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COMPUTER SIMULATION OF THE PREDEVELOPMENT AND CURRENT FLORIDAN AQUIFER SYSTEM IN NORTHEAST FLORIDA

By

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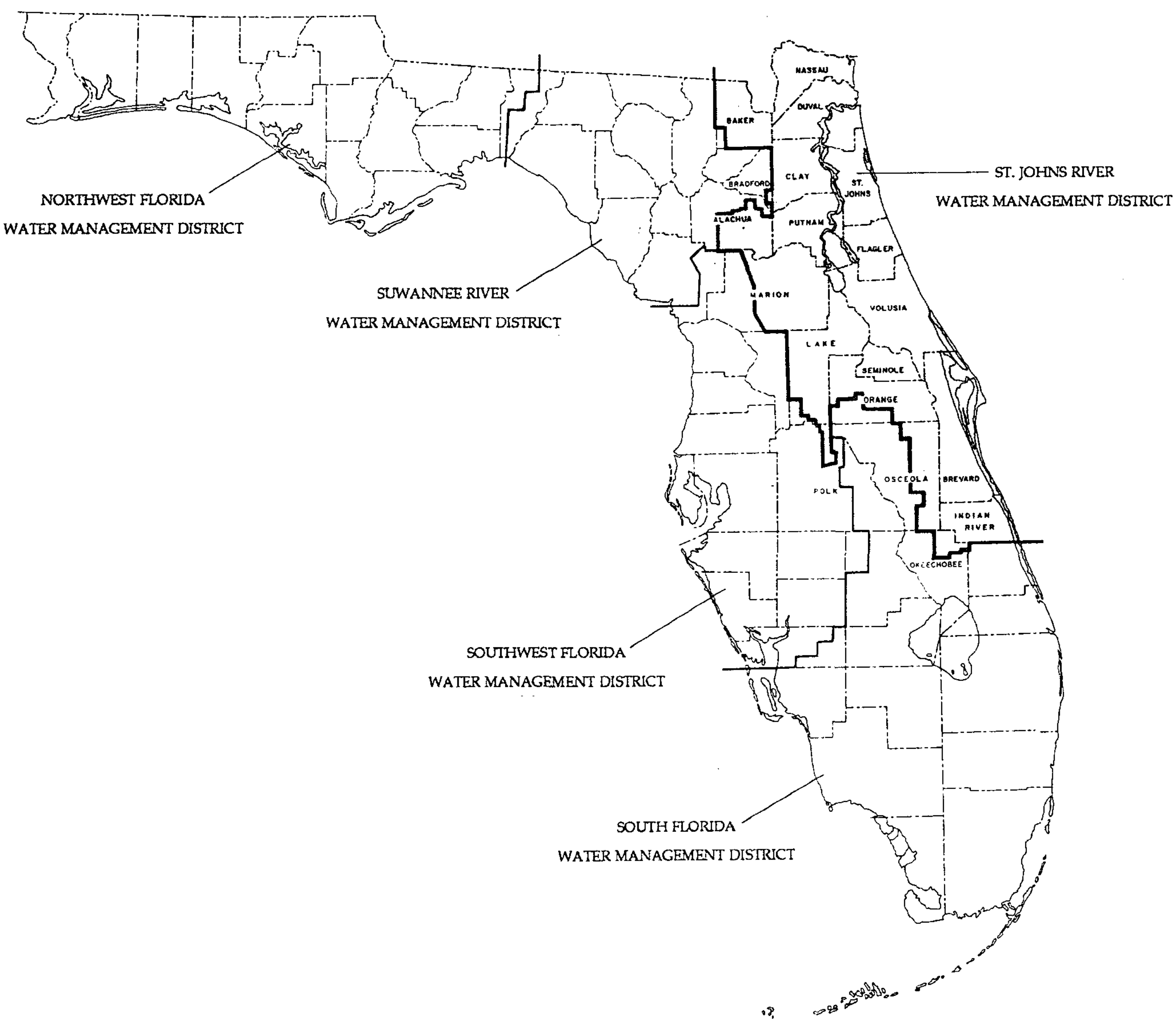

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EXECUTIVE SUMMARY

The primary objective of this research was to develop a finite-difference ground water flow model that could be used to predict the response of the Floridan aquifer system of the Jacksonville area of northeast Florida to various pumping scenarios. The study area includes parts of Duval, St. Johns, Nassau, Clay, and Putnam counties, as well as a sizable area in the Atlantic Ocean. This research was submitted as a thesis for a masters degree in engineering at the University of Florida

The model used was the modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW) developed by M. G. McDonald and A. W. Harbaugh of the U. S. Geological Survey (USGS). The predevelopment (prior to 1880) and current Floridan aquifer systems were modeled as steady-state systems consisting of three aquifer layers (the surficial aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer) separated by three confining-unit layers (the upper confining unit, the middle confining unit, and the lower confining unit).

The overall calibration process consisted of two phases. The predevelopment flow model was initially calibrated using a USGS predevelopment potentiometric surface map. Using the distributions of leakance and transmissivity that resulted from the predevelopment calibration as starting values, the current-system model was calibrated using the May 1985 potentiometric surface map. The distributions of leakance and transmissivity that resulted from the current-system calibration were taken as final and best estimates; they were then used to construct a new, presumably more accurate predevelopment flow model, the modified predevelopment flow model.

Comparison of results from the current-system and modified predevelopment models indicates that areas of high leakance in the middle confining-unit that separates the Upper and Lower Floridan aquifers suggest that in parts of the study area the Upper and Lower Floridan aquifers are hydraulically well connected. Two such areas were identified in the current-system model calibration in the north-central and south-central areas of

the study area. Relatively little downward leakage from the surficial aquifer system to the Floridan aquifer system actually occurs within the study area; by far the most inflow to the Floridan aquifer system occurs as upward leakage from the Lower Floridan aquifer and lateral flow through the western boundary of the study area.

A mass balance analysis of the Upper Floridan aquifer based on results of the model of the current flow system indicates that approximately 2.5 in of flow per year currently enter the Upper Floridan aquifer from several different sources. About 98 percent of all flow entering the entire Floridan aquifer system in the study area eventually enters the Upper Floridan aquifer. Model results indicate that of the flow sources, the Lower Floridan aquifer is the greatest contributor, supplying about 63 percent of the total yearly recharge to the Upper Floridan aquifer. Lateral flow through the western boundary of the study area accounts for approximately 29 percent of the recharge to the Upper Floridan aquifer, according to the model simulation, while the surficial aquifer system contributes approximately 7.5 percent of the total inflow to the Upper Floridan aquifer of the study area. Lateral flow across the eastern and southern boundaries occurs in only negligible amounts, according to the model results, accounting for less than 1 percent of the total inflow to the Upper Floridan aquifer.

The model indicates that ground water withdrawals from the Upper Floridan aquifer of the study area have brought about significant changes in the rates of recharge to and discharge from the Floridan aquifer. Model results indicate that the Lower Floridan aquifer now contributes more than twice the amount of flow to the Upper Floridan aquifer that it contributed in predevelopment times. Proportionally, its contribution has increased from approximately 50 percent of the total inflow to the Upper Floridan aquifer to approximately 63 percent, indicating that its importance in the overall flow system has increased.

Since predevelopment times, lowering of the potentiometric surface of the Upper Floridan aquifer (by an average of approximately 25 ft) relative to the water table has affected rates of recharge and discharge of the Upper Floridan aquifer within the study area. Upward leakage from the Upper Floridan aquifer to the surficial aquifer system has decreased both absolutely and proportionally, according to simulations of the modified predevelopment and current-system models, while downward leakage from the surficial aquifer system into the Upper Floridan aquifer has increased absolutely but has decreased somewhat proportionally.

The average transmissivity of the Upper Floridan aquifer is 148,000 ft^2/d. The average transmissivity of the Lower Floridan aquifer is greater than that of the Upper Floridan aquifer, 230,000 ft^2/d, according to the results of the calibration of the current-system model. Possible reasons for this are that the Lower Floridan aquifer is about twice as thick as the Upper Floridan aquifer throughout most of the study area and that a zone of high transmissivity, the Fernandina permeable zone, exists in the Lower Floridan aquifer of the study area and contributes to higher average transmissivities there.

The model calibrations indicate that more data is needed describing pumping rates, the potentiometric surface of the Lower Floridan aquifer, and the elevation of the water table within the study area.

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INTRODUCTION

OBJECTIVES OF STUDY

The increasing demand for ground water being placed on the Floridan aquifer system in the Jacksonville area of northeast Florida has resulted in the need for better planning and allocation of the ground water resources of the area. Effective planning and allocation can be aided with the use of ground water flow models to predict the effects of future hydrologic events such as proposed changes in pumping rates.

Types of ground water flow models include mathematical models, which may be numerically or analytically derived. The assumptions necessary to solve the equations of ground water flow analytically often do not enable a realistic representation of complex aquifer systems. For instance, many analytical solutions require that represented aquifers be homogeneous and isotropic (Wang and Anderson 1982). Numerical finite-difference models are capable of taking into account many complexities of aquifer systems, such as spacial variations of hydraulic conductivity and non-uniform thicknesses of hydrologic layers. Therefore, they are capable of providing a more realistic representation of the aquifer systems under consideration. The Floridan aquifer system of northeast Florida is a complex, multilayer, heterogeneous aquifer system. It is, therefore, represented in this study by a numerical finite-difference ground water flow model.

Previous studies using finite-difference ground water flow models have encompassed northeast Florida, but none had sufficient resolution to evaluate with sufficient precision the impact of various pumping scenarios within the area. This study had the following objectives:

(1) to develop a finite-difference ground water flow model that could accurately predict the responses of the Floridan aquifer system of the area to various pumping scenarios

(2) to increase overall understanding of the ground water flow between aquifers within the Floridan aquifer system in the study area

(3) to improve previous estimates of transmissivity and leakance

This study was prepared as a thesis for a masters degree in engineering at the University of Florida.

PREVIOUS STUDIES

Previous hydrogeological studies that encompassed parts of northeast Florida include the Regional Aquifer-System Analysis (RASA) of the U.S. Geological Survey (USGS), which has resulted to date in several significant studies, including the regional ground water flow model by Bush (1982) and the subregional ground water flow model by Krause (1982). Other recent hydrogeological studies by the USGS that focused on parts of northeast Florida include the works of Johnston and Bush (1988) and Miller (1986), whose work also resulted from the RASA study, as well as Causey (1975). The subregional ground water flow model by Tibbals (1981), whose study focused on the Floridan aquifer system of nearby east-central Florida, resulted from the USGS RASA study as well. Reports by Bermes et al. (1963), Clark et al. (1964), Leve (1966), Fairchild (1972), and Scott (1983) also have discussed the hydrogeology of northeast Florida.

METHODOLOGY

The hydrogeological information and data needed to calibrate this ground water flow model were obtained from the publications of the USGS, the Florida Bureau of Geology, and St. Johns River Water Management District (SJRWMD). The overall calibration process consisted of two phases: an initial calibration using the estimated potentiometric surface of the predevelopment ground water flow system (prior to 1880), and a subsequent calibration using the observed potentiometric surface of the current ground water flow system for a month and year chosen to be representative of average conditions in the current flow system during its seasonal low-water level (May 1985). The estimates of transmissivity and leakance obtained from the initial calibration were used as starting values in the subsequent calibration. The transmissivity and leakance distributions resulting from the subsequent calibration were considered to be the final results of the calibration process. These values were used to construct a new predevelopment model, the "modified predevelopment model", which is presumably more accurate than the initial predevelopment model. The progress of the calibrations was monitored by calculating the means of differences between simulated and observed hydraulic-head distributions and corresponding standard deviations. Progress was also monitored by comparisons of observed potentiometric surfaces to model-derived potentiometric surfaces.

DESCRIPTION OF STUDY AREA

LOCATION AND EXTENT

The study area includes most of Duval and St. Johns counties, large parts of Nassau and Clay counties, a small part of Putnam County, as well as a sizable offshore area in the Atlantic Ocean (Figure 1). The study area encompasses approximately 2,700 square miles, and its boundaries range from longitude 81°52.0′ in the west to longitude 81°7.0′ in the east and from latitude 29°46.0′ in the south to latitude 30°41.5′ in the north.

CLIMATE

The climate of the study area is humid subtropical (Bermes et al. 1963). From 1951 to 1980, the average annual rainfall for Jacksonville, which is near the center of the study area, was 51.43 in. The months June through October, during which about 60 percent of the average annual rainfall occurs, constitute the wet season in the area, and the months November through May constitute the dry season (Rao et al. 1989). The average annual temperature at Jacksonville was 68.0^{0}F, as measured by the National Oceanic and Atmospheric Administration (NOAA), during the period 1951 to 1980 (NOAA 1981-87).

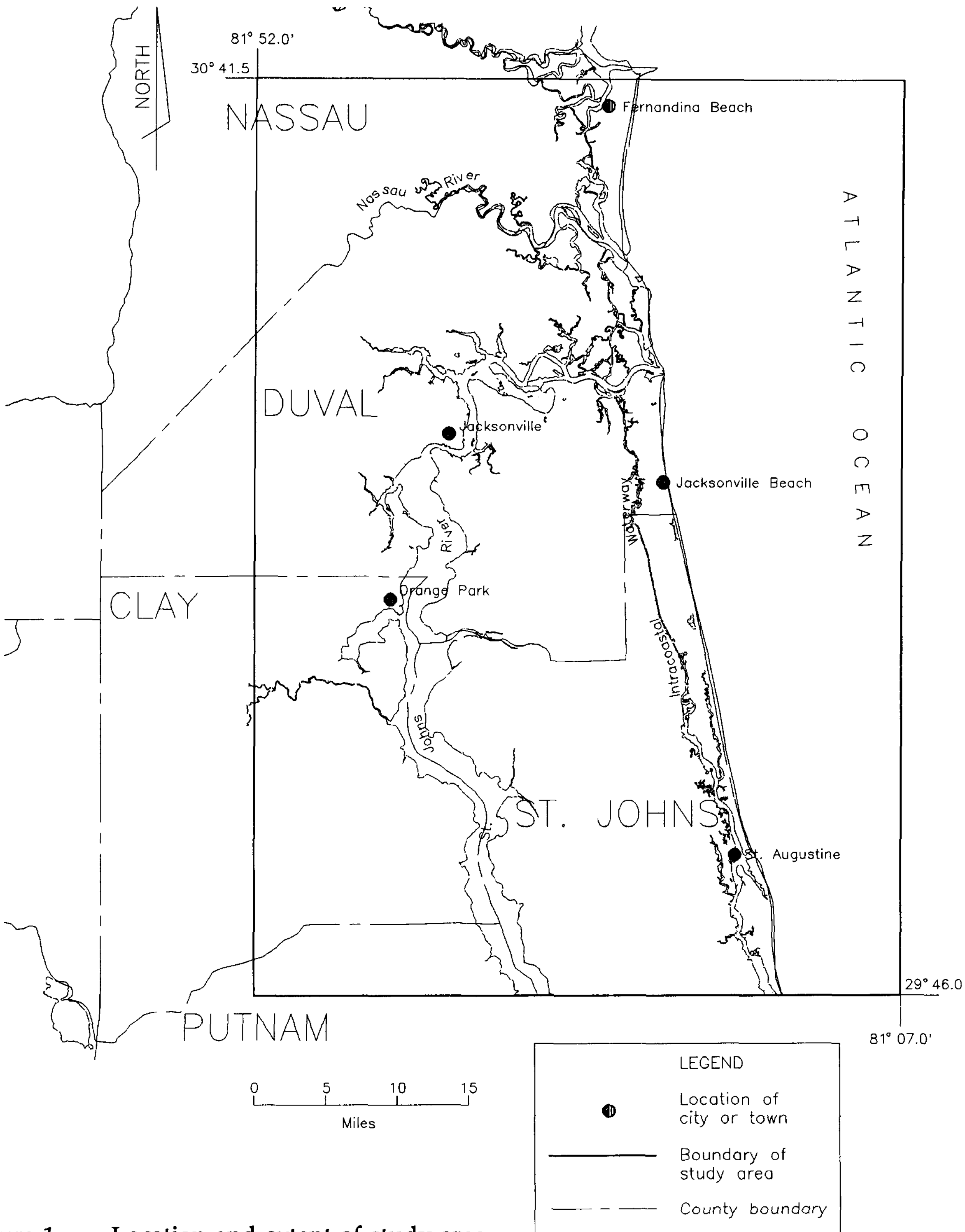


Figure 1. Location and extent of study area

POPULATION AND INDUSTRY

Jacksonville is the major industrial center of northeast Florida and is by far the largest municipality within the study area. Major industries there include manufacturing of paper, food products, chemicals, building materials,and shipbuilding and repair. Several major military installations are located in the area as well. Elsewhere within the study area, primary industries include agriculture and the production of wood pulp and paper.

Population centers within the study area include Jacksonville, Jacksonville Beach, St. Augustine, Fernandina Beach, and Orange Park. The total population of the five counties of the study area was estimated to be 962,782 (Table 1) in 1988, of which approximately 70 percent was concentrated in Duval County (University of Florida 1989).

PHYSIOGRAPHY AND SURFACE WATER FEATURES

The physiography and surface water features of the study area influence the water-table elevations, which are an important element of the model. The topography of the study area reflects the presence of a series of marine terraces that were deposited during Pleistocene time, when sea levels fluctuated in response to alternate periods of glaciation and thawing. The sea level stood below the present shoreline during glaciation and above during thawing. Upon being immersed, during interglacial periods, the immersed land surface was eroded by ocean currents and waves to form a flat, gently sloping plain (a marine terrace). Upon recession of the sea, the land surface was eroded by rivers and streams. Seven such terraces and the elevations of their shorelines have been identified within the study area (Bermes et al. 1963, Leve 1966, Table 2).

The Coharie, Sunderland, and Wicomico terraces are the highest of the seven terraces, and they form the highlands area of western Nassau, Duval, Clay, and Putnam counties, where land elevations within the study area range from approximately 70 to 120 ft above mean sea level (msl). The physiography of this area is characterized by numerous deeply eroded stream valleys and high, steeply sloping hills.

Table 1. Populations of the counties of the study area in 1980 and 1988

County	Population by Year	
	1980	1988
Duval	571,003	677,007
Clay	67,052	99,171
Putnam	50,549	60,717
Nassau	32,894	45,609
St. Johns	51,303	80,278

Source: University of Florida 1989

Table 2. Pleistocene terraces and corresponding approximate shoreline elevations

Terrace	Approximate Elevation of Shoreline (ft msl)*
Coharie	170-215
Sunderland	100-170
Wicomico	70-100
Penholoway	42-70
Talbot	25-42
Pamlico	10-25
Silver Bluff	0-10

*feet above mean sea level
Source: Bermes et al. 1963

Throughout much of eastern Nassau, Duval, and central St. Johns counties, the Penholoway and Talbot terraces form a broad ridge known as the coastal ridge. This feature ranges in elevation in most of the area from 25 to 40 ft above msl, but it can be as high as 70 ft above msl. The coastal ridge generally runs parallel to the present shoreline. The flanks of the coastal ridge slope gently to the east and west, resulting in moderately good to poor drainage that is evidenced by the presence of numerous swampy areas on the surface of the coastal ridge.

Between the coastal ridge and the western highlands is an area of moderate-to-low relief that is occupied mostly by the Penholoway, Talbot, Pamlico, and Silver Bluff terraces. Elevations within this area range from 0 to 70 ft above msl, and drainage in this area is usually fair to excellent. The areas between the coastal ridge and present shoreline are occupied by the Silver Bluff and Pamlico terraces, which range in elevation from 0 to 25 ft above msl. These areas are often characterized by flat, gently sloping land surfaces and consequently very poor drainage that results in extensive coastal marshlands and numerous meandering streams (Bermes et al. 1963, and Leve 1966).

Surface drainage in the western and central parts of the study area is controlled principally by the St. Johns River and its tributaries and the Nassau River. Drainage in the eastern part of the study area is controlled largely by the Intracoastal Waterway (Bermes et al. 1963, and Leve 1966).

GEOLOGIC SETTING

INTRODUCTION

The geologic units in study area form the framework of its ground water hydrology system. These units include the pre-Hawthorn tertiary carbonate formations, the Hawthorn Group, and the post-Hawthorn deposits (Table 3). The pre-Hawthorn tertiary carbonate formations are composed primarily of interbedded limestone and dolomite, and have been differentiated stratigraphically by age, which ranges from Paleocene to late Eocene (Miller 1986). From oldest to youngest, these units are the Paleocene age Cedar Keys Formation, the early Eocene age Oldsmar Formation, the middle Eocene age Avon Park Formation, and the late Eocene age Ocala Limestone. The Hawthorn Group is of middle Miocene age and consists of a variety of components, including phosphate, carbonate, sand, and clay (Scott 1983). The post-Hawthorn deposits range in age from Pliocene (or late Miocene) to Recent. The primary components of the post-Hawthorn deposits include sand, clay, carbonate, clayey sand, sandy clay, and shell. The age of these units ranges from 55 to 65 million years before present for the Paleocene rocks to 11,000 years before present for the Pleistocene and recent deposits (Table 4).

PRE-HAWTHORN TERTIARY CARBONATE FORMATIONS

Paleocene Series

The Paleocene rocks of the study area are contained entirely within the Cedar Keys Formation, which consists predominantly of interbedded dolomite and anhydride. Extensive anhydride beds that are relatively impermeable

Table 3. Summary of geologic units in the study area

Geologic Epoch	Stratigraphic Unit	Approximate Thickness (ft)	Lithology
Pleistocene and Recent	post-Hawthorn deposits	10-100	Discontinuous beds of loose sand, clayey sand, sandy clay, marl, and shell
Pliocene (or Late Miocene)	post-Hawthorn deposits	10-110	Clay, clayey sand, sandy clay, shell, and limestone
Middle Miocene	Hawthorn Group	100-400	Interbedded clay, quartz, sand, carbonate, phosphate
Late Eocene	Ocala Limestone	200-400	Porous limestone
Middle Eocene	Avon Park Formation	500-1,200	Interbedded limestone and dolomite
Early Eocene	Oldsmar Formation	300-800	Interbedded limestone and dolomite
Paleocene	Cedar Keys Formation	unknown	Interbedded dolomite and anhydride

Sources: Bermes et al. 1963; Clark et al. 1964; Leve 1966; Fairchild 1972; and Miller 1986

Table 4. Time of various geologic ages before present

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

Source: Batten 1987

occur at the base of the upper one-third of this formation and are recognized by Miller (1986) as the base of the Floridan aquifer system.

The surface of the Cedar Keys Formation slopes downward from west to east in the study area (Figures 2, 3, and 4). The elevation of the top of the Cedar Keys Formation ranges from 1,500 ft below msl, in the area of western Clay and Putnam counties to 2,000 ft below msl, in eastern St. Johns County. In Duval County, the elevation of the top of the Cedar Keys Formation ranges from 1,600 ft below msl, in the southwestern area of the county to 2,400 ft below msl, in the northeastern area of the county. In Nassau County, the elevation of the top of the Cedar Keys Formation ranges from 1,700 ft below msl, at the extreme southwestern corner of the county to more than 2,500 ft below msl, along the coastal area of the county. Little is known of the thickness of the Cedar Keys Formation within the study area because few if any wells fully penetrate it.

Eocene Series

Early Eocene Rocks. The rocks of early Eocene age within the study area occupy the full thickness of the Oldsmar Formation and are entirely contained within it. The Oldsmar Formation is composed of interbedded limestone and dolomite. The dolomite beds vary greatly in thickness and commonly contain cavities. The lower part of the unit contains gypsum and thin beds of anhydride, and it is usually more extensively dolomotized than the upper part. The designation of the Oldsmar Formation as a "Formation" rather than "Limestone" is due to the presence within it of significant amounts of dolomite, anhydride, and other rocks in addition to limestone (Miller 1986).

The surface of the Oldsmar Formation slopes from west to east within the study area. In Clay and northern Putnam counties, the elevation of the surface of the Oldsmar Formation ranges from 1,000 to 1,100 ft below msl in the west to 1,400 ft below msl in the east. In Duval and Nassau counties, the elevation ranges from 1,100 to 1,300 ft below msl in the west to 1,700 ft below msl in the east. In St. Johns County, the elevation ranges from 1,400 to 1,500 ft below msl in the west to 1,600 ft below msl in the east.

In western Duval, Clay, and Putnam counties, the thickness of the Oldsmar Formation ranges from 400 to 500 ft. To the east as far as St. Johns County, the thickness ranges from 300 to 400 ft. In Nassau and extreme northern Duval counties, the thickness ranges from 600 to 800 ft or more.

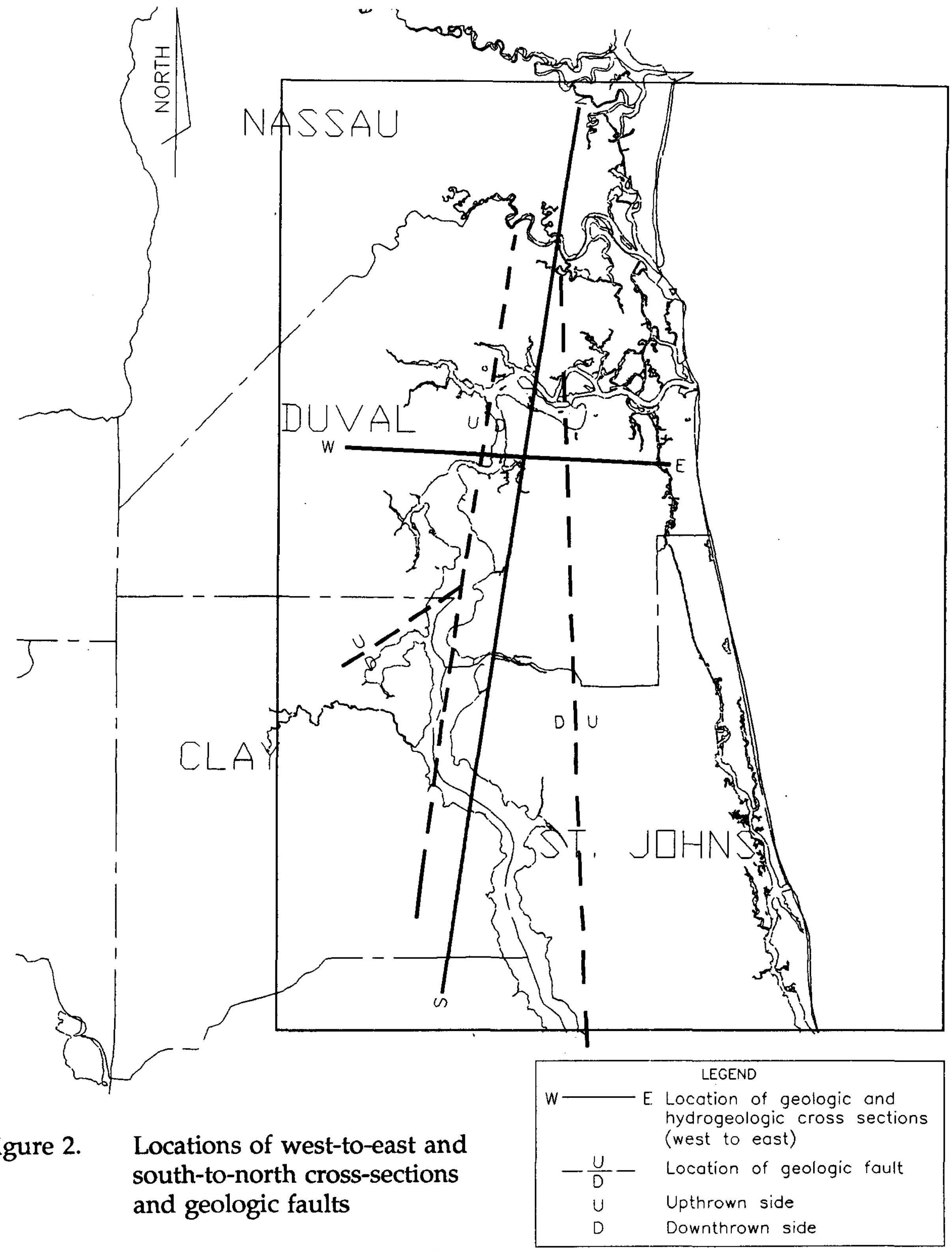


Figure 2. Locations of west-to-east and south-to-north cross-sections and geologic faults

Source: Modified from Miller 1986

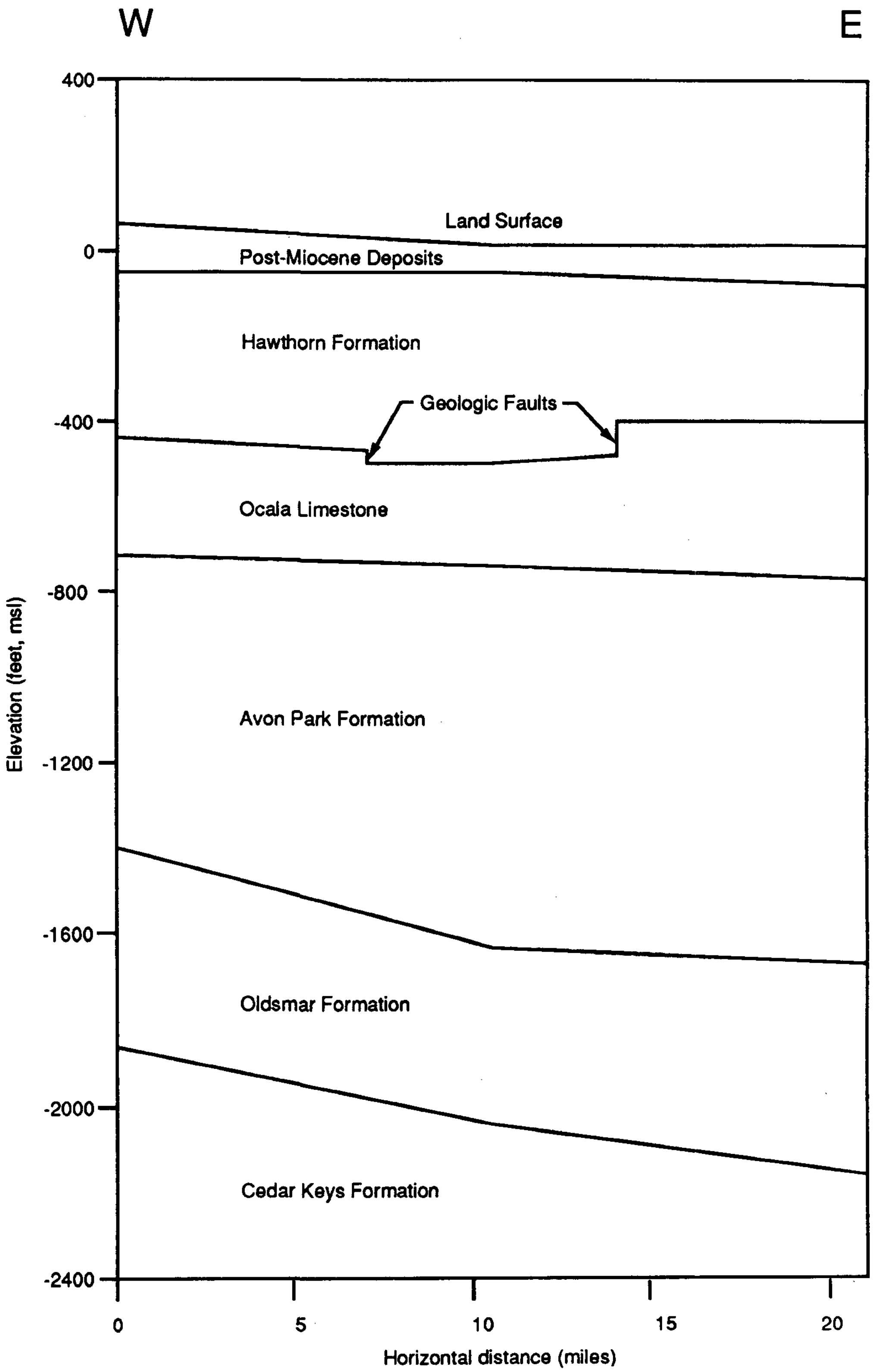


Figure 3. West-to-east geologic cross-section

Source: Derived from Miller 1986

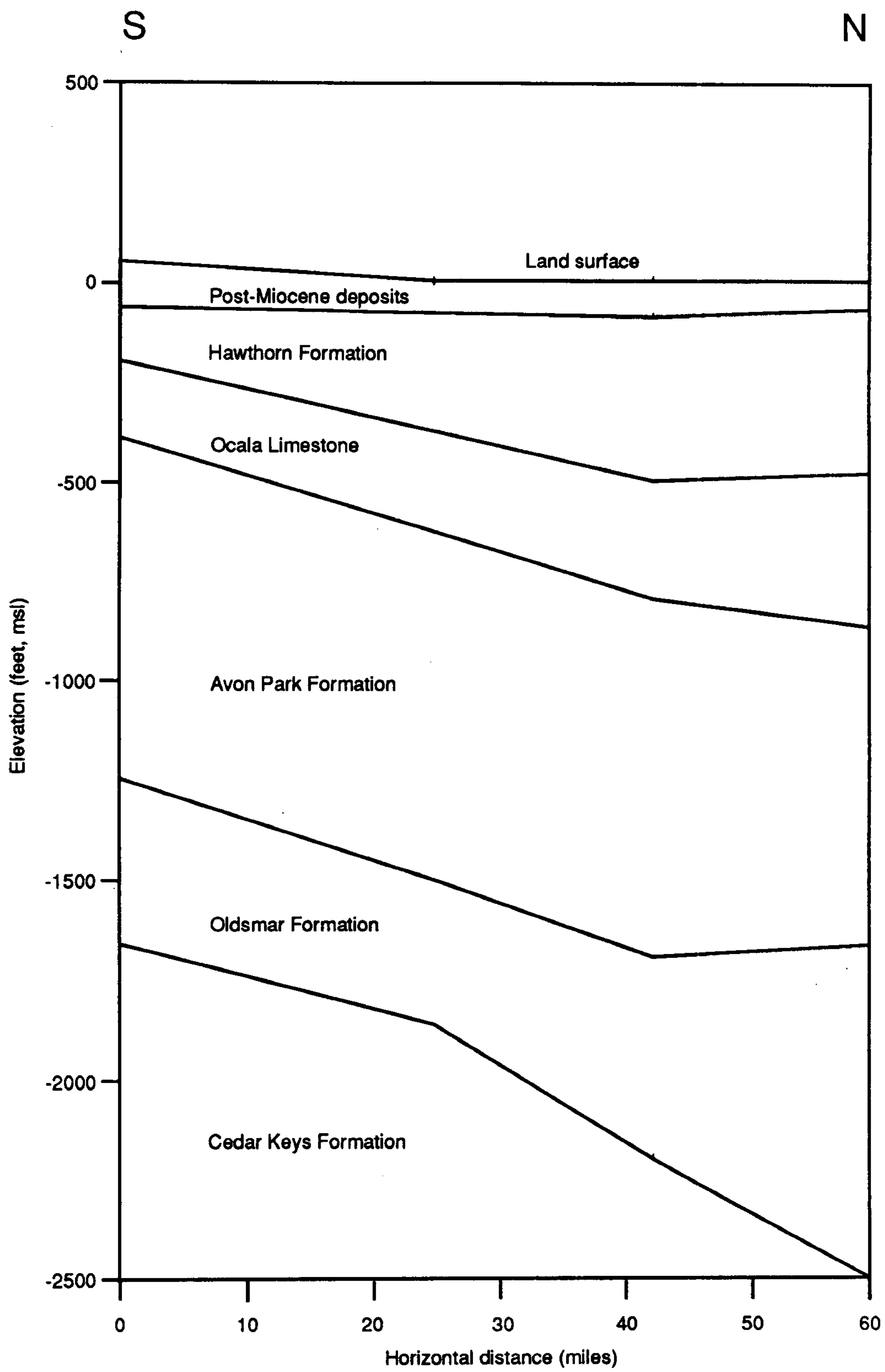


Figure 4. South-to-north geologic cross-section

Source: Derived from Miller 1986

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

The surface of the Avon Park Formation within the study area slopes downward in a northeasterly direction from an elevation of approximately 350 ft below msl in central Putnam and southern St. Johns counties to 900 ft below msl in northeastern Nassau County (Miller 1986).

