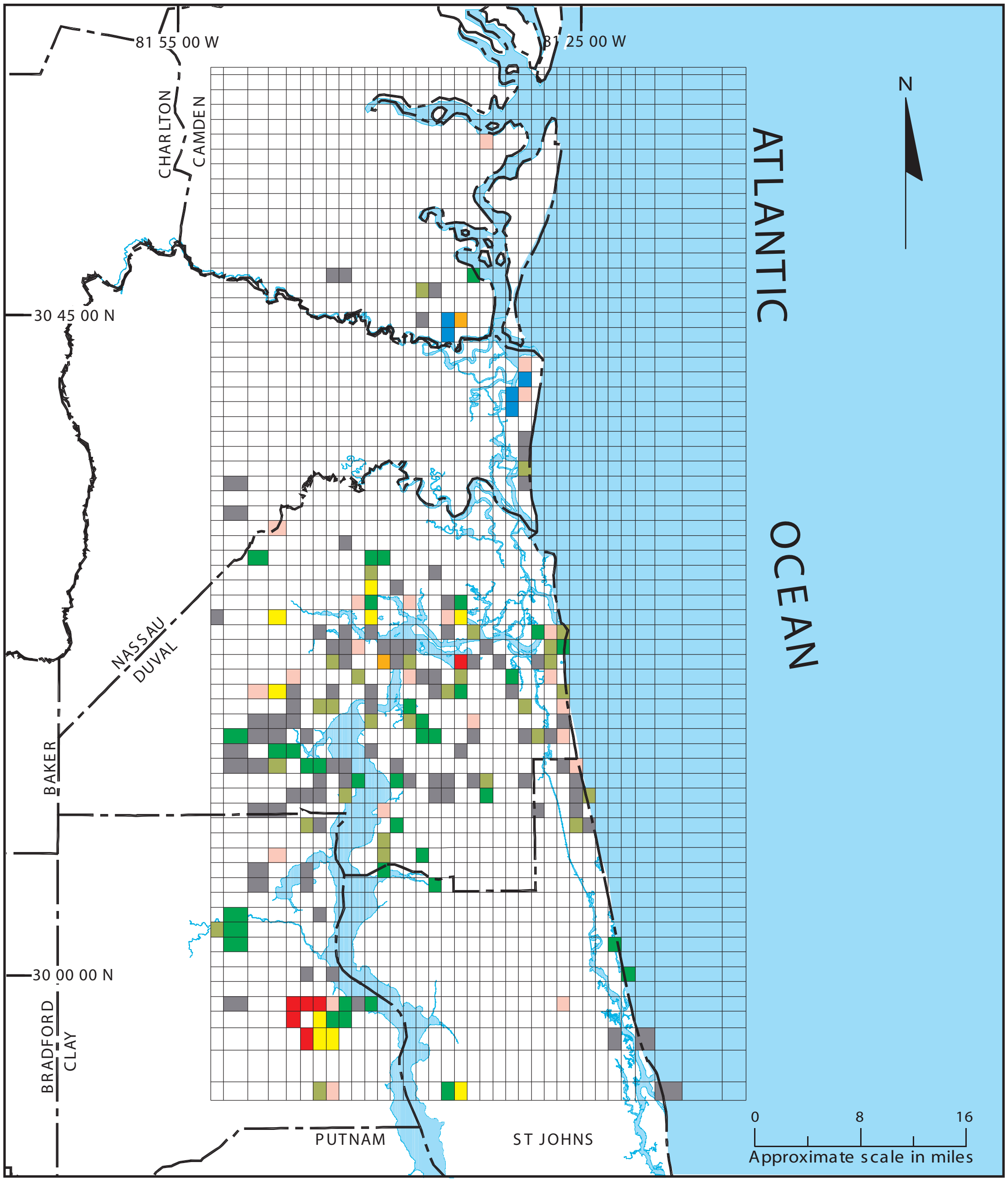
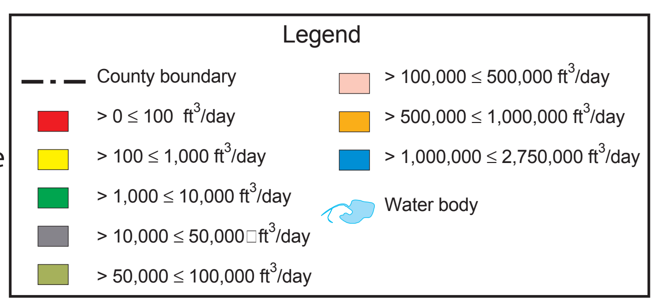


Figure 37a. Estimated withdrawal rates prescribed for aquifer layer 3 (Upper Floridan aquifer) of the 1985 model version



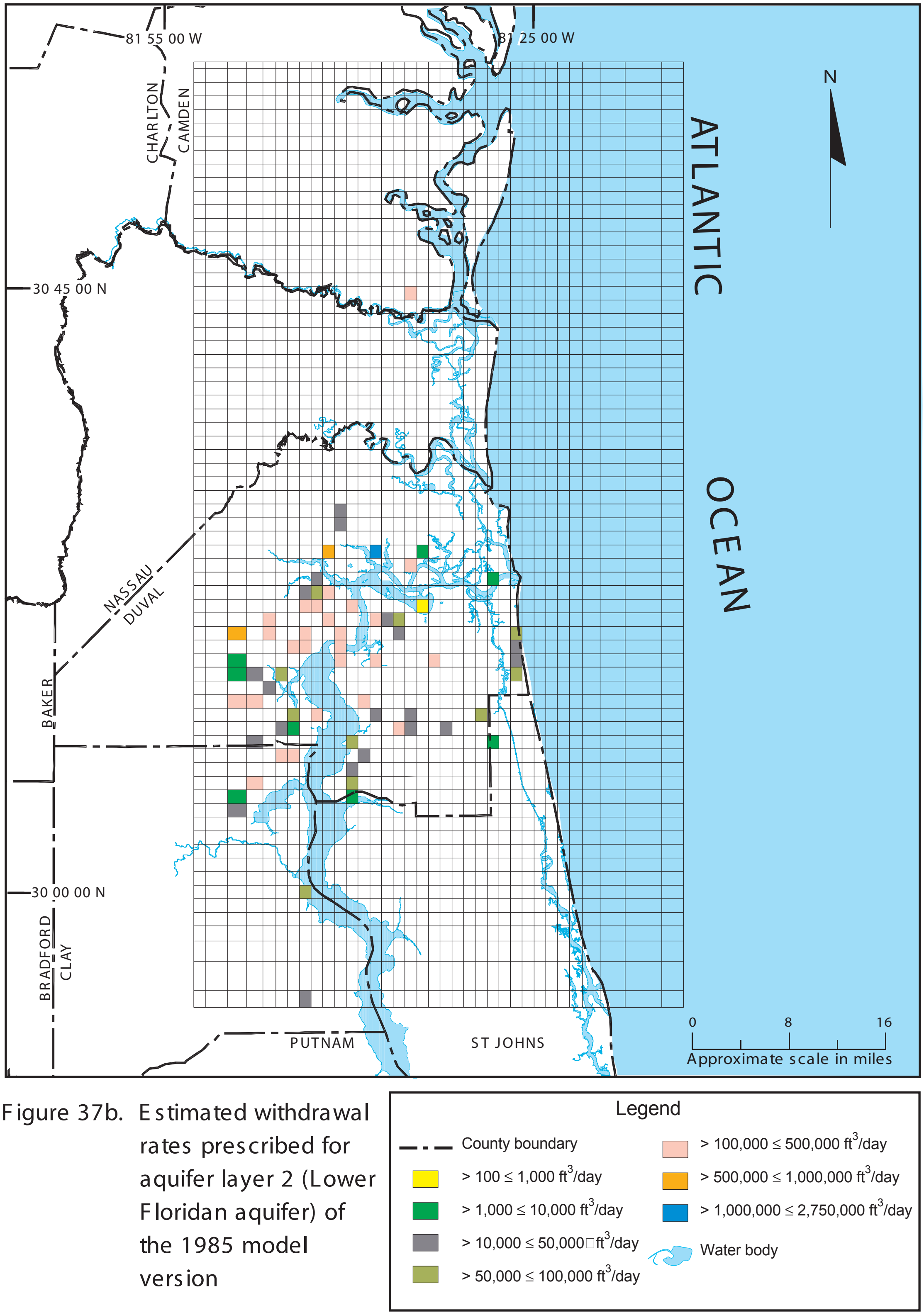


Figure 37b. Estimated withdrawal rates prescribed for aquifer layer 2 (Lower Floridan aquifer) of the 1985 model version

Comparison of Estimated and Simulated Hydraulic-Head and Interface-Elevation Values

The model was calibrated partly by comparing values of hydraulic head that were interpolated from the map of the 1985 potentiometric surface of the Upper Floridan aquifer to values simulated at model nodes. The residual of hydraulic head was determined for each node of the Upper Floridan aquifer (layer 3). The final mean of the residuals was 1.0 ft. The final standard deviation of the residuals was 3.6 ft. The final mean of the absolute values of the residuals was 2.6 ft. The final percentage of the residuals less than or equal to 5 ft was 87.6.

The map of the potentiometric surface of the Upper Floridan aquifer in September 1985 was compared visually to a map of the simulated values of hydraulic head (Figure 38). In addition, a map of the residuals of hydraulic head was created to illustrate the spatial distribution of the residuals (Figure 39).

As a further check on the calibration, simulated values of hydraulic head in the Upper Floridan aquifer (layer 3) were compared to values of hydraulic head that were observed in 138 U.S. Geological Survey monitoring wells (Figure 40) in the Upper Floridan aquifer (Table 2). In each case, a comparison in the hydraulic-head value simulated at a given node and the value observed in a given monitoring well was made only if the monitoring well was located within the area represented by the model node (Figure 40).

Residuals of hydraulic head were calculated using these data. The final mean of the residuals was 0.4 ft. The final standard deviation of the residuals was 9.4 ft. The final mean of the absolute values of the residuals was 4.7 ft. The final percentage of the residuals less than or equal to 5 ft was 79.0.

In the development of the MODFLOW model of Durden (1997), the statistical analysis of residuals based on observed values of hydraulic head was skewed by the extremely large slope of the potentiometric surface of the Upper Floridan aquifer in the area of Fernandina Beach. To remedy this problem, values of residuals corresponding to five of the wells in that area were excluded from the statistical computations. Accordingly, in the present study, the residual values based on the same five hydraulic-head values were excluded from the statistical computations, and the mean, standard deviation, and mean of the absolute values were recalculated. The recalculated values were 1.4 ft, 4.7 ft, and 3.4 ft, respectively. The percentage of the residuals less

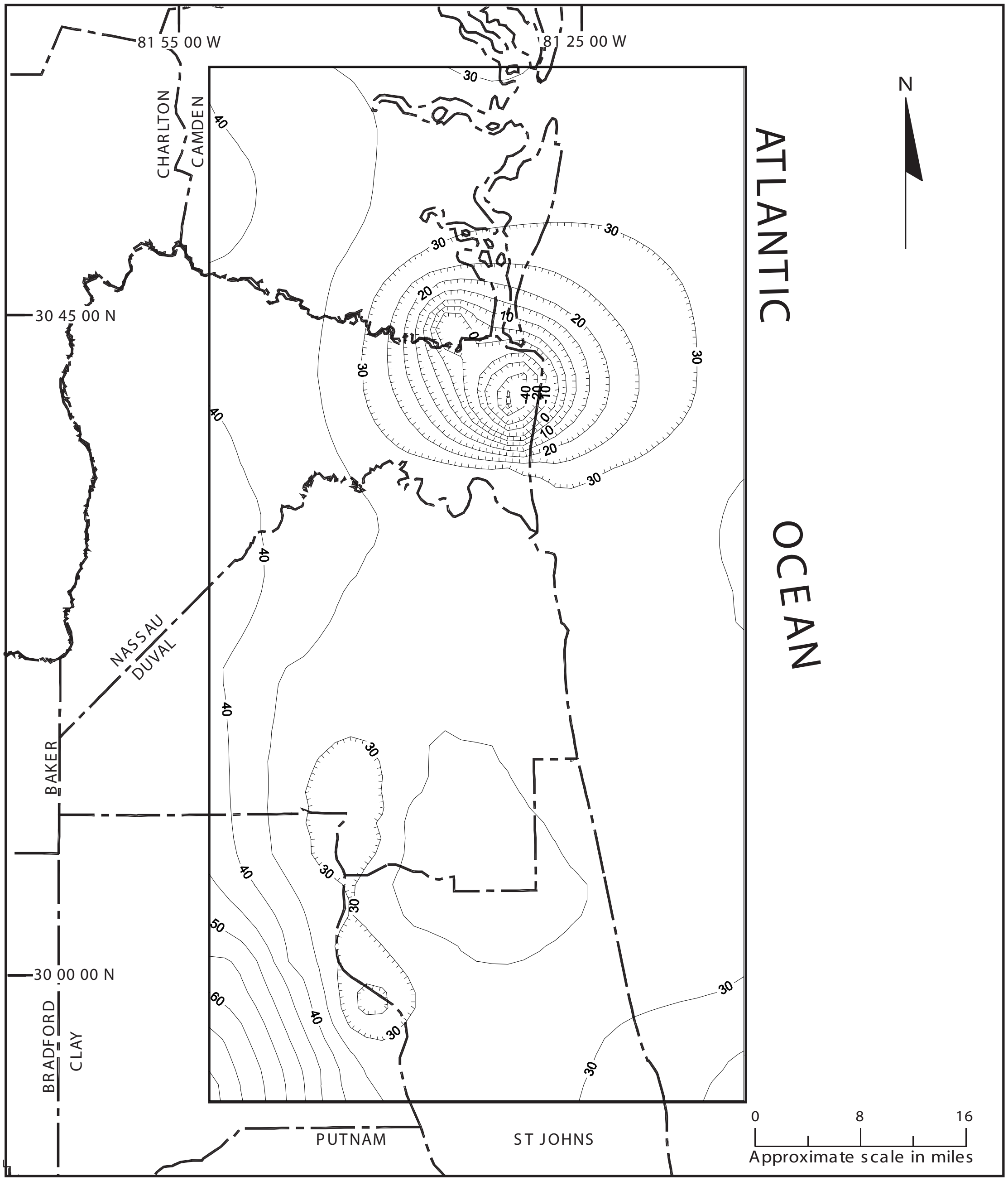


Figure 38. Simulated 1985 potentiometric surface of the Upper Floridan aquifer

Legend

County boundary

30 Line of equal elevation of hydraulic head (ft NGVD) (dashed where inferred)

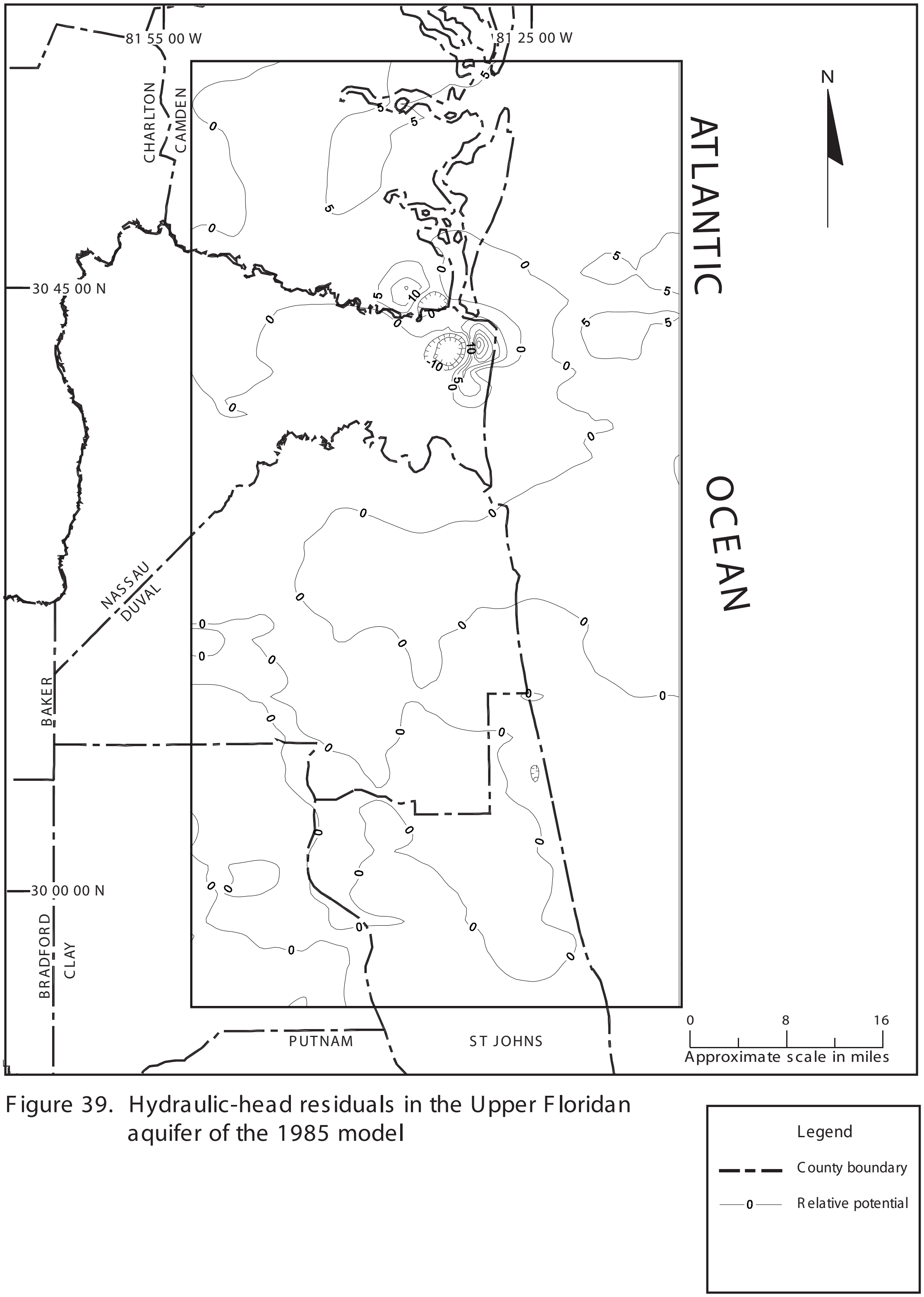


Figure 39. Hydraulic-head residuals in the Upper Floridan aquifer of the 1985 model

Table 2. Residuals between the observed heads at the 138 U.S. Geological Survey (USGS) Upper Floridan aquifer wells and the simulated 1985 model heads

USGS Well Identification Number	Latitude	Longitude	Row	Column	Date	Observed Head (ft NGVD)	Simulated Head (ft NGVD)	Residual (feet)
310106081314501	31 01 06	81 31 45	67	18	5/15/85	37.7	30.6	7.1
305854081502201	30 58 59	81 50 10	65	2	5/15/85	36.3	39.2	-2.9
305804081441301	30 58 04	81 44 13	65	6	5/15/85	39.5	37.2	2.3
305710081315501	30 57 10	81 31 55	64	18	5/21/85	33.2	32.0	1.2
305627081473101	30 56 23	81 48 35	63	3	5/15/85	41.0	39.3	1.7
305610081302901	30 56 11	81 30 28	63	20	5/21/85	31.7	31.0	0.7
305538081305401	30 55 38	81 30 54	62	19	5/21/85	38.7	31.9	6.8
305505081305101	30 55 14	81 30 56	62	19	5/21/85	36.3	31.9	4.4
305313081310401	30 53 14	81 31 03	60	19	5/15/85	35.0	31.9	3.1
305242081263401	30 52 42	81 26 34	59	23	5/13/85	35.0	31.1	3.9
305122081275601	30 51 22	81 27 55	58	22	5/13/85	30.4	30.9	-0.4
305045081334601	30 50 45	81 33 46	57	16	5/15/85	37.0	31.4	5.6
305031081342701	30 50 31	81 34 27	57	16	5/15/85	39.0	31.4	7.6
305032081280101	30 50 32	81 28 01	57	22	5/13/85	33.4	29.6	3.8
305029081265101	30 50 29	81 26 51	57	23	5/13/85	32.4	29.5	2.9
304907081323701	30 49 10	81 32 38	56	17	5/15/85	34.0	29.5	4.5
304830081481201	30 48 30	81 48 12	55	3	5/15/85	40.1	39.2	0.9
304851081274001	30 48 51	81 27 40	55	22	5/13/85	32.1	25.8	6.3
304804081405401	30 48 04	81 40 54	54	9	5/15/85	39.3	34.1	5.2
304627081371201	30 46 27	81 37 12	53	13	5/15/85	28.0	27.6	0.4
304646081280901	30 46 46	81 28 09	53	22	5/13/85	26.5	19.3	7.2
304610081280901	30 46 10	81 28 09	53	22	5/13/85	23.6	19.3	4.3
304514081390201	30 45 16	81 38 59	52	11	5/15/85	35.9	30.4	5.5
304512081343601	30 45 10	81 34 38	52	15	5/15/85	20.7	17.4	3.3
304408081323301	30 44 08	81 32 35	51	17	5/14/85	-15.5	-7.0	-8.5
304317081372301	30 43 17	81 37 23	50	13	9/10/85	25.8	23.4	2.4
304408081323401	30 44 06	81 32 35	50	17	5/14/85	-15.3	-11.6	-3.7
304401081323701	30 44 01	81 32 37	50	17	5/14/85	-60.0	-11.6	-48.4
304401081323601	30 44 01	81 32 37	50	17	5/14/85	-79.0	-11.6	-67.4
304348081323901	30 43 48	81 32 39	50	17	5/15/85	4.6	-11.6	16.2
304313081325701	30 43 13	81 32 57	50	17	5/14/85	7.6	-11.6	19.2
304213081270801	30 42 13	81 27 08	49	23	9/09/85	-15.9	-5.3	-10.6
304150081470301	30 41 50	81 47 03	48	3	9/18/85	39.0	38.0	1.0
304002081381201	30 40 18	81 38 28	47	12	9/10/85	28.6	26.7	1.9
304022081275001	30 40 22	81 27 50	47	22	9/09/85	-29.2	-43.0	13.8
304055081272002	30 40 55	81 27 20	47	23	9/13/85	-90.8	-53.4	-37.4
303939081312601	30 39 39	81 31 26	46	19	9/10/85	0.6	-3.8	4.4
303819081455701	30 38 19	81 45 57	45	4	9/09/85	38.8	37.7	1.1
303836081274201	30 38 36	81 27 42	45	22	9/09/85	-39.6	-70.6	31.0
303754081362701	30 37 54	81 36 27	44	14	9/10/85	28.6	25.7	2.9
303722081295401	30 37 22	81 29 54	44	20	9/09/85	5.9	-0.2	6.1

Table 2—*Continued*

USGS Well Identification Number	Latitude	Longitude	Row	Column	Date	Observed Head (ft NGVD)	Simulated Head (ft NGVD)	Residual (feet)
303805081273901	30 38 05	81 27 39	44	22	9/09/85	-30.6	-21.3	-9.3
303658081422601	30 36 58	81 42 26	43	7	9/10/85	34.0	36.0	-2.0
303518081275001	30 35 18	81 27 50	42	22	9/25/85	20.6	17.2	3.4
303458081364001	30 34 58	81 36 40	41	13	9/11/85	31.6	32.4	-0.8
303417081342201	30 34 17	81 34 22	41	16	9/09/85	30.4	32.3	-1.9
303435081271401	30 34 35	81 27 14	41	23	9/09/85	28.4	28.9	-0.5
303340081500001	30 33 40	81 50 00	40	2	9/11/85	38.3	40.6	-2.3
303357081295601	30 33 57	81 29 56	40	20	9/09/85	29.2	32.5	-3.3
303216081433301	30 32 16	81 43 33	39	6	9/11/85	36.5	38.0	-1.5
303015081343301	30 30 15	81 34 33	37	15	9/11/85	25.1	34.7	-9.6
302801081375101	30 28 01	81 37 51	34	12	9/11/85	36.2	34.1	2.1
302738081290001	30 27 38	81 29 00	34	21	9/11/85	33.4	34.0	-0.6
302724081244801	30 27 24	81 24 48	34	25	9/11/85	34.6	33.7	0.9
302641081454201	30 26 41	81 45 42	33	4	9/12/85	38.0	39.4	-1.4
302616081413901	30 26 16	81 41 39	33	8	9/12/85	38.6	36.3	2.3
302608081354901	30 26 08	81 35 49	33	14	9/11/85	35.7	33.1	2.6
302608081354902	30 26 08	81 35 49	33	14	9/11/85	36.7	33.1	3.6
302608081354903	30 26 08	81 35 49	33	14	9/11/85	35.2	33.1	2.1
302514081393701	30 25 14	81 39 37	32	10	9/12/85	33.6	32.3	1.3
302538081253101	30 25 38	81 25 31	32	24	9/11/85	38.5	33.8	4.7
302502081321001	30 25 02	81 32 10	31	18	9/11/85	35.7	33.7	2.0
302330081463001	30 23 30	81 46 30	30	4	9/12/85	35.9	38.3	-2.4
302351081390201	30 23 51	81 39 02	30	11	9/11/85	32.0	33.3	-1.3
302317081330401	30 23 17	81 33 04	30	17	9/11/85	37.5	33.7	3.8
302345081261301	30 23 45	81 26 13	30	24	9/11/85	35.1	33.3	1.8
302339081254702	30 23 39	81 25 47	30	24	9/10/85	36.1	33.3	2.8
302304081383202	30 23 04	81 38 32	29	11	9/10/85	37.4	33.0	4.4
302307081293801	30 23 07	81 29 38	29	20	9/10/85	37.0	33.7	3.3
302300081295101	30 23 00	81 29 51	29	20	9/10/85	36.3	33.7	2.6
302145081394201	30 21 45	81 39 42	28	10	9/12/85	34.9	33.0	1.9
302112081384701	30 21 12	81 38 47	28	11	9/09/85	35.2	33.1	2.1
302120081362201	30 21 20	81 36 22	28	13	9/09/85	32.7	32.8	-0.1
302142081330701	30 21 42	81 33 07	28	17	9/10/85	31.0	34.1	-3.1
302122081274001	30 21 22	81 27 40	28	22	9/10/85	32.2	33.8	-1.6
302137081240001	30 21 37	81 24 00	28	26	9/10/85	32.1	33.2	-1.1
302037081455301	30 20 37	81 45 53	27	4	9/11/85	35.6	35.7	-0.1
301919081375401	30 19 19	81 37 54	26	12	9/09/85	34.0	33.2	0.8
301900081342801	30 19 17	81 34 54	26	15	9/09/85	31.6	34.6	-3.0
301925081262501	30 19 25	81 26 25	26	23	9/09/85	27.9	33.7	-5.8
301844081403801	30 18 44	81 40 38	25	9	9/11/85	29.1	31.5	-2.4
301902081394601	30 19 02	81 39 46	25	10	9/09/85	27.2	31.5	-4.3