The Avon Park Formation is somewhat less than 500 ft thick in the area of northwestern Clay County and increases in thickness from there in all directions throughout the study area. In the southeastern corner of Clay County, the Avon Park Formation reaches a thickness of about 1,000 ft. In St. Johns County, the thickness of the Avon Park Formation increases from about 800 ft in the northwestern corner of the county to about 1,200 ft in its southeastern corner. The thickness of the Avon Park Formation in Duval and Nassau counties ranges from 500 to 700 ft in the west to 800 ft or more in the east, while in northern Putnam County, the thickness ranges from 600 ft in the west to 1,000 ft in the east.

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

The dissolution of carbonate rocks as a result of contact with ground water commonly results in the formation of cavities and even large caverns within carbonate units (Schultz and Cleaves 1955). The surface of the Ocala

Limestone is marked locally with many irregularities, which are due to dissolution of the limestone (Miller 1986). The dissolution of the limestone has greatly enhanced the primary porosity of the unit, making it "one of the most permeable rock units in the Floridan aquifer system" (Miller 1986, B30).

Two comparably long faults and one relatively short fault occur on the surface of the Ocala Limestone within the study area (Figure 2), according to Miller (1986). The faults run in directions that range from northeast-southwest to approximately north-south (Miller 1986). The westernmost of the two larger faults runs from north-central Duval County to southeastern Clay County. The relatively short fault branches from the westernmost of the two larger faults in a northeast-southwest direction. The easternmost fault runs from the area of north-central Duval County to southwestern St. Johns County. The surface of the Ocala Limestone is vertically displaced at these faults by approximately 50 to 100 ft. These faults apparently are relatively shallow, since they do not occur on the surface map of the underlying Avon Park Formation (Miller 1986).

The surface of the Ocala Limestone is at an elevation of about 200 ft below msl, in the area of northern Putnam County, and it slopes downward in a northeasterly direction to a depth of about 500 ft below msl, in eastern Nassau County. In St. Johns County, the surface lies between 100 and 300 ft below msl. The Ocala Limestone is roughly 200 ft thick in the area of northern Putnam and central Clay counties, and its thickness increases at a fairly constant rate, also in a northeasterly direction, to approximately 400 ft in the area of eastern Nassau and Duval counties. Its thickness ranges from 200 to 300 ft in St. Johns County.

HAWTHORN GROUP

The Hawthorn Group of middle Miocene age is described as consisting of widely varying mixtures of clay, quartz, sand, carbonate, and phosphate (Scott 1983). Phosphate is found virtually everywhere within the Hawthorn Group. Dolomite, the most common form of the carbonate component, is distributed within the Hawthorn Group in significant amounts throughout most of the study area (Scott 1983). Clay and sand are distributed within the Hawthorn Group in significant amounts throughout most of the study area as well (Scott 1983).

The complex stratigraphy of the Hawthorn Group is generalized to consist of three separate units (Scott 1983). These are as follows: a lower carbonate unit, a middle clastic unit, and an upper unit that is a mixture of clastic and carbonate rocks (Miller 1986). The relatively low permeability of the Hawthorn Group is attributed to its heterogeneity and the fine texture of its constituents, both clastic and carbonate (Miller 1986).

The surface elevation of the Hawthorn Group is between 50 and 100 ft above msl, in the area of western Clay and northwestern Putnam counties, and it decreases to between 50 and 100 ft below msl in the area of eastern Clay and northeastern Putnam counties. The surface elevation of the Hawthorn Group increases from below 100 ft below msl in the northwestern area of St. Johns County to somewhat above 50 ft below msl in the southeastern area of the county. The surface elevation of the Hawthorn Group ranges from 0 to 100 ft above msl in the western area of Duval and Nassau counties to 50 ft below msl in the eastern area of these counties (Miller 1986).

The thickness of the Hawthorn Group generally increases from southwest to northeast within the study area. The thickness is between 100 and 200 ft in the areas of central and northern Putnam County and is between 100 and 300 ft in most of St. Johns County. In Clay County, the thickness of the Hawthorn Group ranges from approximately 200 ft in the south to 300 ft in the north. In Duval County, the thickness of the Hawthorn Group is between 200 and 300 ft in the western and southeastern areas of the county and more than 400 ft in the northeastern area of the county. In southwestern Nassau County, the thickness is between 200 and 300 ft and increases to more than 400 ft in the eastern area of the county (Miller 1986).

POST-HAWTHORN DEPOSITS

Post-Hawthorn deposits within the study area range in age from Pliocene (or late Miocene) to Pleistocene and Recent (e.g., Bermes et al. 1963, Leve 1966, and Miller 1986).

Pliocene (or Late Miocene) Deposits

The Pliocene (or late Miocene) deposits of Duval and Nassau counties are composed of interbedded clay and clayey sand; fine-to-medium grained, well sorted sand; shell; and soft limestone. These deposits are differentiated from the Hawthorn Group by the absence or near-absence of phosphate within them (Leve 1966). A typical well log of Pliocene (or late Miocene) deposits in Duval County consists of three general sections: an upper section of clayey sand and sandy clay, a middle section of sandy clay and shell, and a lower section of interbedded sandy clay, clay, and soft, porous limestone (Fairchild 1972).

The contact between the Pliocene (or late Miocene) deposits and the underlying Hawthorn Group is marked by an unconformity consisting of coarse sands and phosphates. No definite marker exists between the Pliocene (or late Miocene) and the overlying Pleistocene and Recent deposits (Leve, 1966). The surface elevation of the Pliocene (or late Miocene) deposits within the study area ranges from approximately 50 ft below msl to 50 ft above msl. The thickness of the Pliocene (or late Miocene) deposits within the study area typically ranges between 10 and 110 ft.

Pleistocene and Recent Deposits

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

Elevations of the surface of the Pleistocene and Recent deposits, which represent the land surface of the study area, range from 0 to 120 ft above msl. The thickness of the Pleistocene and Recent deposits is typically between 10 and 100 ft over most of the study area.

GROUND WATER HYDROLOGY

INTRODUCTION

The ground water hydrology system of the study area consists of a surficial aquifer system, an intermediate aquifer system, and the Floridan aquifer system (Table 5 and Figures 5 and 6). The surficial aquifer system is the uppermost aquifer system within the study area and is under nonartesian conditions there. The intermediate aquifer system, which underlies the surficial aquifer system, consists of discontinuous, relatively thin confined aquifers that are contained in the Hawthorn Group and the Pliocene (or late Miocene) deposits. The Floridan aquifer system is separated from the overlying surficial and intermediate aquifer systems by the lower part of the Hawthorn Group, which serves as its upper confining unit. The Floridan aquifer system is separated internally by a middle confining unit into two permeable zones, the Upper Floridan aquifer and the Lower Floridan aquifer, and it is bounded at its base by extensive beds of low-permeability anhydride, which serve as its lower confining unit.

SURFICIAL AQUIFER SYSTEM

The surficial aquifer system consists primarily of sand, clayey sand, and shell of either the Pliocene (or late Miocene) or Pleistocene and Recent deposits (Bermes et al. 1963, and Clark et al. 1964). The surface of the surficial aquifer system (the water table) is a "subdued replica of the configuration of the land surface" (Miller 1986, B41). In eastern St. Johns County, the surficial aquifer system has been differentiated into an upper zone of relatively high permeability and a lower zone of relatively low permeability that is much less

Table 5. Summary of ground water hydrology systems within the study area

Geologic Age	Geologic Unit(s)	Hydrologic Unit(s)		Description
Pleistocene and Recent	Pleistocene and Recent Deposits	Surficial Aquifer System		Consists of sand, clayey sand, and shell. Thickness varies approximately between 20 and 150 ft.
Pliocene (or late Miocene)	Pliocene (or late Miocene Deposits)			
Middle Miocene	Hawthorn Group	Upper Confining Unit/ Intermediate Aquifer System		Upper confining unit consists of clay, marl, and discontinuous beds of sand, shell, dolomite, and limestone (aquifers of intermediate aquifer system). Confines intermediate aquifer system and underlying Floridan aquifer system. Thickness is 150 to 450 ft. Aquifers of intermediate aquifer system are up to 40 ft thick.
Late Eocene	Ocala Limestone	Upper Floridan Aquifer	FLORIDAN AQUIFER SYSTEM	Consists mainly of limestone of high primary and secondary porosity. Thickness ranges between 300 and 700 ft.
Middle Eocene	Avon Park Formation	Middle Confining Unit		Consists of leaky, low-permeability limestone and dolomite. Thickness ranges between 50 and 200 ft.
Early Eocene	Oldsmar Formation	Lower Floridan Aquifer		Consists primarily of interbedded limestone and dolomite. Contains high-permeability Fernandina permeable zone. Thickness ranges between 1,100 and 1,500 ft.
Paleocene	Cedar Keys Formation	Lower Confining Unit		Consists of low permeability anhydride beds. Thickness unknown.

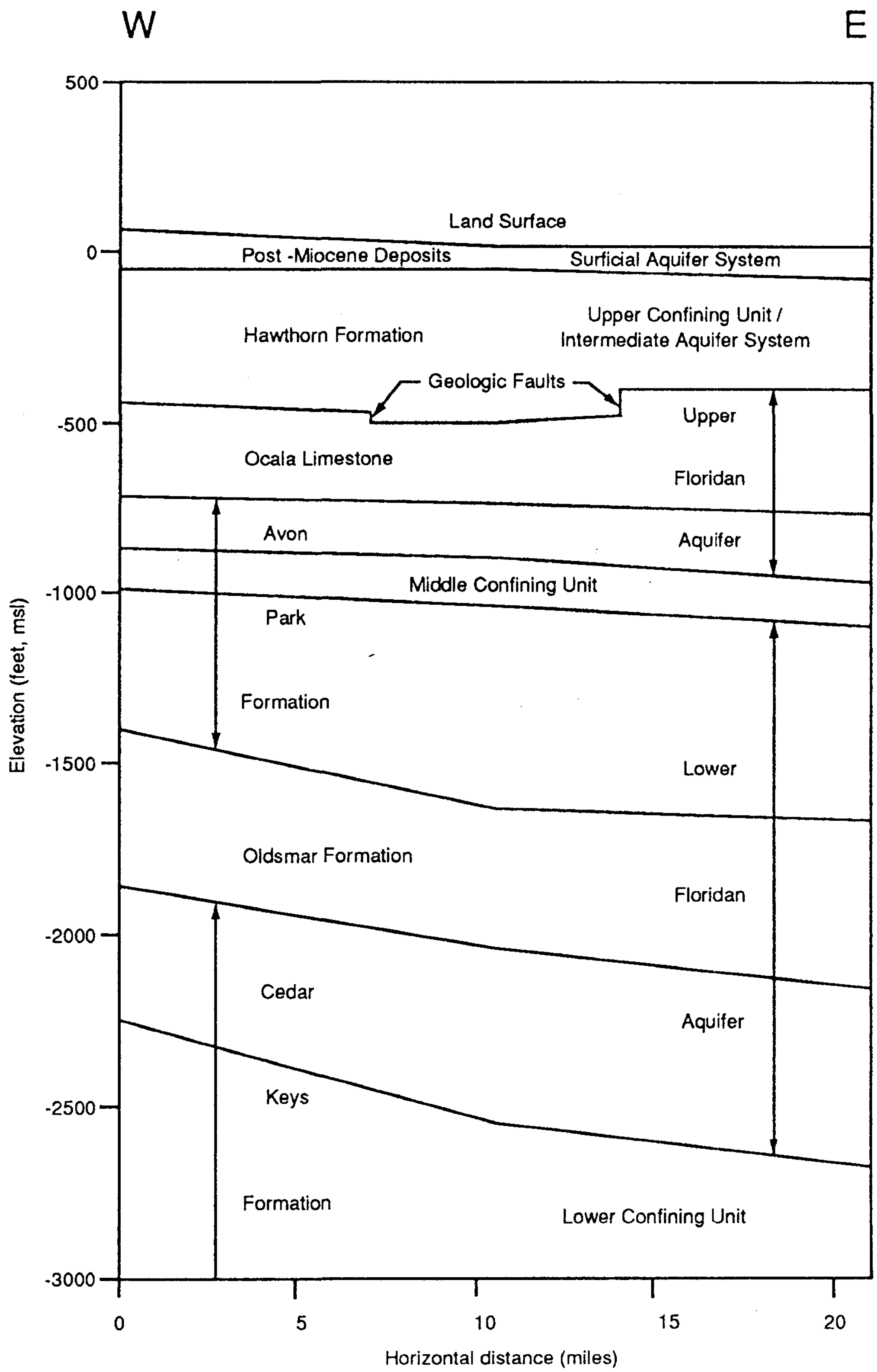


Figure 5. West-to-east hydrologic cross-section

Source: Derived from Miller 1986

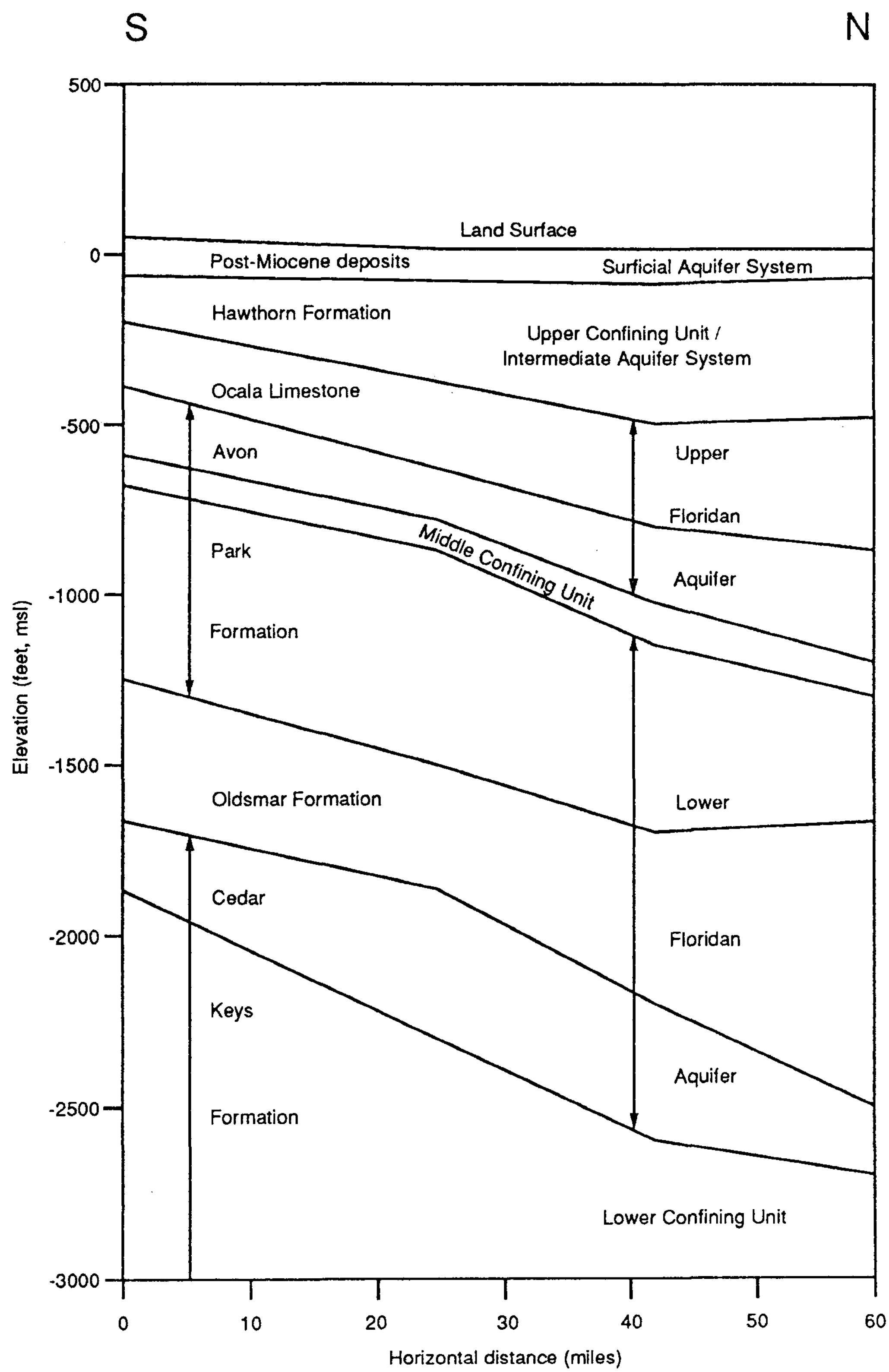


Figure 6. South-to-north hydrologic cross-section

Source: Derived from Miller 1986

productive (Bermes et al. 1963). The upper permeable zone thins to the west so that in western St. Johns County and most of Putnam County the lower zone, which consists of discontinuous lenses of permeable sand and limestone contained in marl and clay beds, is at or near the surface of the surficial aquifer system. The thickness of the surficial aquifer system ranges from 100 to about 150 ft or more.

INTERMEDIATE AQUIFER SYSTEM

The intermediate aquifer system consists principally of discontinuous limestone, shell, and sand beds in the middle Miocene age Hawthorn Group and Pliocene (or late Miocene) deposits above the Hawthorn Group (Bermes et al. 1963). The degree of hydraulic connection between the intermediate aquifer system and the surficial aquifer system varies, often depending on the depth of the aquifers of the intermediate aquifer system (Bermes et al. 1963). The potentiometric surfaces of the deeper aquifers of the intermediate aquifer system tend to fluctuate with the potentiometric surface of the underlying Floridan aquifer system, whereas the potentiometric surfaces of the shallower aquifers within the intermediate aquifer system tend to fluctuate with the surface of the overlying surficial aquifer system (Clark et al. 1964). Within the study area, the elevations of the potentiometric surfaces of the aquifers of the intermediate aquifer system usually are greater than the corresponding elevations of the water table and less than the corresponding elevations of the potentiometric surface of the Floridan aquifer system (Clark et al. 1964). In places within the study area, the elevations of the potentiometric surfaces of the aquifers of the intermediate aquifer system are above the corresponding elevations of the land surface, particularly in low areas adjacent to the banks of streams (Leve 1966). The tops of the aquifers of the intermediate aquifer system generally range in elevation from 10 to 300 or more ft below msl, and they vary in thickness from less than 1 ft to 40 ft or more (Bermes et al. 1963 and Leve 1966).

Upper Confining Unit

The upper confining unit of the Floridan aquifer system consists of the middle Miocene age deposits of clay, sand, sandy clay, clayey sand, marl, limestone, and dolomite of the Hawthorn Group and the Pliocene (or late

Miocene) post-Hawthorn deposits (Leve 1966). The effectiveness of the upper confining unit depends largely on its thickness, its local lithology, which often varies greatly over short distances within the study area, and the presence or absence of breaches due to karst features in the underlying limestone units of the Floridan aquifer system. Where it is thick and/or contains much clay, leakage is much less than where it is thin and/or sandy (Miller 1986).

In most of the study area, the upper confining unit is quite thick. The thickness ranges from 150 ft or so in northern Putnam and central St. Johns counties to a maximum of more than 450 ft over large parts of Duval County (Miller 1986). In Nassau County, the thickness ranges from 350 to 400 ft. Sinkholes usually occur in areas where the thickness of the upper confining unit is 100 ft or less (Miller 1986), and there are few, if any, sinkholes within the study area.

FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system of the study area consists of the late Eocene age Ocala Limestone, the middle Eocene age Avon Park Formation, the early Eocene age Oldsmar Formation, and the Paleocene age Cedar Keys Formation (Miller 1986). The interbedded layers of limestone and dolomite 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 confining beds that restrict the vertical movement of water between the high-permeability zones (Leve 1966).

The Floridan aquifer system of the study area has been differentiated into three hydrologic layers by Miller (1986): an upper zone of high permeability (the Upper Floridan aquifer), a middle zone of low permeability (the middle confining unit), and a lower zone of low-to-high permeability (the Lower Floridan aquifer) (Figures 5 and 6). The boundaries of these hydrologic units do not necessarily coincide with the boundaries of time-stratigraphic units or rock types, because the differentiation of the units is based on vertical variations in permeability (Miller 1986).

Upper Floridan Aquifer

The zone of high permeability that extends from the top of the Ocala Limestone through the upper one-third or so of the Avon Park Formation is called the Upper Floridan aquifer. The high permeability of the Upper Floridan aquifer is attributed to the combination of high primary and secondary porosity of the limestone (Miller 1986). The high secondary porosity has resulted from the formation of dissolution cavities within the limestone (Miller 1986).

The elevation of the top of the Upper Floridan aquifer ranges from 100 ft below msl, in northern Putnam County to 500 ft below msl, in north-central Duval County and northeastern Nassau counties (Miller 1986). The thickness of the Upper Floridan aquifer generally increases from west to east within the study area. It ranges from 300 to 400 ft in the west to 600 to 700 ft along the Atlantic coastline (Miller 1986).

Middle Confining Unit

The middle confining unit of the study area, called middle confining unit I by Miller (1986), extends roughly from the base of the upper third to the middle of the Avon Park Formation throughout most of the study area. At Jacksonville, the top of the middle confining unit is in the base of the Ocala Limestone. The middle confining unit is composed mainly of beds of limestone and dolomite that are of lower permeability than those beds above and below it. It is the leakiest of the eight internal confining units of the Floridan aquifer system identified by Miller (1986). The thickness of the middle confining unit ranges from about 50 ft in southern Clay County to as much as 200 ft in the area of northern Duval County.

Lower Floridan Aquifer

The Lower Floridan aquifer in the study area extends from the top of the lower half of the Avon Park Formation to the base of the upper third of the Cedar Keys Formation. Little is known about the hydraulic characteristics of the Lower Floridan aquifer because few wells fully penetrate it. In general, the permeability of rocks in the Lower Floridan aquifer is thought to be much less than that of rocks in the Upper Floridan aquifer (Miller 1986). However, throughout the study area, a zone of high permeability, known as the

Fernandina permeable zone, exists in the lower depths of the Lower Floridan aquifer. The Fernandina permeable zone underlies the entire study area and is usually found in the Cedar Keys Formation. It is separated from the rest of the Lower Floridan aquifer by a local confining unit (Miller 1986).

The elevation of the top of the Lower Floridan aquifer ranges from about 600 ft below msl, in northwestern Putnam County to about 1,300 ft below msl, in northeastern Nassau County (Miller 1986). The thickness of the Lower Floridan aquifer within the study area ranges from 1,100 to 1,200 ft in northern Putnam County to more than 1,500 ft in east-central Duval County (Miller 1986).

Lower Confining Unit

The base of the Floridan aquifer system, which is also the base of the Lower Floridan aquifer, is characterized by the presence of thick anhydride beds at the base of the upper third of the Cedar Keys Formation. These beds, whose permeability is "everywhere much less than that of the carbonate rocks that lie above them" (Miller 1986, B72), form the lower confining unit of the Floridan aquifer system.

RECHARGE AND DISCHARGE

Surficial Aquifer System

Recharge to the surficial aquifer system is supplied chiefly by rainfall that percolates downward to the water table and also by upward leakage from underlying artesian aquifers (Clark et al. 1964). In most of the study area, the elevation of the water table is less than the corresponding elevation of the potentiometric surface of the Floridan aquifer system (Phelps 1984), resulting in leakage from the Floridan aquifer system to the surficial aquifer system.

Discharge from the surficial aquifer system occurs primarily by evapotranspiration, downward leakage to underlying artesian aquifers, seepage to lakes and streams, and/or pumping (Clark et al. 1964).

Intermediate Aquifer System

Sources of recharge for the intermediate aquifer system within the study area are the underlying Floridan aquifer system and the overlying surficial aquifer system (Clark et al. 1964).

The Floridan aquifer system and surficial aquifer system may also receive discharge from the intermediate aquifer system, depending on the elevations of their potentiometric surfaces relative to the elevations of the potentiometric surfaces of the aquifers of the intermediate aquifer system (Clark et al. 1964). The other major mode of discharge from the intermediate aquifer system is pumping from domestic wells within the study area.

Floridan Aquifer System

The Floridan aquifer system in the study area is recharged primarily by inflow through the western boundary of the study area. This water originally enters the Floridan aquifer system outside the study area by recharge from the surficial aquifer system. A small-to-moderate amount of direct recharge to the Floridan aquifer system does occur within the study area (Phelps 1984). Recharge areas within the study area include parts of northwestern Putnam and southwestern Clay counties and central St. Johns County (Figure 7).

The study area is primarily an area of discharge from the Floridan aquifer system to the surficial aquifer system (Phelps 1984). The major modes of discharge from the Floridan aquifer system within the study area are leakage through the upper confining unit, pumping, and discharge from springs (Bermes et al. 1963).

HYDRAULIC CHARACTERISTICS

Values for transmissivity and storativity of the Upper Floridan aquifer and leakance of the upper confining unit vary widely throughout the study area (see Glossary for definitions of terms). The following presentation of these parameters is based on the results of aquifer pumping tests and previous computer-model investigations that focused on the study area and/or nearby

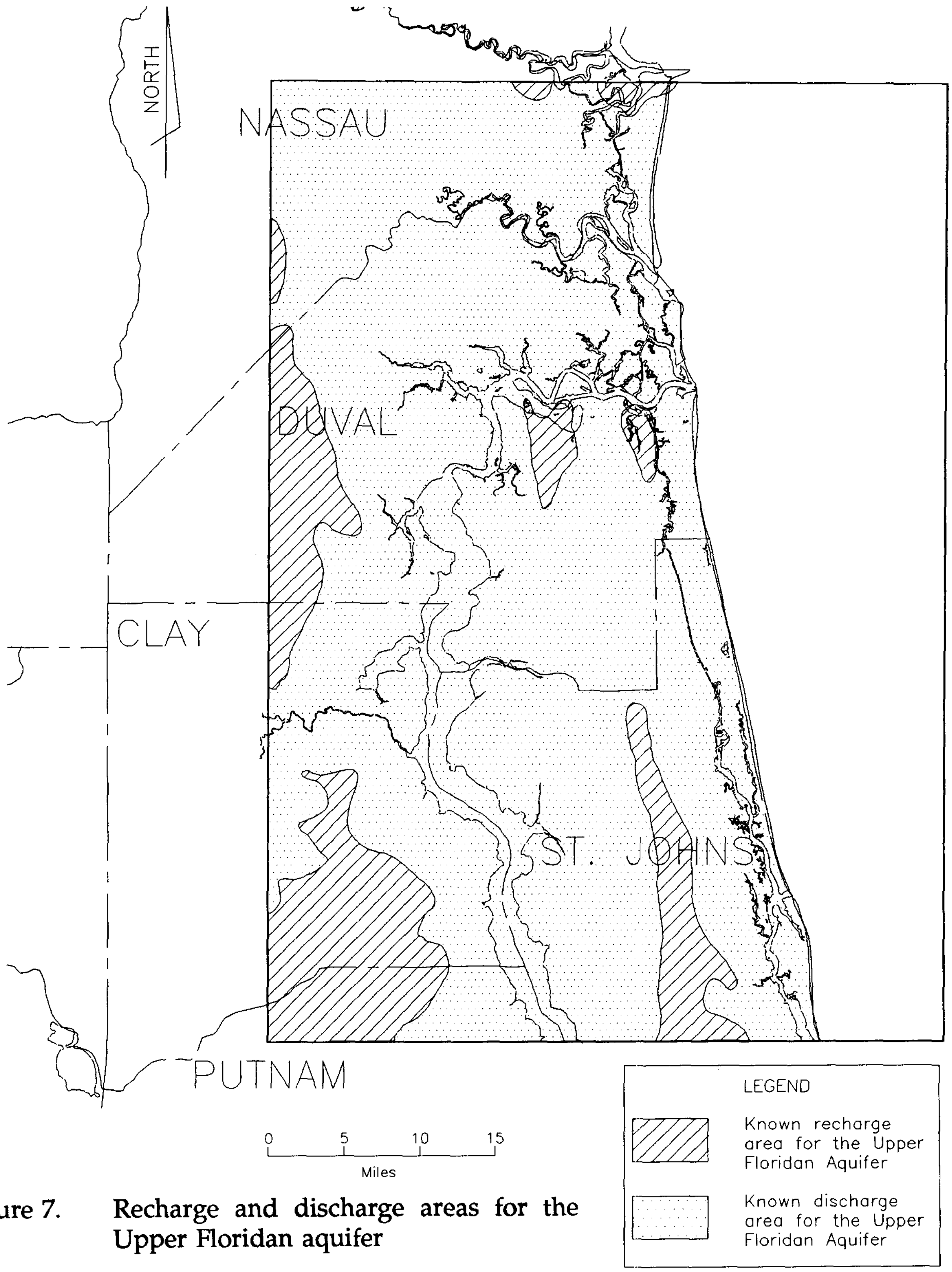


Figure 7. **Recharge and discharge areas for the Upper Floridan aquifer**

Source: Modified from Phelps 1984

areas. Reliable estimates of the hydraulic parameters of the Lower Floridan aquifer and of the middle and lower confining units are not available, because the Lower Floridan aquifer has not been tapped by wells to any significant extent. Values for the Lower Floridan aquifer that resulted from calibration of the model were all inferred from the potentiometric surface values for the Upper Floridan aquifer.

Transmissivity

Surficial Aquifer System. Estimates for transmissivities of the surficial aquifer system are not widely reported. Estimates of transmissivity of the surficial aquifer system in eastern Nassau County range from 60 to 1,000 square ft per day (ft^2/d) (Brown 1984).

Intermediate Aquifer System. Estimates for transmissivities of the aquifers of the intermediate aquifer system in the study area are also not widely reported. Reported values of transmissivity for the aquifers of the intermediate aquifer system in Duval and St. Johns counties range from 250 to 7,000 ft^2/d, (Brown 1984).

Upper Floridan Aquifer. Results of the regional finite-difference ground water flow model of the Floridan aquifer system by Bush (1982), which simulates flow in the predevelopment Floridan aquifer system throughout the southeast United States, indicate that transmissivity in the Upper Floridan aquifer is generally high to moderately high in the western and northern parts of the study area and low to moderately low in the eastern parts. In extreme northeastern Nassau County, the transmissivity ranges from 250,000 to 1,000,000 ft^2/d. Throughout western Putnam and western and central Nassau, Duval, counties, transmissivity is moderately high, ranging from 100,000 to 250,000 ft^2/d, while in the eastern coastal areas, southeastern Clay, northeastern Putnam, and southern St. Johns counties, the transmissivity ranges from 50,000 to 100,000 ft^2/d. Farther east, beneath the Atlantic Ocean, the transmissivity decreases even more to a range of 10,000 to 50,000 ft^2/d.

The results of Krause (1982), whose study area encompassed the present study area, also included a presentation of an areal distribution of transmissivity in the predevelopment Floridan aquifer. The results of Krause's (1982) study indicate moderate to low values of transmissivity throughout most of the area that often are less than corresponding values of the Bush (1982) study. In western Nassau, north-central Duval, most of St. Johns, and northern Putnam counties, results from Krause's (1982) study indicate a range of transmissivity between 50,000 and 100,000 ft^2/d. In a few isolated areas, mainly in central Duval County, transmissivity ranged from 100,000 to 500,000 ft^2/d (Krause 1982). In most of the remainder of the area, transmissivity ranges between 10,000 and 50,000 ft^2/d. In the area of Fernandina Beach, the results of Krause's (1982) study compare favorably with the results of aquifer pumping tests performed by Bentley (1979). The transmissivity value estimated from the aquifer pumping tests was 30,000 ft^2/d, which falls within the range of transmissivity for that area reported by Krause (1982).

Leakance

Areawide estimates of leakance are difficult to obtain because they were not published in the areawide studies by Bush (1982) or Krause (1982). Furthermore, the estimates obtained from well tests are often unrealistically high because they "can reflect not only downward leakage from the surficial aquifer, but upward leakage from permeable rocks beneath the pumped interval, as well as leakage from beds of relatively low permeability that might exist within the pumped interval" (Johnston and Bush 1988, A12). On the basis of computer models, Johnston and Bush (1988) stated that leakance ranges from 2.3×10^{-6} per day in tightly confined areas to 2.3×10^{-4} per day in semiconfined areas. The leakance in the area of Fernandina Beach, an area of tight confinement, was estimated from a laboratory permeability test of core samples from wells and known thickness of the upper confining unit to be about 2.5×10^{-6} per day (Brown 1984).

Storativity

Surficial and Intermediate Aquifer Systems. The specific yield of the surficial aquifer system in Nassau County is about 0.2 (Brown 1984). The storativity of the aquifers of the intermediate aquifer system ranges from 1×10^{-5} to 1×10^{-3} (Brown 1984).

Upper Floridan Aquifer. Estimates of storativity in the Upper Floridan aquifer usually range from 1×10^{-4} to 1×10^{-3} (Johnston and Bush 1988). At Fernandina Beach, the storativity ranges from 2.5×10^{-4} to 4.0×10^{-4} (Bentley 1979). Values of storativity were not reported by Bush (1982) or Krause (1982) because their finite-difference ground water flow models were steady-state simulations.

POTENTIOMETRIC SURFACES

The potentiometric surface of an aquifer is an imaginary surface to which water will rise in tightly cased wells that penetrate the aquifer (Bermes et al. 1963). The elevation of the potentiometric surface at a given point in an aquifer is the hydraulic head of the ground water within the aquifer at that point. The hydraulic head is the sum of the pressure head and the elevation head (Freeze and Cherry 1979). Ground water flows from areas of higher hydraulic head to areas of lower hydraulic head. In isotropic aquifers, ground water flows normal to hydraulic-head contours, which are imaginary lines that connect points of equal hydraulic head on the potentiometric surface. Thus, a map that displays the potentiometric surface of an isotropic aquifer using hydraulic-head contours may be used to infer the origin, path, and destination of the ground water within the aquifer.

Predevelopment Potentiometric Surface

The Floridan aquifer system prior to the onset of significant pumping (prior to 1880) is referred to in this study as the predevelopment Floridan aquifer flow system.

The map used in this study to represent the potentiometric surface of the Upper Floridan aquifer prior to development was prepared by the USGS (Johnston et al. 1980) and is based on newer maps of areas where little ground water development has taken place and on older maps of areas where much ground water development has taken place (Figure 8). Because of the limited amount of accurate information available on the predevelopment ground water flow system of the Upper Floridan aquifer, the map does not provide completely accurate values of hydraulic head at specific locations but is intended to illustrate the general features of the predevelopment flow system of the Upper Floridan aquifer (Johnston et al. 1980). Hydraulic heads on this map are accurate to within approximately 10 ft (based on Krause 1982).

The predevelopment potentiometric surface map of the Upper Floridan aquifer indicates that the potentiometric surface of the predevelopment Upper Floridan aquifer sloped downward from the west to the east and south within the study area (Figure 8). Hydraulic-head contours lay approximately north-south in the northwestern portion of the study area but tended to bend

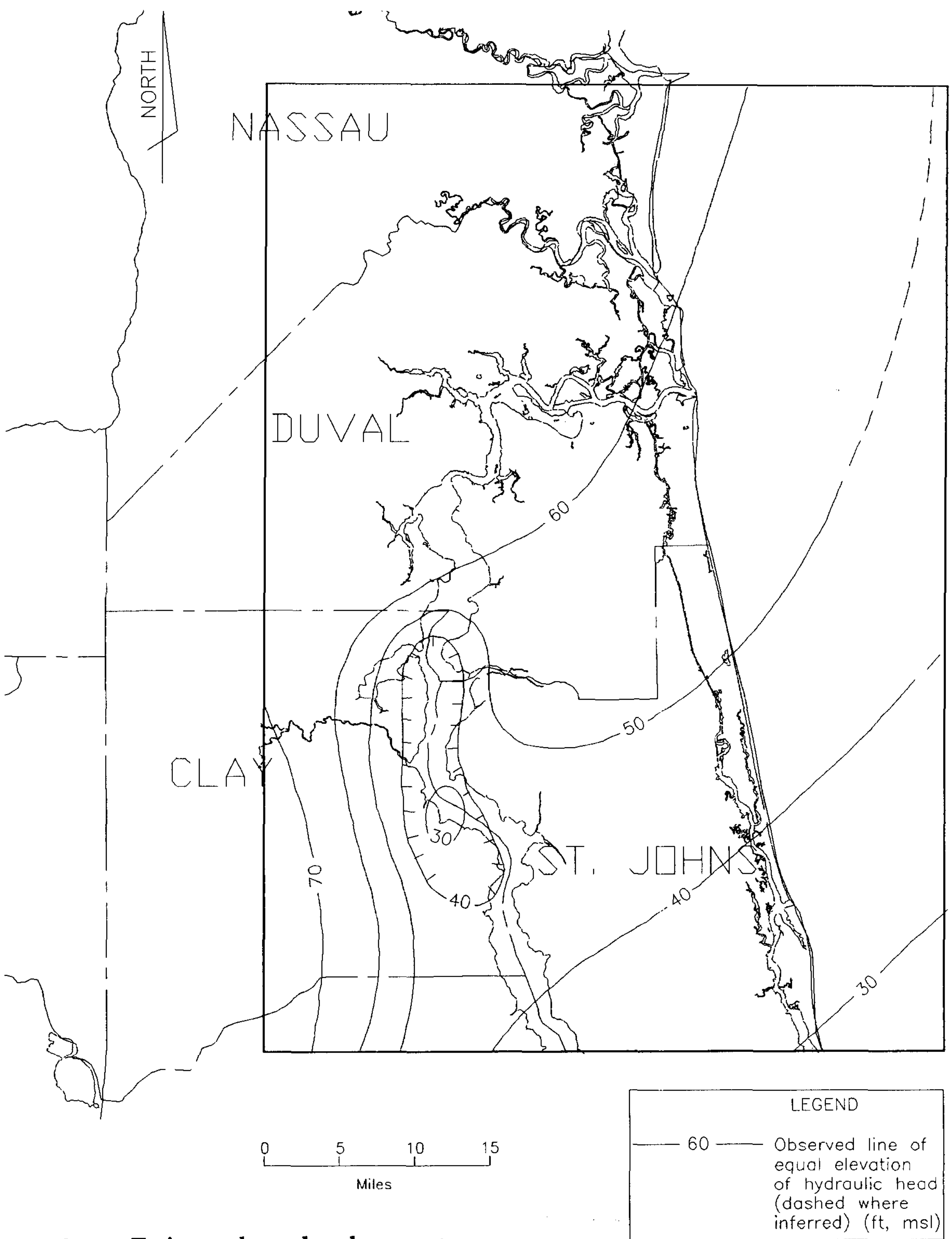


Figure 8. Estimated predevelopment potentiometric surface (prior to 1880)

Source: Modified from Johnston et al. 1980 increasingly to the northeast toward the Atlantic coastline. Thus, water that entered the northwestern part of the study area initially flowed toward the east, but subsequently flowed toward the south. Near the Atlantic coastline, most of the water flowed in a southeasterly direction. A major potentiometric depression, caused by spring discharge into the St. Johns River, occurred in the southwestern section of the study area.

The gradient of the potentiometric surface was comparatively small in the northwest, and it became increasingly greater to the southeast along the Atlantic coastline. It was extremely steep in the southwestern portion of the study area, where a potentiometric high protruded into the study area.

Little information and no map is available for the potentiometric surface of the Lower Floridan aquifer prior to development.

Current-System Potentiometric Surface

The potentiometric surface map of the current ground water flow system (May 1985) was prepared by the USGS in cooperation with the SJRWMD (Schiner and Hayes 1985). It is much more complex than that of the predevelopment ground water flow system (Figure 9). Similarities, however, are still apparent. Most of the water in the aquifer still enters along the western boundary, and some discharge still occurs through the southeastern corner of the study area. The potentiometric depression of the southwestern section of the study area appears to extend farther to the north, perhaps because of pumping in the Jacksonville area. It thus provides a more extensive capture area for water moving from west to east within the Upper Floridan aquifer. In the Fernandina Beach area, a deep, areally extensive depression in the potentiometric surface occurs as a result of pumping. In northern St. Johns and southern Duval counties, an area of higher residual hydraulic heads exists, possibly being maintained by upward leakage from the Lower Floridan aquifer through the middle confining unit into the Upper Floridan aquifer. Hydraulic heads in the current flow system average approximately 25 ft less than those of the predevelopment flow system within the study area (Figure 10).

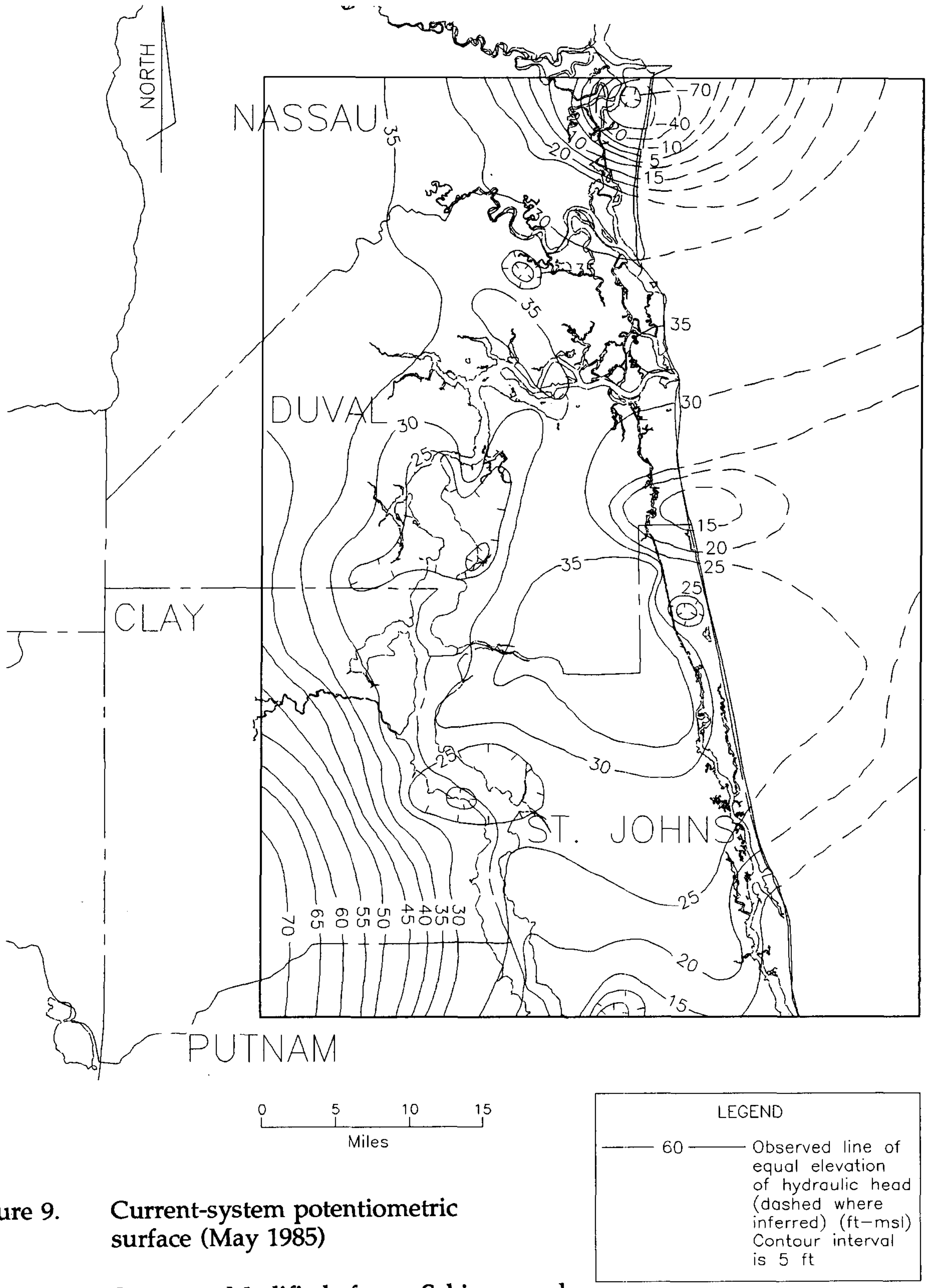


Figure 9. Current-system potentiometric surface (May 1985)

Source: Modified from Schiner and Hayes 1985

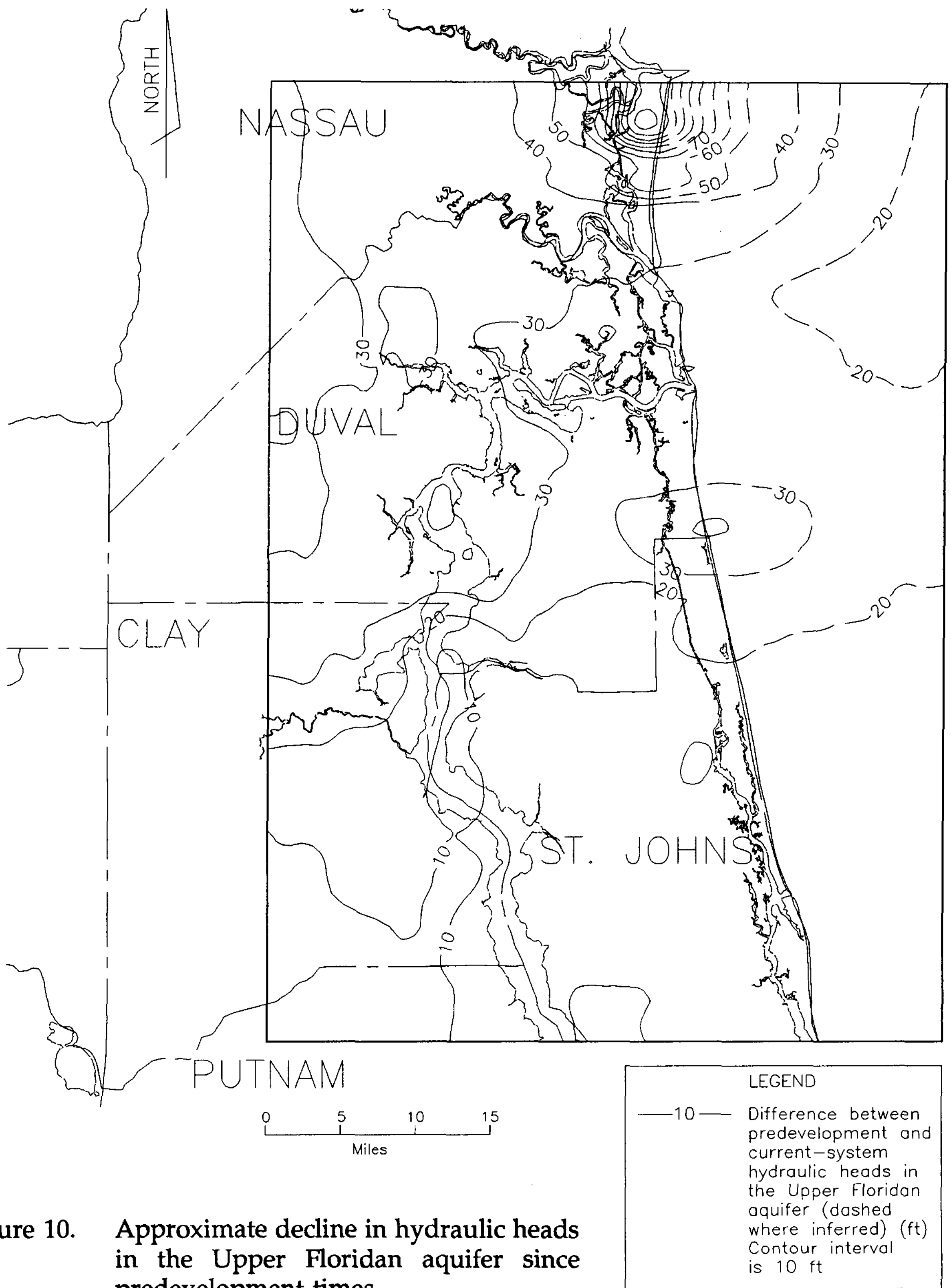


Figure 10. Approximate decline in hydraulic heads in the Upper Floridan aquifer since predevelopment times

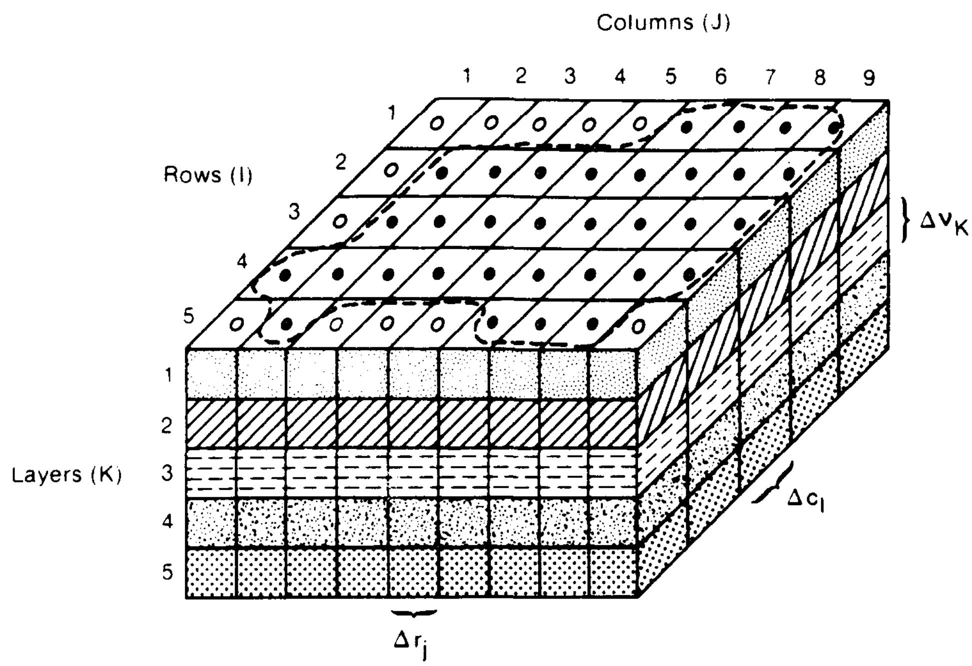
MODEL PROGRAM AND CONFIGURATION

MODFLOW

The McDonald-Harbaugh (1988) modular three-dimensional finite-difference ground water flow model (MODFLOW) was used to represent the Floridan aquifer system of the study area. MODFLOW can be used to discretize a ground water flow system horizontally into rectangular cell matrices as well as vertically into alternating layers of aquifers and confining units (Figure 11). MODFLOW allows steady-state and transient simulations of the effects of pumping, precipitation, rivers, drains, and evapotranspiration on the ground water flow system. The program output is in the form of hydraulic-head and volumetric-flow data that may be used to calculate water budgets of the simulated flow system or of specified aquifer layers within the flow system.

The cells of a model grid may be designated as active, no-flow, or constant-head cells within the program. Active cells are those in which the hydraulic head varies during the course of the model simulation from the initial values entered by the modeler. Constant-head cells are those in which the initial values of hydraulic head are held constant throughout the simulation. No-flow cells act as impermeable barriers to flow, and hydraulic head values need not be specified for them. No-flow cells are often used to simulate no-flow boundaries in ground water flow models.

Thickness estimates of model layers are not entered into MODFLOW explicitly, but are included implicitly in program input parameters such as values of confining-unit leakance and aquifer transmissivity in cases of confined aquifers. For an unconfined aquifer, the bottom elevation of the aquifer is entered with the corresponding elevation of the water table at the centers of each of the active and constant-head cells in the model grid, and the saturated thickness of the unconfined aquifer is calculated as the difference in



Legend

----	Aquifer Boundary
●	Active Cell
0	No-Flow Cell
Δr_J	Dimension of Cell Along the Row Direction. Subscript (J) Indicates the Number of the Column
Δc_I	Dimension of Cell Along the Column Direction. Subscript (I) Indicates the Number of the Row
Δv_K	Dimension of the Cell Along the Vertical Direction. Subscript (K) Indicates the Number of the Layer.

Figure 11. Hypothetical aquifer system grid

Source: Modified from McDonald and Harbaugh 1988 these values. Transmissivity is then calculated as the product of hydraulic conductivity and saturated thickness of the unconfined aquifer at each of theactive and constant-head cells contained in the model grid. Flow within aquifer layers is simulated as entirely horizontal, while flow in confining-unit layers is simulated as entirely vertical.

The well-simulation and general-head-boundary (GHB) options of MODFLOW were used in the models of the study area. The well-simulation option allows simulation of pumping from a specified layer, row, and column of the ground water model. The GHB option allows constant-head boundaries to be specified outside of the model grid as far away from its edges as desired, thereby eliminating the need to extend the model grid outside the area of interest in order to establish constant-head boundaries for the model. The magnitude of simulated flow from outside the modeled area into a grid cell located in an outer row or column of the model grid is proportional to the difference in the hydraulic head specified at the boundary and the hydraulic head at the node of the grid cell in question. The distance from the node of a grid cell to its corresponding constant-head boundary may vary from one grid cell to the next. The distance is usually chosen to be far enough away from major pumping centers within the modeled area so that the hydraulic head at the boundary in the actual flow system would not be affected significantly by changes in pumping rates within the modeled area and, therefore, could be simulated accurately as a constant hydraulic head.

MODEL CONFIGURATION

Model Layering

MODFLOW was used to develop three ground water flow models in the study: the predevelopment, current-system, and modified predevelopment flow models. The general configurations of the predevelopment, current-system, and modified predevelopment models were the same. The flow system of the study area was approximated as steady-state in all three models, and all three models consisted of three aquifer layers and three confining-unit layers (Figure 12). In descending order, the layers represented the surficial aquifer system, the upper confining unit, the Upper Floridan aquifer, the middle confining unit, the Lower Floridan aquifer, and the lower confining unit.

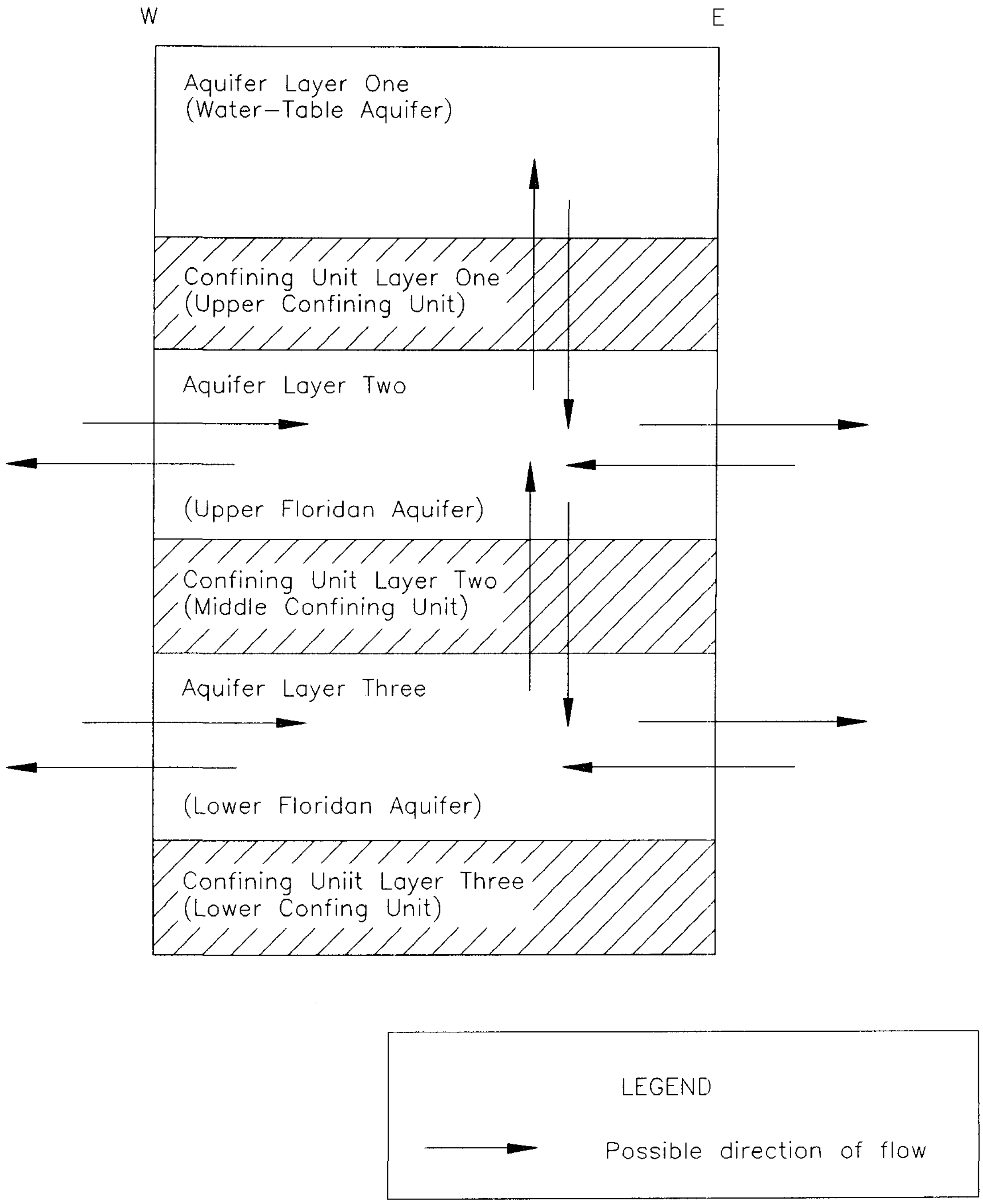


Figure 12. General configuration of the flow models of the study

All cells of aquifer layer one, which represented the surficial aquifer system in the models, were designated as constant-head cells. The function of aquifer layer one was that of a "constant-head source-sink bed", meaning that it merely received flow from or transmitted flow to the underlying Upper Floridan aquifer, depending on the direction of the vertical hydraulic gradient across confining-unit layer one. Thus, accurate values of water-table elevation were required for aquifer layer one, but values of hydraulic conductivity and aquifer bottom elevation of the surficial aquifer system were not required in order to model either the predevelopment or current flow systems. The presence of aquifer layer one, however, was essential to the accuracy of the predevelopment, current-system, and modified predevelopment models in order to enable the effects of the surficial aquifer system on the Floridan aquifer system to be simulated.

Aquifer layers two and three, which represented the Upper and Lower Floridan aquifers, respectively, in the models of the study, consisted almost entirely of active cells but also contained some no-flow cells that were used to simulate boundary conditions. Aquifer layers two and three, along with confining-unit layer two, which represented the middle confining unit, represented the Floridan aquifer system in the models.

Confining-unit layer three, the lowermost layer of the models, represented the lower confining unit of the Floridan aquifer system. The existence and complete impermeability of this layer are presumed in MODFLOW; therefore, it was not necessary to specify its properties.

Boundary Conditions

Boundary conditions were specified for aquifer layers two and three in the models of the study. This specification involved the designation of grid cells on the outermost rows and columns of the model grids as either no-flow cells or active cells to which GHBs were assigned. These designations were based on the maps of the potentiometric surfaces of the flow systems of the study area (Figures 8 and 9). Such maps were available only for the Upper Floridan aquifer. Because general patterns of flow within the Upper and Lower Floridan aquifers are believed to be similar, it was assumed that designations made for grid cells in aquifer layer three would be the same as aquifer layer two.

The designation of a given grid cell as a no-flow or active GHB cell depended on the orientation of the outer row or column to which the grid cell belonged relative to that of ground water flow lines. The directions of the ground water flow lines were inferred from the configuration of potentiometric contours. Where ground water flow lines were generally parallel to part of an outermost row or column of the model grids, cells in that part of the row or column were designated as no-flow cells in the models of the study area. Where flow lines were generally perpendicular to a part of an outermost row or column, the grid cells in that part of the row or column were designated as active cells to which GHBs were assigned. Where flow lines were oriented diagonally relative to a row or column, no flow and active cells were mixed.

Boundary conditions were not specified for aquifer layer one of the models of the study, because all grid cells of aquifer layer one were designated constant-head cells. Consequently, finite-difference equations were not assembled for the grid cells of aquifer layer one, and boundary conditions were not required.

Required Data Input

Aquifer Layers. Required input data for aquifer layer one included distributions of hydraulic conductivity, aquifer bottom elevation, and water-table elevation (Table 6). Required input data for aquifer layers two and three were identical. Both layers required estimates of transmissivity and hydraulic-head distributions. Both also required estimates of conductance for each of their GHB cells. Conductance is derived from Darcy's equation for ground water flow; it is the product of the hydraulic conductivity and the cross-sectional area of flow divided by the length of the flow path (McDonald and Harbaugh 1988). This may be written as

equation 1: $C = KA/L$

where:

C = conductance

K = hydraulic conductivity

A = the cross-sectional area perpendicular to the direction of flow

L = the length of the flow path.

Table 6. Summary of the configuration of the models of the study

Hydrologic Unit	Model Representation	Required Input Data
Surficial aquifer system	Aquifer layer one	Hydraulic conductivity, aquifer bottom elevation, and water table elevation
Upper confining unit	Confining-unit layer one	Leakance
Upper Floridan aquifer	Aquifer layer two	Transmissivity, conductance, and hydraulic head
Middle confining unit	Confining-unit layer two	Leakance
Lower Floridan aquifer	Aquifer layer three	Transmissivity, conductance, and hydraulic head
Lower confining unit	Confining-unit layer three	None (zero leakance assigned)

Conductance may also be expressed in terms of transmissivity as

equation 2: $C = TW/L$

where:

T = transmissivity, which equals the product of hydraulic conductivity and the saturated thickness of the aquifer

W = the width of the cross-sectional area normal to the direction of flow

Confining-Unit Layers. Confining-unit layers one and two required estimates of leakance. Confining-unit layer three did not require data input. It is assumed to be impermeable in MODFLOW, and its leakance is therefore assigned a value of zero in the model.

THE PREDEVELOPMENT CALIBRATION AND FLOW MODEL

PURPOSE AND SCOPE

The predevelopment flow model was calibrated to obtain estimates for leakance and transmissivity that were used subsequently as initial estimates in the current-system calibration. The accuracy of the predevelopment calibration was limited by the accuracy (±10 ft, based on Krause (1982)) of the available predevelopment potentiometric map of the Upper Floridan aquifer.

The primary focus of the predevelopment calibration was on the Upper Floridan aquifer to the exclusion of the Lower Floridan aquifer, because no map of the predevelopment potentiometric surface of the Lower Floridan aquifer exists. Therefore, values of transmissivity in the Lower Floridan aquifer and leakance of the middle confining unit were adjusted on the basis of how the adjustments affected the hydraulic-head distribution of the Upper Floridan aquifer.