Table 2—*Continued*

USGS Well Identification Number	Latitude	Longitude	Row	Column	Date	Observed Head (ft NGVD)	Simulated Head (ft NGVD)	Residual (feet)
301817081374901	30 18 17	81 37 49	25	12	9/09/85	35.4	32.3	3.1
301852081234201	30 18 52	81 23 42	25	26	9/10/85	29.9	32.0	-2.2
301846081240201	30 18 46	81 24 02	25	26	9/10/85	29.4	32.0	-2.7
301725081392101	30 17 25	81 39 21	24	10	9/09/85	25.4	30.8	-5.4
301715081300001	30 17 15	81 30 00	24	20	9/09/85	32.8	34.2	-1.4
301712081233301	30 17 12	81 23 33	24	26	9/10/85	28.9	31.1	-2.2
301617081421601	30 16 17	81 42 16	23	8	9/11/85	29.0	30.8	-1.8
301551081415701	30 15 51	81 41 57	22	8	9/11/85	27.1	29.6	-2.5
301607081301001	30 16 07	81 30 10	22	20	9/09/85	33.3	35.2	-1.9
301415081284801	30 14 15	81 28 48	21	21	9/20/85	33.4	35.3	-1.9
301339081433401	30 13 39	81 43 34	20	6	9/11/85	30.7	30.5	0.2
301347081353301	30 13 47	81 35 33	20	14	9/09/85	33.1	32.4	0.7
301333081324101	30 13 33	81 32 41	20	17	9/09/85	37.3	35.4	1.9
301408081253101	30 14 08	81 25 31	20	24	9/12/85	23.5	33.3	-9.8
301411081224201	30 14 11	81 22 42	20	27	9/09/85	38.4	30.5	7.9
301216081451201	30 12 16	81 45 12	19	5	9/11/85	27.1	31.9	-4.8
301255081371001	30 12 55	81 37 10	19	13	9/09/85	24.9	31.9	-7.0
301212081252401	30 12 12	81 25 24	19	24	9/12/85	39.7	34.4	5.3
301304081222701	30 13 04	81 22 27	19	27	9/09/85	23.7	31.1	-7.4
301249081225801	30 12 49	81 22 58	19	27	9/09/85	29.0	31.1	-2.1
301144081413801	30 11 44	81 41 38	18	8	9/11/85	29.7	28.3	1.4
301018081415101	30 10 18	81 41 51	17	8	9/10/85	29.9	28.5	1.4
301032081380401	30 10 32	81 38 04	17	12	9/09/85	31.6	30.6	1.0
301037081243901	30 10 37	81 24 39	17	25	9/12/85	30.8	35.2	-4.4
301005081225901	30 10 05	81 22 59	16	27	9/09/85	20.2	33.1	-12.9
300834081421301	30 08 34	81 42 13	15	8	9/10/85	27.8	28.6	-0.8
300812081390801	30 08 12	81 39 08	15	11	9/09/85	32.1	29.7	2.4
300820081354001	30 08 20	81 35 40	15	14	9/09/85	38.4	36.0	2.4
300824081305401	30 08 24	81 30 54	15	19	9/10/85	39.7	36.8	2.9
300717081381001	30 07 17	81 38 10	14	12	9/09/85	33.8	32.1	1.7
300758081230501	30 07 58	81 23 05	14	27	9/10/85	34.7	35.0	-0.3
300649081485901	30 06 49	81 48 59	13	2	9/10/85	40.4	42.6	-2.2
300656081463401	30 06 56	81 46 34	13	4	9/10/85	36.7	37.1	-0.4
300632081334301	30 06 32	81 33 43	13	16	9/10/85	38.1	37.5	0.6
300604081441501	30 06 04	81 44 15	12	5	9/10/85	33.5	36.0	-2.5
300555081290601	30 05 55	81 29 06	12	21	9/10/85	38.6	36.5	2.1
300450081482801	30 04 50	81 48 28	11	2	9/10/85	46.7	46.4	0.3
300341081395401	30 03 41	81 39 54	10	10	9/10/85	33.2	29.3	3.9
300322081342801	30 03 22	81 34 28	10	15	9/13/85	33.6	34.9	-1.3
300354081301201	30 03 54	81 30 12	10	20	9/10/85	35.6	36.1	-0.5
300300081422501	30 03 00	81 42 25	9	7	9/12/85	29.8	34.1	-4.3

Table 2—*Continued*

USGS Well Identification Number	Latitude	Longitude	Row	Column	Date	Observed Head (ft NGVD)	Simulated Head (ft NGVD)	Residual (feet)
300307081234201	30 03 07	81 23 42	9	26	9/10/85	39.2	34.8	4.4
300048081414301	30 00 48	81 41 43	7	8	9/10/85	31.8	31.9	-0.1
300019081363301	30 00 19	81 36 33	7	13	9/10/85	32.8	28.7	4.1
300036081213501	30 00 36	81 21 35	7	28	9/11/85	32.5	33.6	-1.1
295900081403201	29 59 00	81 40 32	5	9	9/10/85	25.8	29.0	-3.2
295847081380601	29 58 47	81 38 06	5	12	9/10/85	22.8	22.7	0.1
295903081334301	29 59 03	81 33 43	5	16	9/10/85	33.0	31.6	1.4
295713081203401	29 57 13	81 20 34	4	29	9/11/85	30.5	31.1	-0.6
295615081394701	29 56 15	81 39 47	3	10	9/10/85	38.5	31.4	7.1
295556081342101	29 55 56	81 34 21	3	15	9/10/85	33.6	32.0	1.6
295353081381901	29 53 53	81 38 19	2	11	9/10/85	32.8	33.9	-1.1
295357081294301	29 53 57	81 29 43	2	20	9/10/85	30.0	32.2	-2.2
295341081263705	29 53 41	81 26 37	2	23	9/10/85	30.4	32.2	-1.8
295333081191401	29 53 33	81 19 14	2	31	9/11/85	20.9	28.6	-7.7
295502081175401	29 55 02	81 17 54	2	32	9/11/85	22.3	28.2	-5.9

Note: ft NGVD = feet, National Geodetic Vertical Datum

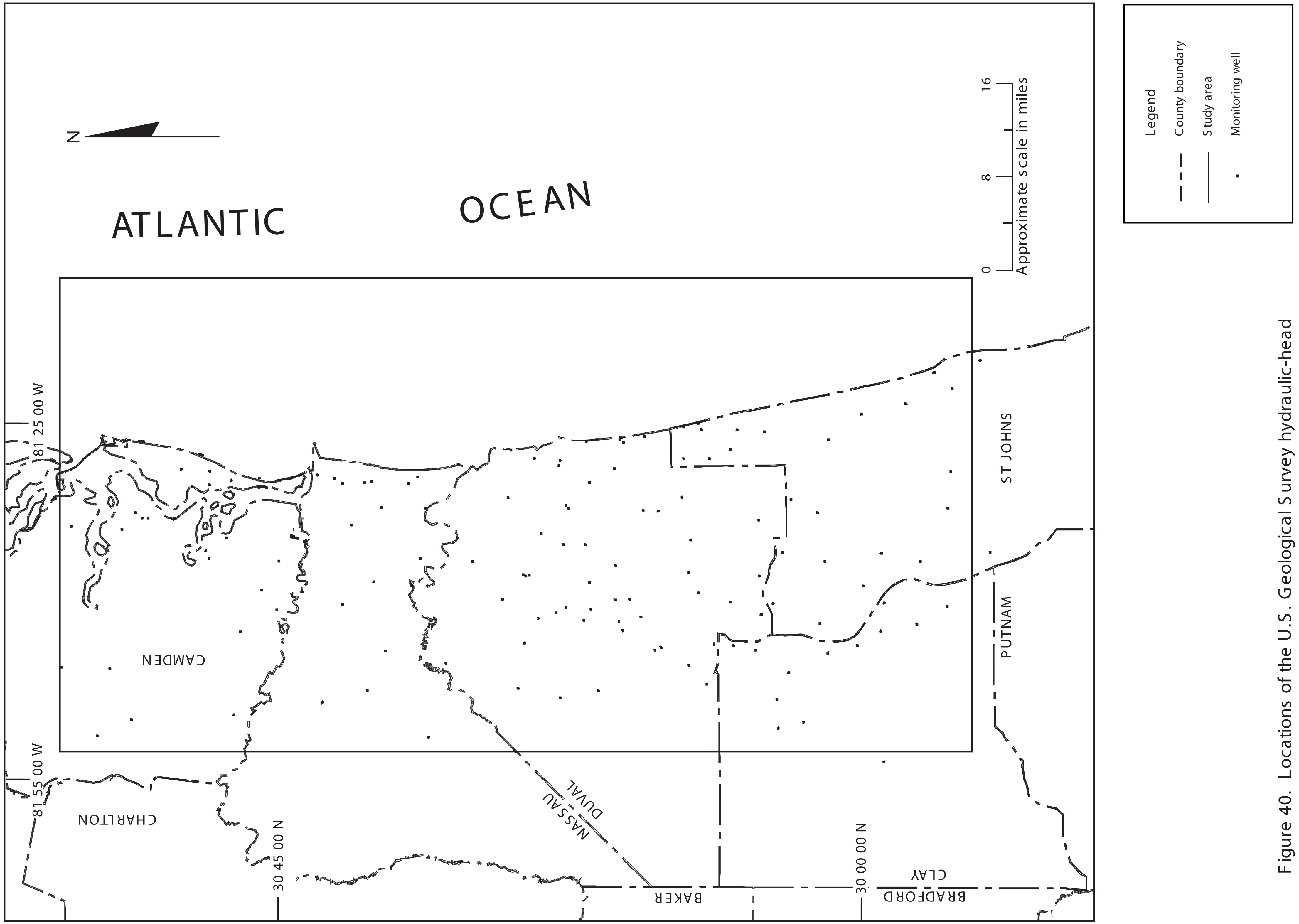


Figure 40. Locations of the U.S. Geological Survey hydraulic-head monitoring wells in the Upper Floridan aquifer in 1985

than or equal to 5 ft was 82.4. These values are more comparable to the statistics that were based on the values of hydraulic head interpolated from the map of the potentiometric surface of the Upper Floridan aquifer (Figure 36).

In addition to comparisons of values of hydraulic head in the Upper Floridan aquifer, simulated values of hydraulic head were compared to values observed or estimated based on observations in nearby monitoring wells in the Lower Floridan aquifer and the Fernandina permeable zone (respectively, Tables 3 and 4).

The model was calibrated also by comparing visually the normalized-interface maps of the Upper and Lower Floridan aquifers and the Fernandina permeable zone (Figures 41a, 42a, and 43a) to corresponding maps that were based on the simulated elevations of the interface (Figures 41b, 42b, and 43b). The 1985 position of the interface differed very little with that of the predevelopment position of the interface. This result is consistent with the assumption of little or no interface movement between the end of the predevelopment period and 1985.

2010 Version of the Model

The 2010 version of the model is identical to the 1985 version in every respect except in the representation of groundwater withdrawals. Estimates of the locations and rates of groundwater withdrawals in 2010 in the present model are identical to those specified in the MODFLOW model of Durden (1997). Approximately 44.1 million cubic feet per day of groundwater withdrawals from the Upper and Lower Floridan aquifers are represented in the 2010 version of the model (Figures 44a and 44b). A detailed discussion of the projection of groundwater withdrawals to the year 2010 may be found in Durden (1997).

Identical lateral boundary conditions of the 1985 version were applied to the version 2010 model. It was assumed that changes in fresh- and saltwater hydraulic heads and interface elevations at the lateral boundaries of the model are relatively small.

Table 3. Hydraulic-head residuals in the Lower Floridan aquifer (layer 2) of the 1985 model version at nodes corresponding to locations of observation wells

Node Number	USGS Well Identification Number	SJRWMD Well Identification Number	Location		Model Coordinates		Date of Observation	Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (feet)
			Latitude	Longitude	Row	Column				
3366	302227081435001	D-0592	30 22 27	81 43 50	29	6	10/06/86	39.1[a]	38.3	0.8
3120	301537081441901	D-0075	30 15 37	81 44 19	22	5	10/06/86	32.3[a]	40.6	-8.3
3129	301604081361501	D-0450	30 16 04	81 36 15	22	14	10/06/86	38.1[a]	35.7	2.4
3167	301639081330802	D-1155	30 16 39	81 33 08	23	17	10/06/86	35.7[a]	34.6	1.1
3002	301132081225801	SJ-0025	30 11 32	81 22 58	18	27	Aug.–Oct. 1985	38.1[b]	33.6	4.5
3351	302159081235601	D-2386	30 21 59	81 23 56	28	26	Nov. 1980–July 1981	34.9[c]	33.0	1.9
3307	302052081323201	D-3060	30 20 52	81 32 32	27	17	Oct. 1982–Feb. 1983	33.7[d]	33.7	0.0

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

[a]Observations reported in Brown et al. 1986.
[b]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1986.
[c]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1984.
[d]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1985.

Table 4. Hydraulic-head residuals in the Fernandina permeable zone (layer 1) of the 1985 model version at nodes corresponding to locations of observation wells

Node Number	USGS Well Identification Number	SJRWMD Well Identification Number	Location		Model Coordinates		Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (feet)
			Latitude	Longitude	Row	Column			
622	301132081225801	SJ-0025	30 11 32	81 22 58	18	27	38.6[a]	35.3	3.3
971	302159081235601	D-2386	30 21 59	81 23 56	28	26	34.6[b]	35.0	-0.4
927	302052081323201	D-3060	30 20 52	81 32 32	27	17	32.8[c]	36.0	-3.2
792	304001081280301	N-0117	30 40 01	81 28 03	23	22	42.8[d]	38.6	4.2
852	301817081374902	D-425B	30 18 17	81 37 49	25	12	38.2[e]	37.4	0.8

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

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

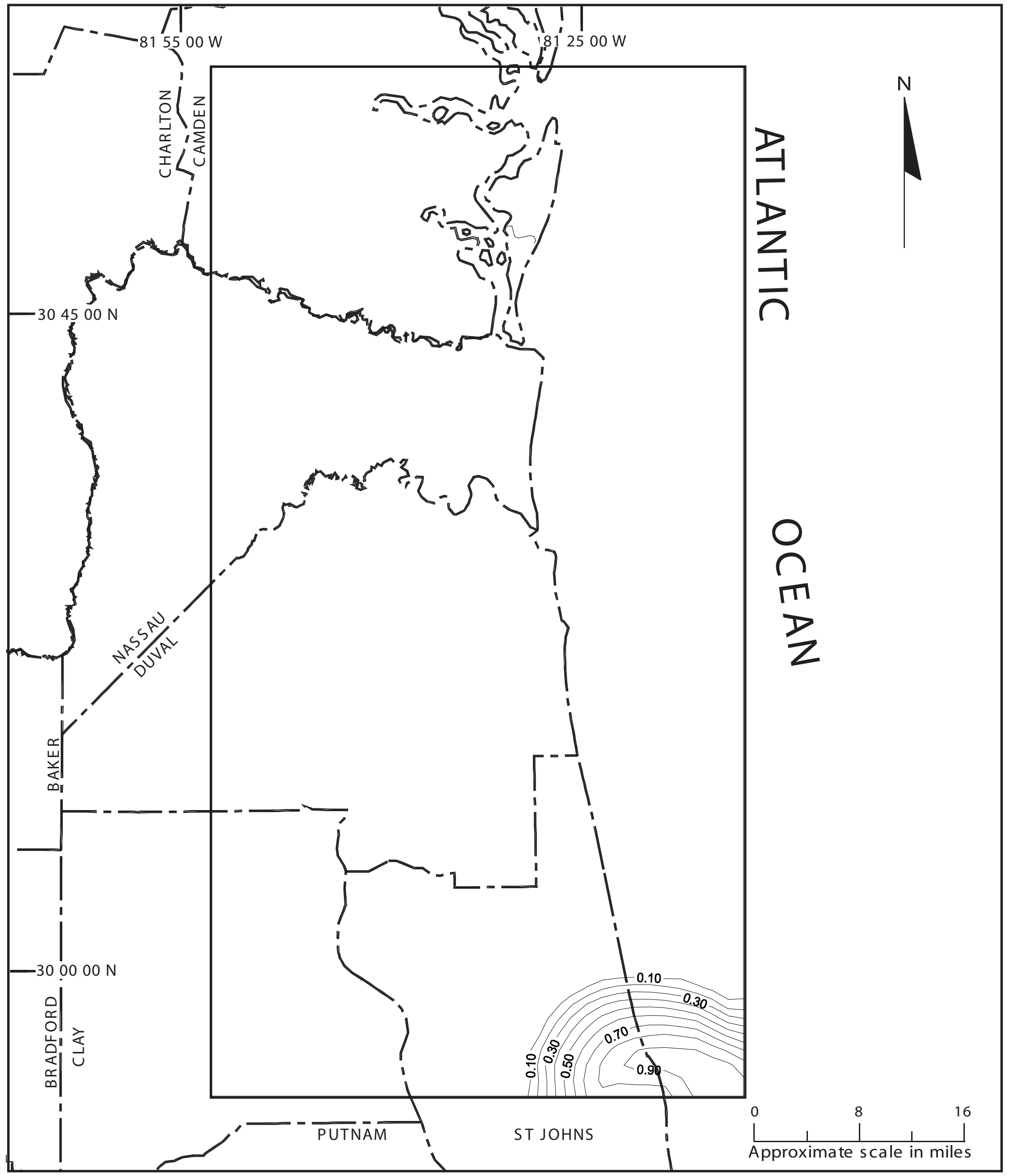


Figure 41a. Estimated normalized interface plot of the Upper Floridan aquifer

Legend

County boundary

0.90 Line of equal percentage of occupation (decimal percent)

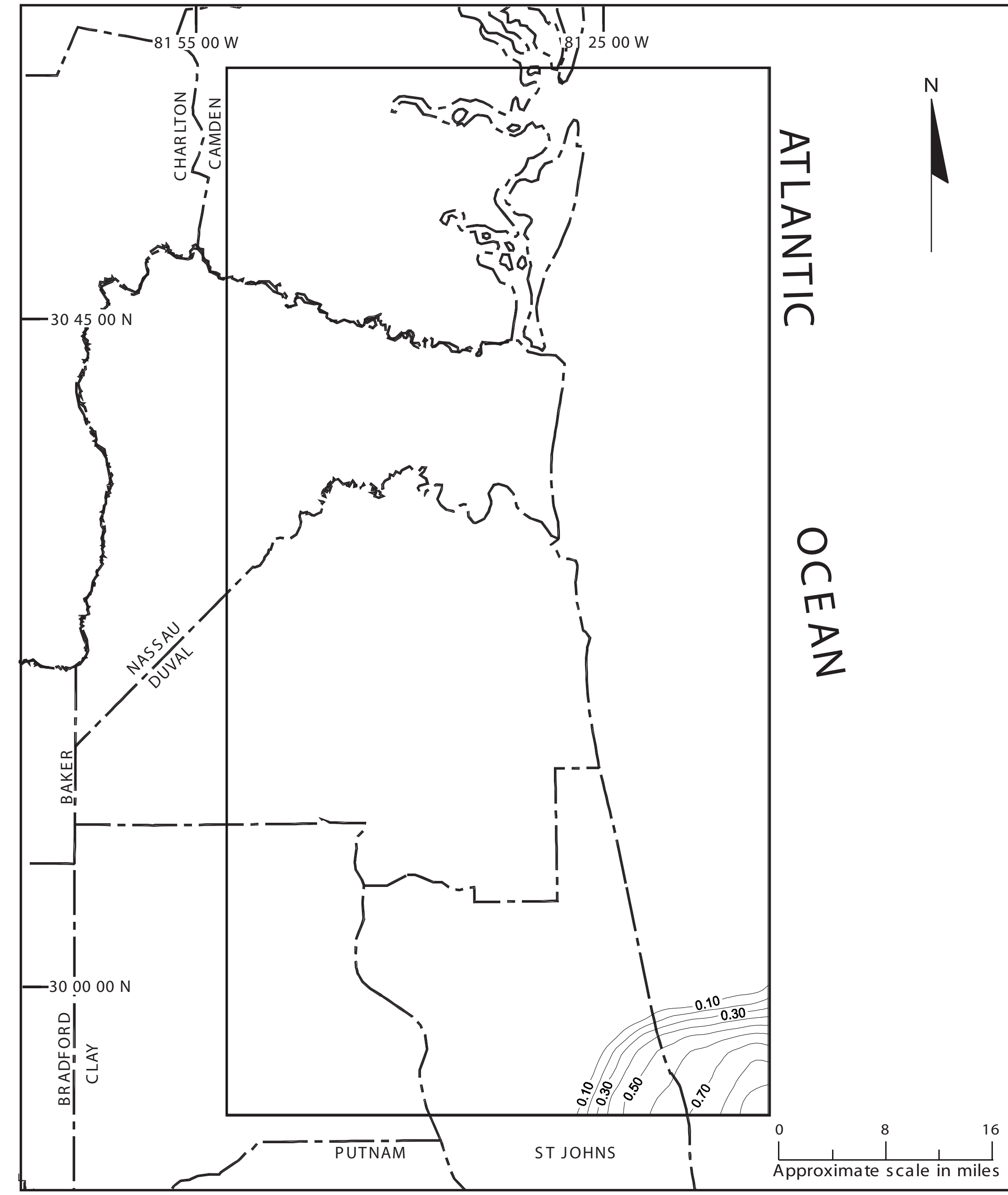


Figure 41b. Simulated 1985 normalized interface of the Upper Floridan aquifer

Legend

County boundary

0.70 Line of equal percentage of occupation (decimal percent)

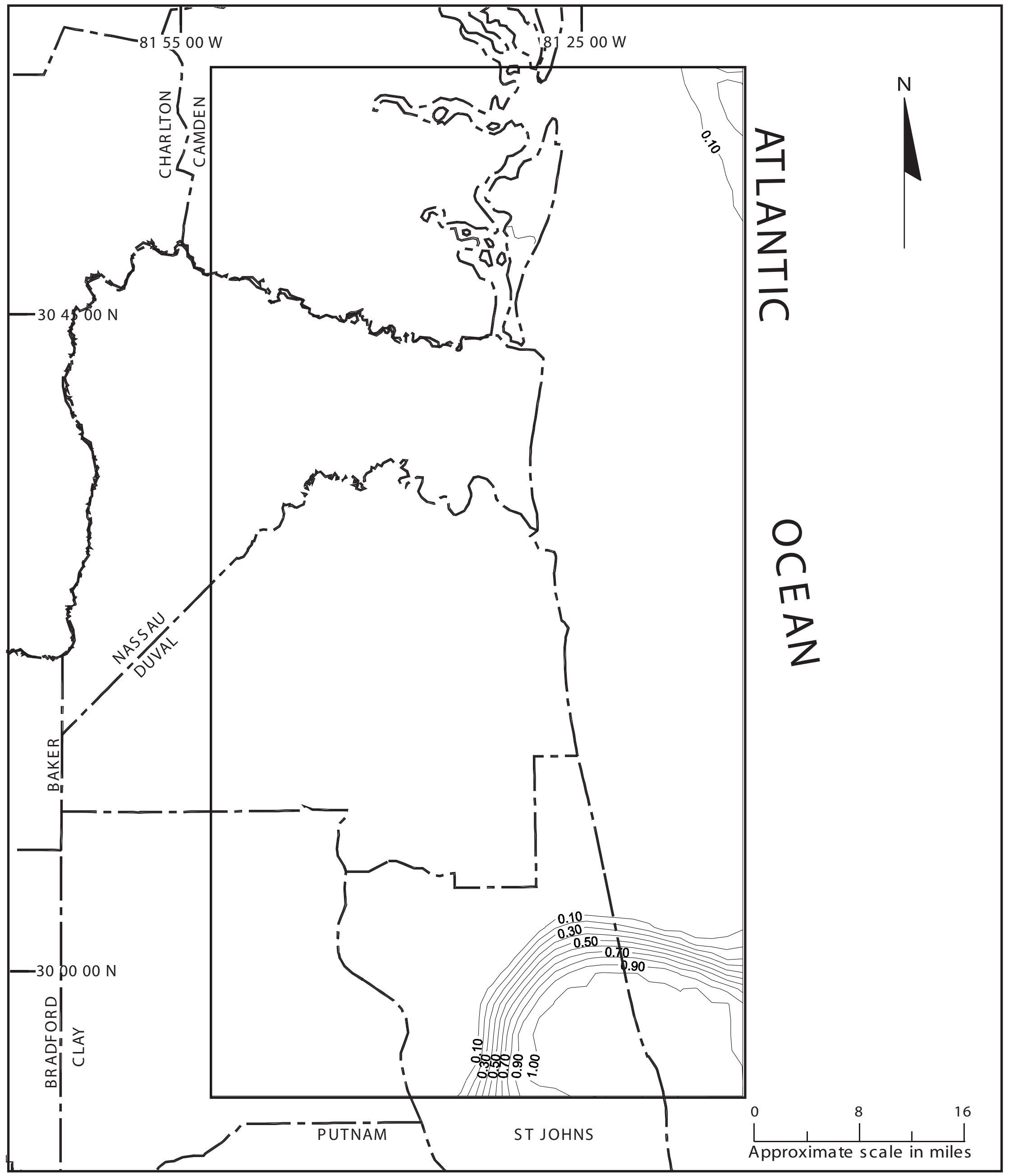


Figure 42a. Estimated normalized interface plot of the Lower Floridan aquifer

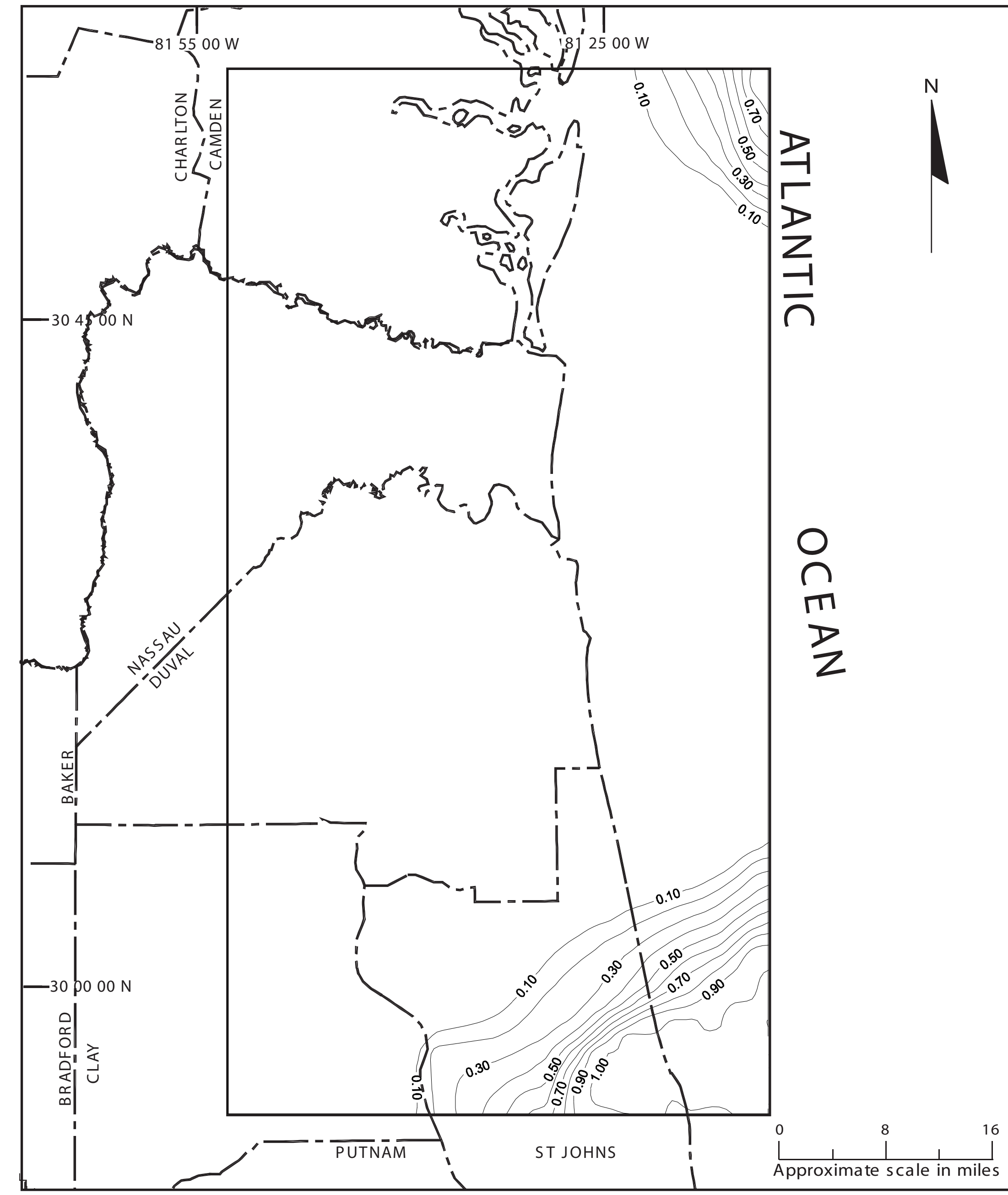


Figure 42b. Simulated 1985 normalized interface of the Lower Floridan aquifer

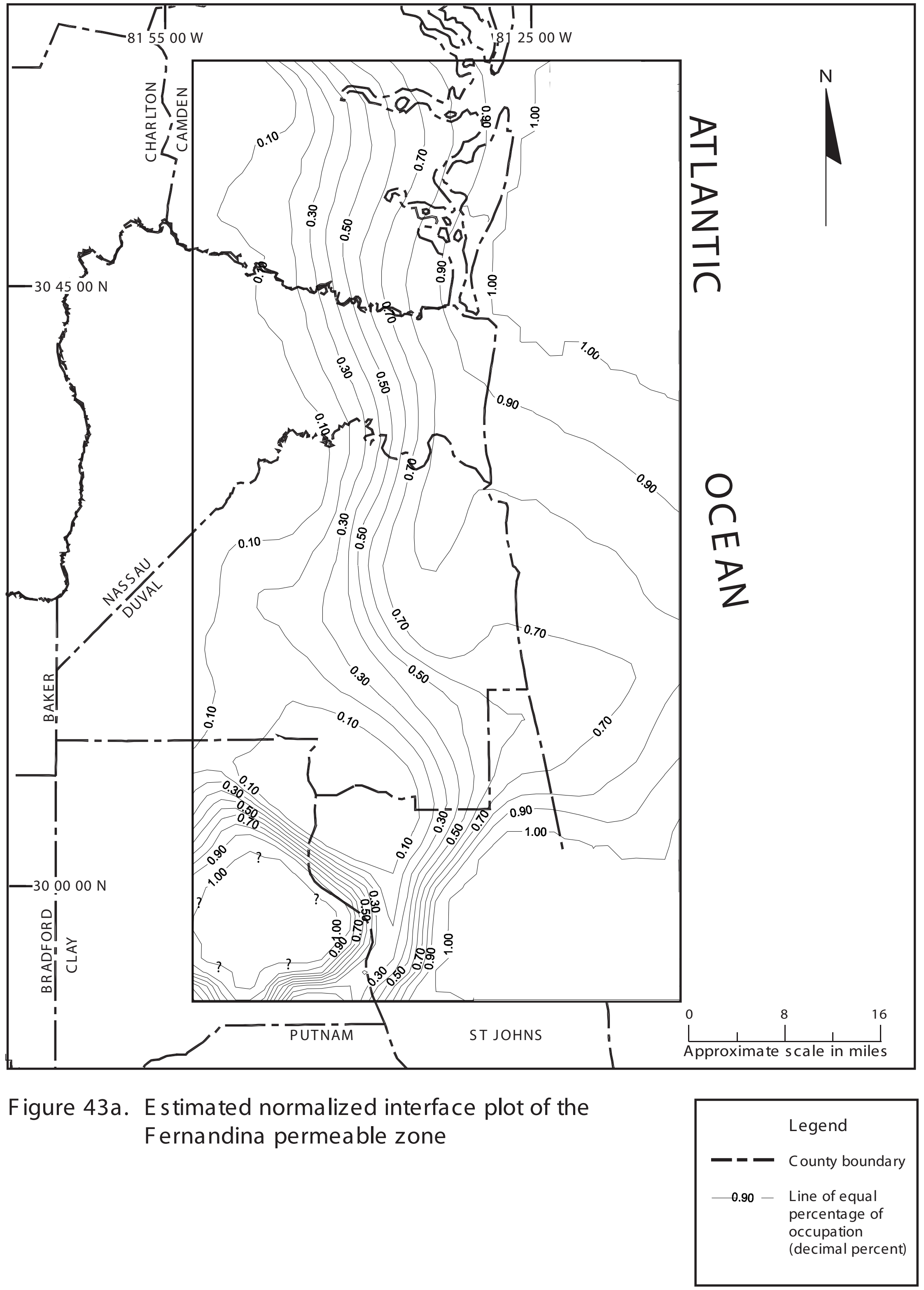


Figure 43a. Estimated normalized interface plot of the Fernandina permeable zone

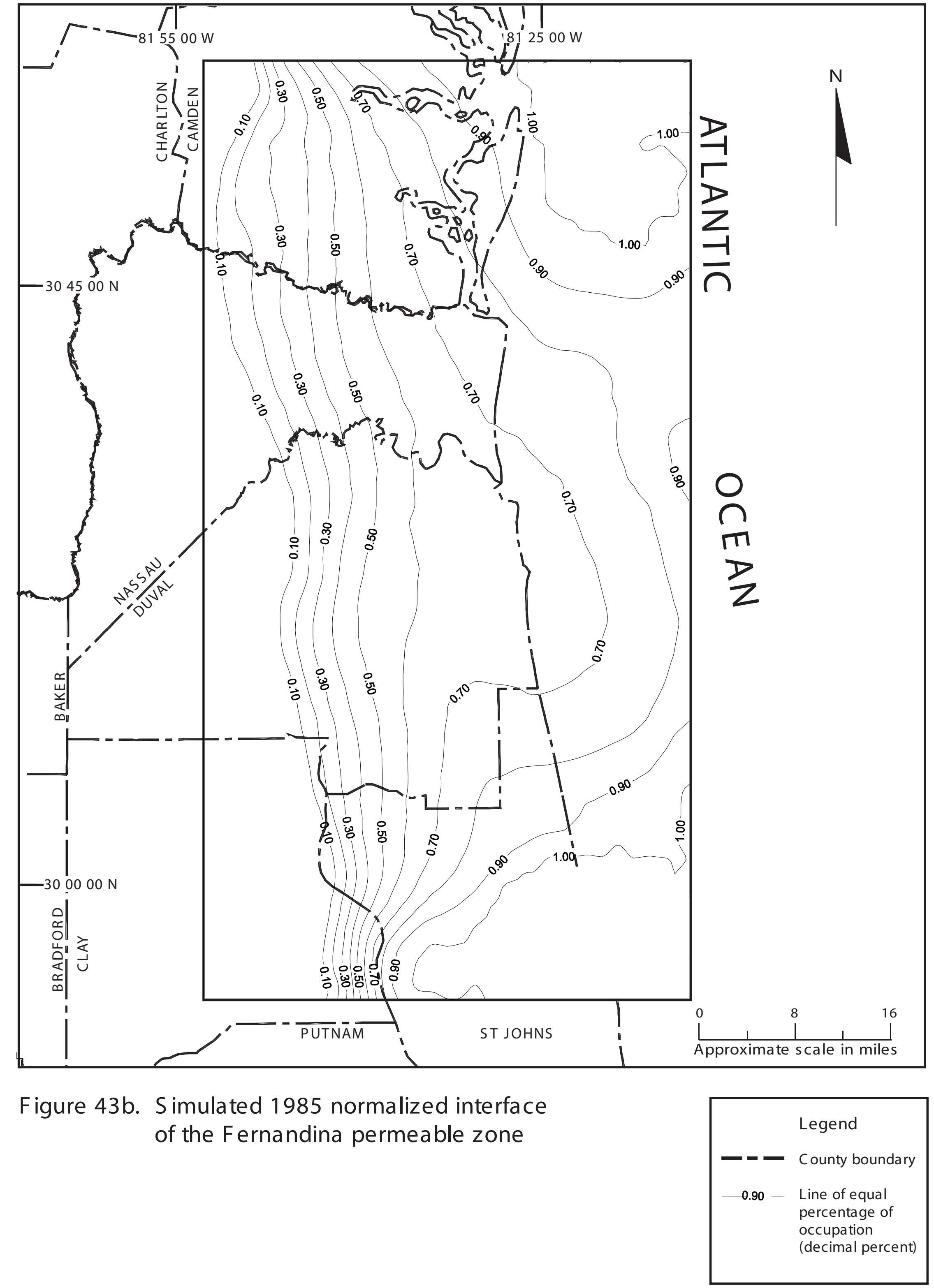


Figure 43b. Simulated 1985 normalized interface of the Fernandina permeable zone

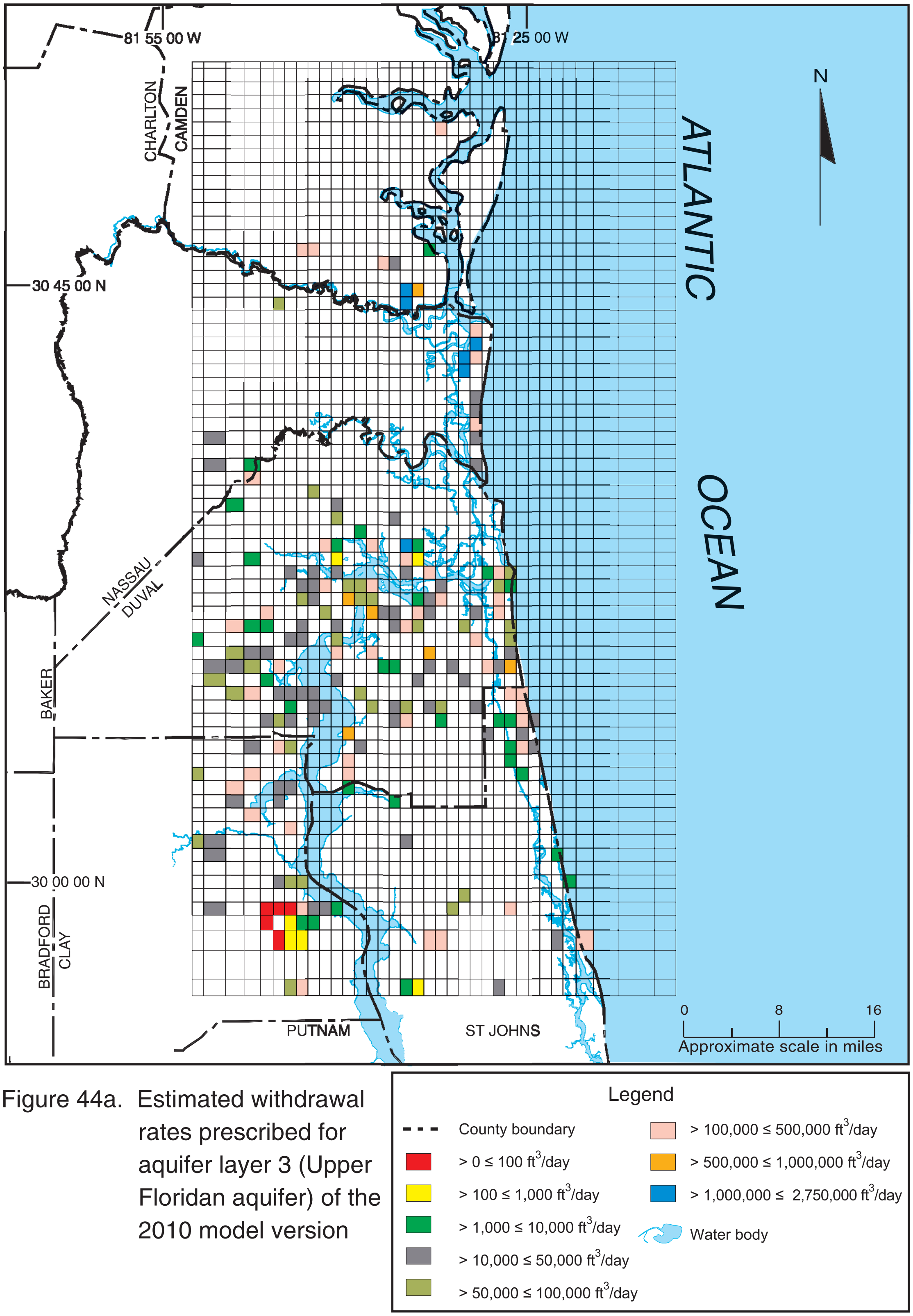


Figure 44a. Estimated withdrawal rates prescribed for aquifer layer 3 (Upper Floridan aquifer) of the 2010 model version

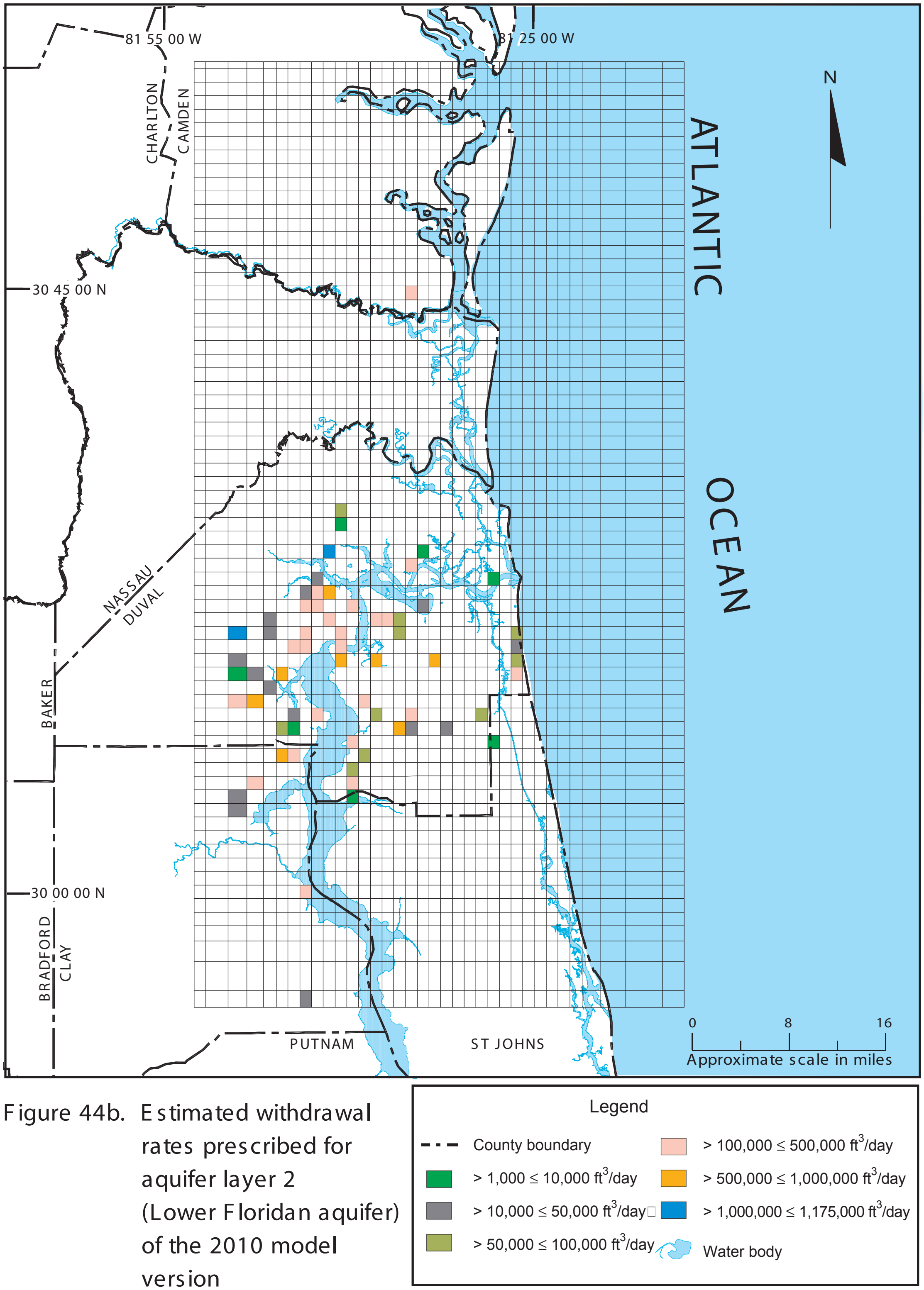


Figure 44b. Estimated withdrawal rates prescribed for aquifer layer 2 (Lower Floridan aquifer) of the 2010 model version

BASE-CASE AND UNCERTAINTY SIMULATIONS

Hereafter, the calibrated predevelopment, 1985, and 2010 versions of the model are referred to collectively as the base-case model. An uncertainty analysis of the base-case model was performed to determine a range of possible behavior of the Floridan aquifer system in response to past, present, and projected groundwater withdrawals (Table 5). In this uncertainty analysis, the selected model parameter was scaled by a uniform multiplication factor or increased or decreased by a constant amount while all other parameters of the model were unchanged. The results of the relative position change on the interface elevations of freshwater and salt water between the uncertainty and base-case simulations were therefore used to determine the impact of the selected parameter change on groundwater system response. The base-case simulation is referred to hereafter as the base case.

In the base case and in each of the uncertainty analyses, the predevelopment versions of the model were run initially to steady-state to represent the 1885 hydrologic conditions in the groundwater system. The results of the predevelopment simulations (i.e., the simulated values of fresh- and saltwater hydraulic head and interface elevations of the final time-step of the simulation) were specified as initial conditions for subsequent runs of the 1985 versions of the model. The 1985 versions of the model were run for a simulated period of 100 years to simulate, in approximate fashion, the effects of groundwater withdrawals that occurred between the end of the predevelopment period and 1985. The results of the simulations of the 1985 versions of the model were specified as initial conditions for the subsequent runs of the 2010 versions of the model, which were run for simulated periods of 8,000 years. In this approach, pumping in the period between roughly 1885 and 1985 was represented by estimated 1985 groundwater withdrawals. Pumping in the period after 1985 was represented by projected 2010 groundwater withdrawals. This approach results in a conservative representation of the effects of groundwater withdrawals in the period of 1885–1985 because actual withdrawal rates during most of that period were less than 1985 values. Two groundwater withdrawal scenarios after 1985 are included in the uncertainty analysis.

Two cross sections were specified to represent the results of the base case and the uncertainty simulations, an east-west cross section and a south-north cross section. The west-east (W-E) cross section corresponds to nodal row 27,

Table 5. Summary of uncertainty simulations

Uncertainty Simulation	Type of Change Relative to Base Case	Results of Change Relative to Base Case
1	Horizontal intrinsic permeability, aquifer layer 1, multiplied by 15	Predevelopment interface elevation lower. Rate of interface movement much higher. Thus, year 9985 interface position about same
2	Horizontal permeability, aquifer layer 2, multiplied by 0.5	Predevelopment interface elevation in aquifer layer 1 much higher; extends farther north in southern region of model domain. Rate of increase in interface elevation much greater in aquifer layer 2. “Spiking” of interface in response to local pumping effects apparent in later time-steps
3	Horizontal permeability, aquifer layer 3, multiplied by 0.5	Predevelopment interface slightly lower. Rate of increase in interface elevation about the same
4	Horizontal permeability, aquifer layer 3, multiplied by 2	Predevelopment interface somewhat higher. Rate of increase in interface elevation about the same
5	Vertical leakage factors, semiconfining unit layer 3, multiplied by 0.5	Predevelopment interface generally lower. Rate of increase in interface elevation about the same at most locations; greater in southern portion of aquifer layer 1
6	Vertical leakage factors, semiconfining unit layer 3, multiplied by 2	Predevelopment interface generally higher. Rate of increase in interface elevation greater. Spiking apparent on year 9985 interface
7	Water table and surface water elevations multiplied by 0.85	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
8	Water table and surface water elevations multiplied by 1.15	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
9	Vertical leakage factors, semiconfining unit layer 1, multiplied by 0.5	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
10	Vertical leakage factors, semiconfining unit layer 1, multiplied by 2	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
11	Vertical leakage factors, semiconfining unit layer 2, multiplied by 0.5	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
12	Vertical leakage factors, semiconfining unit layer 2, multiplied by 2	Predevelopment interface at about the same location. Rate of increase in interface elevation about the same
13	Freshwater GHFB-condition source heads multiplied by 0.85	Predevelopment interface much higher. Rate of increase in interface elevation much greater. Much intrusion in aquifer layer 2. Spiking apparent at later time-steps in aquifer layer 2
14	Freshwater GHFB-condition source heads multiplied by 1.15	Predevelopment interface much lower. Rate of increase in interface elevation somewhat lower. Interface location much farther to south at year 9985

Table 5—*Continued*

Uncertainty Simulation	Type of Change Relative to Base Case	Results of Change Relative to Base Case
15	Saltwater GHFB-condition source heads decreased by 2.0 ft	Predevelopment interface lower. Rate of increase in interface elevation about the same
16	Saltwater GHFB-condition source heads increased by 2.0 ft	Predevelopment interface higher. Rate of increase in interface elevation about the same
17	Aquifer volume compressibility multiplied by 0.1	Predevelopment interface unaffected. Rate of increase in interface elevation virtually unaffected
18	Aquifer volume compressibility multiplied by 10	Predevelopment interface unaffected. Rate of increase in interface elevation virtually unaffected
19	Aquifer effective porosity multiplied by 0.5	Predevelopment interface unaffected. Rate of increase in interface elevation approximately doubled
20	Aquifer effective porosity multiplied by 2	Predevelopment interface unaffected. Rate of increase in interface elevation approximately halved
21	Projected 2010 withdrawal rates multiplied by 0.85	Predevelopment interface unaffected. Rate of increase in interface elevation slightly less
22	Projected 2010 withdrawal rates multiplied by 1.15	Predevelopment interface unaffected. Rate of increase in interface elevation higher. Some spiking apparent
23	Replacement of saltwater GHFB-condition source heads in excess of 0 ft NGVD with value of 0 ft NGVD	Predevelopment interface much lower. Rate of increase in interface elevation generally greater

Note: GHFB = general head-dependent flux boundary
ft NGVD = feet, National Geodetic Vertical Datum

and the south-north (S-N) cross section corresponds to nodal column 20 (Figure 45). These cross sections were selected because they are located centrally with respect to the boundaries of the model domain and because they pass through areas of concentrated groundwater withdrawals.

DESCRIPTION OF THE BASE CASE

In the base case simulation, salt water located in the Lower Floridan aquifer in the areas of northern and central St. Johns County is found to move laterally as far north as Jacksonville over the next 8,000 years. The movement of salt water laterally and vertically in the areas of northern and central St. Johns County is projected to be generally greater than in other areas, probably because salt water in that area is closer to the bottom of well intakes. Along the S-N (row 27) cross section (Figure 46a), the maximum amount of vertical movement over the 8,000-year simulation is projected to be

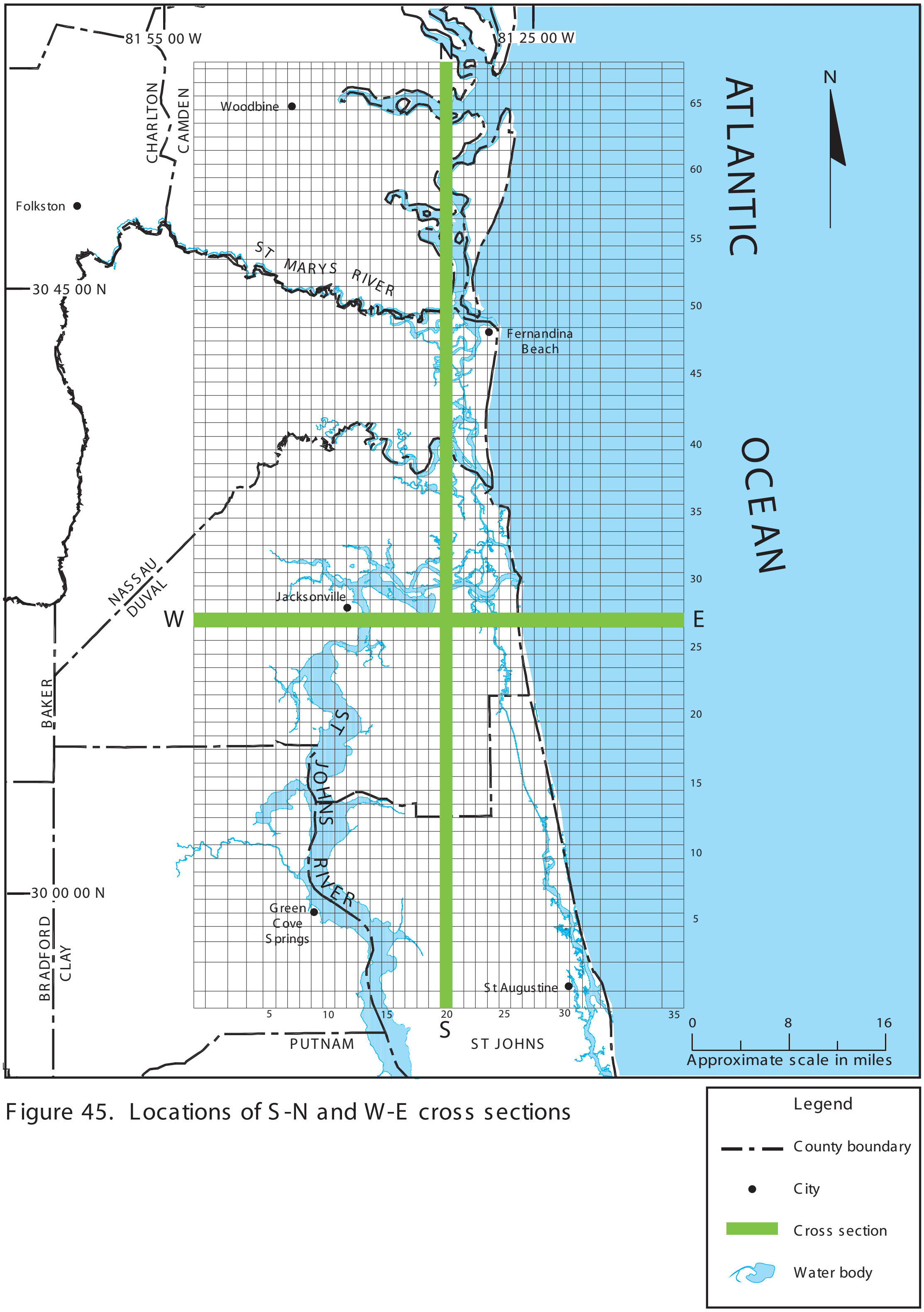


Figure 45. Locations of S-N and W-E cross sections

approximately 270 ft in the Fernandina permeable zone. In the Lower Floridan aquifer, the interface is projected to move laterally a distance of approximately 23 miles from the northern and central areas of St. Johns County in the south to the area of Jacksonville in the north over the 8,000-year period between 1985 and 9985. A similar amount of lateral encroachment is projected to occur in the Fernandina permeable zone.

Along the W-E (column 20) cross section (Figure 46b), the maximum amount of vertical movement is projected to be approximately 280 ft in the Fernandina permeable zone. However, no significant lateral movement was observed at W-E cross sections in the Lower Floridan aquifer or the Fernandina permeable zone. In the part of the study area north of Fernandina Beach, salt water in the Fernandina permeable zone and the Lower Floridan aquifer is projected to intrude laterally from the east. The maximum amount of saltwater intrusion in that general area is projected to occur along a line corresponding to nodal row 68 (Figure 47). Along that line, salt water is projected to intrude approximately 8 miles into the Fernandina permeable zone and 10 miles into the Lower Floridan aquifer over the next 8,000 years. No significant vertical movement was observed in the Fernandina permeable zone.

In the areas of Ponte Vedra Beach and Orange Park, a significant amount of both lateral and vertical intrusion is projected to occur. Along a line corresponding to nodal row 14 (Figure 48), salt water in the Lower Floridan aquifer is projected to intrude from east to west a distance of approximately 25 miles and to move vertically a maximum of about 225 ft. Along the same east-west segment, the interface in the Fernandina permeable zone is projected to move vertically a maximum of about 235 ft. No significant lateral interface movement was observed in the Fernandina permeable zone. The body of salt water located in northern and central St. Johns County will serve partly as a source of lateral intrusion to this area, as will offshore areas beneath the Atlantic Ocean.

The most widespread vertical movement is projected to occur in the Jacksonville area, primarily in the area between the St. Johns River and the Atlantic coast just south of the east-west reach of the river. The projected vertical movement in this area is sufficiently widespread to be described as subregional in nature. The maximum amount of vertical movement of the interface in this area is projected to be a little less than 300 ft (Figures 46a and 46b).