FINITE-DIFFERENCE GRID

The finite-difference grid of the predevelopment model consisted of 36 rows and 31 columns, which resulted in a total of 1,116 grid cells, of which 1,051 were active cells (Figure 13). The rows of the grid were parallel to lines of latitude, and the columns of the grid were parallel to lines of longitude. Widths of the rows and columns were variably sized increments of minutes. The total width of the grid was 45 minutes longitude, and the total length of the grid was 55.5 minutes latitude. The smallest grid cells were one minute by one minute in area, which is approximately one square mile. These cells

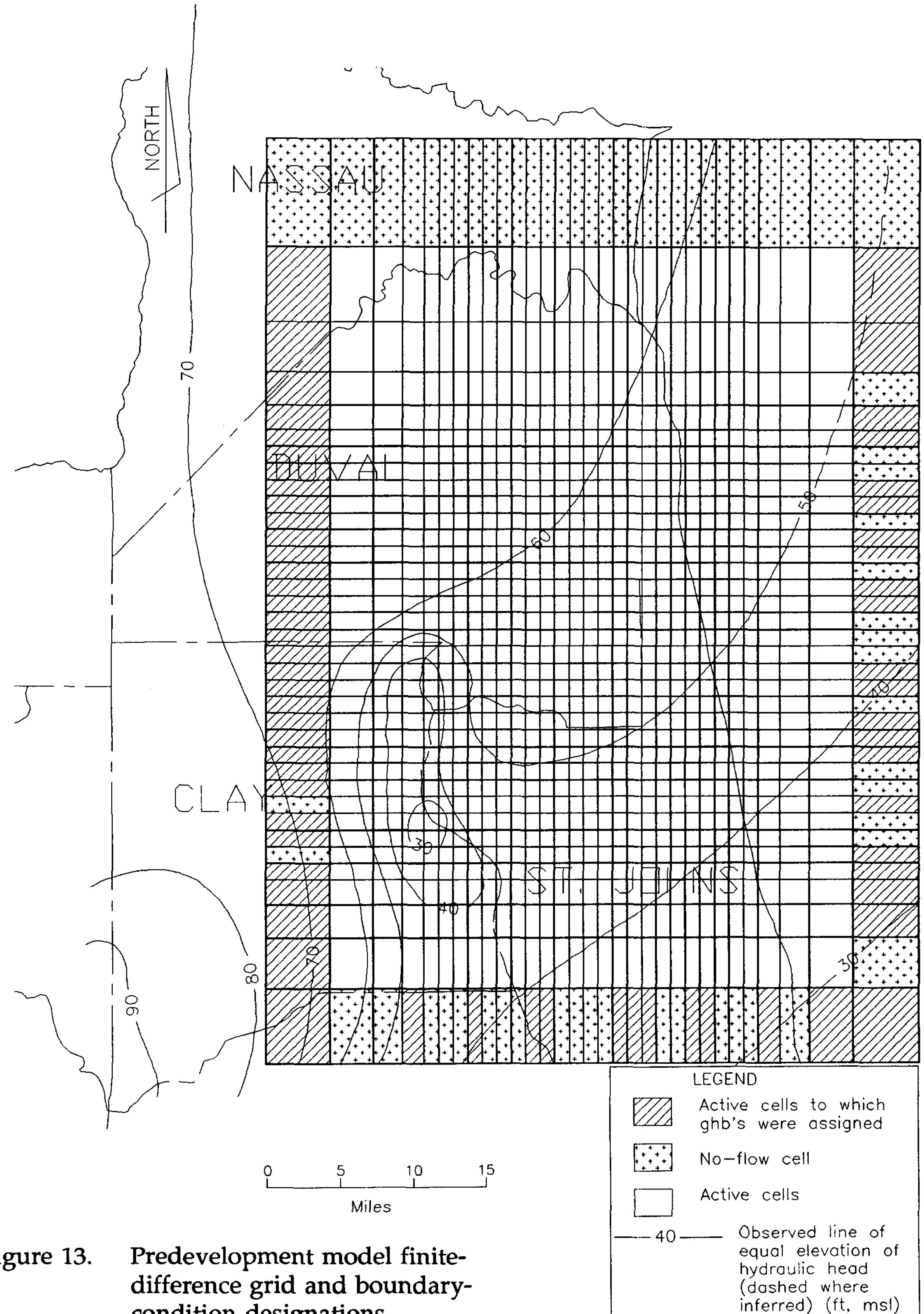


Figure 13. Predevelopment model finite-difference grid and boundary-condition designations

occupied the central area of the grid. From this central area, the sizes of rows and columns were increased toward the edges of the grid. The maximum rowsize was 6.5 minutes (along the northernmost row of the grid), and the maximum column size was 4.5 minutes (along both the eastern- and westernmost columns).

BOUNDARY CONDITIONS

Boundary conditions for aquifer layer two of the predevelopment model were established by first superimposing the finite-difference grid of the model onto the potentiometric map of the predevelopment flow system of the Upper Floridan aquifer (Figure 13). Hydraulic-head contours and flow lines were then drawn into the outermost rows and columns of the finite-difference grid. Hydraulic-head contours were interpolated on land and extrapolated into the Atlantic Ocean as necessary. Sixty-five cells in the predevelopment model were designated no-flow cells, including all the cells that comprised the northernmost row of the finite-difference grid. Also, sixty-five cells were designated active-flow GHB cells. In order to determine systematically the parameters needed to calculate the conductance for each of the GHB active-flow cells (length of flow path, width of cell face, and transmissivity from equation 2) and the points at which the boundary heads would be interpolated, the finite-difference grid was conceptually extended on the east, west, and south by one additional column (or row) equal in width to the existing outermost column (or row) at the eastern, western, and southern edges of the finite-difference grid (i.e., 4.5 minutes longitude or latitude). The nodes of the resulting imaginary grid cells were the locations of the boundary heads. The length of the flow path for all GHB active-flow cells was therefore 4.5 minutes longitude or latitude.

DATA INPUT REQUIREMENTS

Estimated Water-Table Elevations

Before the predevelopment calibration began, the average elevation of the water table at the node of each cell of the model grid was estimated. The resulting estimates of water-table elevation were then used in both the predevelopment and current-system calibrations. Elevations of the water table were based on correlations that were established between water-table and land-surface elevation and on land-surface details taken from USGS 1:100,000 scale topographic maps. The study area was partitioned into three subareas whose predominant topographic features differed from one another.

Subarea one was south of 30° 24′ latitude and east of 81° 39′ longitude (Figure 14) and consisted mainly of southeastern Duval County and northern St. Johns County. Land-surface elevations in subarea one range from approximately 0 to 40 ft above msl; land-surface elevations range from 25 to 40 ft above msl on the coastal ridge, the predominant topographic feature of subarea one.

Subarea two was west of 81° 39′ longitude and encompassed central to western Duval and Nassau counties and central to eastern Clay and Putnam counties. Land-surface elevations range from 0 ft msl, on or near the St. Johns River to as much as 120 ft above msl or more farther west in the central highlands, which occupy most of subarea two.

Subarea three was north of 30° 24′ latitude and east of 81° 39′ longitude and consisted of northeastern Duval and eastern Nassau counties, where land-surface elevations range from 0 to 40 ft above msl. In the marshy lowland areas that occupy a large part of subarea three, land-surface elevations range from 0 to 25 ft above msl.

The correlations of water-table and land-surface elevations were based on values of water-table elevations obtained from published reports (Causey 1975 and Clark et al. 1964) that included scattered well locations in Duval and Clay counties. The data taken from the report by Causey (1975) are limited to Duval County, and the data taken from the report by Clark et al. (1964) are limited to Clay County. No data were available for water-table elevations in either Nassau or St. Johns counties; all three subareas were represented by the available data from Duval and Clay counties.

Causey's (1975) report provided the minimum and maximum depths to the water table below the land surface that occurred between March 21, 1972, and June 30, 1975, at well locations scattered fairly evenly throughout Duval County. The elevation of the water table corresponding to the maximum depth below land surface at the same locations also were obtained from this report.

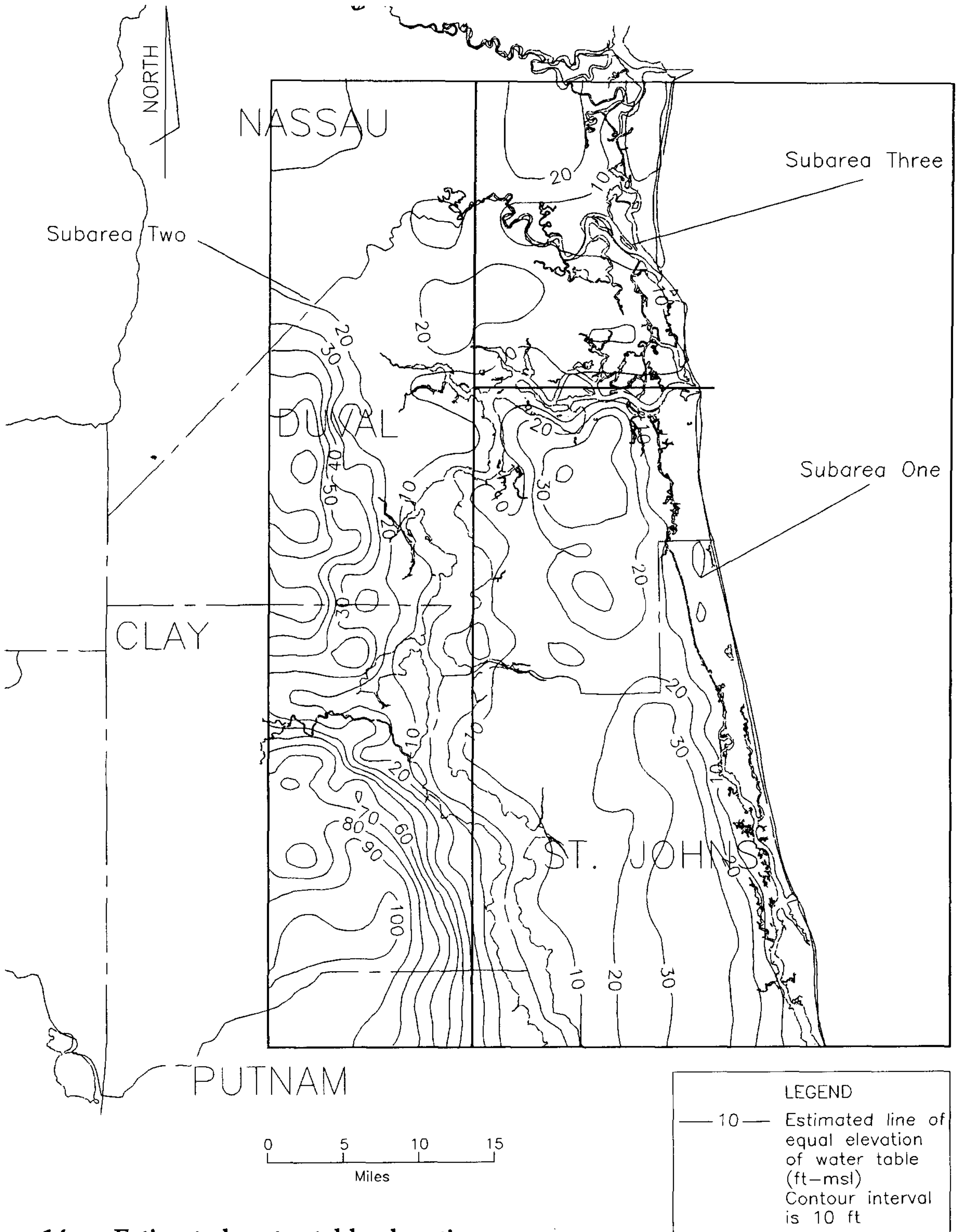


Figure 14. Estimated water-table elevations

Source: Derived from Clark et al. 1964; Causey 1975

Land-surface elevations were established by adding the maximum depth below land surface to the corresponding water-table elevation at each of the locations. At each well location, the minimum and maximum depths to the water table below land surface were averaged to obtain an estimate of the average depth to the water table. The estimated average depth to the water table was then subtracted from the land-surface elevation to establish the estimated average water-table elevation at each well location.

The water-table elevations reported by Clark et al. (1964) are point values on a water-table contour plot of their study area, so the locations of the data points were scaled from the map. Corresponding land-surface elevations were scaled from USGS quad maps. Most of these data points were just outside the boundaries of the present study area but were at locations that are representative of the topography of subarea two.

Once compiled, the data were plotted in the form of water-table elevation versus land-surface elevation for each of the three subareas, and regression analyses were performed on the data to fit smooth curves through the data points (Figures 15, 16, and 17). The program used to perform the regression analyses of the data was CFIT, which is included with the Hewlett-Packard (HP) Advantage Pac accessory for the HP 41CV model calculator. CFIT uses the least-squares method to fit one of four different functions to a given set of data depending on which of the four functions has the highest coefficient of determination for the data set being considered or on the directive of the program user. The four functions are: a linear function of the form $y = a + bx$, where a and b are function constants and y and x are the dependent and independent variables, respectively; an exponential function of the form $y = ae^{bx}$, where e is the exponential function; a logarithmic function of the form $y = a + b(\ln x)$, where ln is the natural log function; and a power curve of the form $y = ax^b$.

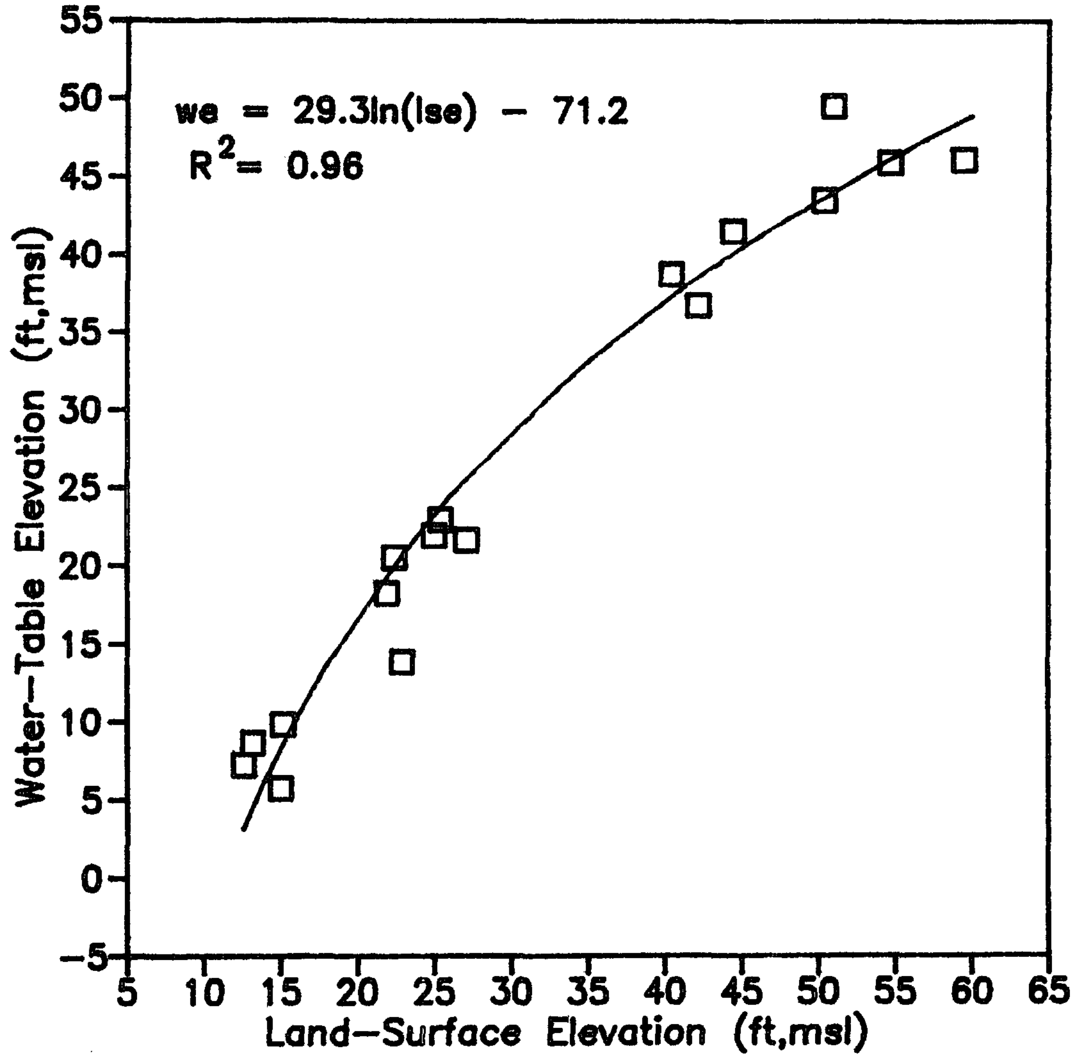


Figure 15. Water-table elevation vs. land-surface elevation--data and fitted curve for subarea three

Source: Based on Causey 1975

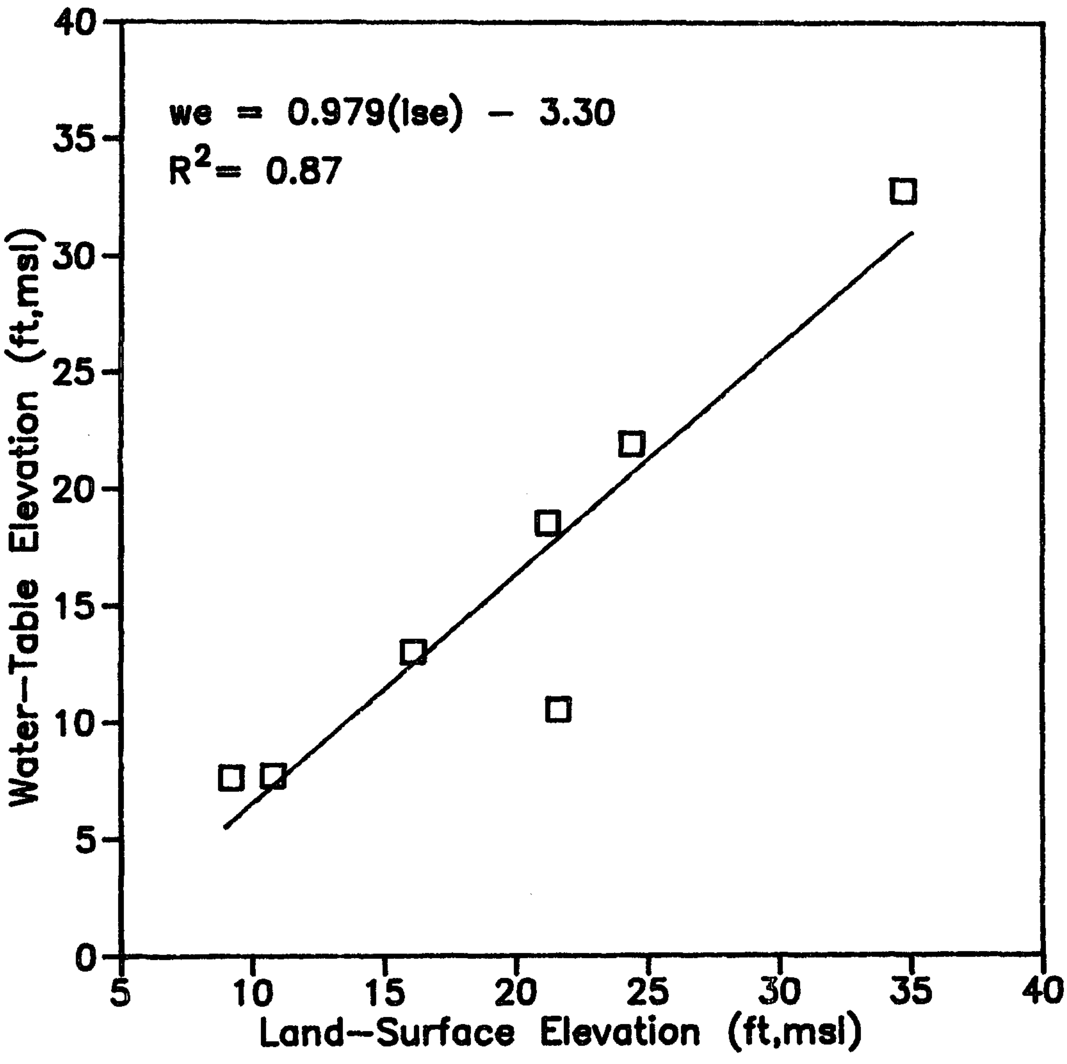


Figure 16. Water-table elevation vs. land-surface elevation–data and fitted curve for subarea two

Source: Based on Clark et al, 1964 Causey 1975

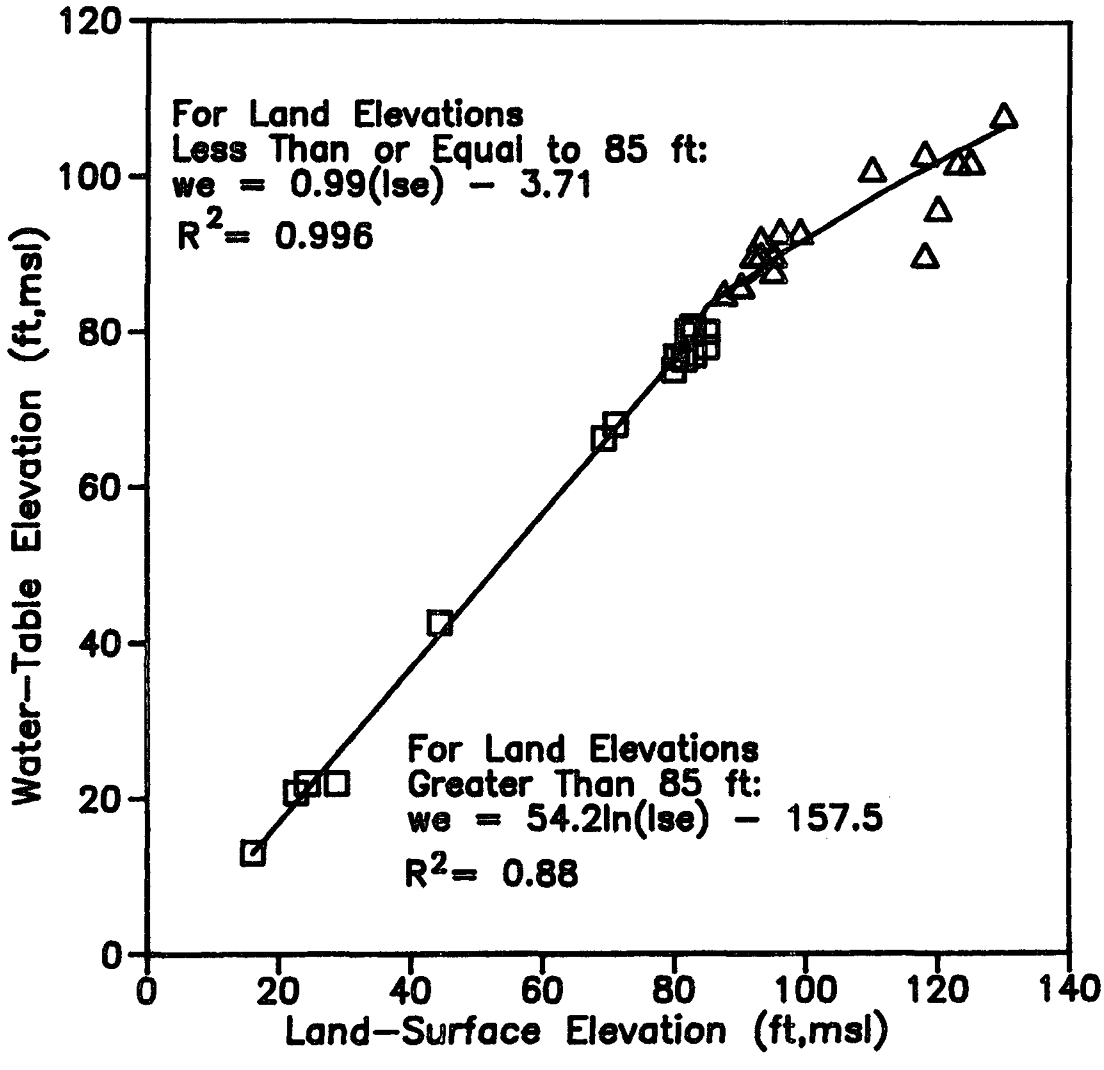


Figure 17. Water-table elevation vs. land-surface elevation–data and fitted curve for subarea one

Source: Based on Causey 1975

For these regression analyses, the choice of the four functions was determined by CFIT based on which of the four functions in each case had the highest coefficient of determination. The fitted curve determined for subarea one was

$$\underline{\text{equation 3}}: \ we = 29.3\ln(lse) - 71.2 \quad (R^2 = 0.96)$$

where:

we = the water-table elevation

lse = land-surface elevation

R^2 = the coefficient of determination

The resulting fitted curve determined for subarea three was

$$\underline{\text{equation 4}}: \ we = 0.979(lse) - 3.30 \quad (R^2 = 0.87)$$

Two curves were determined from the data representing subarea two. These were for land-surface elevations less than or equal to 85 ft, or

$$\underline{\text{equation 5}}: \ we = 0.99(lse) - 3.71 \quad (R^2 = 0.996)$$

and for land-surface elevations greater than 85 ft, or

$$\underline{\text{equation 6}}: \ we = 54.2 \ln(lse) - 157.5 \quad (R^2 = 0.88)$$

Once these equations were determined, land-surface elevations were estimated for each grid cell on land using USGS 1:100,000 scale topographic maps. The equations were used taking into account physical features such as waterbodies and wetlands that were represented on the topographic maps. A map of the estimated average water-table elevation throughout the study area was produced based on the estimates of water-table elevations derived from this analysis (Figure 14).

Initial Hydraulic-Head Distributions

Upper Floridan Aquifer. Initial values of hydraulic head for the Upper Floridan aquifer were interpolated from the predevelopment potentiometric surface map of the Upper Floridan aquifer (Johnston et al. 1980). The procedure involved overlaying the model grid onto the map of the study area and then interpolating a value of hydraulic head at each node of the grid. Contours were extrapolated offshore to allow hydraulic heads to be interpolated at nodes located offshore.

Lower Floridan Aquifer. Hydraulic heads in the Lower Floridan aquifer have been measured at only a few points within the study area, and these measurements were taken only after extensive pumping had taken place in the Upper Floridan aquifer. Therefore, the procedure for estimating the hydraulic-head distribution of the Lower Floridan aquifer was similar to that of Tibbals (1981). To obtain values of hydraulic head in the Lower Floridan aquifer, in areas of discharge from the Upper Floridan aquifer to the surficial aquifer system, Tibbals added a set amount to values of hydraulic head in the Upper Floridan aquifer. In areas of recharge from the surficial aquifer system to the Upper Floridan aquifer, Tibbals subtracted a set amount from values of hydraulic head in the Upper Floridan aquifer to obtain values of hydraulic head for the Lower Floridan aquifer. In the present study, one foot was added to or subtracted from values of hydraulic head in discharge and recharge areas in the Upper Floridan aquifer, respectively, to obtain corresponding values of hydraulic head in the Lower Floridan aquifer.

Transmissivity

Upper Floridan Aquifer. Initial estimates of transmissivity in the Upper Floridan aquifer were interpolated from the results reported by Krause (1982) and the transmissivity contour plot developed by Johnston and Bush (1988).

Lower Floridan Aquifer. Since little is known about the Lower Floridan aquifer, accurate estimates of transmissivity are difficult to obtain, and most modelers do not publish the distributions of transmissivity of the Lower Floridan aquifer that result from their calibrations. Tibbals (1981), however, reported average values of transmissivity based on his calibration for both the Upper and Lower Floridan aquifers within his study area. The average value of transmissivity of the Lower Floridan aquifer resulting from his calibration was approximately half that of the Upper Floridan aquifer. Based on these results, the individual values of transmissivity in the Upper Floridan aquifer were multiplied by 0.5 to produce corresponding estimates of transmissivity in the Lower Floridan aquifer in the predevelopment model. No attempt was made to develop an independent transmissivity distribution for the Lower Floridan aquifer in the calibration of the predevelopment model.

Leakance

Upper Confining Unit. Laboratory permeability tests performed on core samples taken in Duval County resulted in an estimate of vertical hydraulic conductivity for the upper confining unit of 1 x 10^{-3} ft/d (Brown 1984). This value was assumed valid throughout the study area in order to obtain an initial estimate of leakance for all of the grid cells. Average thicknesses of the upper confining unit were estimated for several large subareas of the study area using a thickness map of the upper confining unit (Miller 1986, plate 25). The estimated vertical hydraulic conductivity of the upper confining unit was divided by average thicknesses to obtain initial estimates of leakance (K'/b') for each of the grid cells of the model.

Middle Confining Unit. The initial estimate of leakance of the middle confining unit was 5 x 10^{-5} based on the results of Tibbals (1981).

MODEL CALIBRATION

The calibration of the predevelopment model was a trial-and-error process in which trial transmissivity and leakance distributions were used to simulate distributions of hydraulic heads in the Upper Floridan aquifer. Distributions of differences between observed and simulated hydraulic heads were calculated by the model program, and the mean and corresponding standard deviation from the mean of each of the difference distributions were calculated. The goal of the calibration effort was to discover the most physically realistic distributions of transmissivity and leakance that also minimized the mean difference between simulated and observed hydraulic heads and its standard deviation.

Final Mean and Standard Deviation

The final mean difference between simulated and observed hydraulic heads for the Upper Floridan aquifer in the predevelopment calibration was -2.1 ft, and the final standard deviation from the mean was 2.7 ft. The average absolute difference was 2.9 ft.

These results compared reasonably well with the results of other model calibrations whose areas encompassed the present study area or were located in nearby areas. Tibbals (1981), for instance, ended the calibration effort of his predevelopment flow model when an average absolute difference of 1.3 ft was achieved, and Krause (1982), whose model area encompassed the present study area, ended the calibration effort of his predevelopment model when an average absolute difference of 2.5 ft was achieved. The mean difference and standard deviation for the regional predevelopment calibration of Bush (1982) were -0.1 ft and 6.0 ft, respectively, and the corresponding mean absolute difference was 4.7 ft.

Visual Comparisons of Hydraulic-Head Distributions

Calculation of the mean difference and its standard deviation represented a quantitative measure of the progress of the calibration of the predevelopment flow model. The calibration progress was also measured by comparing hydraulic-head contours based on simulated head distributions with observed hydraulic-head contours (i.e., those shown on the potentiometric map of Johnston et al. 1980) by superimposing the two sets of contours onto a single base map. These hydraulic-head overlays helped to indicate how well the essential features of the flow system were being simulated by the model.

Contours of the differences between observed and simulated hydraulic heads were also plotted. Such plots allowed subareas within the study area to be ranked easily on the basis of how well the simulated hydraulic heads within them compared to corresponding observed hydraulic heads. This allowed more time and effort to be concentrated on the areas of least agreement.

Hydraulic-Head Overlays. Visually, the simulated and observed hydraulic-head contours compared reasonably well (Figure 18). The two sets of hydraulic-head contours had the same basic shapes and positions. Although there was some deviation of the simulated hydraulic-head contours

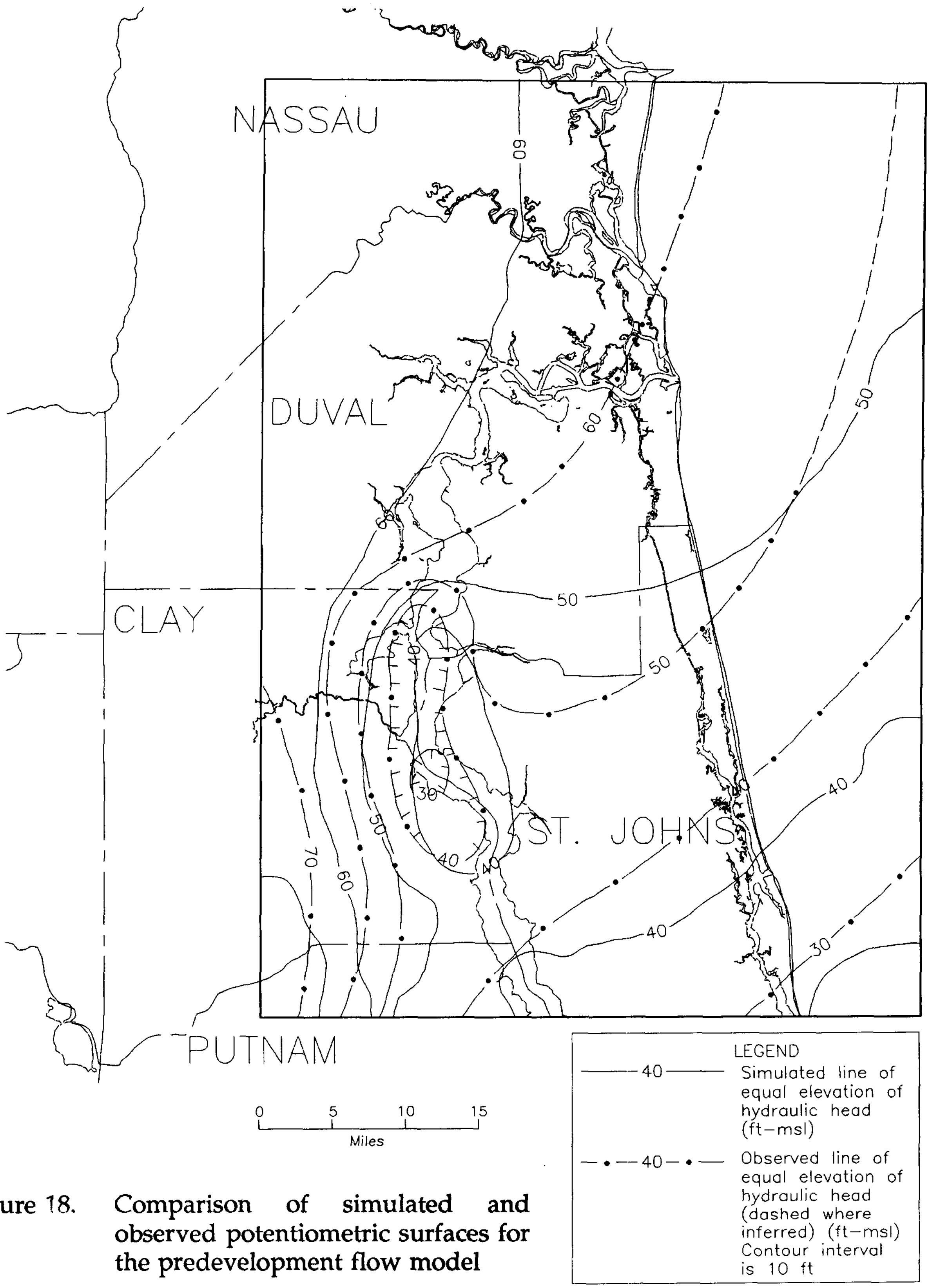


Figure 18. Comparison of simulated and observed potentiometric surfaces for the predevelopment flow model

from the locations of the observed hydraulic-head contours at several places, the essentials of the predevelopment flow system were simulated successfully by the model.