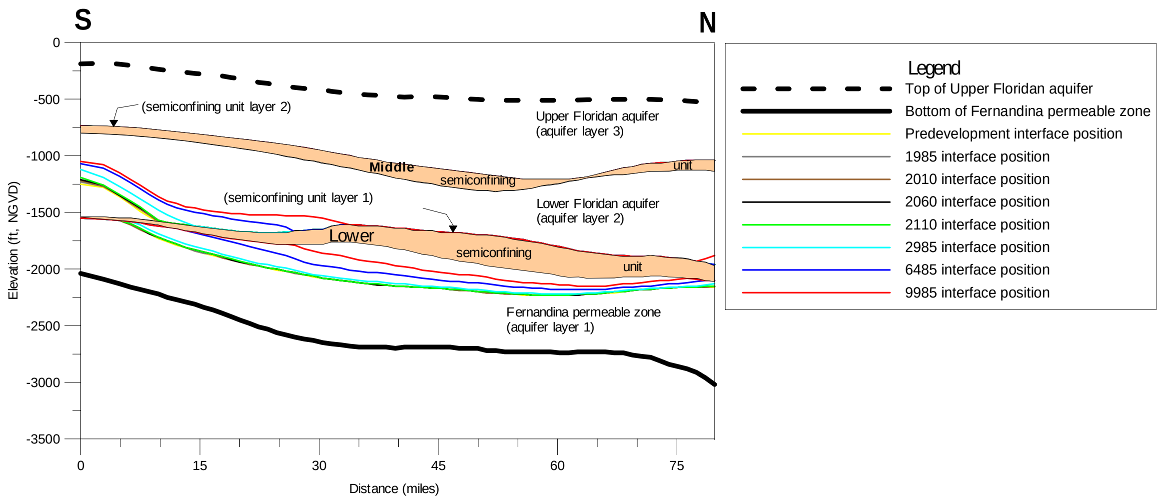


Figure 46a. Simulated interface movement along S-N cross section in base-case model

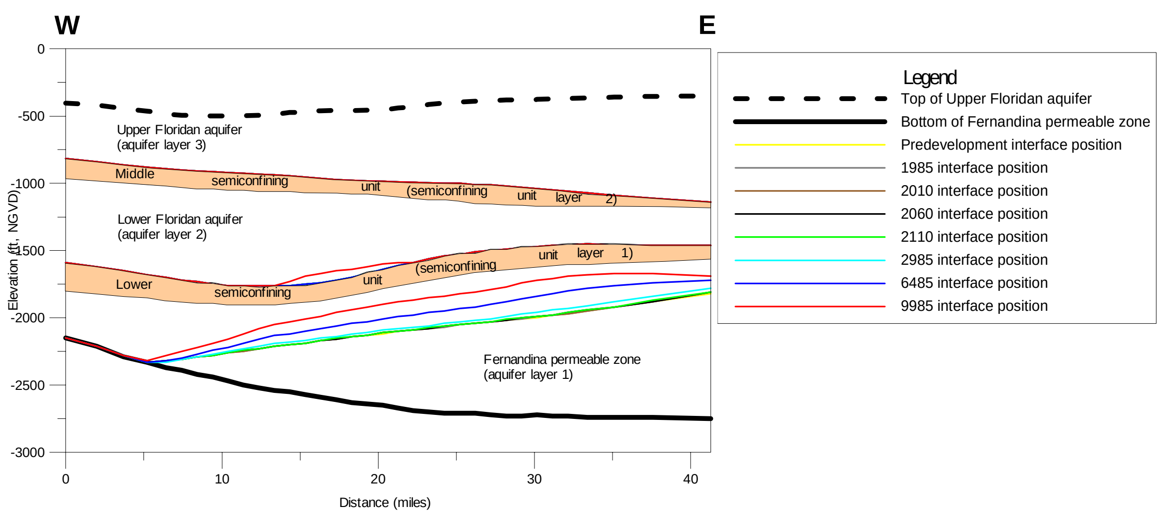


Figure 46b. Simulated interface movement along W-E cross section in base-case model

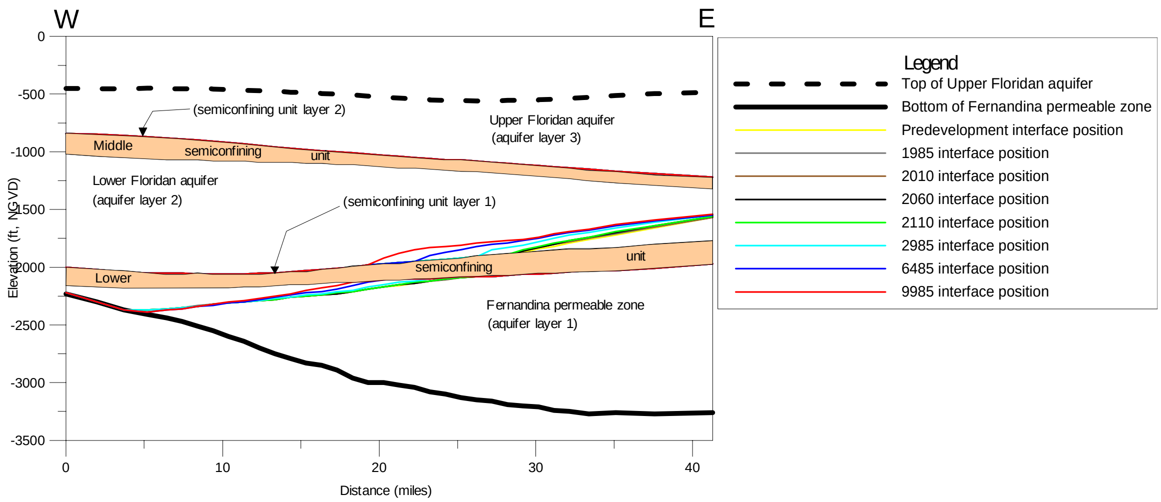


Figure 47. Simulated interface movement along nodal row 68 in base-case model

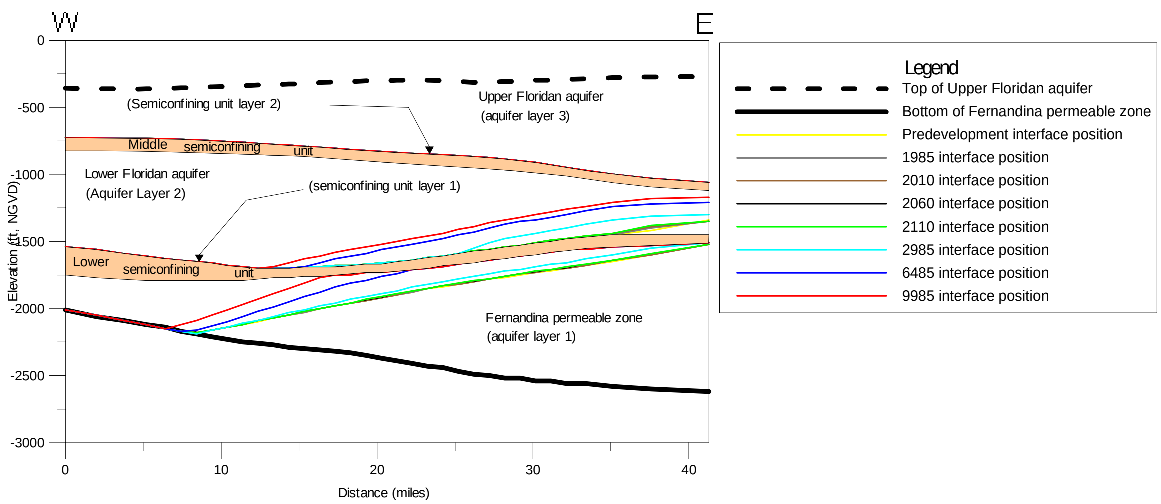


Figure 48. Simulated interface movement along nodal row 14 in base-case model

As stated previously, the Upper Floridan aquifer is projected to remain relatively free of saltwater encroachment throughout the study area over the next 8,000 years. The area of northern and central St. Johns County in the southeast corner of the study area, however, is an exception. In that area, vertical movement on the order of 150 ft and lateral intrusion of as much as 4 miles from south to north in the Upper Floridan aquifer is projected to occur over the next 8,000 years (Figure 49).

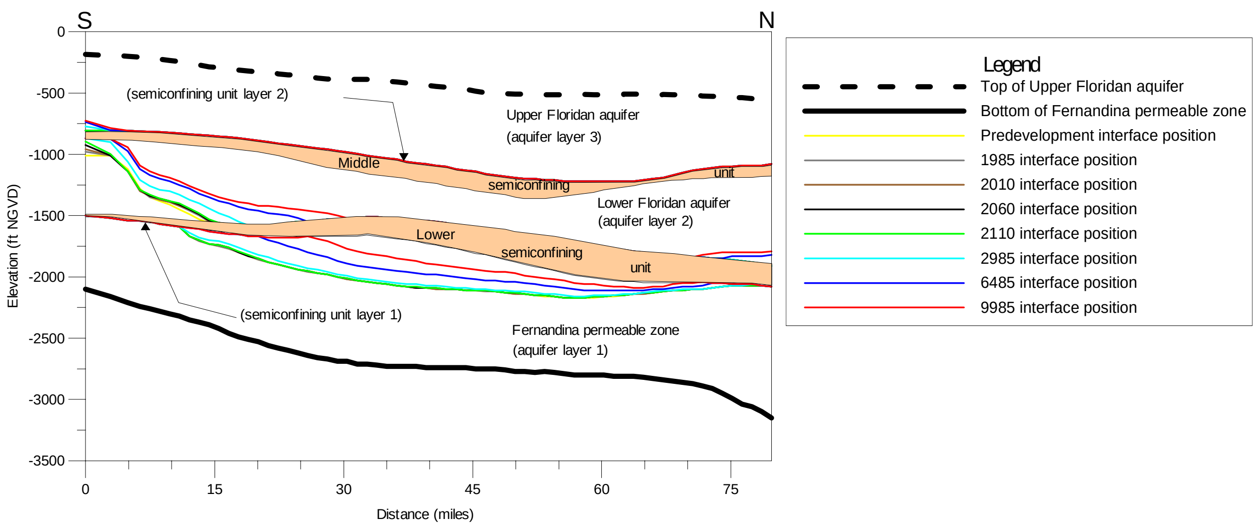


Figure 49. Simulated interface movement along nodal column 25 in base-case model

DESCRIPTIONS OF UNCERTAINTY SIMULATIONS

Uncertainty Simulation 1

In uncertainty simulation 1, the horizontal intrinsic permeability of the Fernandina permeable zone (layer 1) was multiplied by a factor of 15. The values of horizontal intrinsic permeability assigned to aquifer layer 1 are generally low as compared to the values assigned to the Lower Floridan (layer 2) and Upper Floridan (layer 3) aquifers. Expressed as hydraulic conductivity, the arithmetic mean of the values assigned to aquifer layer 1 is 11.6 ft / day, while the means of the values assigned to aquifer layers 2 and 3 are 613 and 122 ft / day, respectively (Figures 33–35). Aquifer performance tests have not been performed on the Fernandina permeable zone; thus, comparisons of the assigned values to the results of such tests are not possible. However, estimates based on the results of tests performed on the Upper Floridan aquifer are generally higher than most of the values assigned to the Fernandina permeable zone. The multiplication factor of 15 was designed to bring the values of horizontal intrinsic permeability assigned to aquifer layer 1 into greater accordance with values observed typically in the Upper Floridan aquifer.

The model results of this uncertainty simulation indicated that the steady-state, predevelopment interface in aquifer layer 1 (Figures 50a and 50b) along both the S-N and W-E cross sections is lower in vertical movement than at corresponding positions in the base-case model (Figures 46a and 46b). The differences in the positions of the predevelopment interface of the present uncertainty simulation (Figure 50a) and that of the base case (Figure 46a) are most pronounced near the southern and northern ends of the S-N cross section. The predevelopment interface in aquifer layer 2 is also somewhat lower than in the base case but not as much as in aquifer layer 1.

While the predevelopment interface is generally lower in elevation in uncertainty simulation 1 than in the base case, the rate of increase in the elevation of the interface over the 8,100-year simulation period is considerably greater in both the S-N and W-E cross sections. Therefore, the position of the interface in aquifer layer 1 at the end of the 8,100-year simulation period is generally higher than in the base case. The rate of lateral movement of the interface in aquifer layer 2 is increased, but less than the increase in aquifer layer 1. The uncertainty model results indicated that at the end of the 8,100-year simulation period, the location of the interface in aquifer layer 2 in both cross sections is roughly the same as at corresponding positions in the base-case model. No significant impact on the interface position in layer 2 was observed in this uncertainty analysis.

Uncertainty Simulation 2

In uncertainty simulation 2, the horizontal permeability of the Lower Floridan aquifer (layer 2) was multiplied by a factor of 0.5. As a result, the predevelopment interface in the Fernandina permeable zone (layer 1) along both the S-N and W-E cross sections (Figures 51a and 51b) is substantially higher in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). In addition, the predevelopment interface in the Lower Floridan aquifer (layer 2) in the S-N cross section is substantially farther north (Figure 51a).

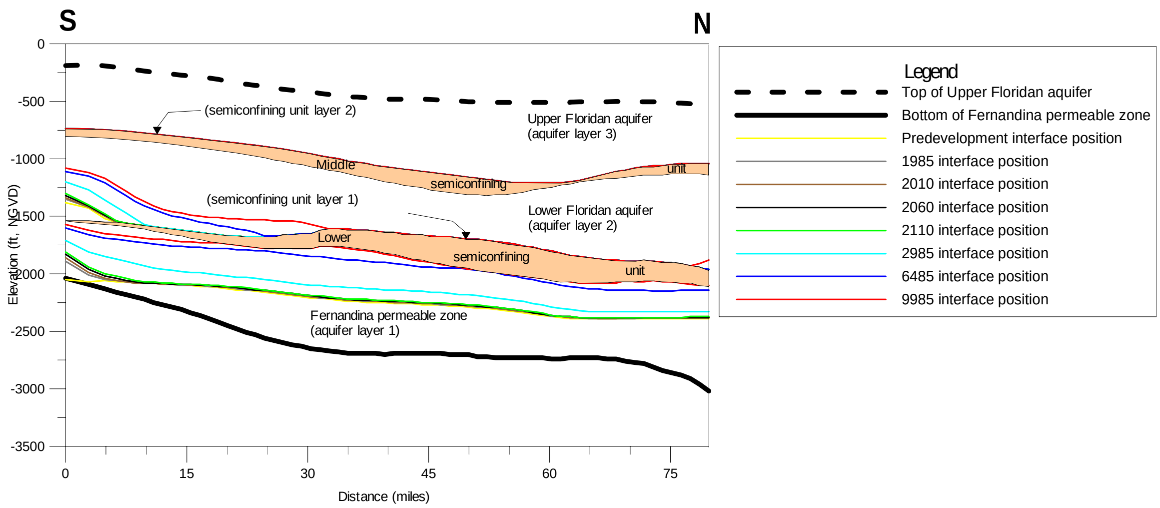


Figure 50a. Simulated interface movement along S-N cross section, uncertainty simulation 1

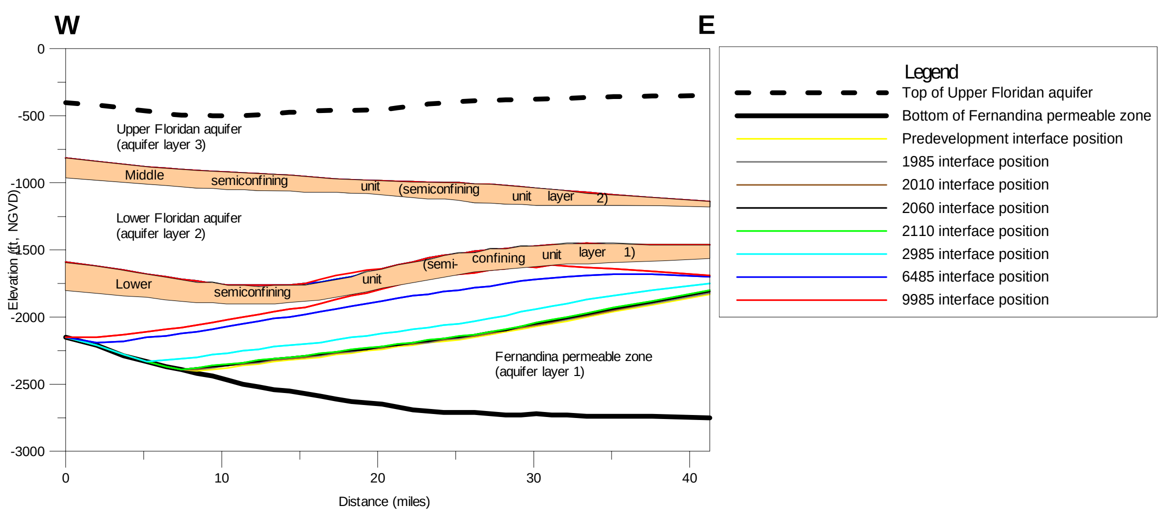


Figure 50b. Simulated interface movement along W-E cross section, uncertainty simulation 1

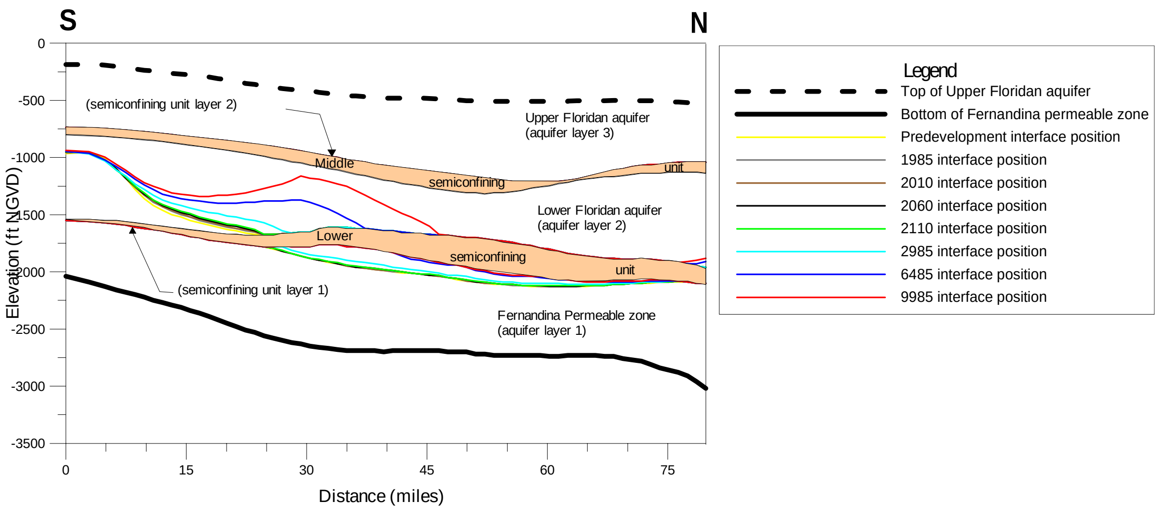


Figure 51a. Simulated interface movement along S-N cross section, uncertainty simulation 2

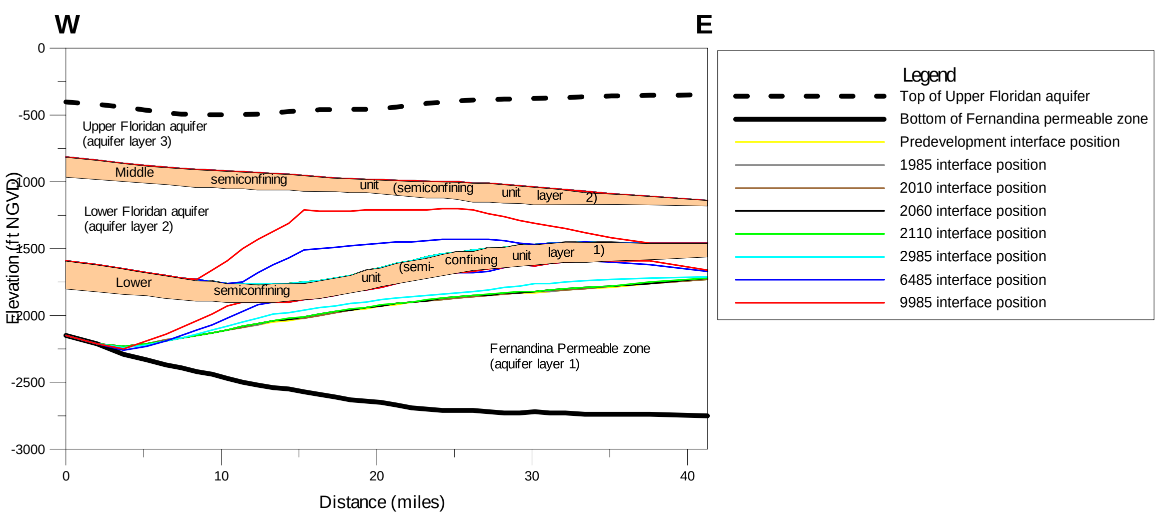


Figure 51b. Simulated interface movement along W-E cross section, uncertainty simulation 2

The difference in the rate of increase in interface elevation in aquifer layer 1 over the simulation period is difficult to judge because in both the S-N and W-E cross sections, the interface starts out close to the bottom of the lower semiconfining unit and ends up coinciding with it. In aquifer layer 2, however, the rate of increase in elevation along both cross sections is greater than in the base case. Along both cross sections, the general rise in the interface in aquifer layer 2 is accentuated by spikes on the line representing the interface in the year 9985. These spikes indicate local responses of the interface to pumping stress of particular wellfields on the aquifer system. Two such spikes are apparent along the W-E cross section and one along the S-N cross section.

Uncertainty Simulation 3

In uncertainty simulation 3, the horizontal permeability of the Upper Floridan aquifer (layer 3) was multiplied by a factor of 0.5. As a result, the predevelopment interface in aquifer layers 1 and 2 along both the S-N and W-E cross sections is only slightly lower in this simulation (Figures 52a and 52b) than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface in both cross sections appears to be approximately the same as in the base case.

Uncertainty Simulation 4

In uncertainty simulation 4, the horizontal permeability of the Upper Floridan aquifer (layer 3) was multiplied by a factor of 2. As a result, the predevelopment interface in aquifer layers 1 and 2 along both cross sections is somewhat higher in this simulation (Figures 53a and 53b) than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface in aquifer layers 1 and 2 over the 8,100-year simulation period appears to be approximately the same as in the base case.

Uncertainty Simulation 5

In uncertainty simulation 5, the vertical leakage factors of semiconfining unit layer 3 (the upper confining unit) were multiplied by a factor of 0.5. As a result, the predevelopment interface (Figures 54a and 54b) in aquifer layers 1 and 2 along both the S-N and W-E cross sections is generally lower in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). The greatest differences in the elevation of the predevelopment

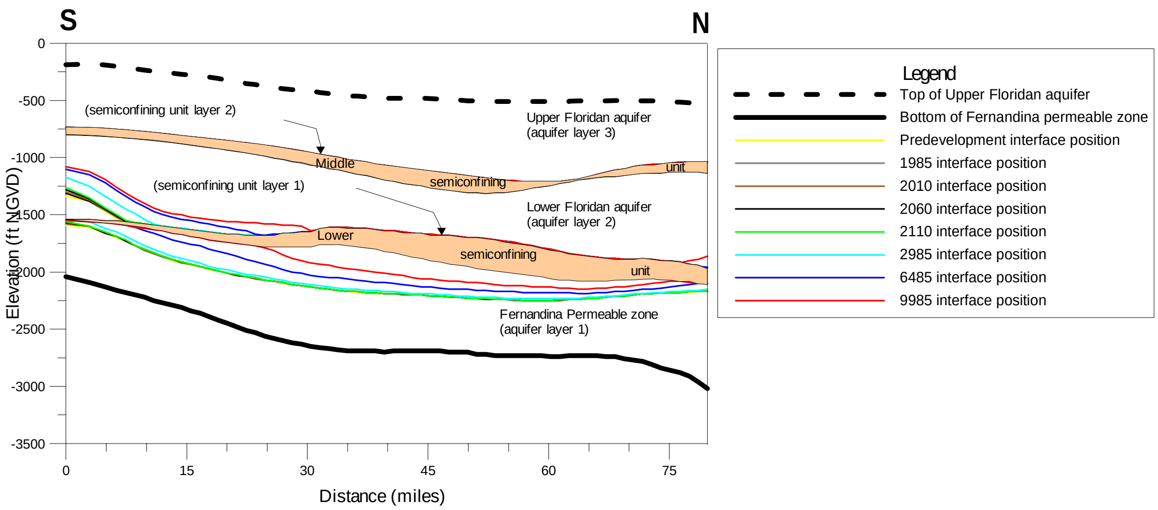


Figure 52a. Simulated interface movement along S-N cross section, uncertainty simulation 3

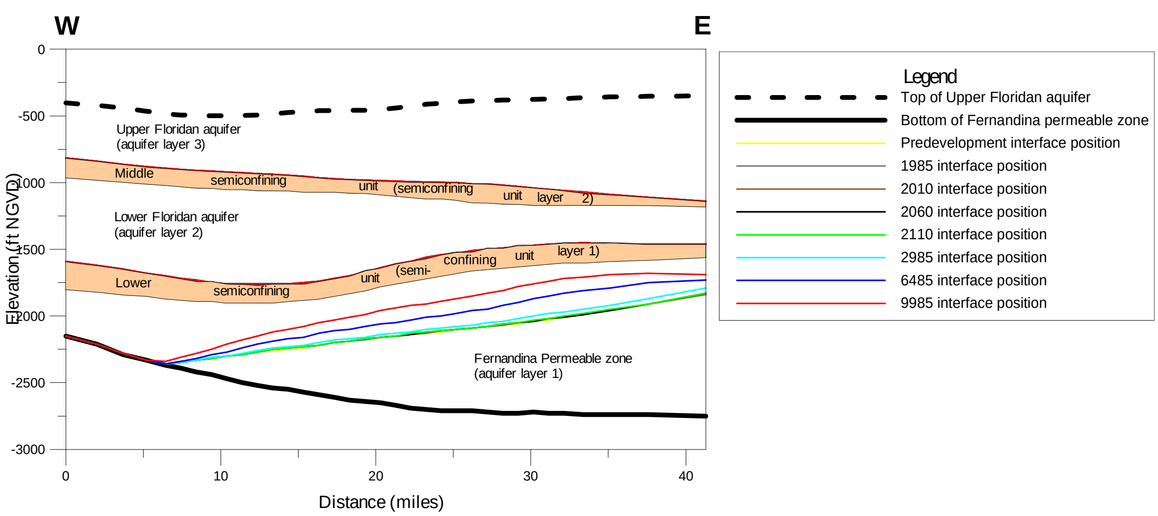


Figure 52b. Simulated interface movement along W-E cross section, uncertainty simulation 3

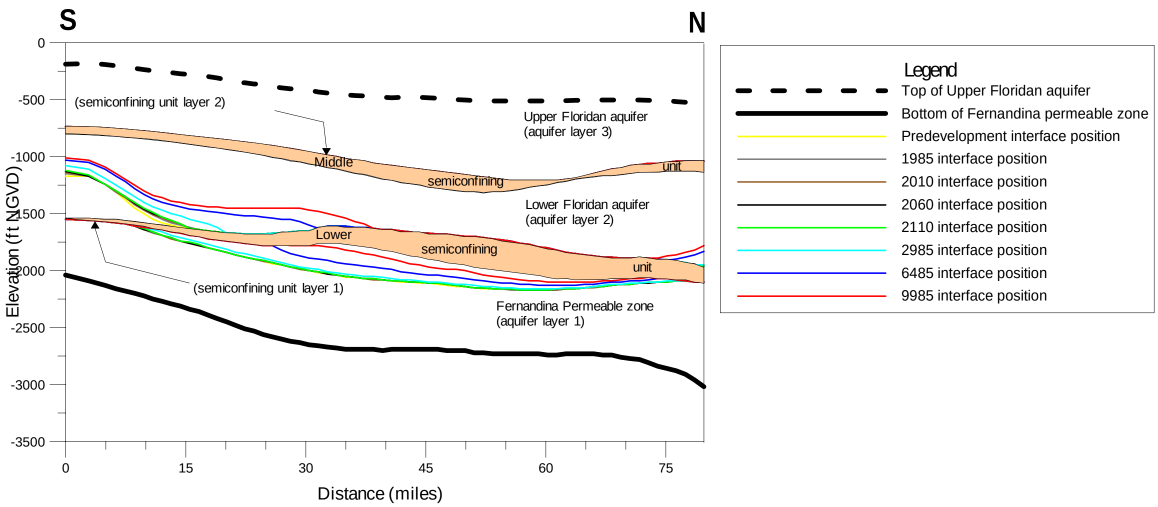


Figure 53a. Simulated interface movement along S-N cross section, uncertainty simulation 4

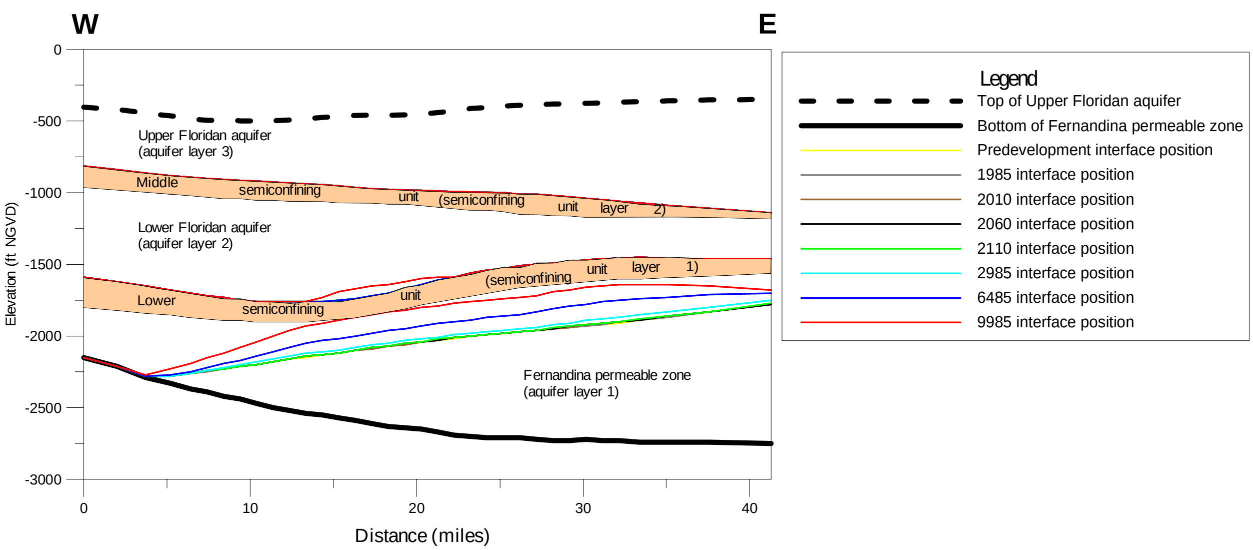


Figure 53b. Simulated interface movement along W-E cross section, uncertainty simulation 4

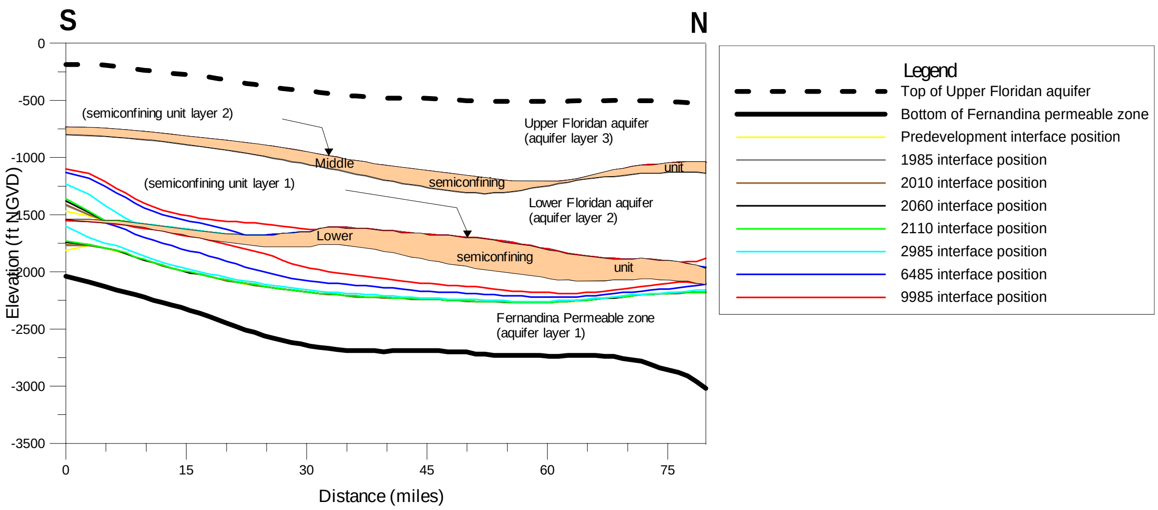


Figure 54a. Simulated interface movement along S-N cross section, uncertainty simulation 5

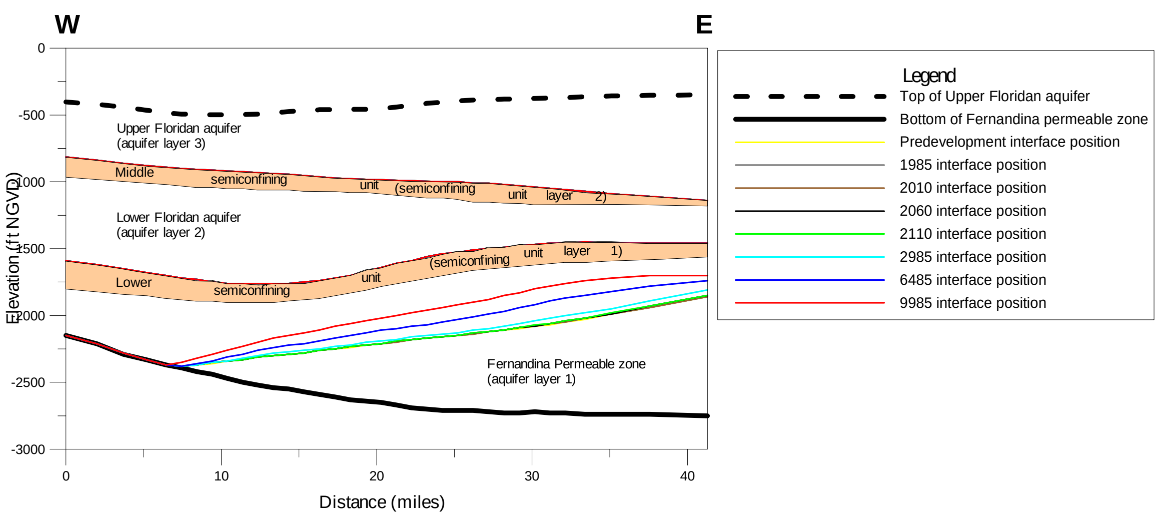


Figure 54b. Simulated interface movement along W-E cross section, uncertainty simulation 5

interface are apparent along the southern portion of the S-N cross section. The rate of increase in the elevation of the interface is generally about the same along both cross sections. The rate of increase in the elevation of the interface in the Fernandina permeable zone along the southern portion of the S-N cross section, however, is noticeably higher than in the base case.

Uncertainty Simulation 6

In uncertainty simulation 6, the vertical leakage factors of semiconfining unit layer 3 (the upper confining unit) were multiplied by a factor of 2. As a result, the predevelopment interface (Figures 55a and 55b) along both cross sections is generally higher in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface in aquifer layers 1 and 2 along both cross sections appears to be somewhat greater than in the base case. As a result, the degree of saltwater intrusion along the W-E cross section in aquifer layer 2 is substantially greater than that of the base case after 4,600 years (Figure 55b). A spike on the 9985 interface line in aquifer layer 2 along the S-N cross section is readily apparent (Figure 55a).

Uncertainty Simulation 7

In uncertainty simulation 7, the distribution of water table and surface water elevations was multiplied by a factor of 0.85. This modification of the model appears to have little effect on the results of simulations. Along both cross sections, the predevelopment interface is in approximately the same location as in the base case at corresponding positions. In addition, the rate of increase in the elevation of the interface appears to be approximately the same as in the base case.

Uncertainty Simulation 8

In uncertainty simulation 8, the distribution of water table and surface water elevations was multiplied by a factor of 1.15. As a result, the predevelopment interface along both the S-N and W-E cross sections is in approximately the same location as in the base case at corresponding positions. In addition, the rate of increase in the elevation of the interface along both cross sections is approximately the same as in the base case.

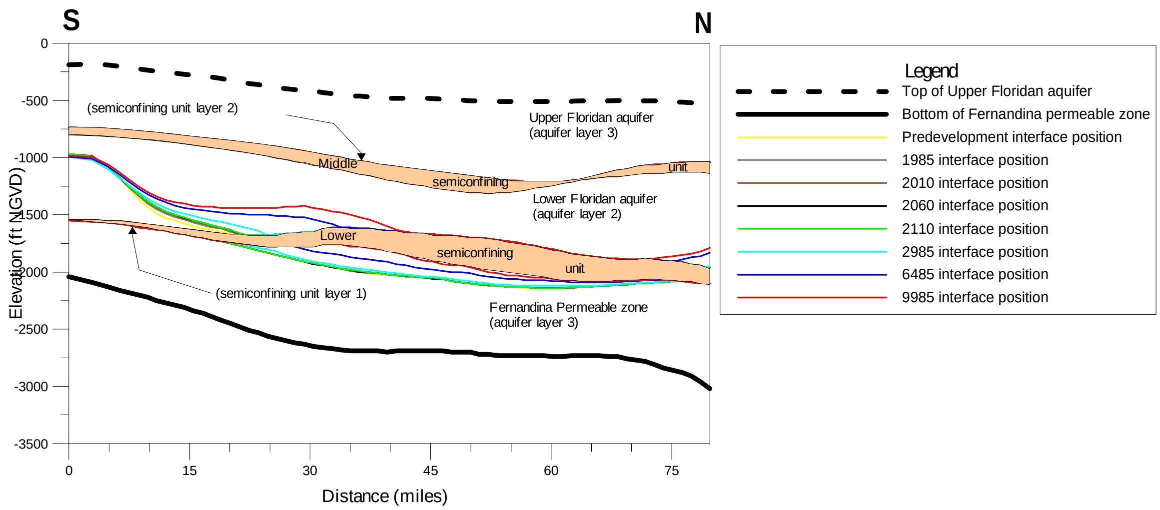


Figure 55a. Simulated interface movement along S-N cross section, uncertainty simulation 6

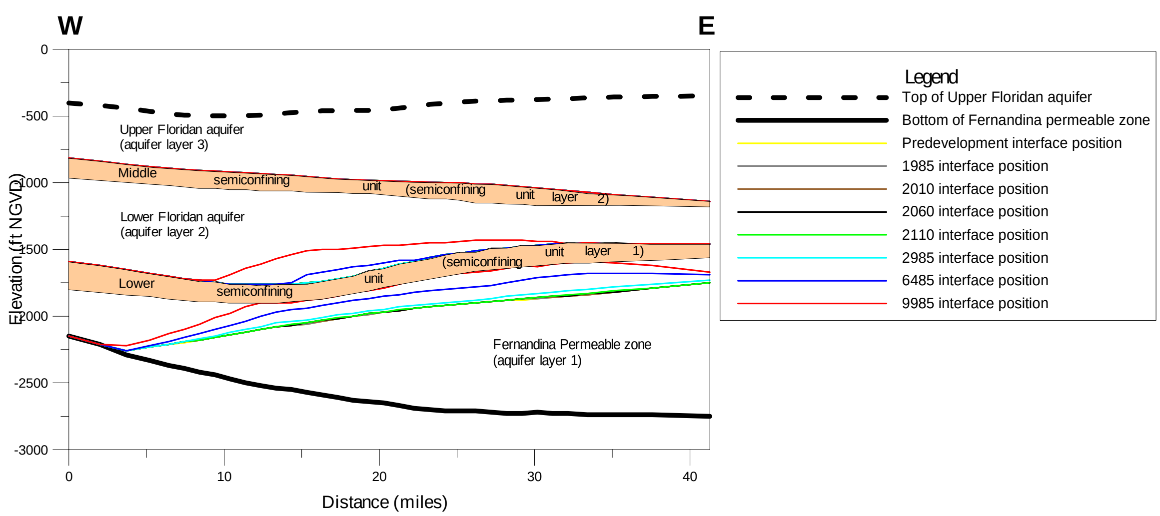


Figure 55b. Simulated interface movement along W-E cross section, uncertainty simulation 6

Uncertainty Simulations 9, 10, 11, and 12

Uncertainty simulations 9 and 10 are defined as the vertical leakage factors of the lower semiconfining unit (layer 1), multiplied by factors of 0.5 and 2.0, respectively. Uncertainty simulations 11 and 12 are defined as the vertical leakage factors of the middle semiconfining unit (layer 2), multiplied by factors of 0.5 and 2.0, respectively.

The model of those uncertainty simulations indicated that results of the predevelopment interface along both the S-N and W-E cross sections is in approximately the same location as in the base case at corresponding positions. In addition, the rate of increase in the elevation of the interface along both cross sections is approximately the same as in the base case.

Uncertainty Simulation 13

In uncertainty simulation 13, the freshwater GHFB-condition source heads were multiplied by a factor of 0.85. The results indicate that the model is very sensitive to decreases in the assigned freshwater GHFB-condition source heads. As a result, the predevelopment interface elevation (Figures 56a and 56b) in the Fernandina permeable zone (layer 1) along major portions of both the S-N and W-E cross sections is almost as high in elevation as the 9985 interface (Figures 46a and 46b) in the base case at corresponding positions. The rate of increase in the elevation of the interface along both cross sections is significantly higher than in the base case. A significant amount of both lateral and vertical movement occurs in the Lower Floridan aquifer (layer 2) along the S-N cross section during the 8,100-year simulation period. Along the W-E cross section, a significant amount of vertical movement is apparent during the 8,100-year simulation period (Figure 56b). Along both cross sections, the portions of the Lower Floridan aquifer (layer 2) corresponding to the Jacksonville area are occupied almost completely with salt water at the end of the 8,100-year simulation period. Along the S-N cross section, saltwater intrusion in the north results in the occupation of a significant portion of the Lower Floridan aquifer (layer 2) with salt water by the end of the 4,600-year simulation period (Figure 56a). The Fernandina permeable zone (layer 1) is occupied entirely with salt water along both cross sections by the end of the 8,100-year simulation period, except for the westernmost portion of the W-E cross section and the southernmost portion of the S-N cross section. Spiking of the 6485 and 9985 interface lines due to local pumping effects is apparent at points within both cross sections.

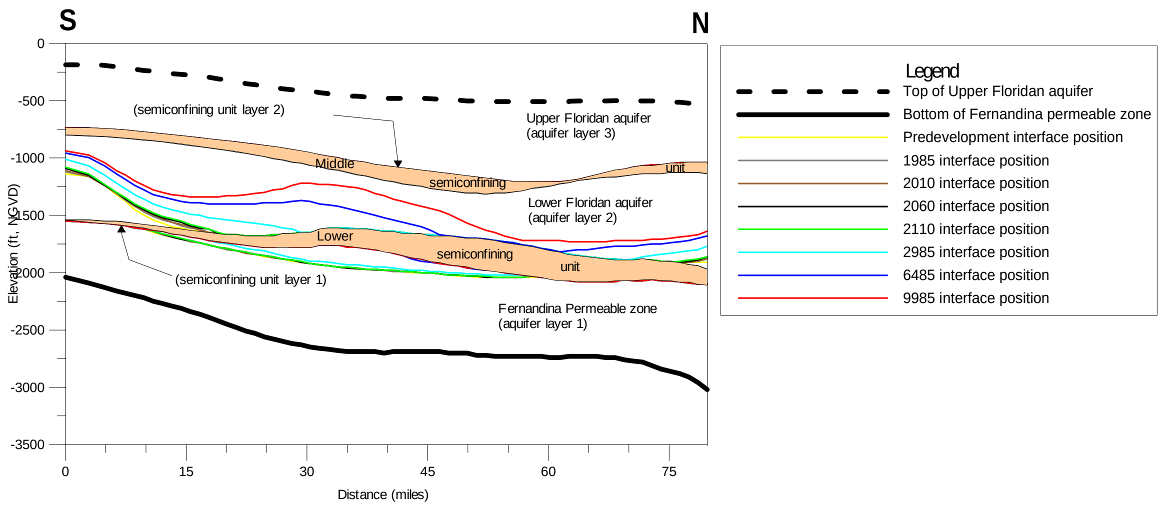


Figure 56a. Simulated interface movement along S-N cross section, uncertainty simulation 13

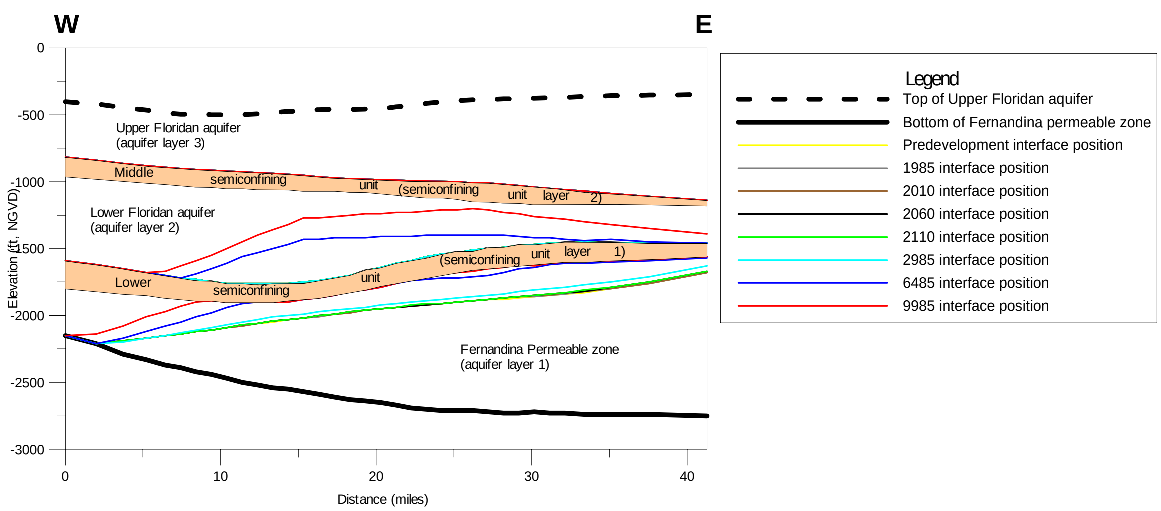


Figure 56b. Simulated interface movement along W-E cross section, uncertainty simulation 13

Uncertainty Simulation 14

In uncertainty simulation 14, the freshwater GHFB-condition source heads were multiplied by a factor of 1.15. As a result, the predevelopment interface (Figures 57a and 57b) of aquifer layer 1 along both cross sections is generally much lower in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface is somewhat lower in the Fernandina permeable zone (layer 1) along both cross sections and substantially lower in the Lower Floridan aquifer (layer 2) of the S-N cross section. Therefore, at the end of the 8,100-year simulation period, the location of the interface in the Lower Floridan aquifer (layer 2) along the S-N cross section is substantially farther south than in the base case.

Uncertainty Simulation 15

In uncertainty simulation 15, the saltwater GHFB-condition source heads were decreased by 2.0 ft. As a result, the predevelopment interface (Figures 58a and 58b) along both cross sections is substantially lower in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface, however, does not appear to be affected substantially along either cross section.

Uncertainty Simulation 16

In uncertainty simulation 16, the saltwater GHFB-condition source heads were increased by 2.0 ft. As a result, the predevelopment interface (Figures 59a and 59b) along both cross sections is substantially higher in elevation than at corresponding positions in the base-case model (Figures 46a and 46b). The rate of increase in the elevation of the interface along both cross sections, however, appears to be approximately the same as in the base case.

Uncertainty Simulations 17 and 18

Uncertainty simulations 17 and 18 are defined as the volume compressibility multiplied by factors of 0.1 and 10, respectively. This modification resulted in virtually no changes along either cross section relative to the base case. This result is to be expected because the volume compressibility affects primarily the rate of change in hydraulic head and has no effect on the values of hydraulic head attained at steady-state. In the Floridan aquifer system, steady-state with respect to freshwater values of hydraulic head is usually

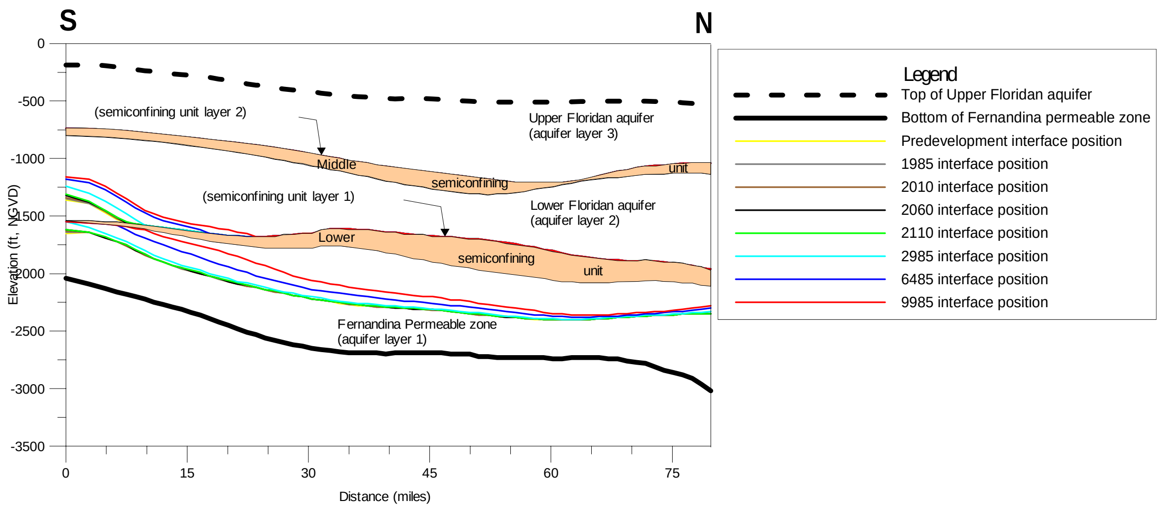


Figure 57a. Simulated interface movement along S-N cross section, uncertainty simulation 14

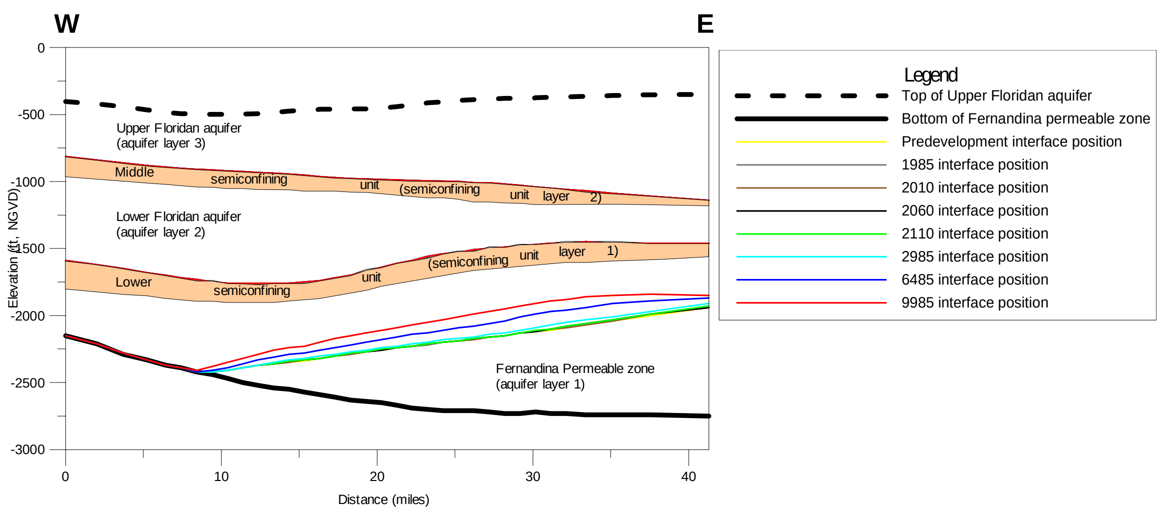


Figure 57b. Simulated interface movement along W-E cross section, uncertainty simulation 14

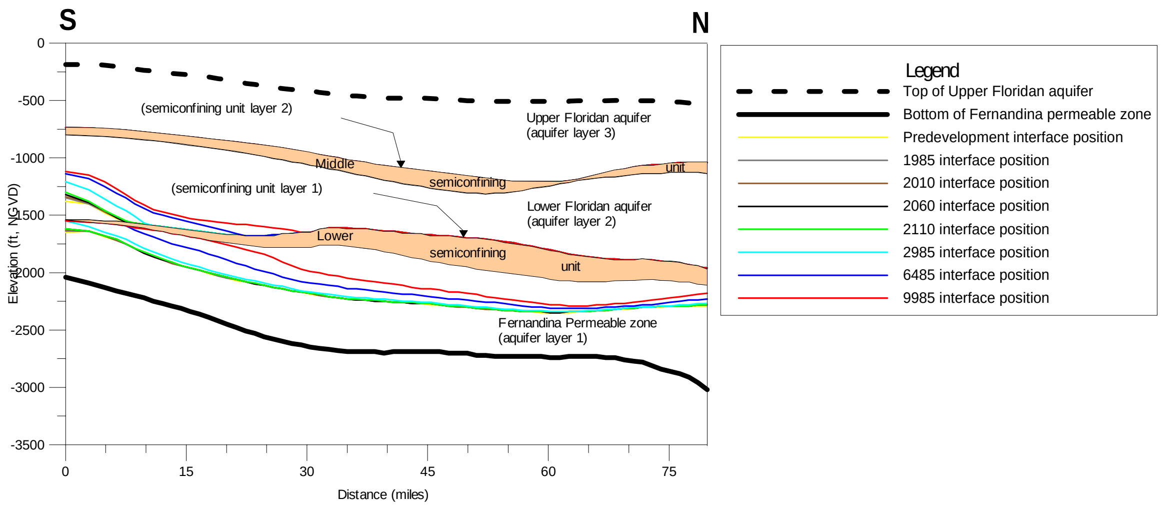


Figure 58a. Simulated interface movement along S-N cross section, uncertainty simulation 15

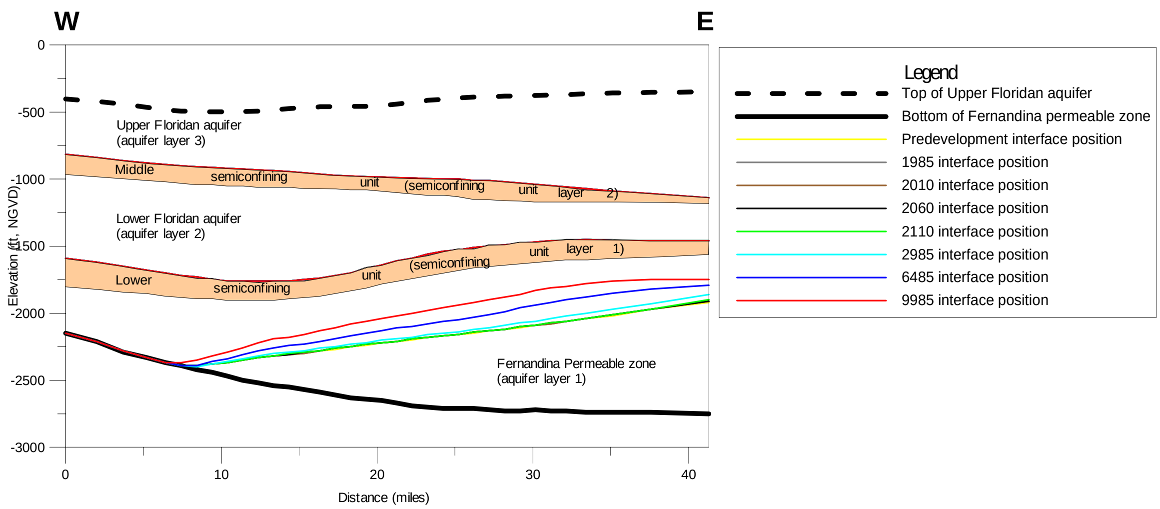


Figure 58b. Simulated interface movement along W-E cross section, uncertainty simulation 15

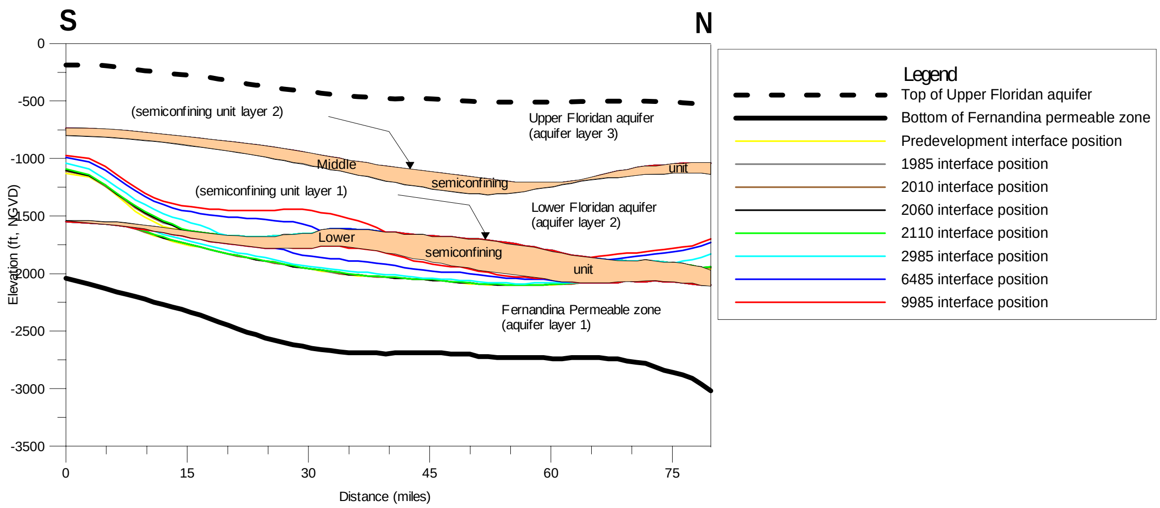


Figure 59a. Simulated interface movement along S-N cross section, uncertainty simulation 16

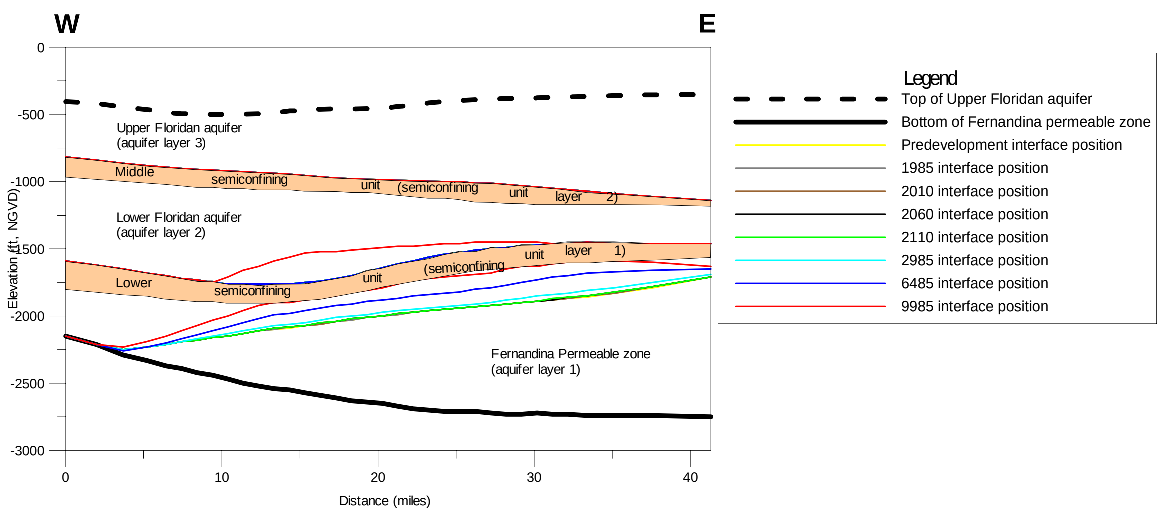


Figure 59b. Simulated interface movement along W-E cross section, uncertainty simulation 16

attained within 1 to 3 years of a change in aquifer stress. By contrast, steady-state with respect to the location of the interface is attained over relatively long periods of time—millennia, in the present case. Thus, hydraulic-head levels in both the present uncertainty simulation and the base case were different for only a relatively small interval of the overall simulation period, leading to almost identical results with respect to the locations of the interface at various points in simulated time.