Hydraulic-Head Difference Contours. Differences between simulated and observed hydraulic heads were greatest in the area of the large potentiometric depression in the southwestern section of the study area (Figure 19). Differences between simulated and observed hydraulic heads were less than 5 ft throughout most of the rest of the study area.

RESULTANT DISTRIBUTIONS OF INPUT PARAMETERS

Transmissivity

Upper Floridan Aquifer. The predevelopment calibration indicated that the transmissivity of the Upper Floridan aquifer is quite high (between 100,000 and 320,000 ft^2/d) in the northeastern and central areas of the study area and moderately low to high elsewhere in the study area (between 35,000 and 100,000 ft^2/d) (Figure 20). The predevelopment calibration indicated that transmissivity tends to decrease rather rapidly towards the south and towards the Atlantic Ocean. The maximum value of transmissivity that resulted from the calibration of the predevelopment model was 320,000 ft^2/d; it occurred in the northeastern section of the study area. The minimum value was 35,000 ft^2/d, and it occurred near the southern boundary of the study area. The arithmetic average of transmissivity values of the cells of aquifer layer two (the Upper Floridan aquifer) was 148,000 ft^2/d.

Lower Floridan Aquifer. An independent distribution of transmissivity for the Lower Floridan aquifer was not developed in the calibration of the predevelopment flow model.

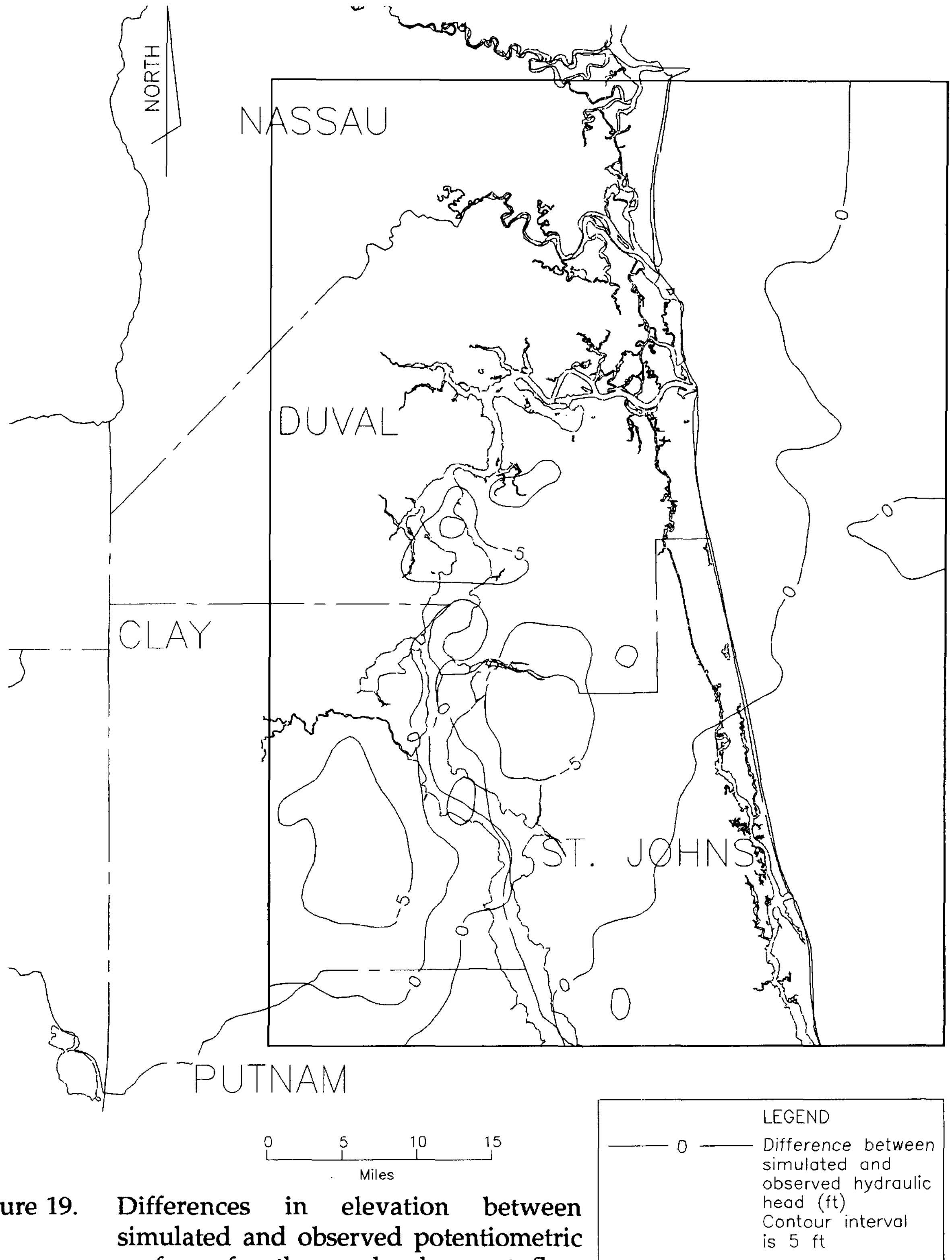


Figure 19. **Differences in elevation between simulated and observed potentiometric surfaces for the predevelopment flow model**

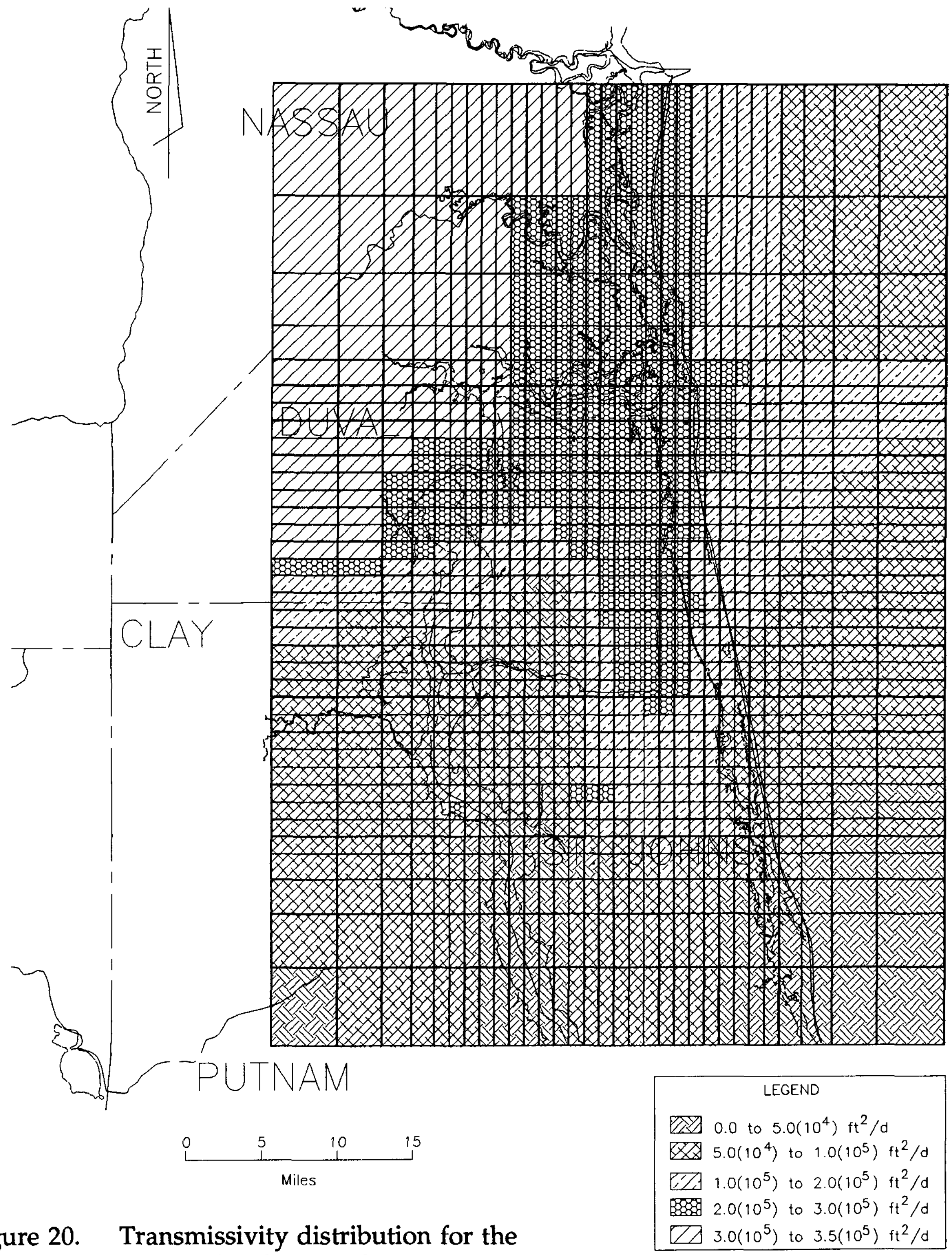


Figure 20. **Transmissivity distribution for the Upper Floridan aquifer resulting from the predevelopment calibration**

Leakance

Upper Confining Unit. The calibration of the predevelopment model indicated that values of leakance of the upper confining unit are rather low, i.e., on the order of magnitude of 10^{-7} per day over most of the study area (Figure 21). Values of leakance in the southwestern area of the model where the areally extensive potentiometric low is located were several orders of magnitude higher than this, however. These values typically were on the order of magnitude of 10^{-5} per day to 10^{-4} per day. The minimum value of leakance in the model was 1.1×10^{-8} per day, and the maximum value was 2.0×10^{-3} per day.

Middle Confining Unit. The leakance distribution of the middle confining unit in the predevelopment model was represented by a single value of leakance. After all other parameters of the model were fixed, this value was varied until the mean difference in observed and simulated predevelopment hydraulic heads and its standard deviation were minimized. The value at which this occurred was 1.0×10^{-4} per day.

SENSITIVITY ANALYSIS

The sensitivity of the model to change in model parameters was analyzed to ascertain the influence of each model parameter on the simulated hydraulic-head distributions of the Upper Floridan aquifer. Every value in a given parameter distribution was multiplied by the same factor (first by .5, then by 2.0) and the resultant parameter distribution used to simulate hydraulic heads for the Upper Floridan aquifer. All other parameter distributions were unchanged. Relative degrees of influence of all of the important model-parameter distributions were established by repeating this process for each parameter. The parameters considered were elevation of the water table (WTE), leakance of the upper confining unit (LK1), transmissivity of the Upper Floridan aquifer (T2), leakance of the middle confining unit (LK2), and transmissivity of the Lower Floridan aquifer (T3) (Tables 7 and 8). Changes in the transmissivity distributions were accompanied by changes of the same factor in the corresponding values of conductance that were assigned to the GHBs of the layer under consideration.

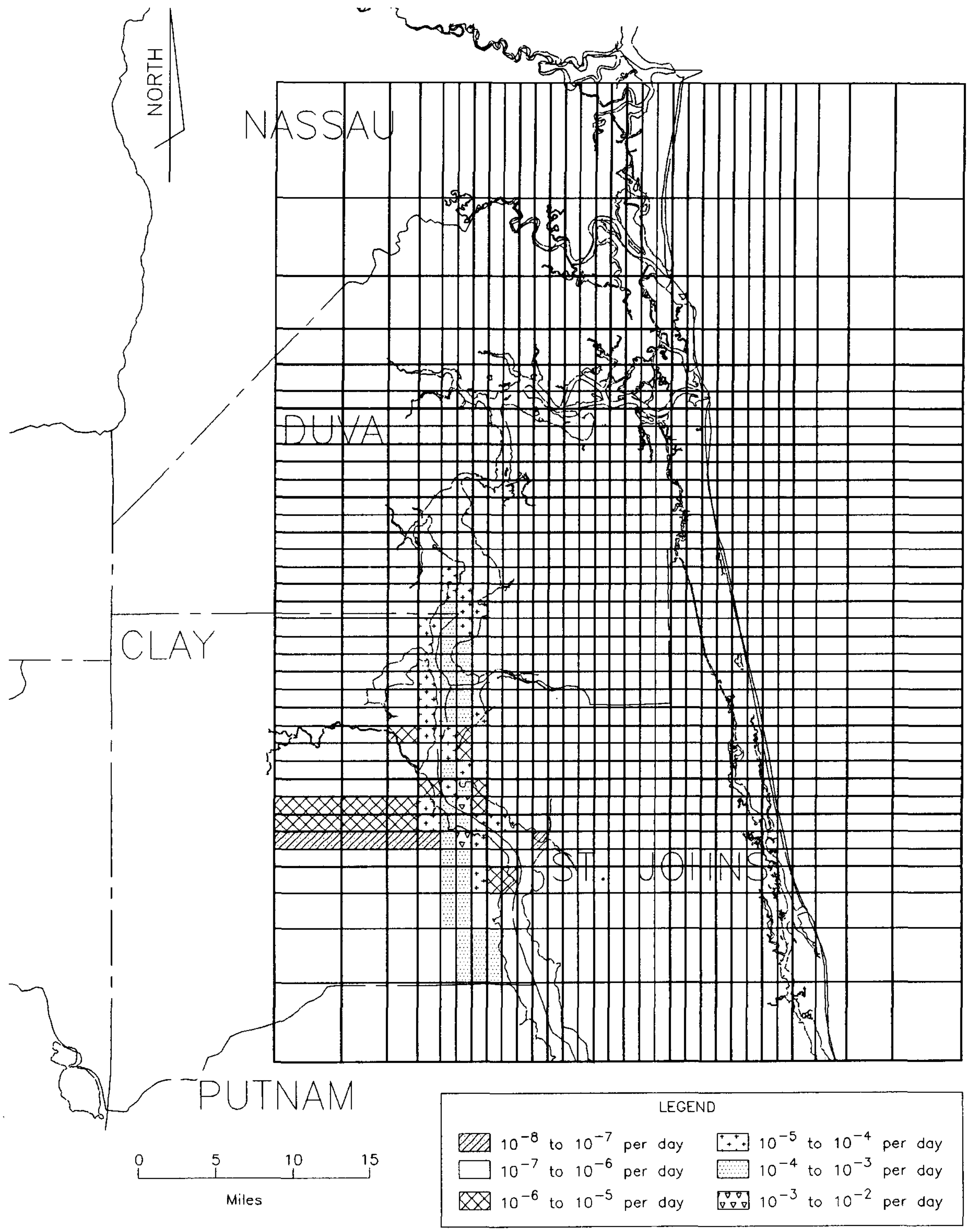


Figure 21. Leakance distribution for the upper confining unit resulting from the predevelopment calibration

Table 7. Results of the sensitivity analysis of the predevelopment flow model

Input Data Change	Mean Difference (ft)	Standard Deviation (ft)	Maximum Absolute Difference (ft)	Model Flux (ft)
Calibration	-2.06	2.69	11.0	5.5×10^9
LK1 x 2.0	-5.38	3.34	16.2	7.1×10^9
LK1 x 0.5	0.93	3.24	15.5	4.2×10^9
LK2 x 2.0	-2.07	2.70	11.1	5.5×10^9
LK2 x 0.5	-2.11	2.72	11.0	5.5×10^9
T2 x 2.0	0.09	3.06	13.7	7.6×10^9
T2 x 0.5	-3.65	2.94	12.7	4.1×10^9
T3 x 2.0	-0.63	2.70	9.5	6.4×10^9
T3 x 0.5	-3.09	2.77	12.0	5.0×10^9
WTE x 2.0	-1.37	5.12	44.4	6.1×10^9
WTE x 0.5	-3.77	3.15	18.9	5.4×10^9

Table 8. Percent differences resulting from the sensitivity analysis of the predevelopment flow model

Input Data Change	PERCENT CHANGE OF			
	Mean Difference	Standard Deviation	Maximum Absolute Difference	Model Flux
LK1 x 2.0	-161.2	24.2	48.2	29.1
LK1 x 0.5	145.1	20.4	40.9	23.6
LK2 x 2.0	-0.5	0.4	0.9	0.0
LK2 x 0.5	-2.4	1.1	0.0	0.0
T2 x 2.0	104.4	13.8	24.5	38.2
T2 x 0.5	-77.2	9.3	15.5	-25.5
T3 x 2.0	69.4	0.4	-13.6	16.4
T3 x 0.5	-50.0	3.0	9.1	-9.1
WTE x 2.0	33.5	90.3	303.6	10.9
WTE x 0.5	-83.0	17.1	71.8	-1.8

The mean difference, its corresponding standard deviation, and the maximum absolute difference of the resulting hydraulic-head distribution were then calculated and recorded along with the total model flux, which was calculated by MODFLOW. The percent change of the adjusted results from the original results indicated the degree of influence of the parameter on the model.

The results indicated that hydraulic heads simulated by the predevelopment model are relatively sensitive to changes in the distributions of elevation of the water table and leakance of the upper confining unit. The hydraulic heads are moderately sensitive to changes in the distributions of transmissivity of the Upper and Lower Floridan aquifers, and they are relatively insensitive to changes in the distribution of leakance of the middle confining unit.

CURRENT-SYSTEM CALIBRATION AND FLOW MODEL

SCOPE

The estimates of leakance and transmissivity obtained in the calibration of the predevelopment model were modified and refined during the calibration of the current-system flow model. The distributions of leakance and transmissivity that resulted from the current-system calibration were accepted as the final results of the study.

As in the case of the predevelopment calibration, the primary focus of the current-system calibration was on the Upper Floridan aquifer to the exclusion of the Lower Floridan aquifer because no potentiometric surface map exists for the Lower Floridan aquifer. The final distributions of transmissivity and leakance for the Lower Floridan aquifer and middle confining unit, respectively, were derived by making adjustments to the existing distribution of leakance or transmissivity and then observing the effect on the simulated potentiometric surface of the Upper Floridan aquifer. Values of transmissivity for the Lower Floridan aquifer and leakance for the middle confining unit were adjusted to match the hydraulic-head distribution of the Upper Floridan aquifer as closely as possible with actual values.

SELECTION OF CURRENT-SYSTEM POTENTIOMETRIC SURFACE

The May 1985 potentiometric surface map was chosen to represent the current flow system. Maps of the potentiometric surface of the Upper Floridan aquifer are prepared annually by the USGS in cooperation with the SJRWMD for the month of May, which usually marks the end of the dry season, and for the month of September, which usually coincides approximately with the end of the wet season. The dry season is the period in which pumping stresses on the Upper Floridan aquifer are greatest, and, consequently, the elevation of the potentiometric surface of the Upper Floridan aquifer is lower during the dry season in most places. Because conservatively low, "worst-case" model projections were desired, the May potentiometric surface map was chosen rather than the September potentiometric surface map. The choice of the year 1985 was based on an analysis of rainfall departures from normal for the years 1981 to 1987 (NOAA 1981-87) for gaging stations located within and in the vicinity of the study area. Gaging stations used in the analysis were located at Fernandina Beach, Jacksonville, Jacksonville Beach, Glen St. Mary, Palatka, Federal Point, and Crescent City (Figure 22).

The objective of the analysis was to find the two consecutive years during the stated time period for which the averages of the absolute annual departures at the gaging stations were lowest, thus indicating that these two years were the most "average" rainfall years for the study area within the time period of the analysis. An average rainfall year was desired to represent the current flow system because the water-table elevations used in the model were average values. The year was chosen to follow an average year in order to reduce the possibility that its potentiometric surface would be significantly affected by extreme rainfall patterns of previous years.

Data for the analysis were obtained from NOAA (1981-1987). The data were not available at all the stations for every year of the analysis. Nevertheless, in order to simplify the analysis, simple arithmetic averages of the annual absolute values of departures that were available were used with the knowledge that other methods of determining areawide average departures are more thorough and reliable but also more time consuming.

FINITE-DIFFERENCE GRID

In creating the finite-difference grid of the current-system flow model, row one of the finite-difference grid of the predevelopment model was divided into three rows. This was done to represent the areally extensive potentiometric depression of the Fernandina Beach area in greater resolution so that its influence on the flow system of the study area could be represented more accurately in the model. Thus, the current-system model consisted of 38 rows and 31 columns (compared with 36 rows and 31 columns for the

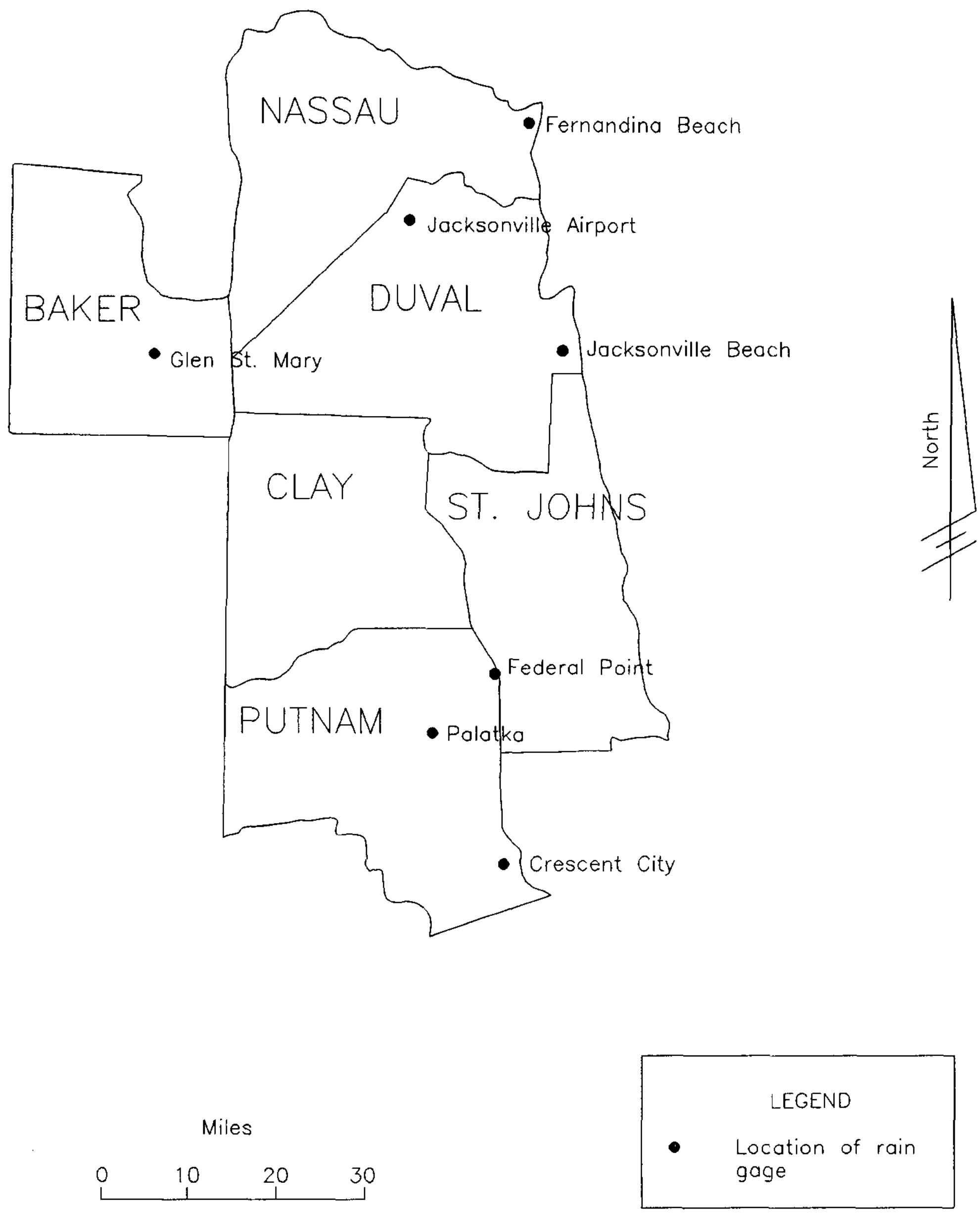


Figure 22. Locations of rainfall gages within and in the vicinity of the study area

Source: Modified from NOAA 1981-1987

predevelopment model), which resulted in 1,178 grid cells (Figure 23). In allother respects, the finite-difference grid of the current-system flow model was identical to that of the predevelopment flow model.

BOUNDARY CONDITIONS

The general procedures used to establish boundary conditions in the predevelopment model were used to establish boundary conditions in the current-system model; therefore, the boundary conditions of the current-system model have the same general configuration as the predevelopment model. Once again, the boundary-condition designations assigned to aquifer layers two and three were identical. Of the 1,178 grid cells in each of aquifer layers two and three, 69 were designated no-flow cells, and 67 were designated GHB active-flow cells (Figure 23). All grid cells of aquifer layer one were designated constant-head cells as before, and, therefore, no boundary conditions were specified for aquifer layer one.

The boundary heads assigned to the GHB active-flow cells in the current-system flow model were estimated by taking into account actual measurements of heads in the Lower Floridan aquifer. Brown et al. (1984, 1985, and 1986) reported vertical distributions of hydraulic head and chloride concentration in the Lower Floridan aquifer at three locations within the study area. To obtain estimates of the hydraulic head in the Lower Floridan aquifer at the three locations in the current flow system, the reported distributions were expressed in the present study as freshwater hydraulic heads and vertically averaged. Values of hydraulic head were simulated by the predevelopment model for the three well locations from Brown et al. (1984, 1985, and 1986) and were used to represent the hydraulic head at the three locations in the predevelopment flow system. The decline in hydraulic head at each of the three locations in the Lower Floridan aquifer since predevelopment time was estimated to be the difference between the vertically averaged values of hydraulic head that were based on data from Brown et al. and the values resulting from the predevelopment simulation.

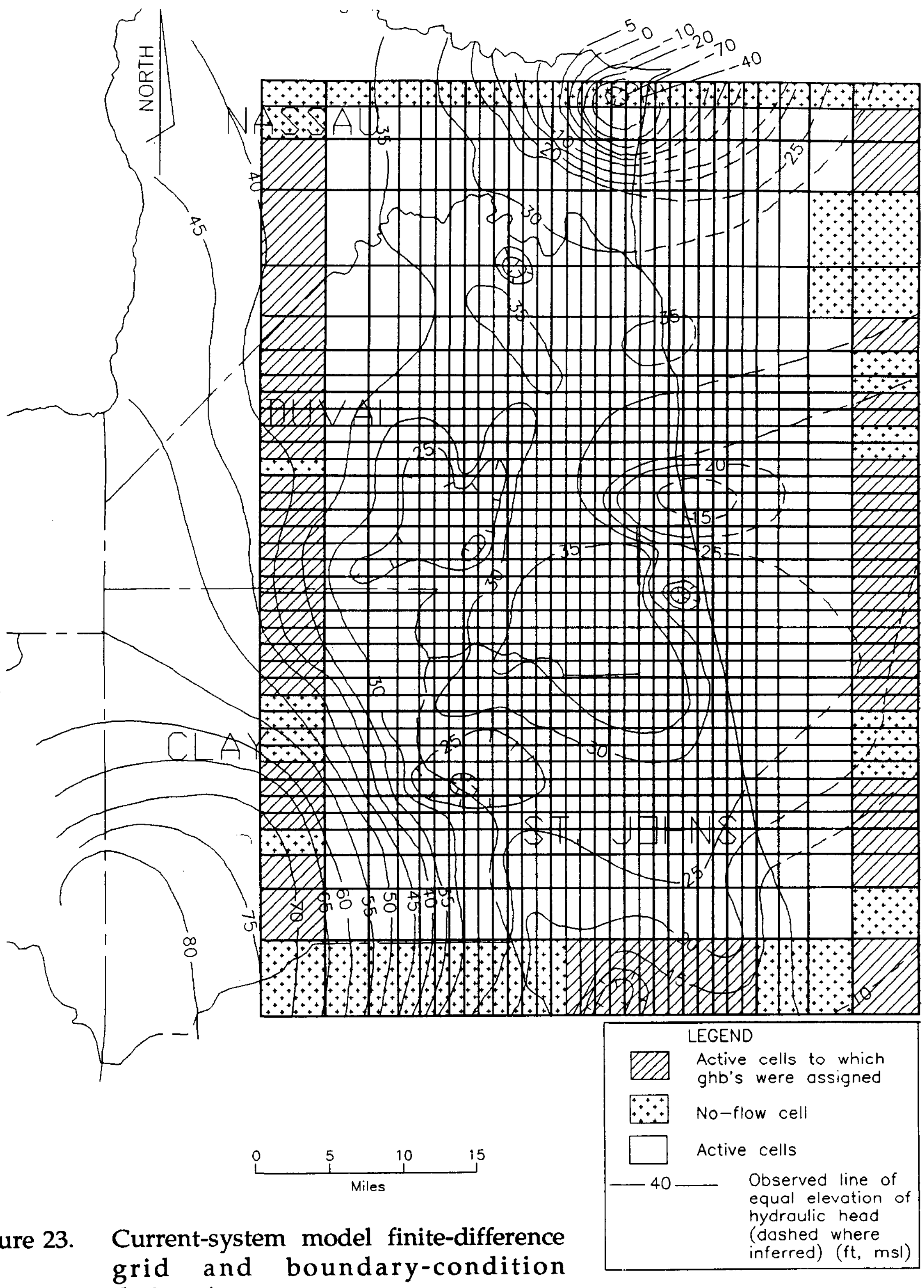


Figure 23. Current-system model finite-difference grid and boundary-condition designations

The declines in the hydraulic head of the Upper Floridan aquifer at the three locations were calculated as the differences between the hydraulic head interpolated from the potentiometric surface maps of the predevelopment flow system and that of the current flow system for years closest to the dates of completion of the three test wells.

The decline in hydraulic head in the Lower Floridan aquifer at the three locations was found to average about 70 percent of the decline in hydraulic head in the Upper Floridan aquifer.

Declines in hydraulic head in the Upper Floridan aquifer since predevelopment times at the locations of the boundary heads assigned to the GHB active-flow cells were then calculated by interpolation from the contour maps of the predevelopment and May 1985 potentiometric surfaces. The estimate of a given decline in hydraulic head at the boundary heads in the Lower Floridan aquifer since predevelopment times was then calculated by multiplying the corresponding decline in hydraulic head of the Upper Floridan aquifer by 0.70. This value was then subtracted from the estimated hydraulic head in the Lower Floridan aquifer at that location in the predevelopment flow system to obtain an estimate of the corresponding boundary-value hydraulic head in the Lower Floridan aquifer of the current flow system.

DATA INPUT REQUIREMENTS

Water-Table Elevations

The distribution of water-table elevations used in the current-system model was the same as that used in the predevelopment model.

Initial Hydraulic-Head Distributions

Initial values of hydraulic head for the Upper Floridan aquifer were interpolated from the May 1985 potentiometric surface map. Hydraulic-head contours were extrapolated offshore to allow hydraulic heads to be interpolated at nodes located offshore. The initial values of hydraulic head for the Lower Floridan aquifer in the current-system calibration were calculated the same as in the predevelopment calibration.

Transmissivity

The initial estimates of transmissivity of the Upper and Lower Floridan aquifers were the final estimates of the corresponding values in the predevelopment model.

Leakance

The initial estimates of leakance of the upper and middle confining units in the current model were the final estimates of the corresponding values in the predevelopment model.

Pumping Rates

The pumping rates and well locations used in the current-system model were based on consumptive-use permits issued by the SJRWMD that were effective in 1985 and other data collected by the SJRWMD. Over 400 well locations within the study area and corresponding allocated pumping rates, which ranged from 500 gallons per day (gpd) to 15.6 million gallons per day (mgd), were thus compiled (written communication, Bruce Florence, SJRWMD, 1989) for this study. In addition, the measured May 1985 pumping rates for 50 wells scattered throughout Duval County were compiled (Marella 1986). This enabled a comparison of allocated pumping rates to the measured pumping rates that occurred in May 1985 at these 50 locations. The results showed that measured pumping rates averaged about 85 percent of allocated pumping rates at the 50 locations. On this basis, pumping rates for all wells throughout the study area were reduced by 15 percent except for those located on D. Dot Ranch.

D. Dot Ranch (located in southern Duval and northern St. Johns counties encompassing the general area bounded by U.S. 1, S.R. 115, S.R. 202, Intracoastal Waterway, and S.R. 210) has a large number of wells and a large allocation for water use. The 1985 consumptive-use permit for the D. Dot Ranch allowed an average daily withdrawal of 21.98 mgd. The pumping rates of individual wells on D. Dot Ranch were initially estimated by simply dividing this amount by the total number of wells on D. Dot Ranch, resulting in the same estimated pumping rate for each of the wells located on D. Dot Ranch. According to information obtained from the SJRWMD, however, (written communication, Bruce Florence, 1989) an average total of about 9.5 mgd were actually used at D. Dot Ranch in 1986. On the assumption that the average daily withdrawal there was approximately the same in 1985 as in 1986, the pumping rate used in the model to represent withdrawals at individual wells in the D. Dot Ranch was reduced by 57 percent from the amount estimated on the basis of the consumptive-use permit.

MODEL CALIBRATION

In the calibration of the current-system flow model, trial transmissivity and leakance distributions were used to simulate distributions of hydraulic heads in the Upper Floridan aquifer. The goal of the calibration was to find the most physically realistic distributions of transmissivity and leakance that also minimized the mean difference in hydraulic heads and its standard deviation.