Uncertainty Simulation 19

In uncertainty simulation 19, the assigned value of the effective porosity was multiplied by a factor of 0.5. In the SIMLAS governing equations, the effective porosity is the coefficient of the derivative of the interface elevation with respect to time (see appendix). Thus, the effective porosity affects the rate of change in the elevation of the interface. It does not, however, affect the simulated location of the interface at steady-state. Thus, the location of the predevelopment interface along both cross sections is the same as in the base-case model at corresponding positions.

Given the role of the effective porosity in the SIMLAS governing equations, the reduction in the assigned effective porosity by a factor of 0.5 should be expected to affect the rate of increase in the elevation of the interface significantly. Inspection of the S-N and W-E cross sections shows that the 6485 interface line in this uncertainty simulation matches closely with that of the 9985 interface line in the base case. This result suggests an approximate inverse relationship between the assigned value of the effective porosity and the rate of change in the elevation of the interface (Figures 60a and 60b).

Uncertainty Simulation 20

In uncertainty simulation 20, the assigned effective porosity was multiplied by a factor of 2. Again, the predevelopment interface along both cross sections occupies the same positions as in the base case at corresponding locations. In addition, the 9985 interface matches very closely in position with the 6485 interface of the base case along both cross sections (Figures 61a and 61b). This result indicates further that an approximate inverse relationship exists between the assigned value of the effective porosity and the rate of increase in the elevation of the interface.

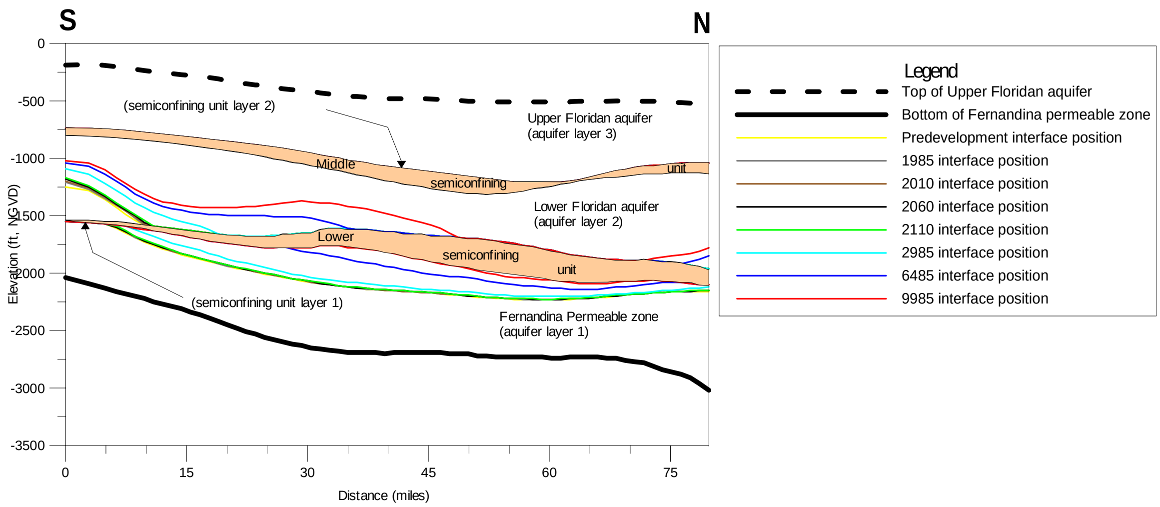


Figure 60a. Simulated interface movement along S-N cross section, uncertainty simulation 19

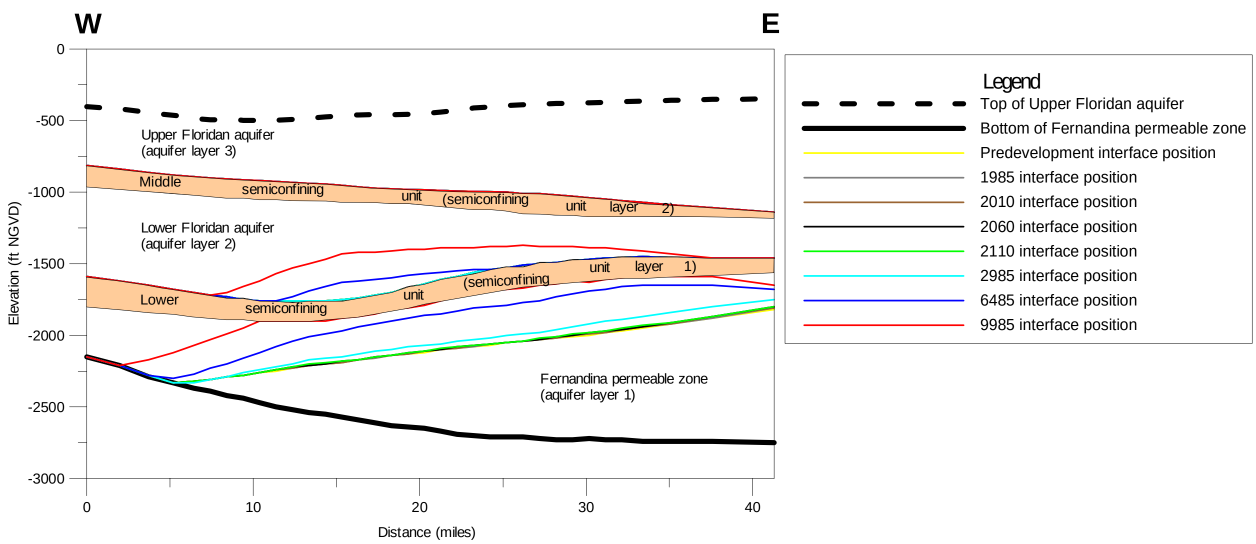


Figure 60b. Simulated interface movement along W-E cross section, uncertainty simulation 19

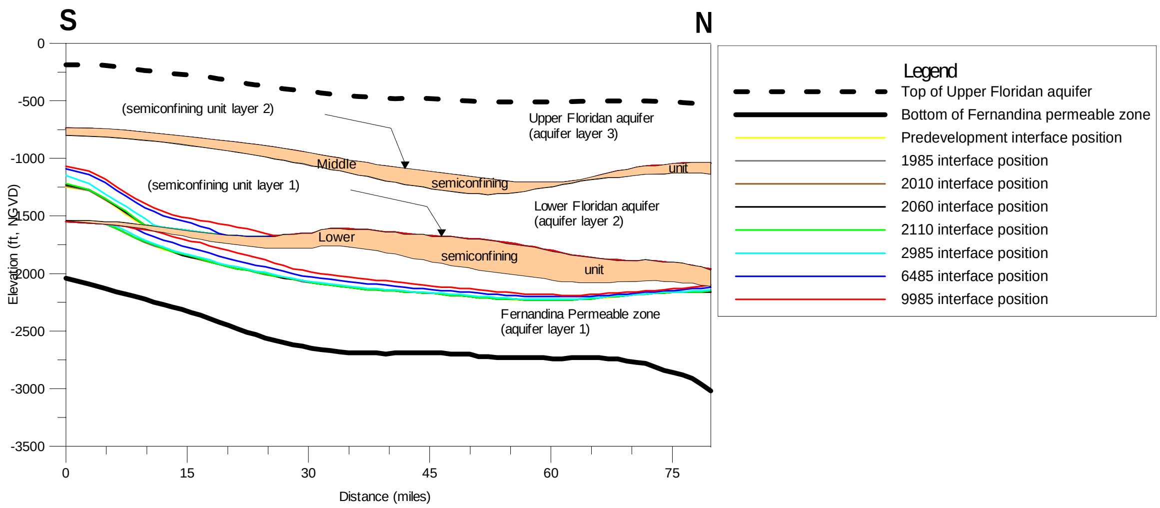


Figure 61a. Simulated interface movement along S-N cross section, uncertainty simulation 20

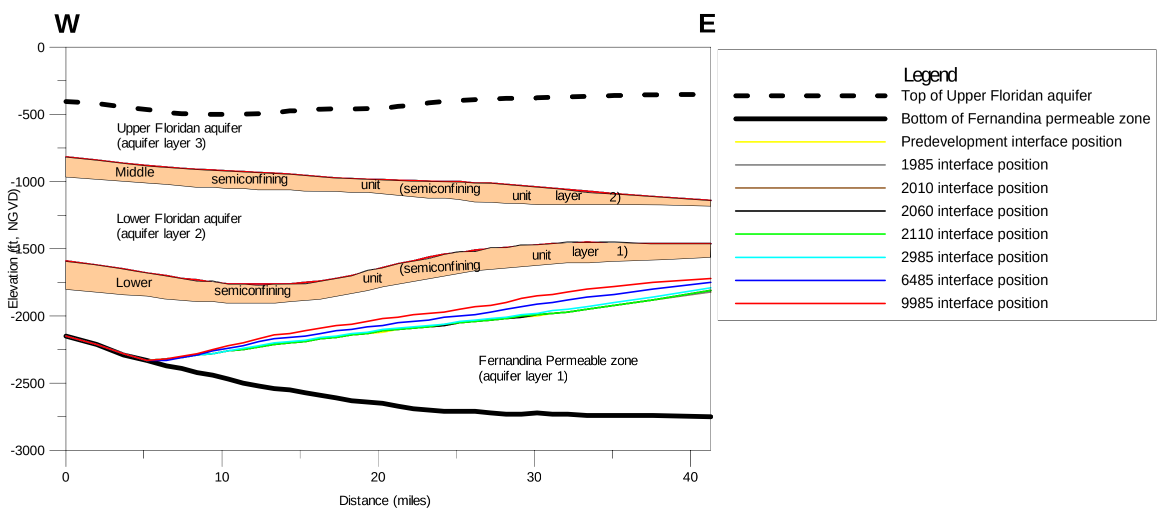


Figure 61b. Simulated interface movement along W-E cross section, uncertainty simulation 20

Uncertainty Simulation 21

In uncertainty simulation 21, the projected 2010 withdrawal rates were multiplied by a factor of 0.85. The predevelopment interface in this simulation is in the same location as in the base case at corresponding positions, since the predevelopment interface is not affected by future withdrawal rates. The rate of increase in the elevation of the interface is slightly lower in this case than in the base case.

Uncertainty Simulation 22

In uncertainty simulation 22, the projected 2010 withdrawal rates were multiplied by a factor of 1.15. Again, the predevelopment interface in this simulation is in the same location as in the base case at corresponding positions, since the predevelopment interface is not affected by future withdrawal rates. The rate of increase in the elevation of the interface is somewhat higher in this case than in the base case.

Uncertainty Simulation 23

Uncertainty simulation 23 was designed to assess the impacts due to overestimation of the saltwater GHFB-condition source heads. Predevelopment saltwater GHFB-condition source heads were used in both the predevelopment and postdevelopment simulations. However, values of source heads in excess of 0 ft NGVD were replaced with values of 0 ft NGVD. As stated previously, saltwater hydraulic heads in the Floridan aquifer system are probably less than 0 ft NGVD—the hydraulic head of the ocean. The determination of values in excess of 0 ft NGVD, based on the Hubbert (1940) equation (see appendix), is probably due to errors in estimated freshwater hydraulic heads, interface elevations, or both. The value of 0 ft NGVD was used in the present simulation as an upper bound of the actual values because the actual values are not known.

The predevelopment interface (Figures 62a and 62b) in this simulation is much lower in elevation along both cross sections than in the base case at corresponding locations (Figures 46a and 46b). The rate of increase in elevation of the interface, however, is higher than in the base case at most locations. The overestimation of the saltwater GHFB-condition source heads, therefore, appears to affect the predevelopment simulation significantly.

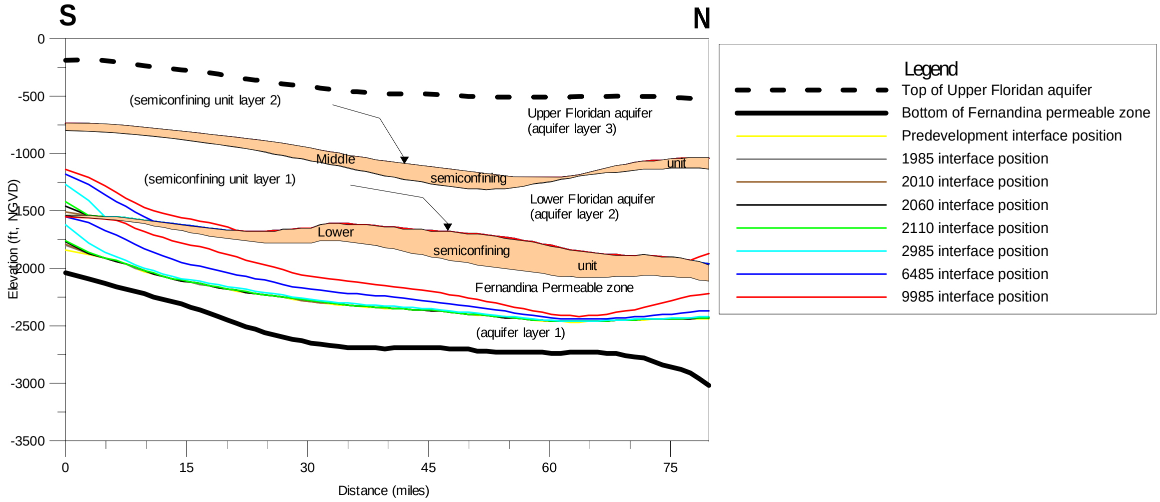


Figure 62a. Simulated interface movement along S-N cross section, uncertainty simulation 23

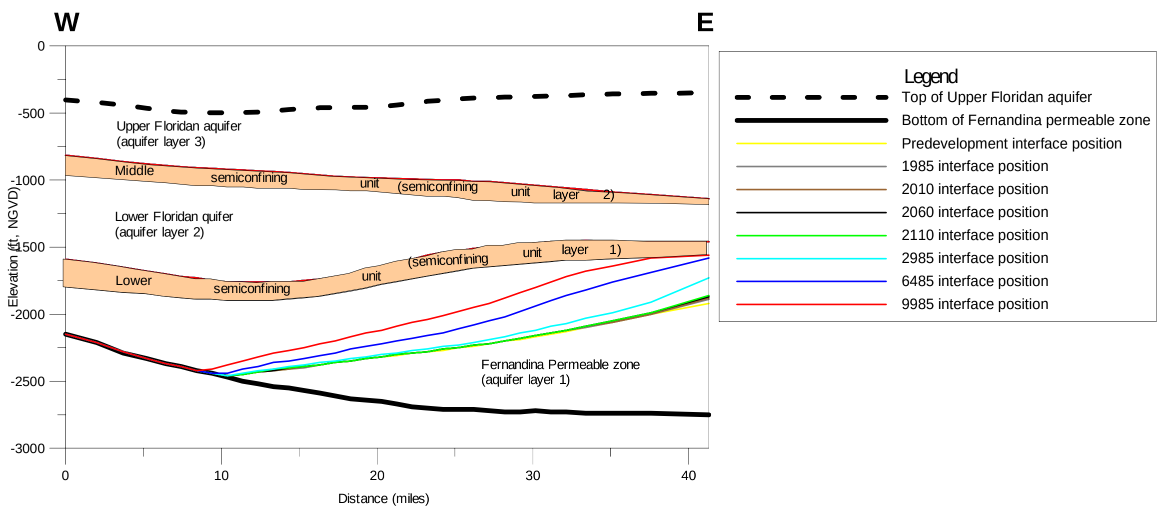


Figure 62b. Simulated interface movement along W-E cross section, uncertainty simulation 23

FURTHER DISCUSSION OF RESULTS OF BASE-CASE AND UNCERTAINTY SIMULATIONS

The key model parameters used in the uncertainty analyses include the horizontal intrinsic permeability values in various model layers, vertical leakage factors, water table elevations, freshwater and saltwater general-head boundary assignments, volume compressibility, porosity, and water withdrawal rates from the aquifer. The results of those uncertainty analyses indicate that the changes of permeability parameters in model layers 2 and 3, vertical leakage in layer 3, and the freshwater and saltwater general-head boundary assignments have impacts on the total rise and rates of interface elevation changes.

Generally speaking, the results of the base case and uncertainty simulations show that significant movement of the interface will not occur for at least the next 1,000 years (Table 5). Significant movement will occur, however, between 1,000 and 4,500 years from present. The primary sources of saltwater encroachment are bodies of salt water already present within the Floridan aquifer system of the study area. Encroaching salt water in the Fernandina permeable zone will originate largely from the body of salt water already present at depth within the Fernandina permeable zone of the study area. Encroaching salt water in the Lower and Upper Floridan aquifers will originate largely from the respective portions of the body of salt water present in these two aquifers in the areas of northern and central St. Johns County. The predominant form of encroachment in the Fernandina permeable zone will be vertical intrusion. The predominant form of encroachment in the Lower and Upper Floridan aquifers will be lateral intrusion. The degree of lateral intrusion into the Lower Floridan aquifer will be quite significant. In the Upper Floridan aquifer, lateral intrusion will occur primarily in the southeast corner of the study area, around the fringes of the existing body of salt water in the Upper Floridan aquifer of that area. The Upper Floridan aquifer will remain free of additional salt water throughout most of the study area, however.

EVALUATIONS OF SALTWATER INTRUSION PROBLEMS WITHIN THE STUDY AREA THROUGH APPLICATIONS OF THE BASE-CASE MODEL

In recent years, rising chloride concentrations have been observed in a number of wells located within the study area (Figure 63). Although the affected wells tend to be clustered in areas of concentrated well withdrawals, the problem does not conform to the typical conceptualization of saltwater upconing. The difference is that some wells are affected while other, nearby wells of similar depth are not (Spechler 1994; Phelps and Spechler 1997). The random distribution pattern of affected wells within the problem areas has prompted the hypothesis that structural anomalies within the rock matrix of the Floridan aquifer system are providing avenues for the upward transport of salt water. The types of anomalies that may be involved include faults, fractures, and solution features such as buried sinkholes (e.g., paleokarst). Such structural anomalies are believed to provide pathways of relatively high permeability in the aquifer system. Such pathways are referred to herein as preferential pathways.

Because the base-case model does not represent preferential pathways explicitly, it cannot be used deterministically to evaluate the difference in the potential for saltwater degradation due to the influence of the preferential pathways. In general, however, a higher rate of simulated movement of the interface at a given location and over a given amount of simulated time implies a higher degree of pumping stress on the interface. Assuming, then, that preferential pathways are equally likely to be present at all locations, a higher stress on the interface at a given well location would seem to imply a greater potential for upward movement of salt water into the well. Thus, assuming that the base-case model can be used to infer relative levels of pumping-induced stress on the interface, a qualitative assessment of the relative potential for saltwater degradation in various wells can be performed. The applications of the model as described in the following paragraphs are based on these concepts.

Two model simulations were performed to evaluate the effectiveness of potential remedies for saltwater intrusion. The two potential remedies are (1) the elimination of projected increases in rates of groundwater withdrawals and (2) the elimination of groundwater withdrawals from the Lower Floridan

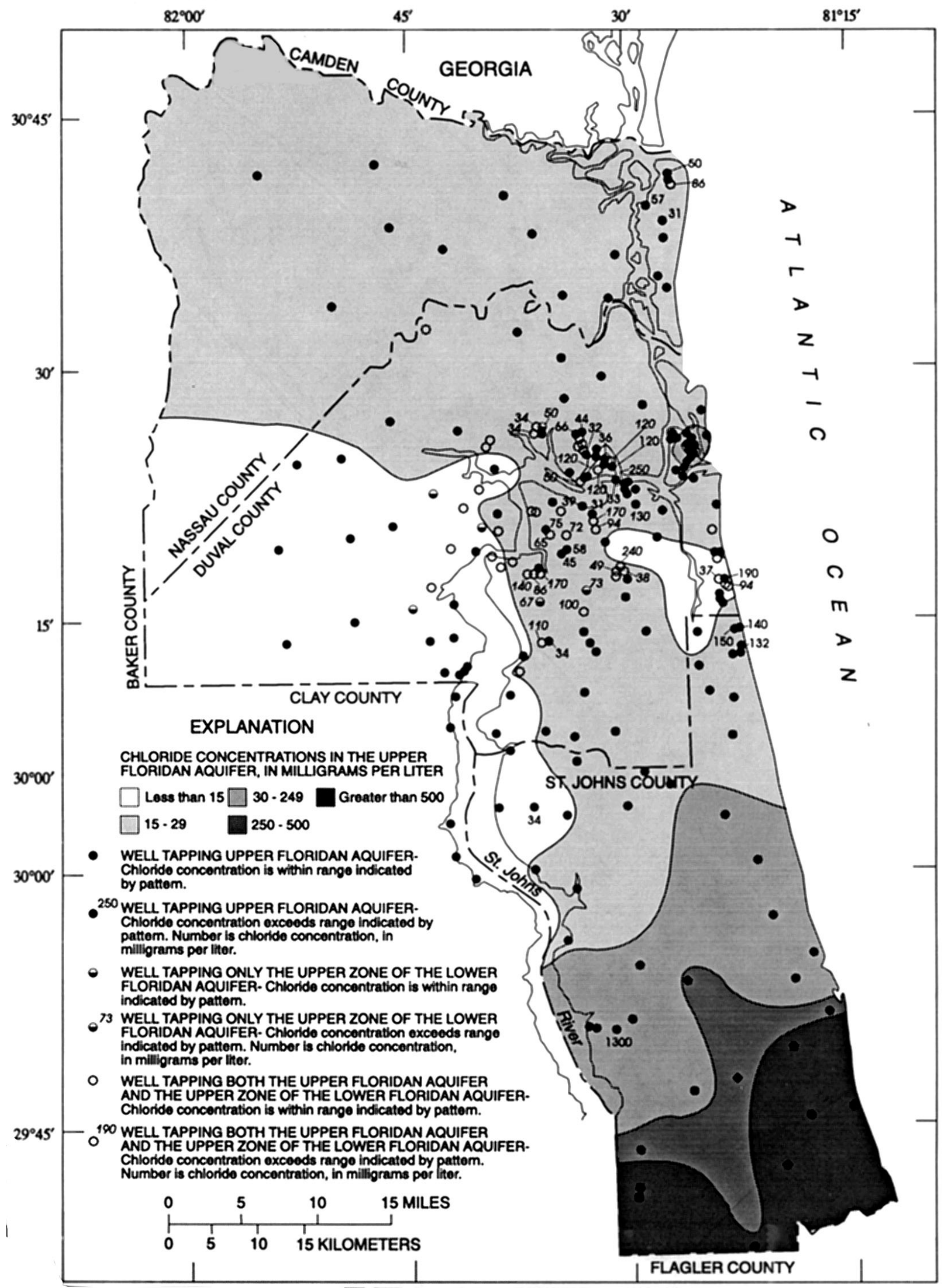


Figure 63. Distribution of chloride concentrations in water from the Upper Floridan aquifer and in selected wells tapping both the Upper Floridan aquifer and the upper zone of the Lower Floridan aquifer (Spechler 1994)

aquifer. The effectiveness of these two options as remedies was evaluated separately using the base-case model.

In addition, the results of the base case were employed in the calculation of the percent-rise of the interface beneath various wells within the model domain. As part of the analysis, a ranking of the wells according to the simulated percent-rise was performed. Comparisons were made of the distribution of percent-rise and the distribution of chloride concentration as observed in various monitoring and production wells throughout the study area.

EVALUATION 1—REDUCTION OF PROJECTED 2010 GROUNDWATER WITHDRAWAL RATES TO 1985 VALUES

The reduction in the rates of the projected 2010 groundwater withdrawals to estimated 1985 values (a reduction of approximately 31%) resulted in a reduction in the amount of simulated interface movement over the 8,000-year simulation period following 1985 (Figures 64a and 64b), as compared with the amount simulated in the base case. However, the simulated upward movement of the interface line still occurred in this scenario.

An explanation of this result requires consideration of drawdowns in the water levels of the predevelopment Floridan aquifer system. A basic assumption of the present study is that the interface within the Floridan aquifer system was in steady-state just prior to the end of predevelopment times. The predevelopment model results were used to generate the initial conditions for the subsequent run using 1985 withdrawal rates. The simulated movements of the interface, therefore, occur ultimately in response to the simulated drawdowns of the predevelopment water levels of the Floridan aquifer system.

In the present simulation, despite the elimination of the projected increases in the rates of groundwater withdrawals between 1985 and 2010, the 1985 rates were still enough to cause relatively large drawdowns relative to the predevelopment water levels of the Floridan aquifer system. Hence, the results of this simulation seem to indicate that capping rates of groundwater withdrawals at estimated 1985 values would result in a reduction in stress on the interface and therefore a reduction in the risk for saltwater degradation in wells within the study area. However, a substantial amount of stress would still be in place, so the risk would still be substantial. The amount of time

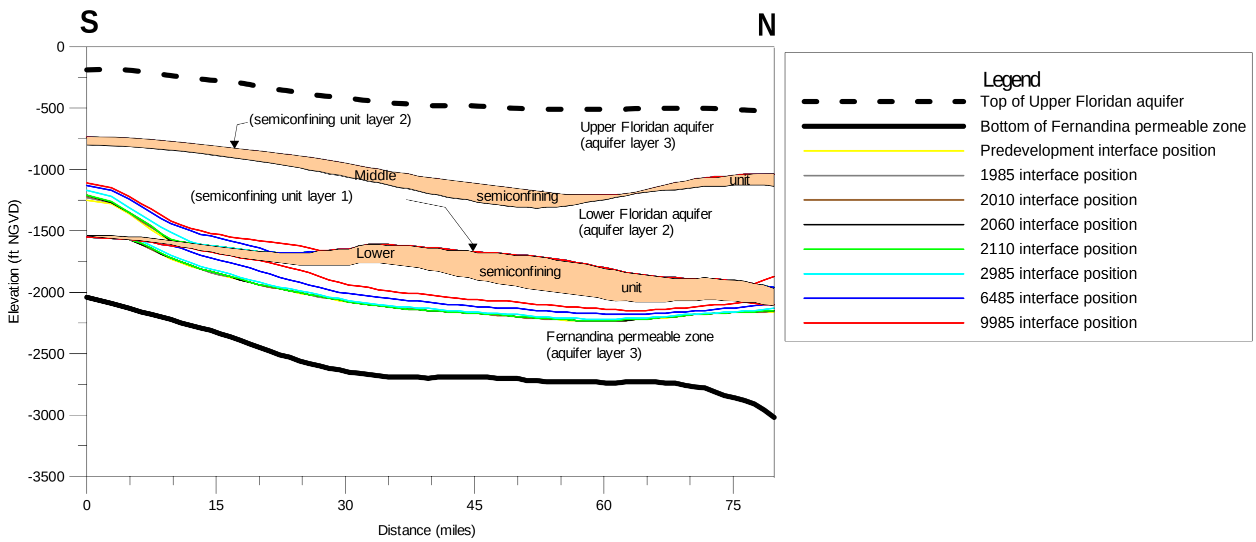


Figure 64a. Simulated interface movement along S-N cross section in response to estimated 1985 rates of groundwater withdrawals

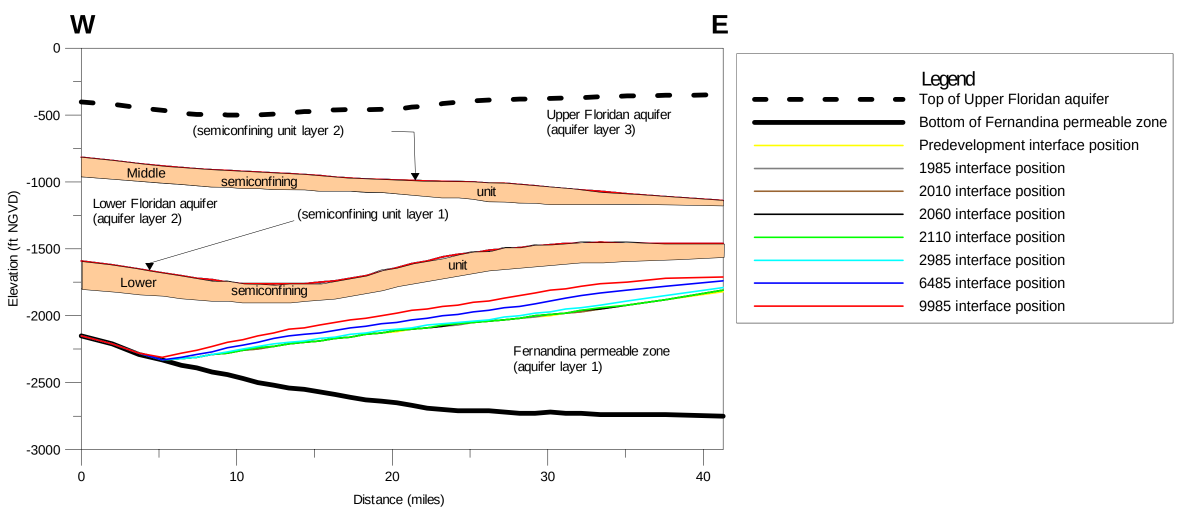


Figure 64b. Simulated interface movement along W-E cross section in response to estimated 1985 rates of groundwater withdrawals

required to incur saltwater degradation in a given well would probably be increased, however.

EVALUATION 2—BACKPLUGGING TO THE UPPER FLORIDAN AQUIFER OF WELLS OPEN TO BOTH THE UPPER AND LOWER FLORIDAN AQUIFERS

The simulated backplugging to the Upper Floridan aquifer of wells open to both the Upper and Lower Floridan aquifers (multi-aquifer wells) resulted in very little reduction in the simulated movement of the interface over the 8,000-year simulation period following 1985 (Figures 65a and 65b). In the base model, approximately 40% of all withdrawals simulated in the model are derived from the Lower Floridan aquifer (layer 2). However, it was assumed that withdrawals of water are solely from the Upper Floridan aquifer for this scenario. The lack of reduction in the movement of the interface in the Lower Floridan aquifer is probably due to increases in the simulated drawdown in the Upper Floridan aquifer (layer 3). Based on these results, a significant change in the amount of stress on the interface should not be expected as a result of backplugging multi-aquifer wells.

The rock layer that lies between the bottom of a well and the interface is a barrier that resists the upward transport of salt water. Preferential pathways in the rock layer are apparently present at a number of well sites within the study area. Nevertheless, for greater thicknesses between the bottom of a well and the interface, the likelihood of a preferential pathway extending from the interface to a given well should be smaller. The likelihood of a preferential pathway extending from the interface to a given well would be likely to be smaller for greater thicknesses between the bottom of the well and the interface. Thus, based on the results of the simulation, backplugging appears to be generally neutral with respect to the amount of stress placed on the interface. However, the resulting increase in distance between the bottom of a backplugged well and the interface should, in general, still lead to a reduction in the likelihood of saltwater degradation in the well.

CALCULATION OF PERCENT-RISE BASED ON RESULTS OF THE BASE CASE AND COMPARISON OF THE RESULTS TO THE DISTRIBUTION OF OBSERVED CHLORIDE CONCENTRATIONS

The regional scale of the base-case model enables comparisons of simulated percent-rise of the freshwater / saltwater interface beneath wells located within the study area. In the present analysis, the simulated percent-rise was

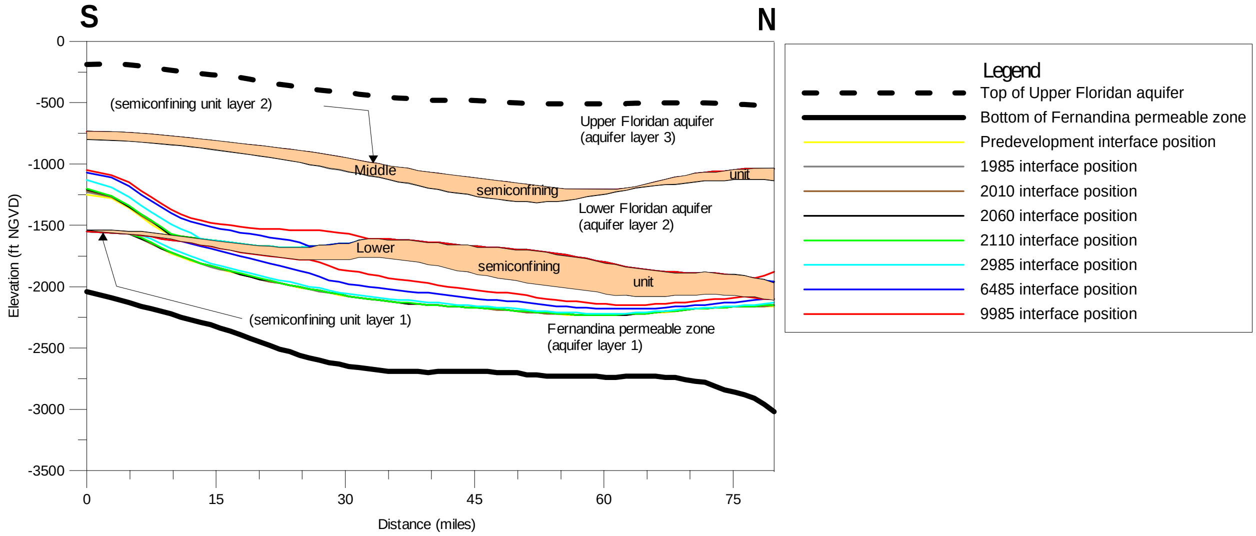


Figure 65a. Simulated interface movement along S-N cross section with wells in the Lower Floridan aquifer backplugged to the Upper Floridan aquifer

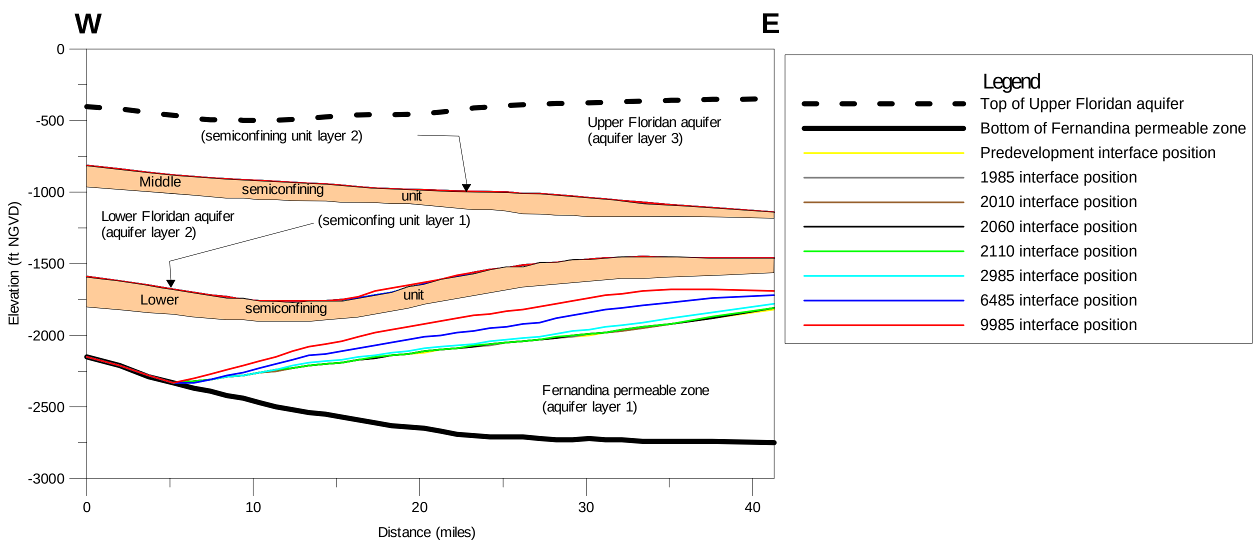


Figure 65b. Simulated interface movement along W-E cross section with wells in the Lower Floridan aquifer backplugged to the Upper Floridan aquifer

determined for a number of wells within the study area, and the wells were then ranked according to the magnitude of the percent-rise. The percent-rise of the interface beneath a given well represents the response of the interface to both local and regional stresses as averaged over the period of time elapsed since the onset of well withdrawals. Percent-rise is defined according to the following formula:

$$\text{Percent-rise} = (d_{wb} - d_i) / (d_{wb} - d_o)$$

where

d_{wb} = depth to the well bottom
d_i = depth to the interface at the well site with time i
d_0 = initial depth to the interface at the well site

Application of the percent-rise evaluation required accounting for three different special cases. One such case was that in which several wells were assigned to the same model node at different depths. In this case, only the deepest well was included in the percent-rise analysis. A second such case was that in which salt water was simulated in the predevelopment simulation as being present only in the deepest aquifer at a given well site. Later, however, in the postdevelopment simulation, the sale water was simulated in a higher-level aquifer also, as a result of lateral intrusion, even though the lower-level aquifer was still not completely filled with salt water. In this case, the percent-rise was determined consistently with respect to the elevations of the interface in the lower-level aquifer. In the third case, salt water was not simulated beneath a given well in the predevelopment simulation; in this case, the well was not included in the percent-rise analysis, regardless of whether lateral intrusion was simulated at the well site in the postdevelopment simulations. Hence, the vertical rise of the interface beneath a well due solely to the simulated lateral movement of salt water into a given subregion of the Floridan aquifer system was ignored in the percent-rise analysis.

For each well included in the analysis, percent-rise estimates were determined at different points in time after the onset of well withdrawals (1,850; 2,600; 3,600; 4,600; 5,600; 6,600; and 8,100 years). For each time-step, the percent-rise values were ordered from highest to lowest, and percentile rankings of the percent-rise values were determined. Wells with percent-rise values falling in the 100th to 75th percentile range were classified arbitrarily as falling within “percent-rise level 1”; wells with percent-rise values falling in the 75th to 50th percentile ranking were classified as falling within "percent-rise level 2," and so forth.

Maps of the distribution of the percent-rise levels were created with respect to each of the aforementioned time-steps. Additionally, tables were created in which the wells included in the analysis were listed from highest to lowest percentile ranking. Comparison of the maps (Figures 66–68) did not indicate a large variation in the distribution of the percent-rise levels between time-steps. Nevertheless, an additional map was created to summarize the temporal variation in the percent-rise levels. Wells were thus differentiated based on whether the percent-rise values associated with the wells were consistently above or below the 50th percentile ranking (Figure 69).

The areas of highest percent-rise were the area of Duval County east and south of the St. Johns River, the area of northeast St. Johns County along the Atlantic coast, and the area of northeast Nassau County within and near Fernandina Beach. The areas of lowest percent-rise are generally those to the west and north of the St. Johns River. A comparison of the distribution of the percent-rise levels to the distribution of above-background chloride concentrations (Figure 63) shows that areas of higher percent-rise and above-background chloride concentration generally coincide. Hence, the results seem to indicate that percent-rise as determined herein is a good general indicator of the relative risk for saltwater degradation in the wells of the study area.

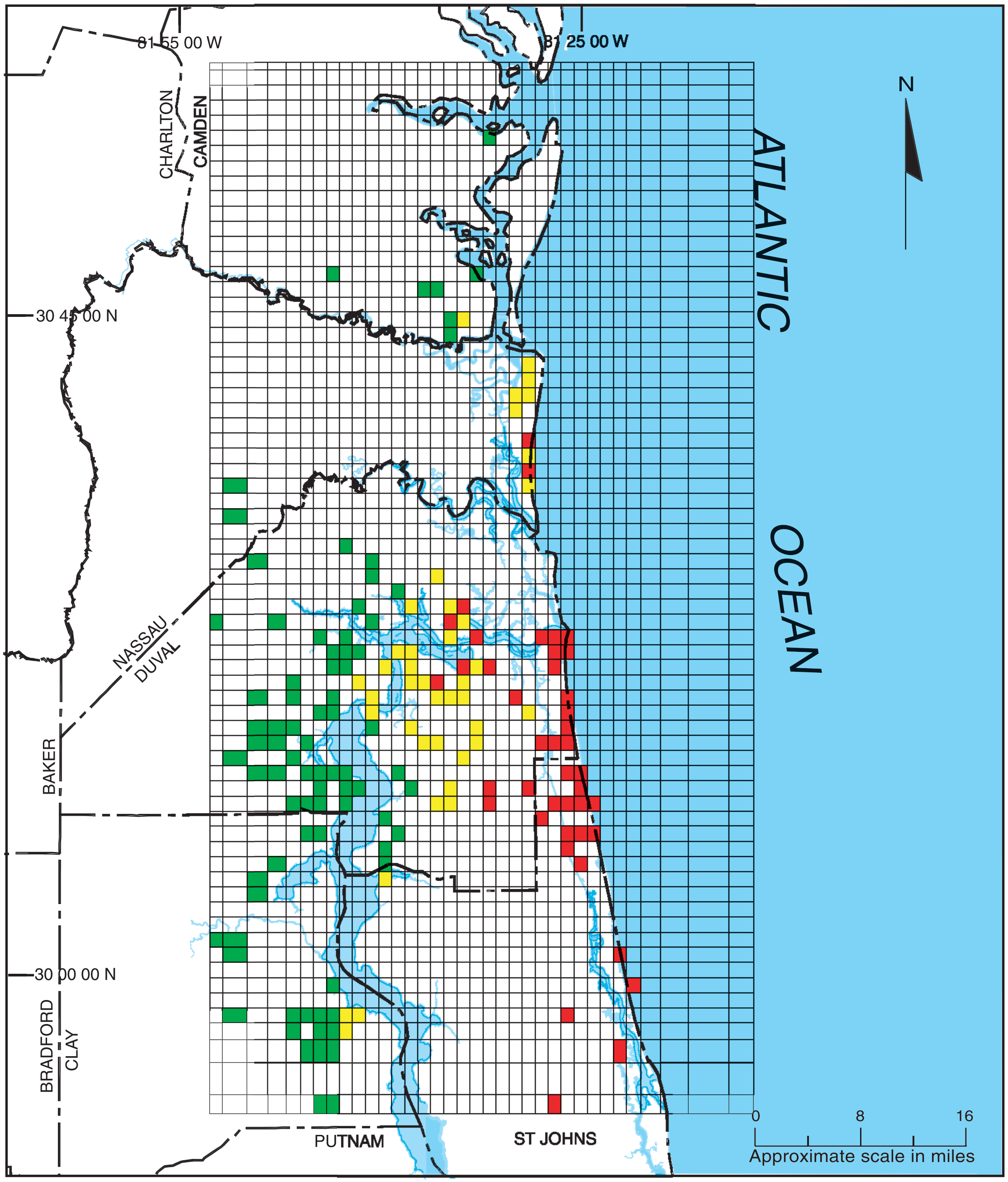


Figure 66. Percent-rise levels at 1,750 years after 1985

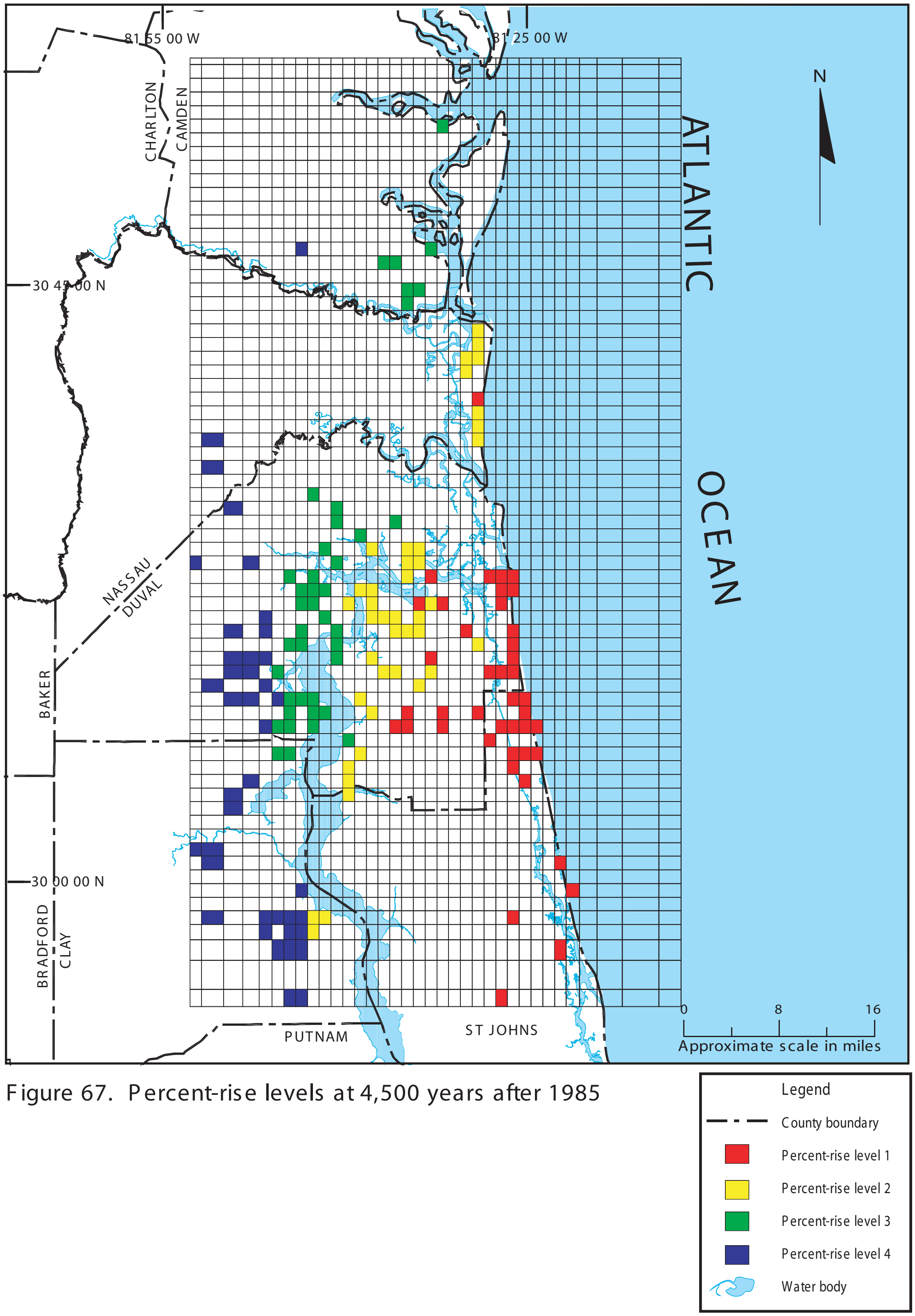


Figure 67. Percent-rise levels at 4,500 years after 1985

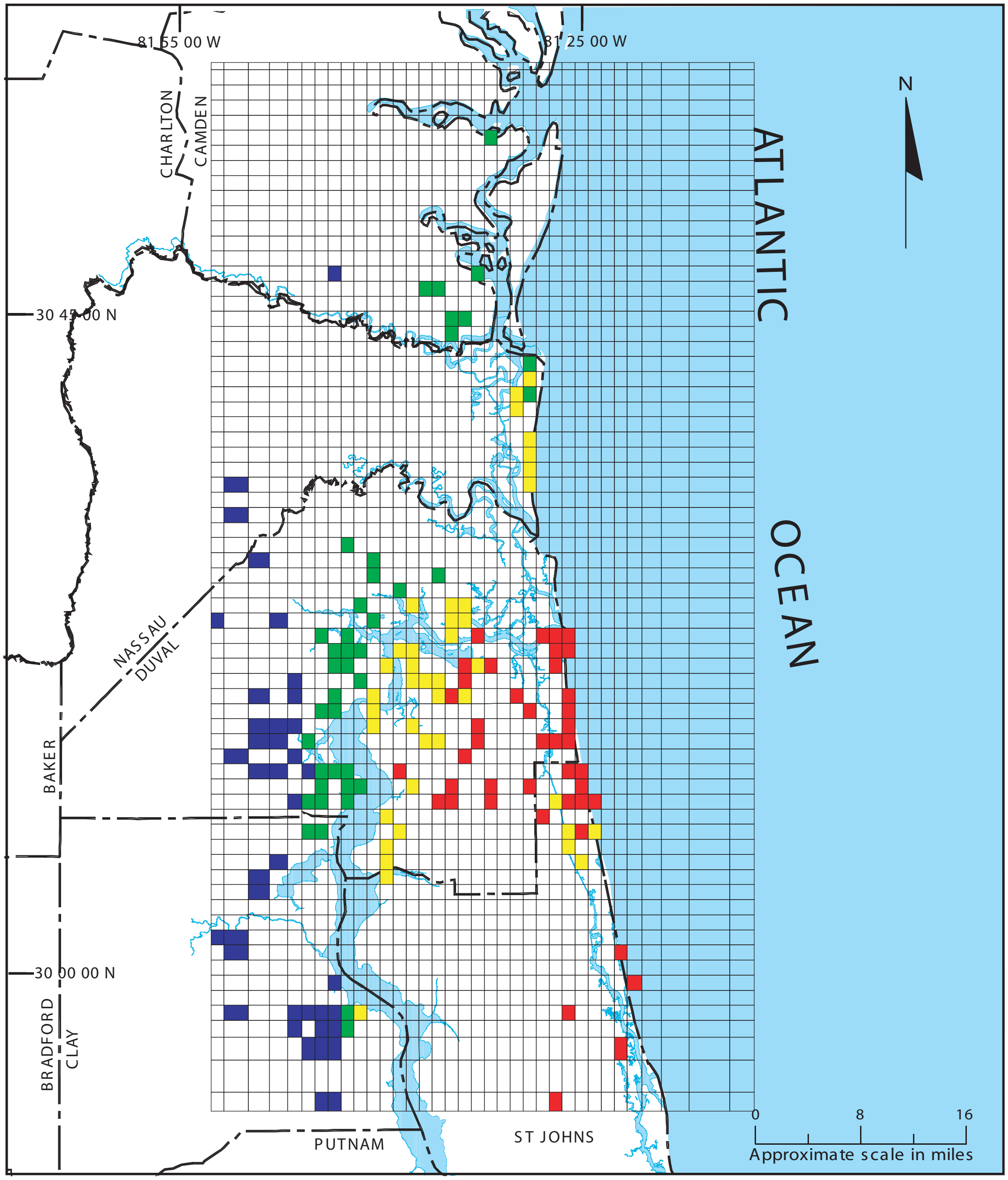
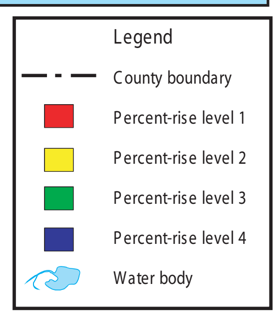


Figure 68. Percent-rise levels at 8,000 years after 1985



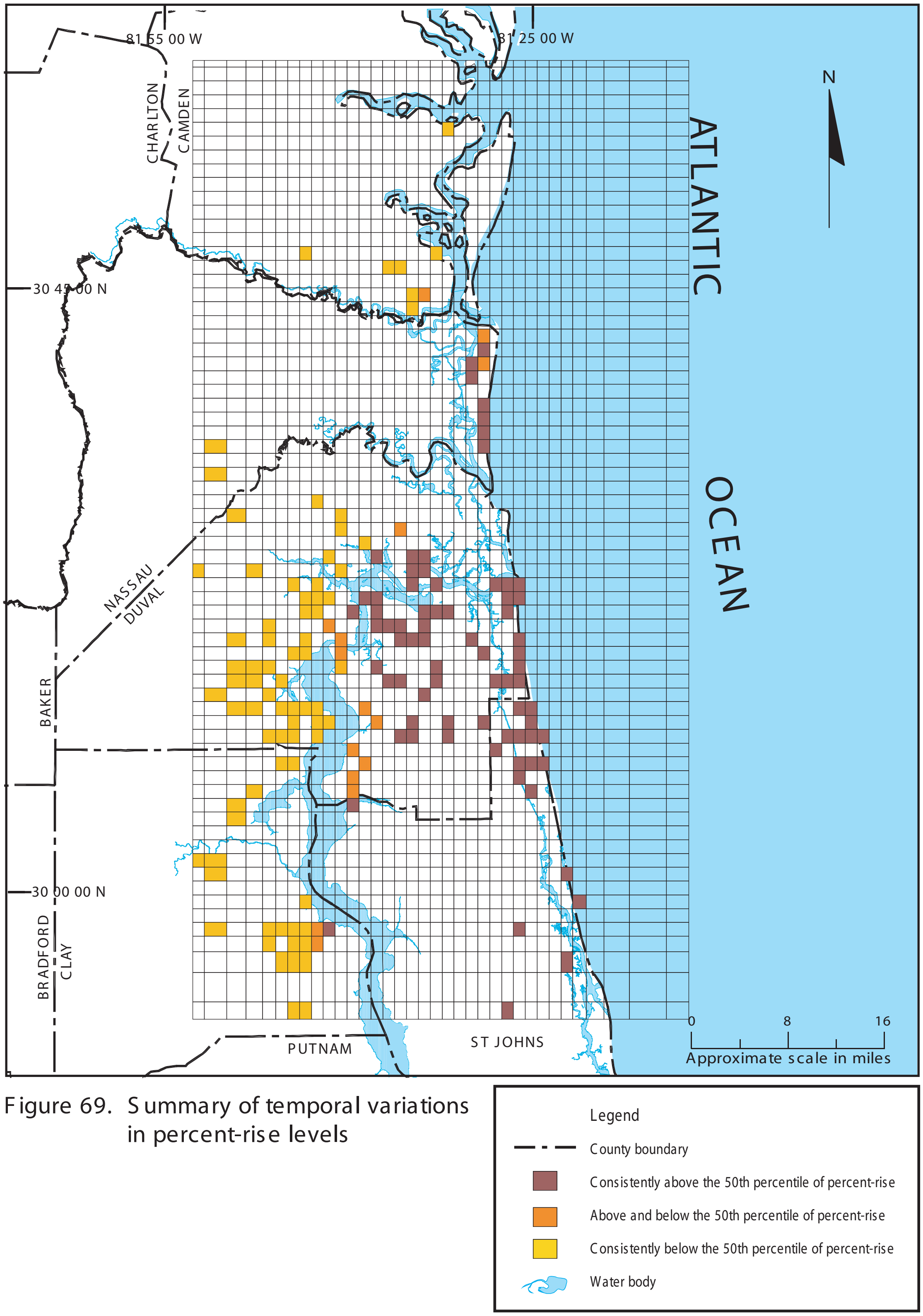


Figure 69. Summary of temporal variations in percent-rise levels

CONCLUSIONS AND RECOMMENDATIONS

Significant movement of the interface within the Floridan aquifer system due to the effects of groundwater withdrawals will require between 1,000 and 4,500 years at most locations within the study area, according to the results of the model simulations. Thus, regional-scale encroachment of salt water into the freshwater zones of the Floridan aquifer system within the study area should not be a practical concern for the foreseeable future.