Final Mean and Standard Deviation

The final mean difference between observed and simulated hydraulic heads for the Upper Floridan aquifer in the current-system calibration was -1.7 ft, and the corresponding standard deviation from the mean was 3.9 ft. The final average absolute difference was 3.4 ft.

Visual Comparisons of Hydraulic-Head Distributions

The progress of the current-system model calibration also was monitored by use of hydraulic-head overlays of observed and simulated hydraulic heads and contour plots of differences between observed and simulated hydraulic heads.

Hydraulic-Head Overlays. A comparison of the observed and simulated hydraulic heads indicated that the essential features of the flow system were simulated fairly well (Figure 24). The deviation was greater in the current-system flow model than in the predevelopment model, however,

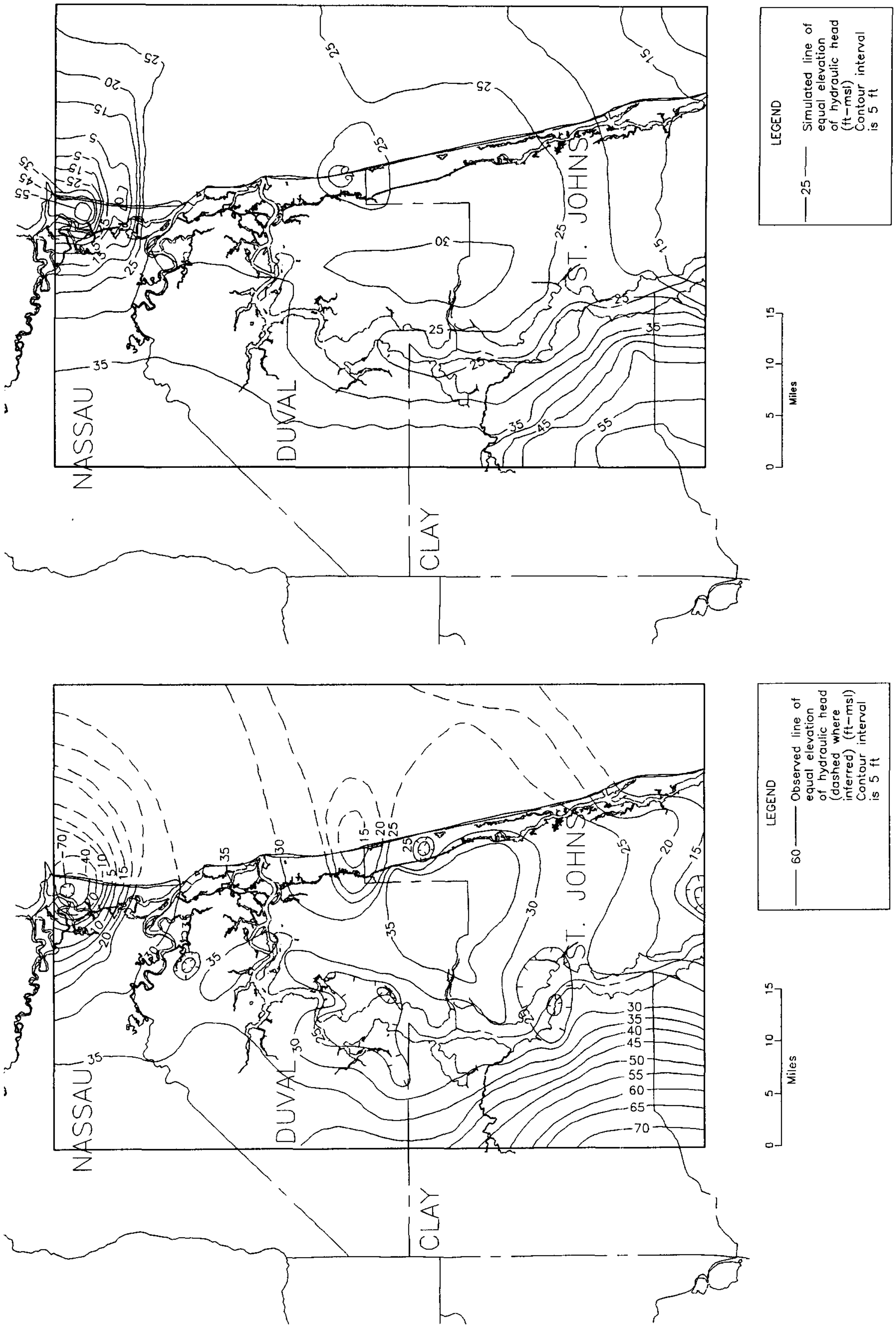


Figure 24. Comparison of simulated and observed potentiometric surfaces for the current-system flow model

but this was expected because the distribution of observed hydraulic heads in the current system was more complex due to the large number of pumping centers in the study area.

Hydraulic-Head Difference Contours. Contours of differences between observed and simulated hydraulic heads were plotted. In most of the study area, the differences were between 0 and 5 ft. In several parts of the study area, however, the differences in observed and simulated hydraulic heads were between 5 and 10 ft, and in several very small parts of the study area, differences were between 10 and 15 ft (Figure 25).

FINAL DISTRIBUTIONS OF INPUT PARAMETERS

The current-system calibration required the introduction of an independent distribution of transmissivity for aquifer layer three (the Lower Floridan aquifer) and a complete distribution of leakance for confining-unit layer two (the middle confining unit) into the current-system model. These features were important departures from the approach used in the calibration of the predevelopment model and imply that the importance of the Lower Floridan aquifer in the flow system of the study area has increased since predevelopment times due to pumping in the Upper Floridan aquifer. The input parameters of these layers were adjusted on the basis of how values of hydraulic head in the Upper Floridan aquifer were affected by such adjustments.

Transmissivity

Upper Floridan Aquifer. The transmissivity distribution of aquifer layer two that resulted from the calibration of the current-system flow model was somewhat different from that which resulted from the calibration of the predevelopment flow model (Figures 26 and 20). Major changes in values of transmissivity of aquifer layer two were made in the northeastern portion of the study area (the area of the Fernandina Beach potentiometric low) and in the east-central area of the study. In both these areas, simulated hydraulic heads were initially much higher than observed hydraulic heads, prompting decreases in the values of transmissivity developed for those areas in the

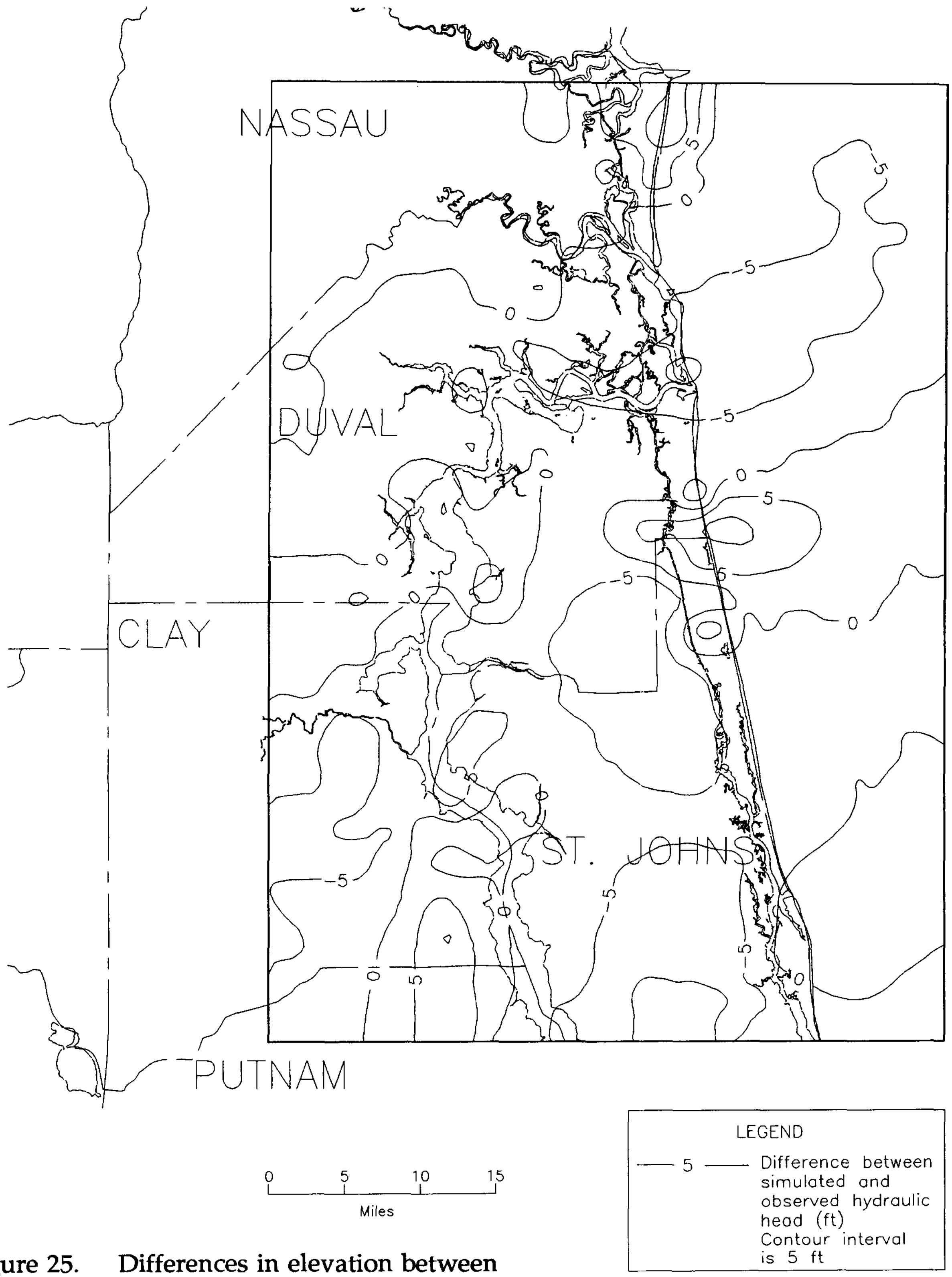


Figure 25. **Differences in elevation between simulated and observed potentiometric surfaces for the current-system flow model**

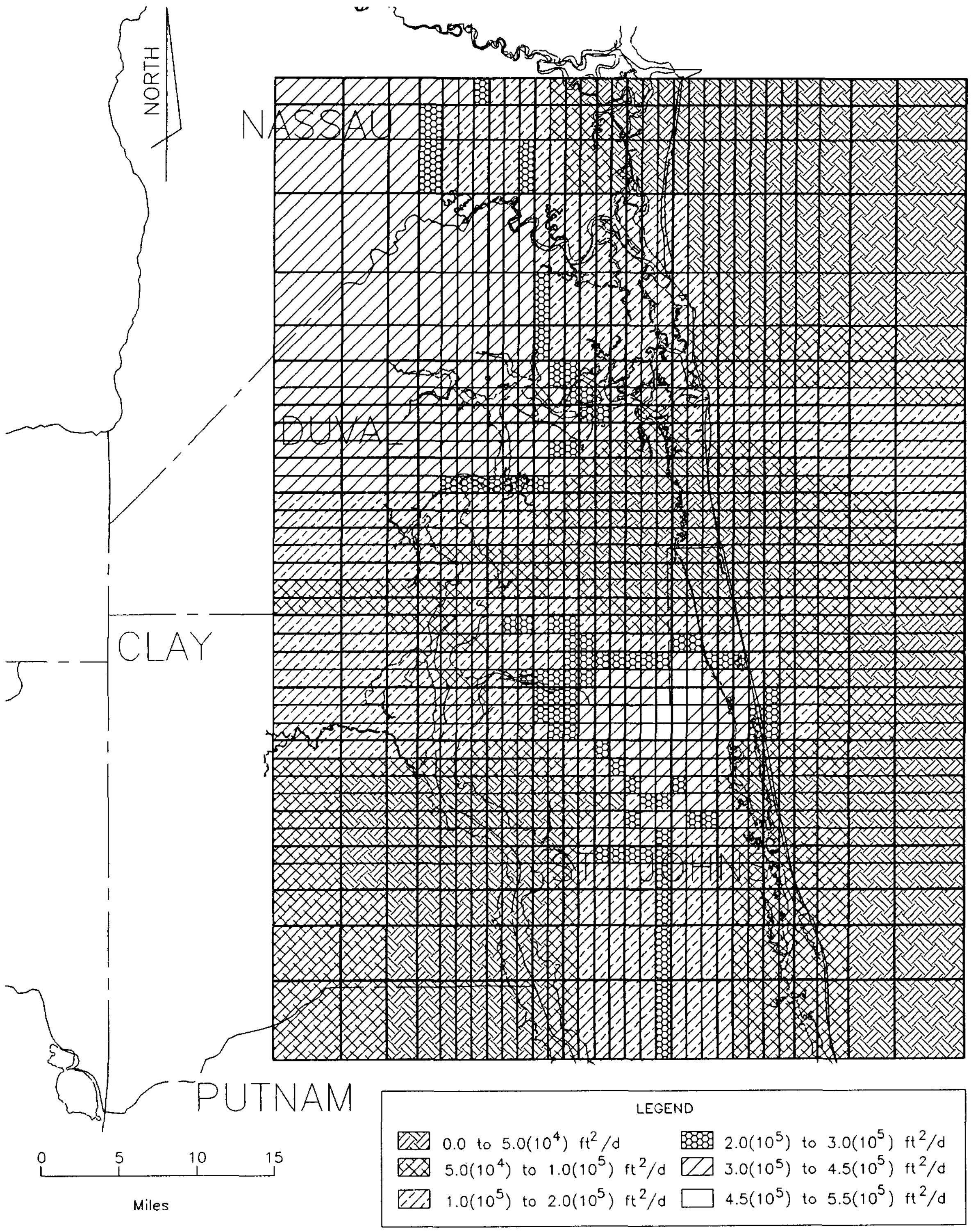


Figure 26. Transmissivity distribution for the Upper Floridan aquifer resulting from the current-system calibration

predevelopment model. In the Fernandina Beach area, values of transmissivity resulting from the predevelopment calibration ranged from 90,000 to 250,000 ft^2/d, but in the current-system calibration, these values were reduced to a range of about 18,000 to 24,000 ft^2/d. In the east-central area of the model, values of transmissivity resulting from the predevelopment calibration ranged from about 50,000 to 200,000 ft^2/d. After adjustments to the current-system calibration, these values ranged from 12,000 ft^2/d to 100,000 ft^2/d.

The maximum value of transmissivity in aquifer layer two resulting from the current-system calibration was 540,000 ft^2/d. This value occurred in the south-central area of the study area. The minimum value of transmissivity in aquifer layer two, which occurred in the northeastern area of the study area, was 2,400 ft^2/d. The arithmetic average of the elements of the transmissivity matrix that represents the transmissivity distribution of the Upper Floridan aquifer in MODFLOW was calculated to be 136,000 ft^2/d. This value was only slightly less than the arithmetic average of 148,000 ft^2/d obtained from the predevelopment calibration for aquifer layer two.

Lower Floridan Aquifer. The need to include an independent distribution of transmissivity for aquifer layer three in the current-system flow model was unexpected. What was even more unexpected was that the resulting arithmetic average of the transmissivity distribution of aquifer layer three, which was 230,000 ft^2/d, was significantly larger than that of aquifer layer two, since the Upper Floridan aquifer is usually thought to be more permeable than the Lower Floridan aquifer (Miller 1986).

There are at least two possible reasons for this difference. First, the Lower Floridan aquifer, as defined by Miller (1986), is about twice as thick as the Upper Floridan aquifer throughout most of the study area. Therefore, if the hydraulic conductivities in the two aquifers at a given location were roughly equal, the transmissivity of the Lower Floridan aquifer would be about twice that of the Upper Floridan aquifer at that location. Second, the Fernandina permeable zone, a zone of high permeability of subregional extent contained in the Lower Floridan aquifer of the study area, may contribute to high average transmissivities in the Lower Floridan aquifer. Very little, however, is known about the Lower Floridan aquifer of the study area, so these reasons are not conclusive. What is certain is that the calibration of the current-system flow model probably would have not been possible if an independent distribution of transmissivity had not been developed for aquifer layer three.

The maximum value of transmissivity contained in aquifer layer three was 420,000 ft^2/d. Values of transmissivity contained in aquifer layer three decrease towards the south and east within the study area (Figure 27). These lower values of transmissivity are between 50,000 ft^2/d and 100,000 ft^2/d over large portions of the eastern and southern parts of the study area. In parts of the extreme eastern and northeastern areas of the study area, values of transmissivity are less than 50,000 ft^2/d. The minimum value of transmissivity contained in aquifer layer three is 18,000 ft^2/d and occurs in the east-central part of the study area.

Leakance

Upper Confining Unit. The leakance distribution developed for confining-unit layer one in the predevelopment calibration was not greatly altered in the current-system calibration (Figure 28). Values of leakance were lowered in several areas by an order of magnitude, however, so that the minimum value of leakance for the upper confining unit resulting from the current-system calibration was 1.0×10^{-9} per day. The maximum value of leakance was 2.0×10^{-3} per day, as in the predevelopment calibration.

Middle Confining Unit. In the predevelopment flow model, the leakance distribution of the middle confining unit was represented by a single value of leakance, 1×10^{-4} per day. In order to calibrate the current-system flow model, values of leakance in confining-unit layer two were varied throughout the study area (Figure 29). Leakance of the middle confining unit was found to be on the order of 10^{-7} to 10^{-6} per day in low-leakance areas, which occupy most of the study area, and as high as 0.5 to 1.0 per day in areas of high leakance. The areas of high leakance in confining-unit layer two suggest that in parts of the study area the Upper and Lower Floridan aquifers are hydraulically well connected. Two such areas were identified in the current-system model calibration in the north-central and south-central areas of the study area. The areas of low leakance suggest areas where the two aquifers are hydraulically isolated from one another. The minimum value of leakance contained in confining-unit layer two was 1.0×10^{-8} per day, and the maximum value was 10.0 per day.

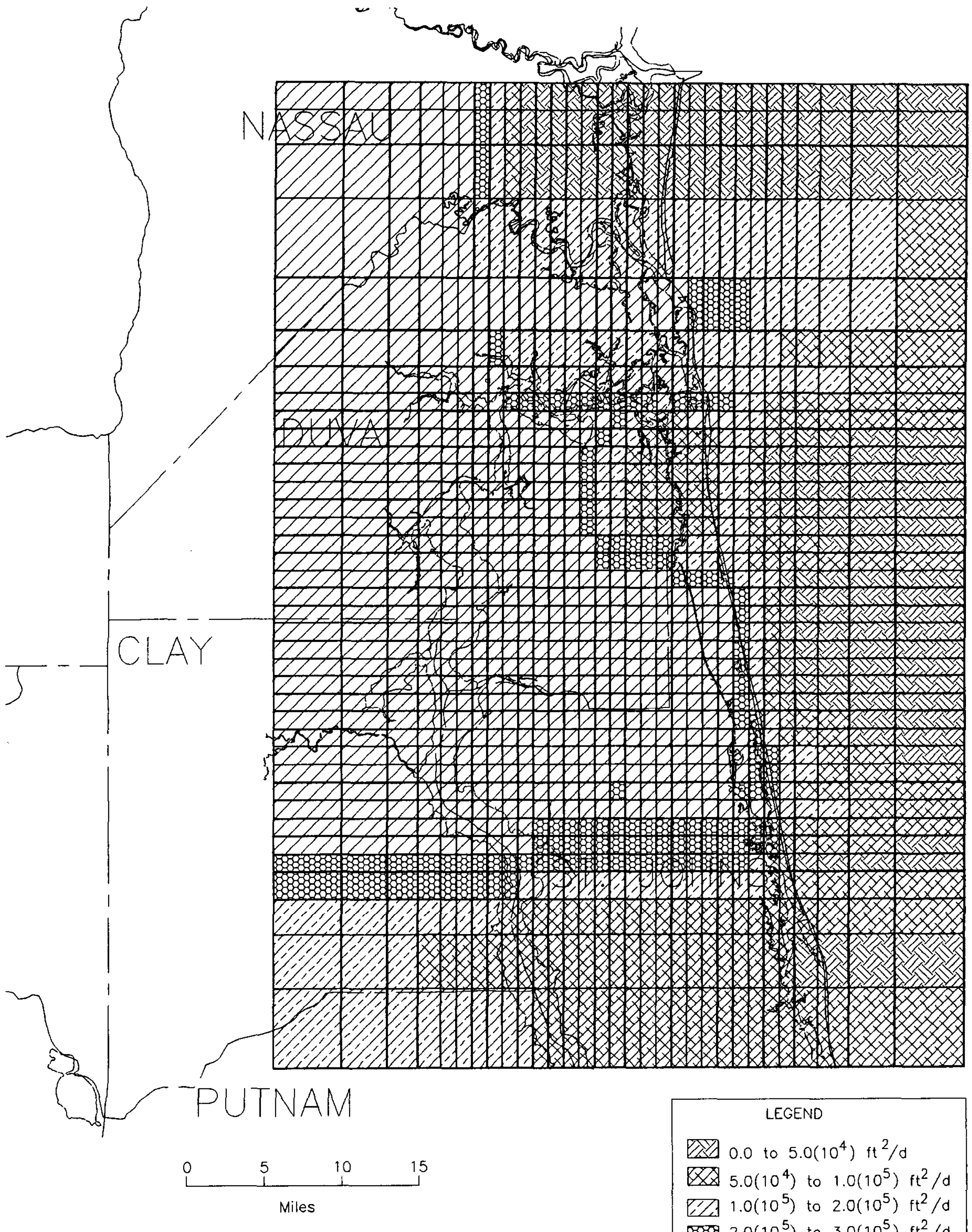


Figure 27. Transmissivity distribution for the Lower Floridan aquifer resulting from the current-system calibration

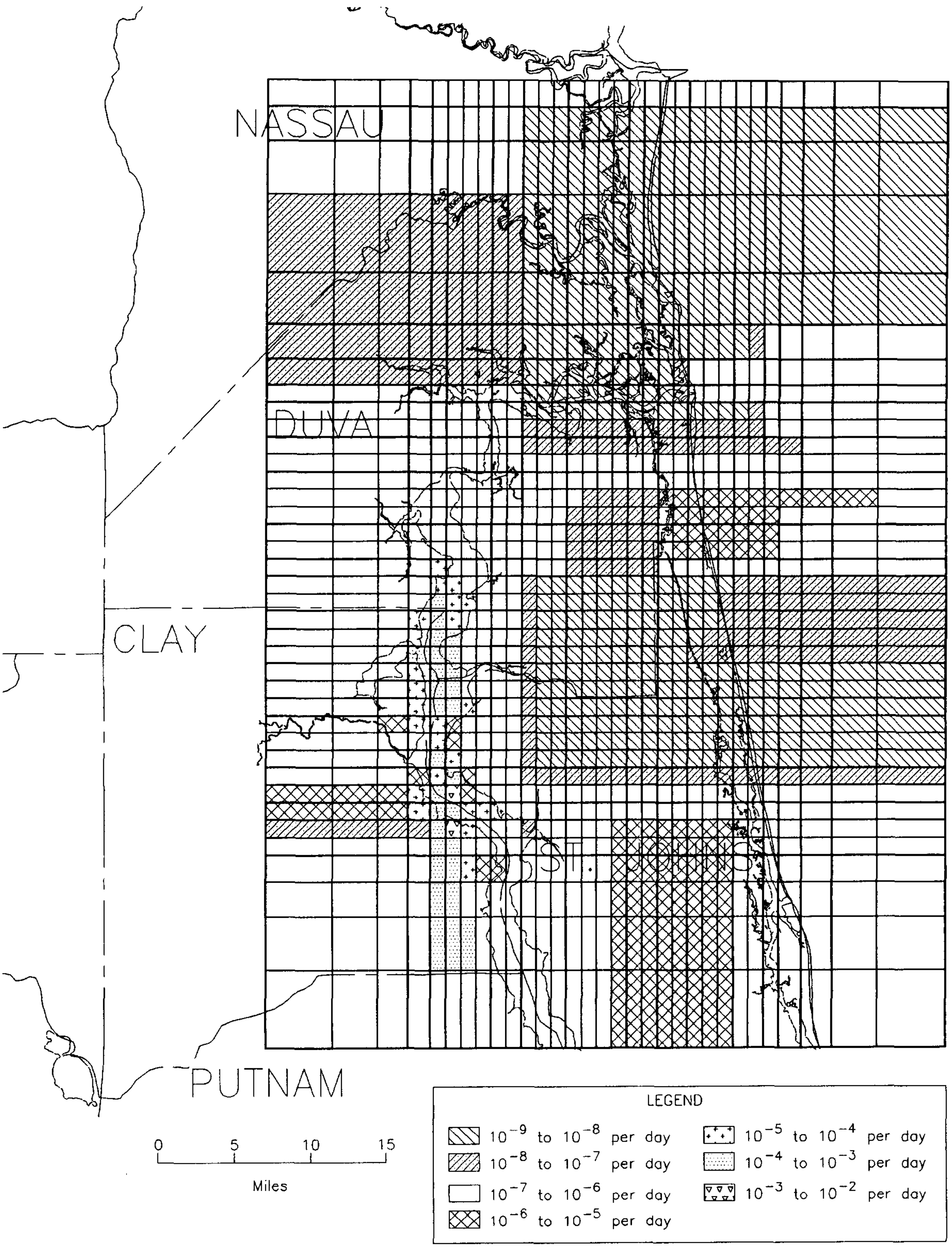


Figure 28. Leakance distribution from the upper confining unit resulting from the current-system calibration

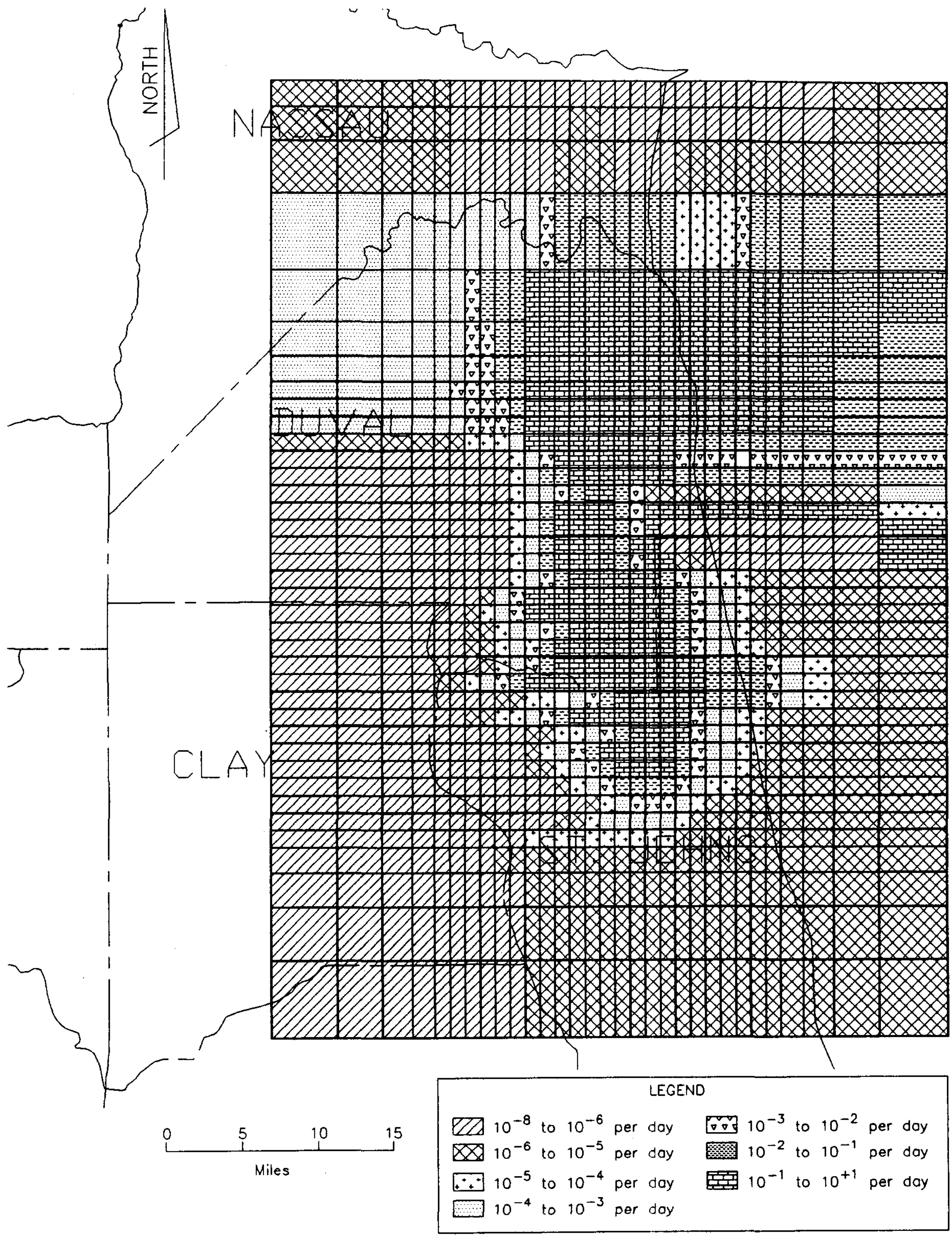


Figure 29. Leakance distribution for the middle confining unit resulting from the current-system calibration

WATER-BUDGET ANALYSIS

A water-budget analysis of the Upper Floridan aquifer in the current flow system indicates that approximately 2.5 in of flow per year currently enters the Upper Floridan aquifer from several different sources (Table 9) and that about 98 percent of all flow entering the entire Floridan aquifer system of the study area eventually enters the Upper Floridan aquifer. Of the flow sources, the Lower Floridan aquifer is the greatest contributor, supplying about 63 percent of the total yearly recharge to the Upper Floridan aquifer. Lateral flow through the western boundary of the study area accounts for approximately 29 percent of the recharge to the Upper Floridan aquifer, according to the model simulation, while the surficial aquifer system contributes approximately 7.5 percent of the total inflow to the Upper Floridan aquifer of the study area. Lateral flow across the eastern and southern boundaries occurs in only negligible amounts, according to the model results, accounting for less than 1 percent of the total inflow to the Upper Floridan aquifer.

Flow exits the Upper Floridan aquifer via several routes (Table 9). Pumping from the Upper Floridan aquifer wells accounts for most of the outflow, approximately 74 percent. Approximately 18 percent exits as leakage through the upper confining unit, while lateral flow across the eastern and southern boundaries of the study area accounts for a total of approximately 6 percent of the outflow from the system. Downward leakage into the Lower Floridan aquifer accounts for less than 2 percent of the total outflow from the Upper Floridan aquifer of the current flow system.

The predevelopment potentiometric surface map (Johnston et al. 1980) indicates that an extensive potentiometric depression existed in the southwestern area of the study area during predevelopment times (Figure 30). The model calibration indicates that leakance in the upper confining unit is exceptionally high in this area as compared to the rest of the study area, and, accordingly, a disproportionate amount of upward leakage from the Upper

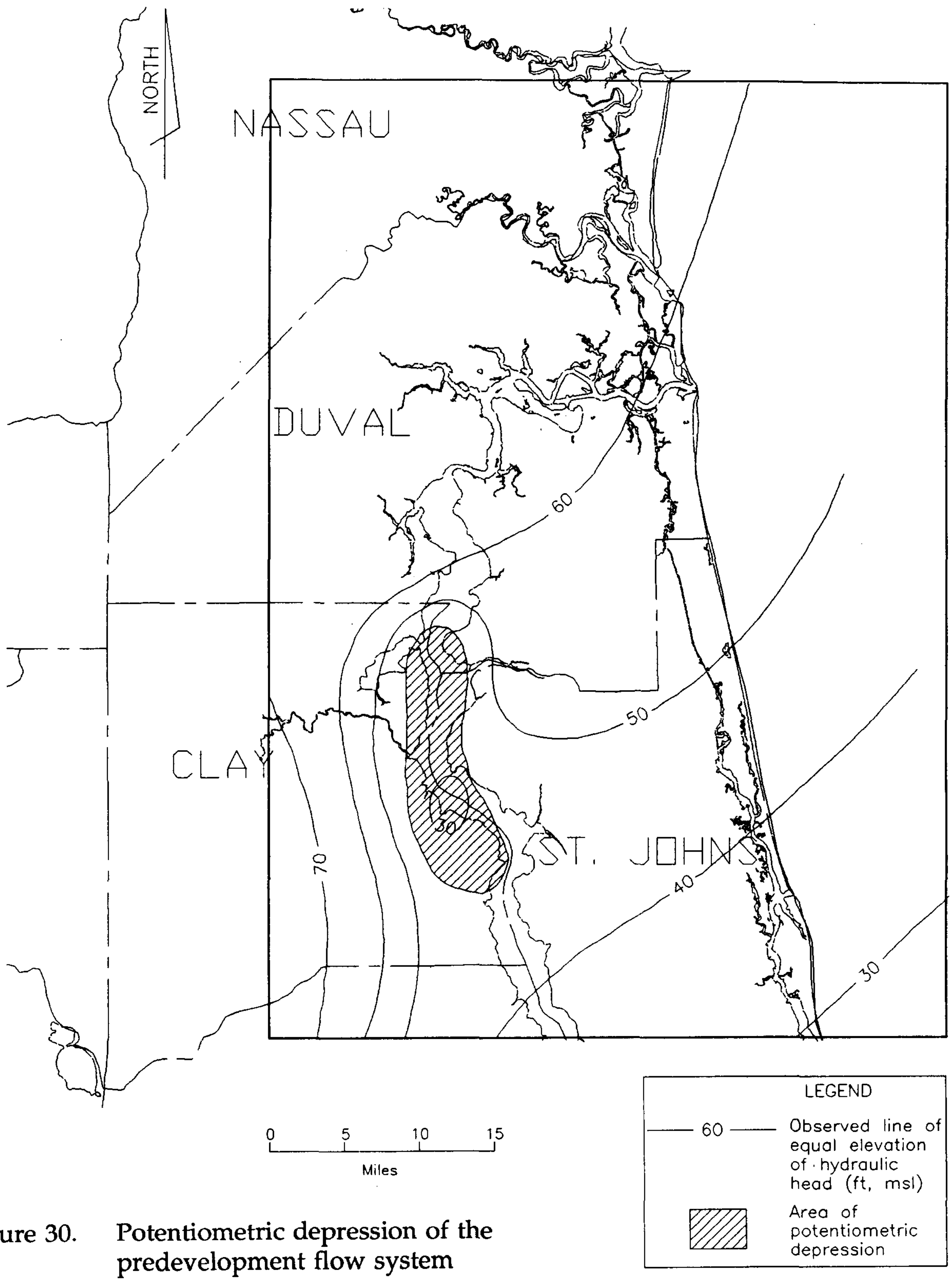


Figure 30. Potentiometric depression of the predevelopment flow system

Source: Modified from Johnston et al. 1980

Table 9. Results of the water budget analysis of the current Upper Floridan aquifer based on the current-system flow model

Flow Source	Flowrate (ft^3/yr)	Flowrate (in/yr)	Percent Total
Surficial aquifer system	1.03×10^9	0.19	7.46
Lower Floridan aquifer	8.69×10^9	1.58	63.15
Western model boundary	3.98×10^9	0.72	28.93
Eastern model boundary	5.88×10^7	0.01	0.43
Southern model boundary	3.93×10^6	0.00	0.03
Totals	1.38×10^{10}	2.50	100.00

Flow Destination	Flowrate (ft^3/yr)	Flowrate (in/yr)	Percent Total
Surficial aquifer system	2.51×10^9	0.46	18.25
Lower Floridan aquifer	2.15×10^8	0.04	1.56
Eastern model boundary	3.98×10^8	0.07	2.90
Southern model boundary	4.29×10^8	0.08	3.12
Wells	1.02×10^{10}	1.85	74.17
Totals	1.38×10^{10}	2.50	100.00

Floridan aquifer to the surficial aquifer system takes place in this area. Approximately 3.95 x 10^6 ft^3/d, or 49 percent of the leakage within the study area from the Upper Floridan aquifer to the surficial aquifer system, is discharged within this area. However, the area encompasses only about 3 percent of the total study area.

SENSITIVITY ANALYSIS

The parameter distributions considered in the sensitivity analysis of the current-system flow model were the distributions of elevation of the water table (WTE), leakance of the upper confining unit (LK1), transmissivity of the Upper Floridan aquifer (T2), leakance of the middle confining unit (LK2), and transmissivity of the Lower Floridan aquifer (T3) (Tables 10 and 11). As in the sensitivity analysis of the predevelopment flow model, changes in the distributions of transmissivity were accompanied by changes of the same factor in the corresponding values of conductance that were assigned to the GHBs of the layer under consideration.

The results indicated that the distribution of hydraulic heads of the Upper Floridan aquifer calculated by the current-system flow model was sensitive to changes in assigned pumping rates, water-table elevations, and distributions of transmissivity; was moderately sensitive to changes in the distribution of leakance of the upper confining unit; and relatively insensitive to changes in the distribution of leakance of the middle confining unit.

Table 10. Results of the sensitivity analysis of the current-system flow model

Input Data Change	Mean Difference (ft)	Standard Deviation (ft)	Maximum Absolute Difference (ft)	Model Flux (ft)
No change	-1.69	3.90	18.3	1.4×10^{10}
LK1 x 2.0	-2.86	4.11	17.8	1.5×10^{10}
LK1 x 0.5	-0.71	3.94	18.6	1.3×10^{10}
LK2 x 2.0	-1.54	3.96	18.6	1.4×10^{10}
LK2 x 0.5	-1.83	3.86	18.0	1.4×10^{10}
T2 x 2.0	0.49	6.03	60.1	1.6×10^{10}
T2 x 0.5	-3.88	6.63	70.0	1.3×10^{10}
T3 x 2.0	3.75	4.15	25.0	1.6×10^{10}
T3 x 0.5	-7.42	4.68	19.0	1.3×10^{10}
WTE x 2.0	0.65	5.96	57.4	1.5×10^{10}
WTE x 0.5	-2.85	4.29	19.1	1.4×10^{10}
P x 2.0	-14.3	8.34	70.0	2.2×10^{10}
P x 0.5	2.2	5.98	19.1	1.3×10^{10}

Table 11. Percent differences corresponding to the results of the sensitivity analysis of the current-system flow model

Input Data Change	PERCENT CHANGE OF			
	Mean Difference	Standard Deviation	Maximum Absolute Difference	Model Flux
LK1 x 2.0	-69.2	5.4	-2.7	7.1
LK1 x 0.5	58.0	1.0	1.6	-7.1
LK2 x 2.0	8.9	1.5	1.6	0.0
LK2 x 0.5	-8.3	-1.0	-1.6	0.0
T2 x 2.0	130.0	54.6	228.4	14.3
T2 x 0.5	-129.6	70.0	282.5	-7.1
T3 x 2.0	321.9	6.4	36.6	14.3
T3 x 0.5	-339.1	20.0	3.8	-7.1
WTE x 2.0	138.5	52.8	213.7	7.1
WTE x 0.5	-68.6	10.0	4.4	0.0
P x 2.0	-746.2	113.8	282.5	57.1
P x 0.5	230.2	53.3	4.4	-7.1

MODIFIED PREDEVELOPMENT FLOW MODEL

PURPOSE AND SCOPE

Upon completion of the current-system flow model, the model of the predevelopment flow system of the study area was modified by replacing the transmissivity and leakance distributions that resulted from the predevelopment calibration with the final transmissivity and leakance distributions of the current-system calibration. These distributions presumably were more accurate than those derived from the calibration of the original predevelopment flow model. The "modified predevelopment flow model", therefore, enabled the attainment of a better representation of the actual predevelopment flow system than did the original predevelopment flow model.

The boundary conditions, numbers of rows and columns, and constant-head values assigned to the GHBs of the modified predevelopment model were identical to those of the original predevelopment model. The values of conductance assigned to the GHBs, however, were based on the transmissivity distributions that were derived in the calibration of the current-system flow model.

Comparisons of Simulated and Observed Hydraulic Heads

The mean difference in simulated and observed hydraulic heads in aquifer layer two (Upper Floridan aquifer) of the modified predevelopment model was +2.3 ft, and the corresponding standard deviation from the mean was 3.3 ft. The mean absolute value of the differences in observed and simulated hydraulic heads was 3.2 ft.

While these values were slightly higher than the corresponding values in the original predevelopment flow model, the contour overlay of the simulated and observed hydraulic-head distributions in the Upper Floridan aquifer (Figure 31) demonstrated a very close agreement in the general features of the two head distributions.

The contour plot of the difference between simulated and observed hydraulic heads (Figure 32) indicated that differences were less than 5 ft throughout most of the study area but were between 5 and 10 ft in some places, most notably in the southeastern portion of the study area.

WATER-BUDGET ANALYSIS

A water-budget analysis of the predevelopment flow system based on the modified predevelopment flow model (Table 12) indicated that about 1.3 in per year entered the Upper Floridan aquifer from three sources during predevelopment times: the Lower Floridan aquifer, the surficial aquifer system, and the western boundary of the study of the area. The Lower Floridan aquifer contributed most of the inflow to the predevelopment Upper Floridan aquifer (about 50 percent). About 41 percent entered as lateral flow across the western boundary of the study area, while about 9 percent entered as downward leakage from the surficial aquifer system.

By far most of the flow leaving the predevelopment Upper Floridan aquifer of the study area (about 78 percent) crossed the upper confining unit into the surficial aquifer system, while only about 7 percent crossed the middle confining unit into the Lower Floridan aquifer. Approximately 10 percent exited the Upper Floridan aquifer via the eastern boundary of the study area, and about 6 percent exited via the southern boundary.

The modified predevelopment model indicated that about 6.74×10^6 ft^3/d, or 49 percent, of the leakage between the Upper Floridan aquifer and surficial aquifer system in the predevelopment flow system of the study area took place within the area encompassed by the potentiometric low of the southwestern area of the study area (Figure 30). The potentiometric depression created by this very large discharge via upward leakage was a very influential factor in the predevelopment flow system.

Pumping in the Upper Floridan aquifer of the study area has brought about significant changes in the flow system of the study area. For instance,

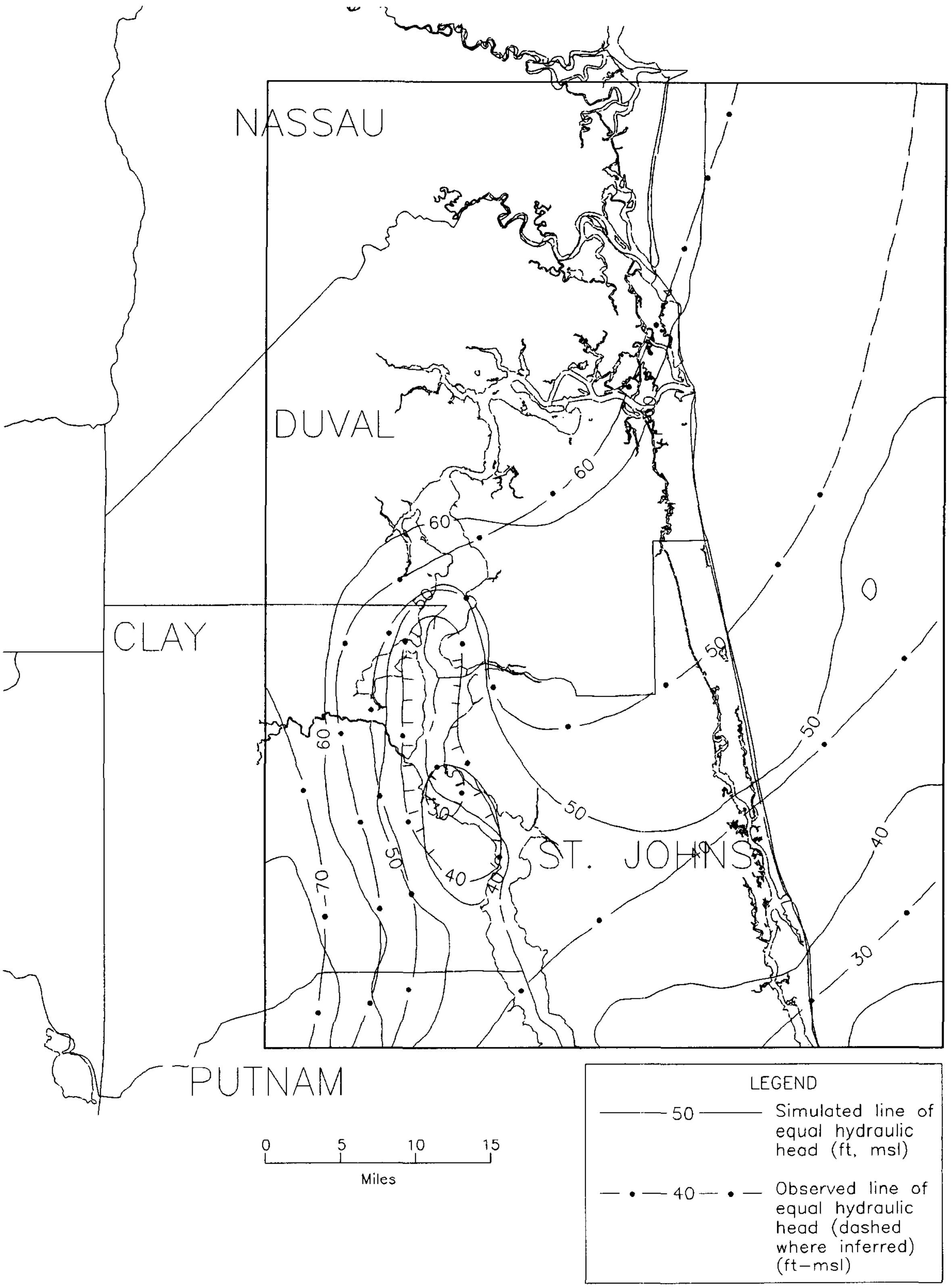


Figure 31. Comparison of simulated and observed potentiometric surfaces for the modified predevelopment flow model

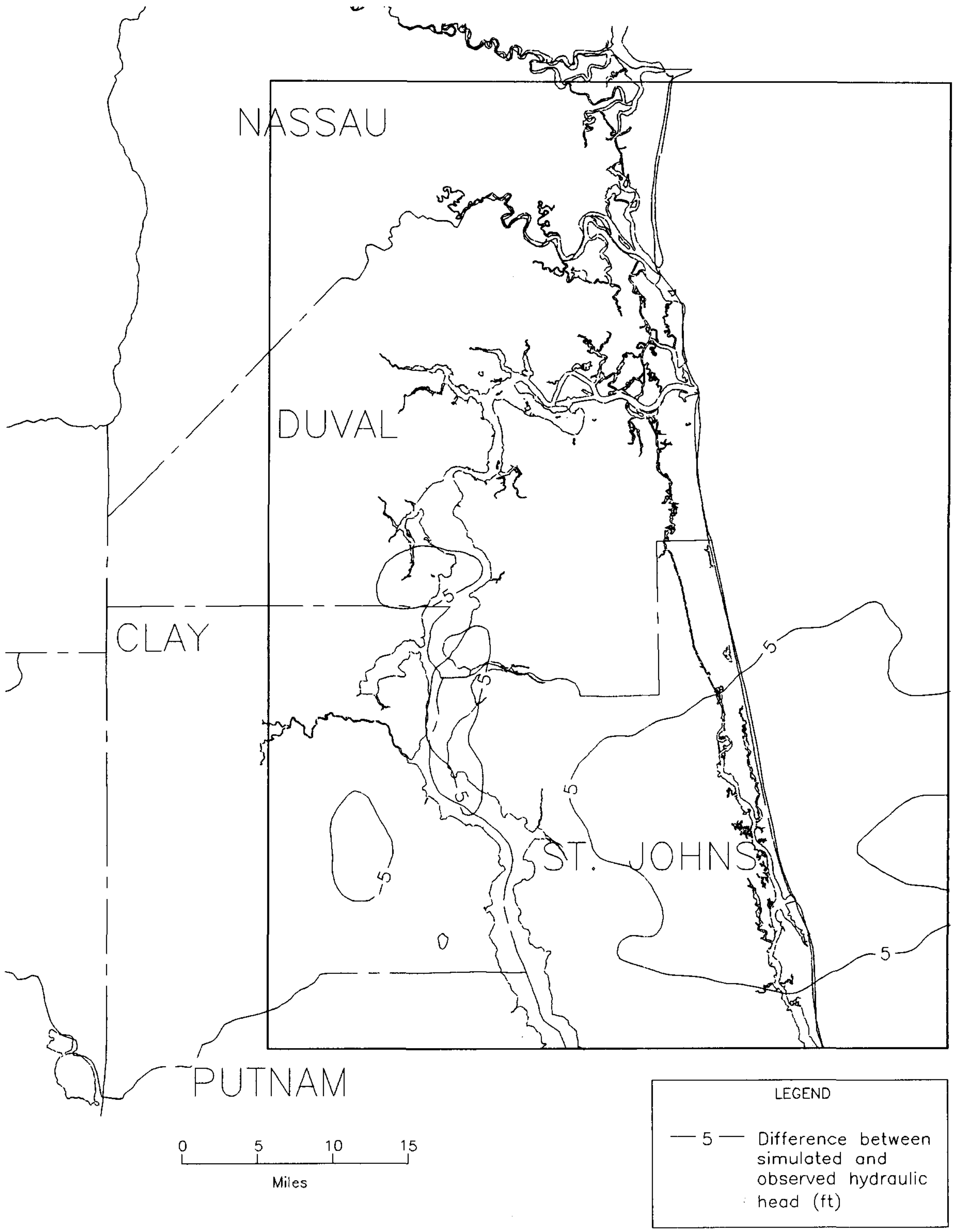


Figure 32. Differences in elevation between simulated and observed potentiometric surfaces for the modified predevelopment flow model

Table 12. Results of the water budget analysis of the predevelopment Upper Floridan aquifer based on the modified predevelopment flow model

Flow Source	Flowrate (ft^3/yr)	Flowrate (in/yr)	Percent Total
Surficial aquifer system	5.97×10^8	0.12	9.15
Lower Floridan aquifer	3.24×10^9	0.63	49.65
Western model boundary	2.69×10^9	0.52	41.20
Totals	6.53×10^9	1.27	100.00

Flow Destination	Flowrate (ft^3/yr)	Flowrate (in/yr)	Percent Total
Surficial aquifer system	5.07×10^9	0.98	77.65
Lower Floridan aquifer	4.30×10^8	0.08	6.58
Eastern model boundary	6.38×10^8	0.12	9.77
Southern model boundary	3.92×10^8	0.08	6.00
Totals	6.53×10^9	1.26	100.00

the Lower Floridan aquifer contributes considerably more flow to the Upper Floridan aquifer in the current flow system than it did in the predevelopment flow system, according to the results. In absolute terms, the results of the simulations of the current-system and modified predevelopment flow models indicated that the Lower Floridan aquifer now contributes more than twice the amount of flow to the Upper Floridan aquifer that it did in predevelopment times. Proportionally, its contribution has increased from approximately 50 percent of the total inflow to the Upper Floridan aquifer to approximately 63 percent, indicating that its importance in the overall flow system has increased since predevelopment times.

In absolute terms, more flow enters the Upper Floridan aquifer of the study area through its western boundary now than in predevelopment times; proportionally, however, much less flow enters the Upper Floridan aquifer via its western boundary now than in predevelopment times because the increase in flow from the Lower Floridan aquifer has been even greater.

The potentiometric surface of the Upper Floridan aquifer has been lowered substantially, about 25 ft, relative to the water table since predevelopment times in most areas of the study area, and this has greatly increased the total area of recharge in the study area (Figures 33 and 34). Upward leakage from the Upper Floridan aquifer to the surficial aquifer system has been reduced both proportionally and in absolute terms according to the results of the simulations, while downward leakage from the surficial aquifer system into the Upper Floridan aquifer has increased in absolute terms but has decreased somewhat proportionally.

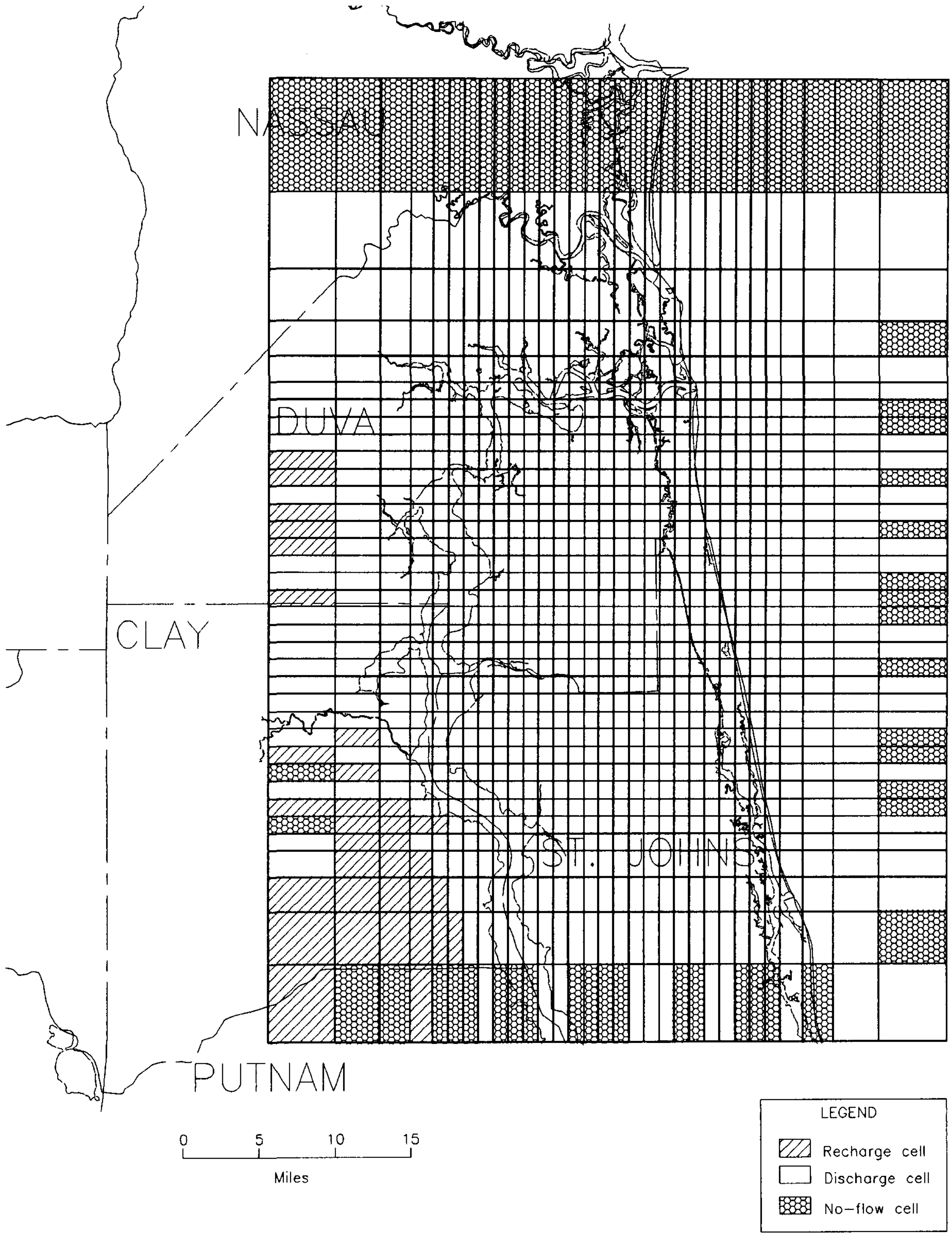


Figure 33. Recharge areas for the predevelopment Upper Floridan aquifer according to the modified predevelopment flow model

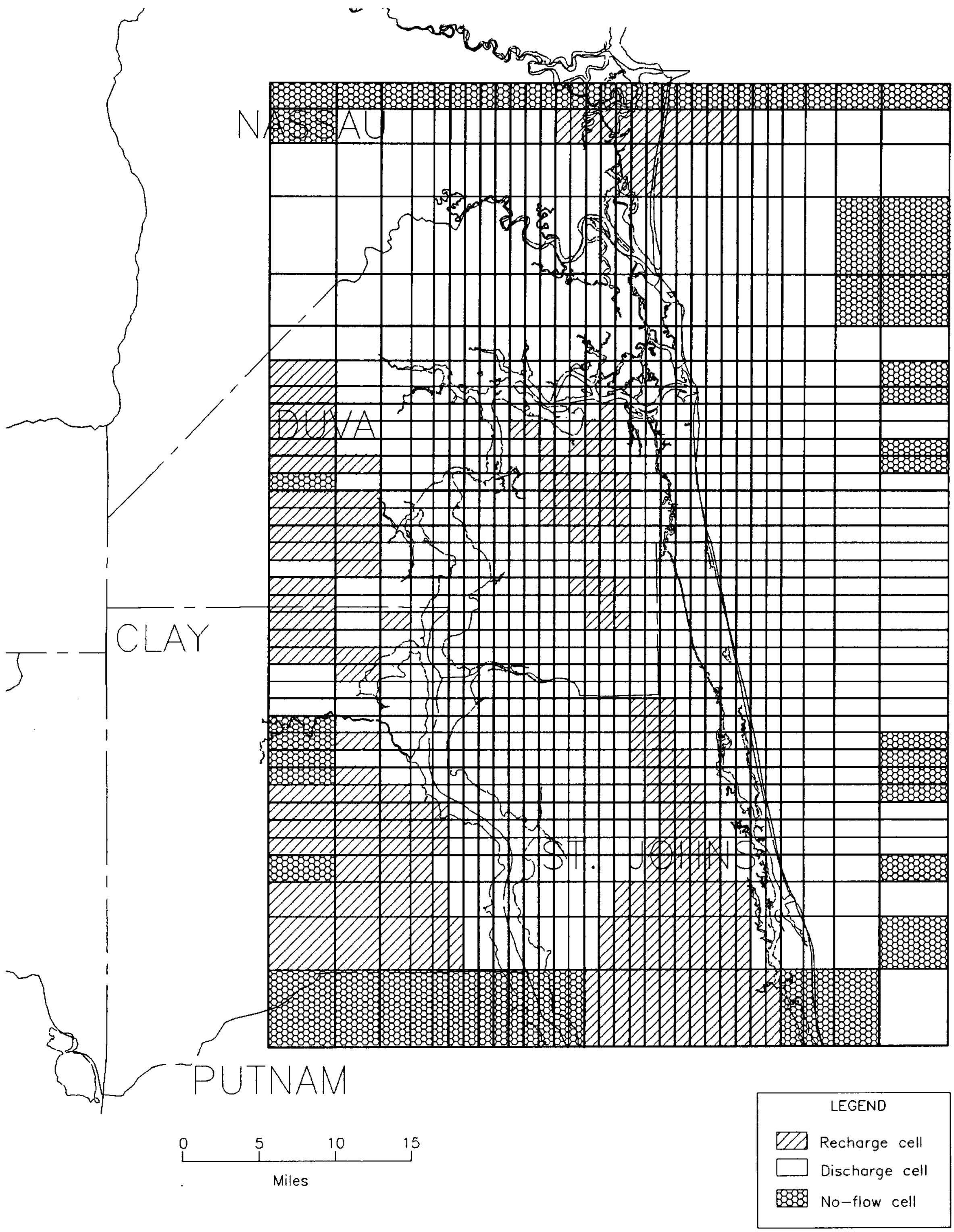


Figure 34. Recharge areas for the current-system (May 1985) Upper Floridan aquifer according to the current-system flow model

EXAMPLE APPLICATION

The current-system flow model was used to determine the effect that pumping in the Jacksonville area has on the hydraulic-head distribution of the Upper Floridan aquifer throughout the study area. The purpose of this exercise was to illustrate the usefulness of the current-system model in predicting the effects of hypothetical pumping scenarios. The Jacksonville area was of interest because the wells within it are densely concentrated, and the resultant pumping is heavy. The area of consideration lies between latitudes 30° 0.50′ and 30° 15′ and longitudes 81° 44.5′ and 81° 30.0′ (Figure 35). The total simulated pumpage within this area was 87.4 mgd in the current-system flow model.

In this application, the model was used to calculate the distributions of hydraulic head in the Upper Floridan aquifer both with and without pumping from within the area of consideration. Differences in hydraulic heads of the two distributions were then calculated at each of the cells of the model grid. The resulting distribution of hydraulic-head differences was then used to create a contour plot of hydraulic-head differences (or drawdowns) due to pumping within the sample area to illustrate the impact that the pumping in Jacksonville has on the hydraulic-head distribution of the Upper Floridan aquifer in the study area (Figure 35).

The model indicated that the maximum drawdown in the Upper Floridan aquifer due to pumping in the Jacksonville area is about 9 ft and occurs near the center of the sample area. The minimum drawdown in the Upper Floridan aquifer within the study area due to pumping in the Jacksonville area is about 1 ft and occurs near the southern boundary of the study area. The results of the application are more reliable in the interior of the study area, because the effects of the constant boundary heads assigned to the GHBs are less prominent at greater distances from the boundaries.

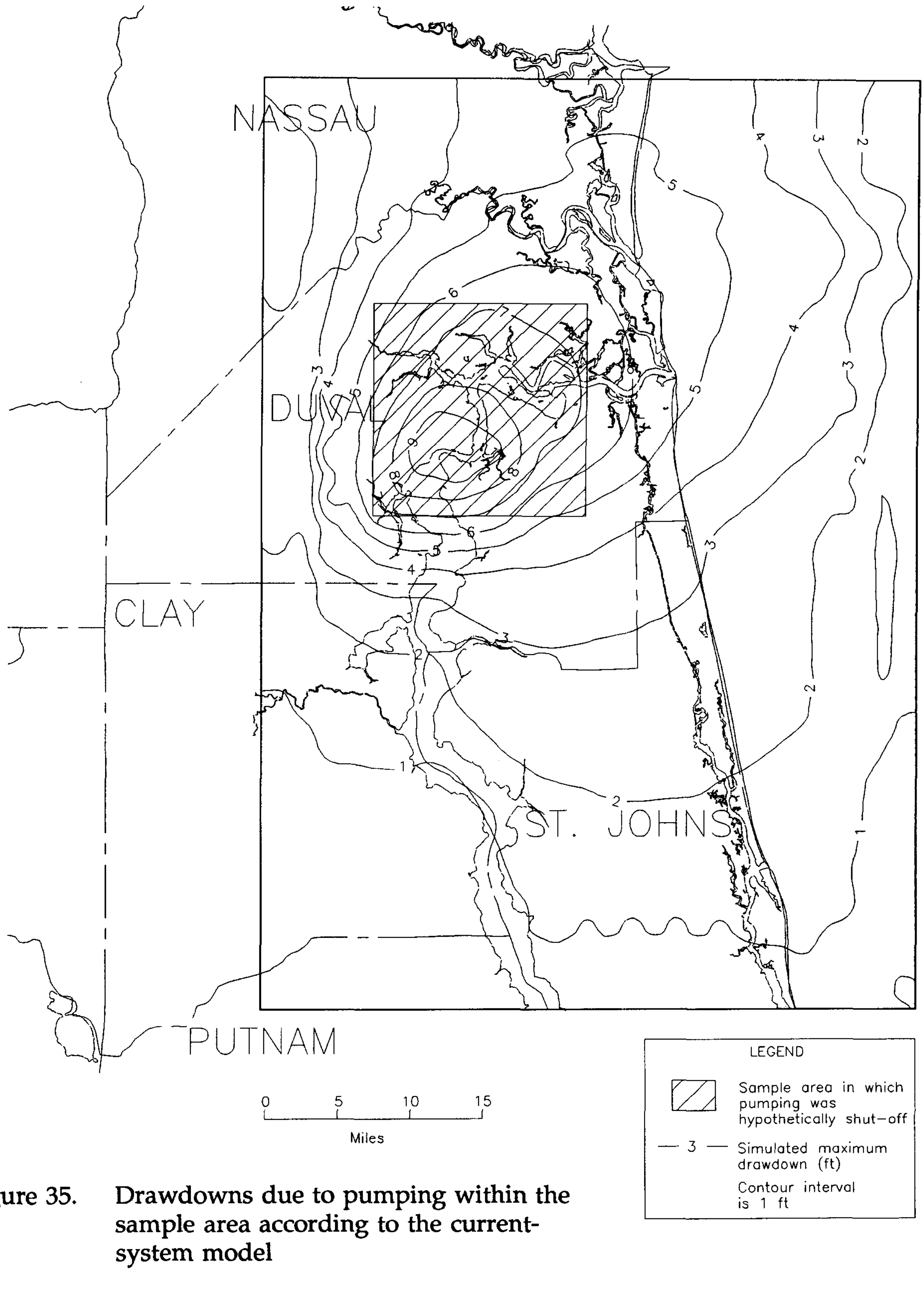


Figure 35. **Drawdowns due to pumping within the sample area according to the current-system model**

SUMMARY

The goal of the study was to model accurately both the predevelopment and current Floridan aquifer systems of the study area. The area of the study includes parts of Duval, St. Johns, Nassau, Clay, and Putnam counties. It lies between latitudes 29° 46.0′ and 30° 41.5′ and longitudes 81° 7.0′ and 81° 52.0′ and encompasses approximately 2,700 square miles.

The geologic units beneath the study area and at its surface form the framework of its ground water hydrology system. From oldest to youngest, these units include the Paleocene age Cedar Keys Formation, early Eocene age Oldsmar Formation, middle Eocene age Avon Park Formation, late Eocene age Ocala Limestone, middle Miocene age Hawthorn Group, Pliocene age (or late Miocene), and Pleistocene age and Recent deposits. The Cedar Keys Formation, Oldsmar Formation, Avon Park Formation, and Ocala Limestone consist predominantly of limestone and dolomite (Miller 1986). The total thickness of the Cedar Keys Formation is not known in the study area. The thicknesses of the Oldsmar Formation, Avon Park Formation, and Ocala Limestone range approximately from 300 to 800 ft, 500 to 1,200 ft, and 200 to 400 ft, respectively (Miller 1986). The Hawthorn Group consists mainly of clay, sand, limestone and dolomite, shells, and phosphates (Scott 1983); its thickness ranges approximately from 100 to 400 ft within the study area. The Pliocene (or late Miocene) deposits consist mainly of clayey sands, sandy clays, shells, sand, and limestone (Leve 1966); their thickness ranges approximately from 10 to 110 ft. The Pleistocene and Recent deposits, whose surface is also the land surface of the study area, consist mainly of loose sands, sandy clays, clayey sands, and shells (Bermes et al. 1963, and Leve 1966); their thickness ranges approximately from 10 to 100 ft.