Of more immediate concern is the possibility of saltwater degradation in various wells due to the transport of salt water via preferential pathways. Two special model simulations and an analysis of the output from the base case were performed to address this problem, albeit indirectly. The base-case model cannot be used to simulate saltwater transport via preferential pathways deterministically. Instead, the model was used to make qualitative judgments of relative stress levels on the interface based on relative amounts of interface movement over given spans of simulation time.

Potential remedies for water quality degradation in wells due to the transport of salt water via preferential pathways include (1) the reduction in projected increases in rates of groundwater withdrawals and (2) the backplugging to the Upper Floridan aquifer of wells open to both the Upper and Lower Floridan aquifers. The effectiveness of these potential remedies was tested by way of simulations performed using the base-case model.

The results of the first simulation indicate that reductions in projected increases in rates of groundwater withdrawals between 1985 and 2010 would result in small to moderate reductions in the potential for water quality degradation due to saltwater transport via preferential pathways. This interpretation is based on a comparison of the amount of simulated interface movement in response to the reduced pumping rate to that of the base case.

The results of the second simulation indicate that the amount of stress on the interface due to groundwater withdrawals would not be changed substantially by the backplugging of multi-aquifer wells to the Upper Floridan aquifer. Again, this interpretation was based on a comparison of the amount of simulated interface movement in the backplugging simulation to that of the base case. Based on the results, backplugging appears to be generally neutral with regard to the amount of stress on the interface. However, the thickness of the rock layer between the bottom of a given well and the interface is increased as a result of backplugging. Therefore, in general, the net effect of backplugging should be to decrease the likelihood of saltwater degradation in multi-aquifer wells.

The results of the base case were used to determine the percent-rise of the simulated interface beneath various wells at various points in time after the onset of simulated well withdrawals. The areas of highest percent-rise were the area of Duval County east and south of the St. Johns River, the area of northeast St. Johns County along the Atlantic coast, and the area of northeast Nassau County near Fernandina Beach. The areas of lowest percent-rise are generally those to the west and north of the St. Johns River. A comparison of the distribution of the percent-rise levels to the distribution of above-background chloride concentrations shows that areas of higher percent-rise and above-background chloride concentration generally coincide. Hence, the results seem to indicate that percent-rise as determined herein appears to be a good general indicator of the relative risk for saltwater degradation in the wells of the study area. Wells that are ranked consistently above the 50th percentile ranking in the analysis but that have not yet experienced water quality problems are at relatively high risk for future saltwater degradation.

The percent-rise analysis suggests that a third potential remedy for reducing the risk of saltwater degradation of wells within the study area may lie in the abandonment of certain problem wellfields located to the east and south of the St. Johns River in Duval County and the corresponding construction of new wellfields to the west of the St. Johns River. The newly constructed wells would be less likely to succumb to saltwater degradation because (1) depending on location, the onset of salt water occurs at a lower elevation or not at all to the west of the river and (2) groundwater withdrawals from the Floridan aquifer system (and consequent drawdowns) are generally less in that area. This approach would also result in a reduction in the likelihood of saltwater degradation of the remaining wells in the area to the east and south of the St. Johns River in Duval County because stress on the interface in that area would be reduced as a result of the reduction of withdrawal from the problem wellfields located to the east and south of the St. Johns River in Duval County.

While all three of the potential remedies discussed herein appear to possess a degree of merit, no one of the three is likely to represent a complete solution. Therefore, the joint application of all three potential remedies will probably prove to be the most effective approach for minimizing the occurrence of saltwater degradation of wells due to the transport of salt water via preferential pathways.

Additional data are required to enhance the reliability in future saltwater intrusion models of the Floridan aquifer system. Increased reliability, therefore, would reduce uncertainty concerning the potential for water quality degradation in wells due to the transport of salt water via preferential pathways. The required data include the following:

- **Locations and geometries of preferential pathways within the study area**

  High-resolution seismic profiling of the Floridan aquifer system in the Atlantic Ocean has enabled a number of buried sinkholes to be located. High-resolution seismic profiling on land is a more difficult task. It has been applied with some success at the wellfield scale within the study area, however. More such studies should be carried out at well sites known to be at high risk of saltwater degradation and at well sites in which saltwater degradation has already occurred.

- **Capacity and likelihood of the evaporite zone to transmit mineralized water into the freshwater zones of the Floridan aquifer system**

  Because the evaporite zone underlies the Floridan aquifer system throughout northeast Florida, it represents a potential source of mineralized water for all wells tapping the Floridan aquifer system in the region, even those located landward of the toe of the interface in the Fernandina permeable zone. Thus, more information concerning the potential degree of interaction of this zone with the freshwater zone of the Floridan aquifer system is needed.

- **Hydraulic properties of the middle semiconfining unit, Lower Floridan aquifer, lower semiconfining unit, and Fernandina permeable zone**

  This information will enable increased accuracy in future saltwater intrusion models of this area. Information concerning the hydraulic properties of the offshore portion of the Floridan aquifer system should be obtained also.

- **Water levels in the Lower Floridan aquifer, the Fernandina permeable zone, the offshore Floridan aquifer system, and the surficial aquifer system**

This information is critical to good model calibration as well as to the accurate specification of model lateral boundary conditions. Water levels should be determined in the freshwater, saltwater, and transition zones of the Floridan aquifer system of the study area.

- **The lateral extent, width, and shape of the transition and saltwater zones of the Floridan aquifer system within the study area**

  Much information concerning the transition zone has been obtained already by way of the five deep-observation wells discussed in this report. More deep-observation wells should be constructed. Future deep-observation wells should penetrate the entire thickness of the Floridan aquifer system, all the way to the evaporite zone and, in some cases at least , into the evaporite zone. Both water quality (i.e., chloride, sulfate, and total dissolved solids concentrations) and hydraulic-head data should be obtained as a function of depth using these wells. These data would enable a more accurate appraisal of the characteristics of the transition and saltwater zones of the Floridan aquifer system. Such information is critical to accurate saltwater intrusion modeling.

- **Hydrogeologic framework of the Floridan aquifer system**

  Knowledge of the hydrogeologic framework of the Floridan aquifer system includes information concerning the top and bottom elevations of the aquifers and the semiconfining units that comprise the Floridan aquifer system. This information is lacking with respect to both the onshore and the offshore portions of the Floridan aquifer system. Additional deep-observation wells in the onshore portion of the study area will add greatly to the knowledge of the hydrogeologic framework of that part of the study area. At least one test well in the offshore portion of the Floridan aquifer system should be constructed to obtain these data and the other types of data as outlined above. Additional knowledge concerning the hydrogeologic framework of the surficial aquifer system should be sought as well.

- **Water use within the study area**

  Information concerning water use, particularly agricultural water use, is needed. Variations in crop type and irrigated acreage should be monitored in greater detail to lessen reliance on permitted irrigated acreage as an estimate of actual irrigated acreage. Knowledge of rates and locations of groundwater withdrawals from the surficial aquifer system should be improved as well.

The application of the SIMLAS model to evaluate the impacts of water use on the location of the freshwater and saltwater interface was limited by several model assumptions which include immiscible liquids, the sharp interface change between freshwater and salt water without a mixing zone, and the limited availability of the discrete vertical trends in water quality data over the regional model domain.

A major drawback of the sharp-interface approach is that the mixing processes of the transition zone are ignored. Misrepresentation of the transition zone can lead to inaccuracies in the simulated head distribution of the saltwater zone, and such inaccuracies can, in turn, lead to inaccuracies in the results of the model calibration. Another major drawback of the sharp-interface approach, at least as applied in the present study, is that its use prevents the explicit representation of preferential pathways.

To avoid potential problems associated with the limitations of the sharp-interface approach, a more rigorous approach should be used in the future. A rigorous representation of the transition zone as well as explicit representation of structural anomalies can be achieved by using a density-dependent, fracture-flow model code.

At the present level of knowledge, the locations, geometries, and flow capacities of preferential pathways cannot be specified with any degree of certainty. However, computer programs exist that can generate hypothetical, random distributions of preferential pathways. Available information, such as the degree of occurrence of paleo-sinkholes as gleaned from seismic profiles, can be taken into account to improve the representation of the distribution of preferential pathways. Reasonable capacities of flow-preferential pathways can be determined based on model calibration and information concerning the hydraulics of preferential pathways. Several different hypothetical distributions of preferential pathways could be generated for use in model predictions to address the lack of knowledge concerning actual locations, geometries, and flow capacities of preferential pathways. This approach would perhaps enable a more realistic representation of the hydraulics of the actual system without necessitating a detailed knowledge of the actual distribution of structural anomalies. By representing the hydraulics of the Floridan aquifer system more realistically, a more precise estimate of the time frame for saltwater intrusion can be determined.

REFERENCES

Bear, J. 1979. *Hydraulics of groundwater*. New York: McGraw-Hill Publishing Company.

Bermes, B.J., G.W. Leve, and G.R. Tarver. 1963. *Geology and ground water resources of Flagler, Putnam, and St. Johns counties, Florida*. Report of Investigations 32. Tallahassee, Fla.: Florida Geological Survey.

Blackhawk Geosciences, Inc. 1990. TDEM test survey, vicinity of Jacksonville, Florida. Golden, Colo.

Boniol, D., M. Williams, and D. Munch. 1993. *Mapping recharge to the Floridan aquifer using a geographic information system*. Technical Publication SJ93-5. Palatka, Fla.: St. Johns River Water Management District.

Brown, D.P. 1980. *Geologic and hydrologic data from a test-monitor well at Fernandina Beach, Florida*. Open-File Report 80-347. Tallahassee, Fla.: U.S. Geological Survey.

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

Brown, D.P., R.A. Johnson, and J.S. Baker. 1984. *Hydrogeologic data from a test well at Kathryn Abbey Hanna Park, City of Jacksonville, Florida*. Open-File Report 84-143. Tallahassee, Fla.: U.S. Geological Survey.

Brown, D.P., R.A. Johnson, and R.A. Broxton. 1985. *Hydrogeologic data from a test well in east-central Duval County, Florida*. Open-File Report 84-802. Tallahassee, Fla.: U.S. Geological Survey.

Brown, D.P., J.A. Miller, and E.C. Hayes. 1986. *Hydrogeologic data from a test well near Ponte Vedra, northeast St. Johns County, Florida*. Open-File Report 86-410W. Tallahassee, Fla.: U.S. Geological Survey.

Bunce, E.T., K.O. Emery, R.D. Gerard, S.T. Knott, L. Lidz, T. Saito, and J. Schlee. 1965. Ocean drilling on the continental margin. *Science* 150(3697):709–716.

Bush, P.W. 1982. *Predevelopment flow in the Tertiary limestone aquifer, southeastern United States: A regional analysis from digital modeling*. Water-Resources Investigations Report 82-905. Atlanta, Ga.: U.S. Geological Survey.

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

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

Causey, L.V., and G.G. Phelps. 1978. *Availability and quality of water from the shallow aquifer system in Duval County, Florida*. Open-File Report FL-75001. Tallahassee, Fla.: U.S. Geological Survey.

CEES-Blackhawk Geosciences Division. 1992. Time domain electromagnetic soundings, St. Johns River Water Management District in northeast Florida. Golden, Colo.

Clark, W.E., R.H. Musgrove, C.G. Menke, and J.W. Cagle Jr. 1964. *Water resources of Alachua, Bradford, Clay, and Union counties, Florida*. Report of Investigations 35. Tallahassee, Fla.: Florida Geological Survey.

Clarke, J.S. 1987. *Potentiometric surface of the Upper Floridan aquifer in Georgia, May 1985, and water-level trends, 1980–85*. Hydrologic Atlas 16. Atlanta: Georgia Geological Survey.

Clarke, J.S., C.M. Hacke, and M.F. Peck. 1990. *Geology and ground water resources of the coastal area of Georgia*. Bulletin 113. Atlanta: Georgia Department of Natural Resources.

Cooper, H.H., Jr., F.A. Kohout, H.R. Henry, and R.E. Glover. 1964. *Sea water in coastal aquifers: Relation of salt water to fresh ground water*. Water-Supply Paper 1613-C. Washington, D.C.: U.S. Geological Survey.

Durden, D.W. 1997. *Finite-difference simulation of the Floridan aquifer system in northeast Florida and Camden County, Georgia*. Technical Publication SJ97-2. Palatka, Fla.: St. Johns River Water Management District.

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

———. 1992. Recharge-discharge relationships in the Floridan aquifer system in northeast Florida. In *Proceedings*, national symposium on the future availability of groundwater resources, Raleigh, N.C. Bethesda, Md.: American Water Resource Association.

Emery, K.O., and E.F.K. Zarudski. 1967. *Seismic reflection profiles along the drill holes on the continental margin off Florida*. Professional Paper 581-A. Washington, D.C.: U.S. Geological Survey.

Fairchild, R.W. 1972. *The shallow-aquifer system in Duval County, Florida*. Report of Investigations 59. Tallahassee, Fla.: Florida Bureau of Geology.

Fairchild, R.W., and C.B. Bentley. 1977. *Saline-water intrusion in the Floridan aquifer in the Fernandina Beach area, Nassau County, Florida*. Water-Resources Investigations 77-32. Tallahassee, Fla.: U.S. Geological Survey.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. *Mixing in inland and coastal waters*. Orlando, Fla.: Academic Press, Inc.

Frazee, J.M., Jr., and D.R. McClaugherty. 1979. *Investigation of groundwater resources and saltwater intrusion in the coastal areas of northeast Florida*. Technical Report 3. Palatka, Fla.: St. Johns River Water Management District.

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

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, N.J.: Prentice-Hall.

Hathaway, J.C., P.F. McFarlin, and D.A. Ross. 1970. *Mineralology and origin of sediments from drill holes on the continental margin off Florida*. Professional Paper 581-E. Washington, D.C.: U.S. Geological Survey.

Hathaway, J.C., et al. 1979. *Preliminary summary of the 1976 Atlantic margin coring project of the U.S. Geological Survey*. U.S. Geological Survey Open-File Report 76-844.

Hayes, E.C. 1981. *The surficial aquifer in east-central St. Johns County, Florida*. Water-Resources Investigations Report 81-14. Tallahassee, Fla.: U.S. Geological Survey.

Hoffman, M.S., ed. 1992. *The world almanac and book of facts*. New York: Pharos Books, Scripps Howard Company.

Hubbert, M.K. 1940. The theory of ground-water motion. *Journal of Geology* 58(8):785–944.

Huddlestun, P.F. 1988. *A revision of the lithostratigraphic units of the coastal plain of Georgia*. Bulletin 104. Atlanta: Georgia Department of Natural Resources.

Huyakorn, P.S., N.S. Park, Y.S. Wu, and S. Panday. 1992. *SIMLAS: saltwater intrusion model for layered aquifer systems, version 1.0: documentation and user's guide.* Herndon, Va.: Hydrogeologic, Inc.

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

Johnston, R.H., P.W. Bush, R.E. Krause, J.A. Miller, and C.L. Sprinkle. 1980. *Summary of hydrologic testing in Tertiary limestone aquifer, Tenneco offshore exploratory well—Atlantic OCS, lease-block 427.* Water-Resources Investigations Report 80-558. Atlanta, Ga.: U.S. Geological Survey.

Johnston, R.H., R.E. Krause, F.W. Meyer, P.D. Ryder, C.H. Tibbals, and J.D. Hunn. 1980. *Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development.* Open-File Report 80-406. Atlanta, Ga.: U.S. Geological Survey.

Jones, L.E., and M.L. Maslia. 1994. *Selected ground-water data and results of aquifer tests for the Upper Floridan aquifer, Brunswick, Glynn County, Georgia, area.* Open-File Report 94-520. Atlanta, Ga.: U.S. Geological Survey.

Krause, R.E. 1982. *Digital model evaluation of the predevelopment flow system of the tertiary limestone aquifer, southeast Georgia, northeast Florida, and southern South Carolina.* Water-Resources Investigations Report 82-173. Atlanta, Ga.: U.S. Geological Survey.

Krause, R.E., S.E. Matthews, and H.E. Gill. 1984. *Evaluation of the ground water resources of coastal Georgia; preliminary report on the data available as of July 1983.* Information Circular 62. Atlanta: Georgia Department of Natural Resources.

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

Leve, G.W. 1966. *Ground water in Duval and Nassau counties, Florida.* Report of Investigations 43. Tallahassee, Fla.: Florida Geological Survey.

Leve, G.W., and D.A. Goolsby. 1966. *Drilling of deep-test monitor well at Jacksonville.* Open-File Report 66-001. N.p. U.S. Geological Survey.

Manheim, F.T. 1967. Evidence for submarine discharge of water on the Atlantic continental slope of the United States, and suggestions for further search. *Academy of Science Transactions* 29(5):839–852.

McDonald, M.G., and A.W. Harbaugh. 1988. *A modular three-dimensional finite-difference ground water flow model*. Techniques of Water-Resources Investigations 6-A1. Washington, D.C.: U.S. Geological Survey.

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

Motz, L.H., and D.L. Strazimiri. 1996. Jacksonville Beach subregional flow and transport model—phase 1. Interim technical report, prepared for St. Johns River Water Management District. University of Florida, Gainesville.

Munch, D.A., B.J. Ripey, and R.A. Johnson. 1979. *Saline contamination of a limestone aquifer by connate intrusion in agricultural areas of St. Johns, Putnam, and Flagler counties, northeast Florida.* Technical Publication SJ79-4. Palatka, Fla.: St. Johns River Water Management District.

Navoy, A.S. 1986. *Hydrogeologic data from a 2,000-foot deep core hole at Polk City, Green Swamp area, central Florida.* Water-Resources Investigations Report 84-4257. Tallahassee, Fla.: U.S. Geological Survey.

[NOAA] National Oceanic and Atmospheric Administration. 1985. *National estuarine inventory, data atlas.* Vol. 1, *Physical and hydrologic characteristics.* National Ocean Service. Rockville, Md.

Paull, C.K., and W.P. Dillon. 1979. *The subsurface geology of the Florida-Hatteras shelf, slope, and Inner Blake Plateau.* Open-File Report 79-448. N.p. U.S. Geological Survey.

Phelps, G.G., and R.M. Spechler. 1997. *The relation between hydrogeology and water quality of the Lower Floridan aquifer in Duval County, Florida, and implications for monitoring movement of saline water.* Water-Resources Investigations Report 96-4242. Tallahassee, Fla.: U.S. Geological Survey.

Popenoe, P., F.A. Kohout, and F.T. Manheim. 1984. Seismic-reflection studies of sinkholes and limestone dissolution features on the northeastern Florida shelf. In *Proceedings*, first multidisciplinary conference on sinkholes, Orlando, Fla. B.F. Beck, editor. Boston: A.A. Balkema.

Rao, V.R., S.A. Jenab, and D.A. Clapp. 1989. *Rainfall analysis for northeast Florida, part III: Seasonal rainfall data.* Technical Publication SJ89-1. Palatka, Fla.: St. Johns River Water Management District.

Reilly, T.E., and A.S. Goodman. 1985. Quantitative analysis of saltwater-freshwater relationships in groundwater systems—a historical perspective. *Journal of Hydrology* 80:125–160.

Roberson, J.A., and C.T. Crowe. 1975. *Engineering fluid mechanics*. Boston: Houghton Mifflin Company.

Schiner, G.R., and E.C. Hayes. 1985. *Potentiometric surface of the Upper Floridan aquifer in the St. Johns River Water Management District and vicinity, Florida, September 1985.* Open-File Report 85-644. Tallahassee, Fla.: U.S. Geological Survey.

Schlee, J. 1977. *Stratigraphy and tertiary development of the continental margin east of Florida*. Professional Paper 581-F. Washington D.C.: U.S. Geological Survey.

Schmorak, S., and A. Mercado. 1969. Upconing of freshwater-seawater interface below pumping wells, field study. *Water Resources Research* 5(6):1290–1311.

Scholle, P.A. 1979. *Geological studies of the COST GE-1 well, United States south Atlantic outer continental shelf area*. Circular 800. Alexandria, Va.: U.S. Geological Survey.

Scott, T.M. 1983. *The Hawthorn Formation of northeastern Florida: Part 1—the geology of the Hawthorn Formation of northeastern Florida*. Report of Investigations 94. Tallahassee, Fla.: Florida Bureau of Geology.

———. 1988. *The lithostratigraphy of the Hawthorn Group (Miocene) of Florida*. Bulletin 59. Tallahassee, Fla.: Florida Department of Natural Resources.

Spechler, R.M. 1994. *Saltwater intrusion and quality of water in the Floridan aquifer system, northeastern Florida*. Water-Resources Investigations Report 92-4174. Tallahassee, Fla.: U.S. Geological Survey.

———. 1997. Stratigraphy and hydrogeology of a submarine collapse sinkhole on the continental shelf, northeastern Florida. In *Proceedings*, sixth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Springfield, Mo. B.F. Beck and J.B. Stephenson, editors. Brookfield, Vt.: A.A. Balkema.

Spechler, R.M., and P.S. Hampson. 1984. *Ground-water resources of St. Johns County, Florida*. Water-Resources Investigations Report 83-4187. Tallahassee, Fla.: U.S. Geological Survey.

Spechler, R.M., and R.B. Stone Jr. 1983. *Appraisal of the interconnection between the St. Johns River and the surficial aquifer, east-central Duval County, Florida*. Water-Resources Investigations Report 82-4109. Tallahassee, Fla.: U.S. Geological Survey.

Sprinkle, C.L. 1989. *Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama*. Professional Paper 1403-I. Washington, D.C.: U.S. Geological Survey.

Streeter, V.L., and E.B. Wylie. 1985. *Fluid mechanics.* Eighth edition. New York: McGraw-Hill Publishing Company.

Subsurface Detection Investigations, Inc. 1994. *Time domain electromagnetic soundings and analysis, St. Johns River Water Management District, northeast Florida/southeast Georgia, November 1993*. Special Publication SJ94-SP2. Palatka, Fla.: St. Johns River Water Management District.

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

Toth, D.J. 1985. *Test drilling report for observation wells at Sebastian Inlet state park, Brevard County, Florida*. Technical Publication SJ85-6. Palatka, Fla.: St. Johns River Water Management District.

———. 1990. *Geohydrologic summary of the Floridan aquifer in coastal areas of Nassau, Duval, and northern St. Johns counties*. Technical Publication SJ90-5. Palatka, Fla.: St. Johns River Water Management District.

APPENDIX—SIMLAS GOVERNING EQUATIONS

FRESHWATER AND SALTWATER GROUNDWATER FLOW EQUATIONS

The freshwater version of the Huyakorn et al. (1992) groundwater flow equation is as follows:

$$\frac{\partial}{\partial x}\left[K_{xx} b \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{YY} b \frac{\partial h}{\partial y}\right] + W = S_s b \frac{\partial h}{\partial t} - \theta \frac{\partial \xi}{\partial t} \qquad \textbf{(1)}$$

The saltwater version of the Huyakorn et al. (1992) groundwater flow equation is stated as follows:

$$\frac{\partial}{\partial x}\left[K_{xx} b \frac{\partial h_s}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{YY} b \frac{\partial h_s}{\partial y}\right] + W = S_s b \frac{\partial h_s}{\partial t} + \theta \frac{\partial \xi}{\partial t} \qquad \textbf{(2)}$$

where

K_{XX}, K_{YY} = values of hydraulic conductivity along the x and y coordinate axes, respectively, which are assumed to be parallel to the principal axes of hydraulic conductivity [LT^{-1}]

h = the freshwater hydraulic head [L]

h_s = the saltwater hydraulic head [L]

W = a volumetric flux per unit area of sources and/or sinks of water [LT^{-1}]

S_S = the aquifer specific storage [L^{-1}]

ξ = the interface elevation [L]

θ = the aquifer effective porosity

b = the aquifer thickness [L]

t = time [T]

The two items on the right-hand side of Equations 1 and 2 represent changes in aquifer storage with respect to time, which occur in response to changes in aquifer stresses. The first item represents the change in storage with respect to time associated with the elastic properties of the porous medium and water. The second item is the change in storage with respect to time that occurs due to the movement of the interface. In the case of the freshwater zone of an aquifer system, storage decreases with increasing interface elevation. Hence, the sign preceding this term in Equation 1 is negative. In the case of the saltwater zone, storage increases with increasing interface elevation. Hence, the sign preceding this term in the saltwater flow equation (2) is positive. In all other respects, the freshwater and saltwater versions of the groundwater flow equation are identical.

Inspection of Equations 1 and 2 shows that saltwater intrusion is represented in the SIMLAS code as a process in which freshwater is removed from storage while being replaced by salt water.

THE HUBBERT EQUATION

The Hubbert (1940) equation relates the interface elevation, freshwater hydraulic head, saltwater hydraulic head, and fresh- and saltwater densities. The equation is applicable to a sharp interface between immiscible fluids. It is derived by equating the pressures on the fresh- and saltwater sides of the interface at a given point on the interface (Hubbert 1940). The equation may be stated as follows (Huyakorn et al. 1992):

$$\xi = \frac{1}{\varepsilon}\left[\left(\rho_f / \rho_s\right) h_s - h_f\right] \qquad \textbf{(3)}$$

where

ξ = the interface elevation [L]
h_s = the saltwater hydraulic head [L]
h_f = the freshwater hydraulic head [L]
ρ_f = the freshwater density [ML^{-3}]
ρ_s = the saltwater density [ML^{-3}]
ε = $(\rho_f - \rho_s)/\rho_f$ [ε = the density difference ratio]

Table 3. Hydraulic-head residuals in the Lower Floridan aquifer (layer 2) of the 1985 model version at nodes corresponding to locations of observation wells

Node Number	USGS Well Identification Number	SJRWMD Well Identification Number	Location		Model Coordinates		Date of Observation	Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (feet)
			Latitude	Longitude	Row	Column				
3366	302227081435001	D-0592	30 22 27	81 43 50	29	6	10/06/86	39.1[a]	38.3	0.8
3120	301537081441901	D-0075	30 15 37	81 44 19	22	5	10/06/86	32.3[a]	40.6	-8.3
3129	301604081361501	D-0450	30 16 04	81 36 15	22	14	10/06/86	38.1[a]	35.7	2.4
3167	301639081330802	D-1155	30 16 39	81 33 08	23	17	10/06/86	35.7[a]	34.6	1.1
3002	301132081225801	SJ-0025	30 11 32	81 22 58	18	27	Aug.–Oct. 1985	38.1[b]	33.6	4.5
3351	302159081235601	D-2386	30 21 59	81 23 56	28	26	Nov. 1980–July 1981	34.9[c]	33.0	1.9
3307	302052081323201	D-3060	30 20 52	81 32 32	27	17	Oct. 1982–Feb. 1983	33.7[d]	33.7	0.0

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

[a]Observations reported in Brown et al. 1986.
[b]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1986.
[c]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1984.
[d]Weighted average of vertically distributed observations made during drilling. Observations reported in Brown et al. 1985.

Table 4. Hydraulic-head residuals in the Fernandina permeable zone (layer 1) of the 1985 model version at nodes corresponding to locations of observation wells

Node Number	USGS Well Identification Number	SJRWMD Well Identification Number	Location		Model Coordinates		Observed or Estimated Hydraulic Head (ft NGVD)	Simulated Hydraulic Head (ft NGVD)	Residual (feet)
			Latitude	Longitude	Row	Column			
622	301132081225801	SJ-0025	30 11 32	81 22 58	18	27	38.6[a]	35.3	3.3
971	302159081235601	D-2386	30 21 59	81 23 56	28	26	34.6[b]	35.0	-0.4
927	302052081323201	D-3060	30 20 52	81 32 32	27	17	32.8[c]	36.0	-3.2
792	304001081280301	N-0117	30 40 01	81 28 03	23	22	42.8[d]	38.6	4.2
852	301817081374902	D-425B	30 18 17	81 37 49	25	12	38.2[e]	37.4	0.8

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

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