The ground water flow system of the study area consists of a surficial aquifer system, an intermediate aquifer system, and the Floridan aquifer system (Leve 1966). The surficial aquifer system is the uppermost aquifer system within the study area and is under nonartesian conditions. The aquifers of the intermediate aquifer system are discontinuous, relatively thin

confined aquifers contained in the Hawthorn Group and the Pliocene (or late Miocene) deposits (Leve 1966). The Floridan aquifer system consists of the Upper and Lower Floridan aquifers and a middle confining unit that separates them (Miller 1986). The middle confining unit consists mainly of limestone and dolomite beds that are of lower permeability than those above and below them (Miller 1986). The surficial and intermediate aquifer systems are separated from the Floridan aquifer system by an upper confining unit that consists mainly of the Hawthorn Group and, in some locations, the lower parts of the Pliocene (or late Miocene) deposits as well (Leve 1966). The Floridan aquifer system is bounded at its base by a lower confining unit that consists of low-permeability anhydrite beds located in the Cedar Keys Formation (Miller 1986).

Relatively little downward leakage from the surficial aquifer system to the Floridan aquifer system actually occurs within the study area; by far most inflow to the Floridan aquifer system occurs as upward leakage from the Lower Floridan aquifer and lateral flow through the western boundaries of the study area. In most of the study area, the Upper Floridan aquifer discharges to the surficial aquifer system via upward leakage across the upper confining unit. The degree of hydraulic connection between the surficial and intermediate aquifer systems and the Floridan aquifer system depends on the local thickness and vertical hydraulic conductivity of the upper confining unit.

Estimates of transmissivity of the surficial aquifer system range from 60 to 1,000 ft^2/d in parts of the study area (Brown 1984). Estimates of transmissivity of the aquifers of the intermediate aquifer system in parts of the study area range from 250 to 7,000 ft^2/d (Brown 1984). Estimates of transmissivity in the Upper Floridan aquifer range from 10,000 to 250,000 ft^2/d or more over most of the study area (Bush 1982). Leakance of the upper confining unit ranges from 2.3×10^{-6} per day in tightly confined areas to 2.3×10^{-4} per day in semiconfined areas (Johnston and Bush 1988). The specific yield of the surficial aquifer system is estimated to be about 0.2, and estimates of storativity of the aquifers of the intermediate aquifer system range from 1×10^{-5} to 1×10^{-3} (Brown 1984). The storativity of the Upper Floridan aquifer usually ranges from 1×10^{-4} to 1×10^{-3} (Johnston and Bush 1988). Reliable estimates of the hydraulic parameters of the Lower Floridan aquifer and of the middle and lower confining units are not available.

The McDonald-Harbaugh (1988) modular three-dimensional finite-difference ground water flow model (MODFLOW) was used to model the flow system of the study area. MODFLOW allows vertical discretization of a ground water flow system into alternating layers of aquifers and confining units and horizontal discretization of layers into rectangular cell matrices. Flow within aquifer layers is simulated as entirely horizontal, and flow within confining-unit layers is simulated as entirely vertical. Both steady-state and transient ground water flow systems can be simulated using MODFLOW.

Three models were developed in the study: the predevelopment, the current-system, and the modified predevelopment flow models. The configurations of the predevelopment and current-system models of the study were essentially the same. Both were approximated as steady-state flow systems, and both consisted of three aquifer layers and three confining-unit layers. The layers represented, in descending order, the surficial aquifer, system upper confining unit, Upper Floridan aquifer, middle confining unit, Lower Floridan aquifer, and lower confining unit. Boundary conditions for aquifer layer one were not specified because all of its grid cells were designated constant-head cells. The boundary conditions specified for aquifer layers two and three involved the designation of grid cells on the outermost rows and columns of the horizontally discretized grid as either no-flow cells or active general-head-boundary (GHB) cells. The GHB option enables constant-head boundaries to be specified outside of the model grid as far away from its edges as desired, thereby eliminating the need to extend the model grid outside the area of interest in order to establish constant-head boundaries for the model. The designations for corresponding grid cells in both of the two layers were identical. Required input data for aquifer layer one included estimates of water-table elevation, hydraulic conductivity, and aquifer bottom elevation for each of its grid cells.

Required input data for aquifer layers two and three were identical and included estimates of transmissivity and distributions of hydraulic heads. Each of the two layers also required estimates of conductance for GHB cells. Confining-unit layers one and two required estimates of leakance. The leakance properties of confining-unit layer three were not specified, because MODFLOW automatically assigns leakance values of zero to the lowermost confining unit.

The calibration of the predevelopment (prior to 1880) flow model was carried out primarily to obtain reliable estimates of distributions of transmissivity of the Upper Floridan aquifer and leakance of the upper confining unit, which were then used as initial estimates in the subsequent current-system (May 1985) calibration. The calibration of the predevelopment model focused primarily on the Upper Floridan aquifer to the exclusion of the

Lower Floridan aquifer, because no potentiometric surface map of the Lower Floridan aquifer exists with which to compare simulated hydraulic-head distributions of the Lower Floridan aquifer. The finite-difference grid of the predevelopment model consisted of 36 rows and 31 columns that were nonuniformly spaced. The overall width of the grid was 45 minutes longitude (approximately 44 miles), and the overall length of the grid was 55.5 minutes latitude (approximately 63 miles).

Estimates of the elevation of the water table throughout the study area were based on correlations that were established between water-table and land-surface elevations using published ground water-level data collected at scattered locations in Duval and Clay counties. The distribution of observed hydraulic heads of the Upper Floridan aquifer was interpolated from the predevelopment potentiometric surface map (Johnston et al. 1980). The corresponding values of hydraulic heads at the boundaries of the model in the Lower Floridan aquifer were estimated to be one foot less in areas of recharge from the surficial aquifer system to the Upper Floridan aquifer and one foot greater in areas of discharge from the Upper Floridan aquifer to the surficial aquifer system, based on a similar procedure used by Tibbals (1981). The initial estimates of transmissivity in the Upper Floridan aquifer were based on results reported by Krause (1982) and Johnston and Bush (1988). The initial estimates of transmissivity in the Lower Floridan aquifer were arbitrarily assumed to be one-half the corresponding values of the Upper Floridan aquifer, and no attempt was made during the predevelopment calibration to establish an independent distribution of transmissivity for the Lower Floridan aquifer of the model. The initial estimates of leakance of the upper confining unit were obtained by dividing a single estimated value of vertical hydraulic conductivity of the upper confining unit by average thicknesses of the upper confining unit. To estimate the average thicknesses of the upper confining unit, the study area was divided into several subareas in which thickness was treated as constant. The leakance distribution of the middle confining unit in the predevelopment calibration was represented by a single value, the initial estimate of which was based on Tibbals' (1981) result of 5×10^{-5} per day.

The predevelopment calibration was monitored by calculating the mean of differences between simulated and observed hydraulic heads of the Upper Floridan aquifer and the corresponding standard deviation and by overlaying simulated and observed hydraulic-head contours for the Upper Floridan aquifer and constructing head-difference contours. The final mean difference was -2.1 ft, and the corresponding standard deviation was 2.7 ft. The final distribution of transmissivity of the Upper Floridan aquifer ranged from 35,000 ft^2/d to 320,000 ft^2/d within the study area, and the arithmetic average of the values of transmissivity assigned to the grid cells of aquifer layer two was 148,000 ft^2/d. The final distribution of leakance of the upper confining unit ranged from 1.0×10^{-8} per day to 2.0×10^{-3} per day.

Sensitivity analysis of the predevelopment model indicated that the distribution of hydraulic heads of the Upper Floridan aquifer produced by the predevelopment model is relatively sensitive to changes in the distributions of water-table elevation and leakance of the upper confining unit. The hydraulic-head distribution is moderately sensitive to changes in the distributions of transmissivity of the Upper and Lower Floridan aquifers, and it is relatively insensitive to changes in the distribution of leakance of the middle confining unit.

The results of the current-system calibration were accepted as the final results of the study. The focus of the current-system calibration was on the Upper Floridan aquifer to the exclusion of the Lower Floridan aquifer, because no map of the potentiometric surface of the Lower Floridan aquifer exists with which to compare simulated hydraulic-head distributions of the Lower Floridan aquifer. The May 1985 potentiometric surface map was chosen to represent the current flow system of the study area. The finite-difference grid of the current-system calibration was identical to that of the predevelopment calibration except that the uppermost row of the finite-difference grid of the predevelopment calibration was divided into three rows in order to represent the potentiometric depression of the Fernandina area in greater resolution. Therefore, the finite-difference grid of the current-system calibration had 38 rows and 31 columns and 1,178 grid cells.

Boundary conditions of the current-system flow model were established in the same way as were the boundary conditions of the predevelopment flow model. Analysis of data obtained from test wells drilled into the Lower Floridan aquifer at three locations within the study area (Brown et al. 1984, 1985, and 1986) indicated that declines in hydraulic heads in the Lower Floridan aquifer since predevelopment times have averaged approximately 70 percent of corresponding declines in hydraulic heads of the Upper Floridan aquifer since predevelopment times. This approximation was used to calculate the boundary heads that were assigned to the GHBs of the current-system model and therefore resulted in values of GHB boundary heads that were less arbitrary than those of the predevelopment flow model.

The estimated distribution of water-table elevations was the same as that used in the predevelopment calibration. The initial hydraulic-head distribution of the Upper Floridan aquifer was interpolated from the estimated representation of the May 1985 potentiometric surface. The initial values of hydraulic heads for the Lower Floridan aquifer were calculated as the initial estimates of transmissivity of the Upper and Lower Floridan aquifers and the leakance of the upper and middle confining units in the current-system model were the final estimates of the values from the predevelopment model. Pumping rates of the model were based on consumptive-use permits issued by the SJRWMD that were effective in 1985 and other data collected by the SJRWMD.

The progress of the current-system calibration was monitored by the calculations of the mean and observed hydraulic-head distributions of the Upper Floridan aquifer and the corresponding standard deviations and by constructing overlays of simulated and observed hydraulic-head contours and head-difference contour plots. The final mean difference of simulated and observed hydraulic heads for the Upper Floridan aquifer was -1.7 ft, and the final corresponding standard deviation from the mean was 3.9 ft. The current-system calibration required the introduction of an independent distribution of transmissivity for aquifer layer three (the Lower Floridan aquifer) and a complete distribution of leakance for confining-unit layer two (the middle confining unit). The transmissivity distribution of the Upper Floridan aquifer that resulted from the current-system calibration was somewhat different from that which resulted from the predevelopment calibration, and the range of transmissivity values was much larger. The maximum value of transmissivity of aquifer layer two was 540,000 ft^2/d, and the minimum value was 2,400 ft^2/d. The arithmetic average of the values of transmissivity assigned to the grid cells of aquifer layer two was 136,000 ft^2/d, which is somewhat smaller than that of the predevelopment model. The corresponding arithmetic average of transmissivity values of aquifer layer three was 230,000 ft^2/d, which is significantly larger than that of aquifer layer two. The values of transmissivity of aquifer layer three ranged from 18,000 ft^2/d to 420,000 ft^2/d. The final distribution of leakance in confining-unit layer one (the upper confining unit) was essentially the same as that which resulted from the predevelopment calibration, and values ranged from 1.0×10^{-9} per day to 2.0×10^{-3} per day. Values of leakance of the middle confining unit were found to be on the order of 10^{-7} to 10^{-6} per day in low-leakance areas of the study area but often as high as 0.5 to 1.0 per day in high-leakance areas. The maximum value of leakance of the middle confining unit was 10.0 per day, and the minimum value was 1.0×10^{-8} per day.

Water-budget analysis of the Upper Floridan aquifer of the current flow system indicated that approximately 2.5 in of flow per year are currently entering the Upper Floridan aquifer, of which about 63 percent enters from the Lower Floridan aquifer. According to the water-budget analysis approximately 74 percent of the flow leaves the Upper Floridan aquifer via pumping.

Sensitivity analysis indicated that the distribution of hydraulic heads of the Upper Floridan aquifer produced by the current-system flow model is relatively sensitive to changes in assigned pumping rates, water-table elevations, and distributions of transmissivity. The hydraulic-head distribution is moderately sensitive to changes in the distribution of leakance of the upper confining unit and is relatively insensitive to changes in the distribution of leakance of the middle confining unit.

The transmissivity and leakance distribution of the predevelopment model were replaced with the final transmissivity and leakance distributions of the current-system calibration to form a "modified predevelopment flow model". The mean difference between simulated and observed hydraulic heads in the modified predevelopment model was 2.3 ft, and the corresponding standard deviation from the mean was 3.3 ft. The water-budget analysis of the modified predevelopment model indicated that about 1.3 in per year entered the Upper Floridan aquifer, of which about 50 percent entered from the Lower Floridan aquifer. About 78 percent of the flow leaving the Upper Floridan aquifer exited as upward leakage across the upper confining unit, according to the modified predevelopment flow model.

An example application was performed to illustrate the use of the current-system model. The purpose of the example was to demonstrate the effect that pumping in the Jacksonville area has on the potentiometric surface of the Upper Floridan aquifer throughout the study area. To do this, the hydraulic-head distribution of the Upper Floridan aquifer of the study area was simulated both with and without pumping in the area of interest. The differences in the corresponding hydraulic heads of the two distributions were plotted. The model indicated that the maximum drawdown in the Upper Floridan aquifer due to pumping in the Jacksonville area is about 9 ft and occurs near the center of the sample area. The minimum drawdown in the Upper Floridan aquifer within the study area due to pumping in the Jacksonville area is about 1 ft and occurs near the southern boundary of the study area.

CONCLUSIONS

Pumping in the Upper Floridan aquifer of the study area has brought about changes in the flow system of the study area. Simulations of the modified predevelopment and current-system models indicate that the Lower Floridan aquifer now contributes more than twice the amount of flow to the Upper Floridan aquifer that it did in predevelopment times. Proportionally, its contribution has increased from approximately 50 percent of the total inflow to the Upper Floridan aquifer to approximately 63 percent, indicating that its importance in the overall flow system has increased.

Since predevelopment times, significant lowering of the potentiometric surface of the Upper Floridan aquifer (by an average of approximately 25 feet) relative to the water table has greatly affected rates of recharge and discharge of the Upper Floridan aquifer within the study area. Upward leakage from the Upper Floridan aquifer to the surficial aquifer system has decreased both proportionally and absolutely, according to simulations of the modified predevelopment and current-system models, while downward leakage from the surficial aquifer system into the Upper Floridan aquifer has increased absolutely but has decreased somewhat proportionally.

The average transmissivity of the Lower Floridan aquifer is significantly greater than that of the Upper Floridan aquifer, according to the results of the calibration of the current-system model. Possible reasons for this are that the Lower Floridan aquifer is about twice as thick as the Upper Floridan aquifer throughout most of the study area and that a zone of high transmissivity, the Fernandina permeable zone, exists in the Lower Floridan aquifer of the study area and may contribute to higher average transmissivities in the Lower Floridan aquifer.

The calibrations of the predevelopment and current-system models indicated the need for the acquisition of more hydrologic data of the ground water flow system of the area. The sensitivity analysis of the current-system model showed that hydraulic heads are relatively sensitive to assigned pumping rates. Therefore, an increase in the reliability of future ground water flow models could be achieved if the pumping rates in the study area were measured more widely and carefully. Sensitivity analyses of the original predevelopment and current-system models showed that distributions of hydraulic heads produced by both models are relatively sensitive to changes in estimates of water-table elevations. Therefore, in order to improve the reliability of future flow models of the Floridan aquifer system of the study area, studies such as the one performed by Causey (1975) in Duval County should be performed in the other four counties of the study area. With greater knowledge of the head distribution of the Lower Floridan aquifer, the boundary conditions assigned to aquifer layer three of future flow models would be more accurate, and the simulated head distributions of the Lower Floridan aquifer could be monitored to help indicate progress of the calibration of the model. More accurate distributions of transmissivity and leakance, particularly those of the Lower Floridan aquifer and middle confining unit, respectively, would probably result. Therefore, more studies such as those performed by Brown et al. (1984, 1985, and 1986) should be performed at evenly distributed locations throughout the study area.

Appendix A

FORMULATION OF THE FINITE-DIFFERENCE APPROXIMATION OF GROUND WATER EQUATIONS OF FLOW

For an incompressible fluid, the difference between the total volume of flow into and out of a control volume over an instant of time equals the change in volumetric storage within the control volume over the instant of time. This may be stated simply as

$$\underline{\textit{Equation 1:}} \quad I - O = \frac{dS}{dt}$$

where I is the total volume of flow into the control volume per unit of time $[L^3/t]$; O is the total volume of flow out of the control volume per unit of time $[L^3/t]$; and dS is a differential change in volumetric storage $[L^3]$ that occurs over a differentially small time interval, dt [t].

For the case of a finite-difference ground water flow model, the control volume can be an individual cell of the finite-difference grid. In such a case, equation 1 can be written

$$\underline{\textit{Equation 2:}} \quad Q_{xIN} + Q_{xOUT} + Q_{yIN} + Q_{yOUT} + Q_{zIN} + Q_{zOUT} + Q_{EXT} = S_S \frac{\Delta h}{\Delta t} \Delta V$$

where Q_{xIN}, Q_{yIN}, Q_{zIN} are volumetric flowrates $[L^3/t]$ into the finite-difference cell; Q_{xOUT}, Q_{yOUT}, Q_{zOUT} are volumetric flowrates $[L^3/t]$ out of the finite-difference cell; Q_{EXT} is a volumetric flux into the control volume via external sources $[L^3/t]$; S_s is the specific storage [1/L]; Δh is the change in hydraulic head [L] over the time interval Δt [t]; and ΔV is the volume of the finite-difference grid cell $[L^3]$. The sign convention used designates inflows as positive and outflows as negative.

Equation 2 (McDonald and Harbaugh 1988) may be expressed more concisely as

$$\underline{\textit{Equation 3:}} \quad \sum_{i=1}^{N} Q_i = S_s \frac{\Delta h}{\Delta t} \Delta V$$

where Q_i is a flowrate into or out one of the faces of the cell [L^3/t], and N is the total number of flowrates into or out of the cell. Equation 3 may be applied to each cell of a finite-difference mesh in order to establish a system of equations to represent a three-dimensional ground water flow system. It must first be adapted to program form, and the following development will show how this has been done.

Figure A-1 depicts a cell i,j,k and six adjacent cells. Flows are assumed to enter cell i,j,k from these adjacent cells and from external sources, such as wells, rivers, drains, etc. Flow to cell i,j,k in the row direction from cell i,j-1,k is given by Darcy's law as

$$\underline{\textit{Equation 4:}} \quad Q_{i,j-1/2,k} = KR_{i,j-1/2,k} \Delta c_i \Delta v_K \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta r_{j-1/2}}$$

where $h_{i,j,k}$ is the head at node i,j,k, and $h_{i,j-1,k}$ is the head at node i,j-1,k [L]; $Q_{i,j-1/2,k}$ is a volumetric flowrate through the face between cells i,j,k and i,j-1,k (Figure A-2) [L^3/t]; $KR_{i,j-1/2,k}$ is the hydraulic conductivity along the row between nodes i,j,k and i,j-1,k [L/t]; $\Delta c_i \Delta v_k$ is the area of the cell face normal to the row direction [L^2]; and $\Delta r_{j-1/2}$ is the distance between nodes i,j,k and i,j-1,k [L]. Similar expressions can be written to approximate the flow into the cell through the remaining five faces. For instance, from cell i,j+1,k,

$$\underline{\textit{Equation 5:}} \quad Q_{i,j+1/2,k} = KR_{i,j+1/2,k} \Delta c_i \Delta v_k \frac{(h_{i,j+1,k} - h_{i,j,k})}{\Delta r_{j+1/2}}$$

From cell i+1,j,k,

$$\underline{\textit{Equation 6:}} \quad Q_{i+1/2,j,k} = KC_{i+1/2,j,k} \Delta r_j \Delta v_k \frac{(h_{i+1,j,k} - h_{i,j,k})}{\Delta c_{i+1/2}}$$

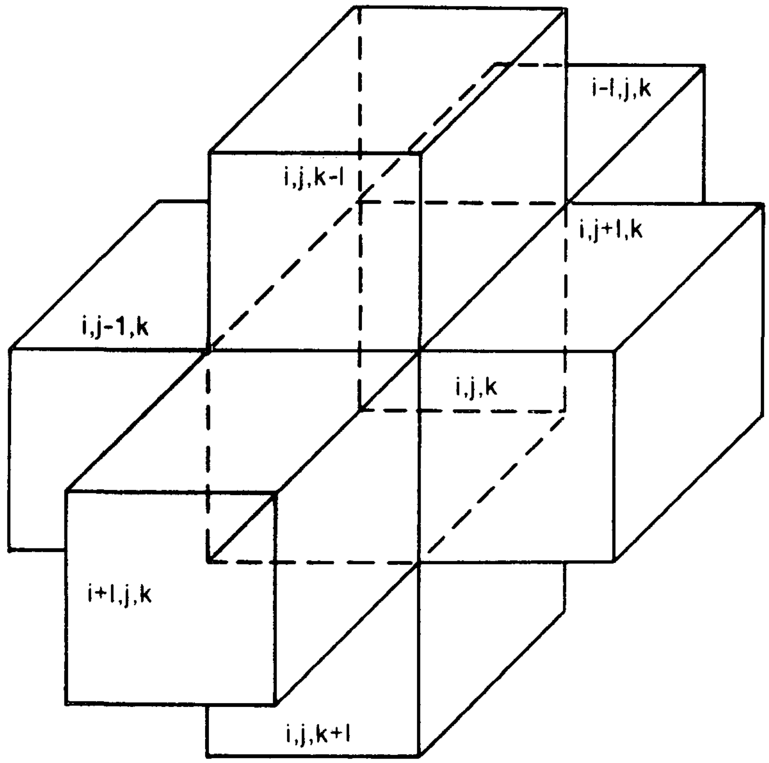


Figure A-1. Cell i, j, k and indices for six adjacent cells

Source: McDonald and Harbaugh 1988

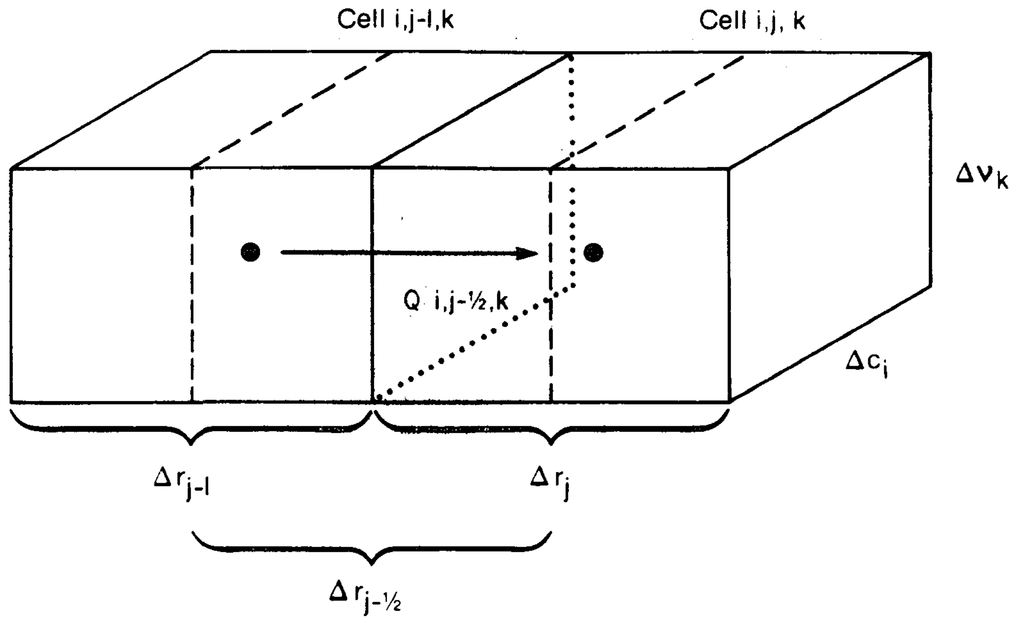


Figure A-2. Flow from cell i, j-1, k to cell i, j, k

Source: Modified from McDonald and Harbaugh 1988

From cell i-1,j,k,

$$\underline{\textit{Equation 7:}} \quad Q_{i-1/2,j,k} = KC_{i-1/2,j,k}\,\Delta r_j\,\Delta v_k\,\frac{(h_{i-1,j,k} - h_{i,j,k})}{\Delta c_{i-1/2}}$$

From cell i,j,k+1,

$$\underline{\textit{Equation 8:}} \quad Q_{i,j,k+1/2} = KV_{i,j,k+1/2}\,\Delta r_j\,\Delta c_i\,\frac{(h_{i,j,k+1} - h_{i,j,k})}{\Delta v_{k+1/2}}$$

From cell i,j,k-1,

$$\underline{\textit{Equation 9:}} \quad Q_{i,j,k-1/2} = KV_{i,j,k-1/2}\,\Delta r_j\,\Delta c_i\,\frac{(h_{i,j,k-1} - h_{i,j,k})}{\Delta v_{k-1/2}}$$

Conductance is the product of hydraulic conductivity and cross-sectional area of flow divided by the length of the flow path (or distance between cell nodes); that is,

$$\underline{\textit{Equation 10:}} \quad CR_{i,j-1/2,k} = \frac{KR_{i,j-1/2,k}\,\Delta c_i\,\Delta v_k}{\Delta r_{j-1/2}}$$

where $CR_{i,j-1/2,k}$ is the conductance in the row i and layer k between nodes i,j-1,k and i,j,k [L^2/t]. Using this, equations 4 through 9 can be rewritten as

$$\underline{\textit{Equation 11:}} \quad Q_{i,j-1/2,k} = CR_{i,j-1/2,k}\,(h_{i,j-1,k} - h_{i,j,k})$$

$$\underline{\textit{Equation 12:}} \quad Q_{i,j+1/2,k} = CR_{i,j+1/2,k}\,(h_{i,j+1,k} - h_{i,j,k})$$

$$\underline{\textit{Equation 13:}} \quad Q_{i-1/2,j,k} = CC_{i-1/2,j,k}\,(h_{i-1,j,k} - h_{i,j,k})$$

$$\underline{\textit{Equation 14:}} \quad Q_{i+1/2,j,k} = CC_{i+1/2,j,k}\,(h_{i+1,j,k} - h_{i,j,k})$$

$$\underline{\textit{Equation 15:}} \quad Q_{i,j,k-1/2} = CV_{i,j,k-1/2}\,(h_{i,j,k-1/2} - h_{i,j,k})$$

$$\underline{\textit{Equation 16:}} \quad Q_{i,j,k+1/2} = CV_{i,j,k+1/2}\,(h_{i,j,k+1} - h_{i,j,k})$$

Flow from outside the aquifer into cell i,j,k may be represented by the expression

$$\underline{\textit{Equation 17:}} \quad a_{i,j,k,n} = p_{i,j,k,n}\, h_{i,j,k} + q_{i,j,k,n}$$

where $a_{i,j,k,n}$ represents flow from the n^{th} external source into cell i,j,k $[L^3/t]$, and $p_{i,j,k,n}$ and $q_{i,j,k,n}$ are constants $[L^2/t]$ and $[L^3/t]$, respectively.

In general, if there are M external sources or stresses affecting a single cell, the combined flow is expressed as

$$\underline{\textit{Equation 18:}} \quad QS_{i,j,k} = \sum_{n=1}^{M} p_{i,j,k,n}\, h_{i,j,k} + \sum_{n=1}^{M} q_{i,j,k,n}$$

Defining $P_{i,j,k}$ and $Q'_{i,j,k}$ by the expressions

$$P_{i,j,k} = \sum_{n=1}^{M} p_{i,j,k,n}$$

$$Q'_{i,j,k} = \sum_{n=1}^{M} q_{i,j,k,n}{}'$$

the general external flow term for cell i,j,k is

$$\underline{\textit{Equation 19:}}\quad QS_{i,j,k} = P_{i,j,k}h_{i,j,k} + Q'_{i,j,k}$$

Substitution of expressions for the flows from the six adjacent cells and the external flowrate, QS, yields

$$\underline{\textit{Equation 20:}}\quad Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2}$$

$$+ QS_{i,j,k} = SS_{i,j,k}\frac{\Delta h_{i,j,k}}{\Delta t}\Delta r_j \Delta c_i \Delta v_k$$

where $\frac{\Delta h_{i,j,k}}{\Delta t}$ is a finite-difference approximation for the derivative of hydraulic head with respect to time [L/t]; $SS_{i,j,k}$ represents the specific storage of cell i,j,k [1/L]; and $\Delta r_j \Delta c_i \Delta v_k$ is the volume of cell i,j,k [L^3].

Equations 11 through 16 may be substituted into equation 20 to give the finite-difference approximation for cell i,j,k as

$$\underline{\textit{Equation 21:}}\quad CR_{i,j-1/2,k}(h_{i,j-1,k} - h_{i,j,k}) + CR_{i,j+1/2,k}(h_{i,j+1,k} - h_{i,j,k})$$

$$+ CC_{i-1/2,j,k}(h_{i-1,j,k} - h_{i,j,k}) + CC_{i+1/2,j,k}(h_{i+1,j,k} - h_{i,j,k})$$

$$+ CV_{i,j,k-1/2}(h_{i,j,k-1} - h_{i,j,k}) + CV_{i,j,k+1/2}(h_{i,j,k+1} - h_{i,j,k})$$

$$+ P_{i,j,k}h_{i,j,k} + Q'_{i,j,k} = SS_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\frac{\Delta h_{i,j,k}}{\Delta t}$$

The value of the $\frac{\partial h}{\partial t}$ derivative at time step m is approximated as the difference in head at cell i,j,k at the present time (t_m) and the time step immediately preceding t_m (t_{m-1}) divided by the value of the time interval. This is written as

$$\left[\frac{\Delta h_{i,j,k}}{\Delta t}\right] m = \frac{h^{m}_{i,j,k} - h^{m-1}_{i,j,k}}{t_m - t_{m-1}}$$

where m indicates the number of the present time step. The approach used is the backward-difference method, so named because the time interval used extends backward in time from t_m, the time of the calculations.

Equation 21 may be rewritten in backward-difference form as

Equation 22:

$$CR_{i,j-1/2,k}\,(h^{m}_{i,j,-1,k} - h^{m}_{i,j,k}) + CR_{i,j,+1/2,k}\,(h^{m}_{i,j+1,k} - h^{m}_{i,j,k})$$
$$+ CC_{i-1/2,j,k}\,(h^{m}_{i-1,j,k} - h^{m}_{i,j,k}) + CC_{i+1/2,j,k}\,(h^{m}_{i+1,j,k} - h^{m}_{i,j,k})$$
$$+ CV_{i,j,k-1/2}\,(h^{m}_{i,j,k-1} - h^{m}_{i,j,k}) + CV_{i,j,k+1/2}\,(h^{m}_{i,j,k+1} - h^{m}_{i,j,k})$$
$$+ P_{i,j,k}\,h^{m}_{i,j,k} + Q'_{i,j,k} = SS_{i,j,k}\,(\Delta r_j\,\Delta c_i\,\Delta v_k)\,\frac{(h^{m}_{i,j,k} - h^{m-1}_{i,j,k})}{t_m - t_{m-1}}$$

This equation is usually rewritten so that all terms containing heads at the end of the current time step are grouped on the left side and all terms that are independent of head at the end of the current time step are on the right side. The resulting equation is

Equation 23:

$$CV_{i,j,k-1/2}\,h^{m}_{i,j,k-1} + CC_{i-1/2,j,k}\,h^{m}_{i-1,j,k} + CR_{i,j-1/2,k}\,h^{m}_{i,j-1,k}$$
$$+ (-CV_{i,j,k-1/2} - CC_{i-1/2,j,j} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k}$$
$$- CV_{i,j,k+1/2} + HCOF_{i,j,k})\,h^{m}_{i,j,k} + CR_{i,j+1/2,k}\,h^{m}_{i,j+1,k} + CC_{i,+1/2,j,k}\,h^{m}_{i,j,l}$$
$$+ CV_{i,j,k+1/2}\,h^{m}_{i,j,k+1} = RHS_{i,j,k}$$

where: $HCOF_{i,j,k} = P_{i,j,k} - SC1_{i,j,k}/(t_m - t_{m-1})$ $[L^2/t]$;
$RHS_{i,j,k} = -Q_{i,j,k} - SC1_{i,j,k}\,h^{m-1}{}_{i,j,k}/(t_m - t_{m-1})$ $[L^3t]$;
and $SC1_{i,j,k} = SS_{i,j,k}\,\Delta r_j \Delta C_i \Delta V_k$ $[L^2]$

The entire system of equations of the form of 23, which includes one equation for each variable-head cell in the mesh, may be written in matrix form as

Equation 24: $[A]\ \{h\} + \{Q\}$

where [A] is a matrix of coefficients of head, from the left side of equation 23, for all active cells in the mesh; {h} is a vector of hydraulic-head values at the end of time step m for all nodes in the mesh; and {Q} is a vector of constant terms, RHS, for all nodes in the mesh. The elements of {h} are determined by an iterative solving routine.

Appendix B

GLOSSARY

Hydraulic conductivity. Hydraulic conductivity (K[L/t]) is the constant of proportionality in Darcy's equation of flow. Hydraulic conductivity is a function of the intrinsic permeability of the porous media through which a fluid is flowing as well as the absolute viscosity and density of the fluid itself. It has relatively high values for sand and gravel and relatively low values for clay (Freeze and Cherry 1979).

Intrinsic permeability. Intrinsic permeability (k[L^2]) is a measure of the influence of the properties of a porous medium on the flow of a fluid through the medium without reference to the properties of the fluid itself. Intrinsic permeability depends on the mean grain diameter, the distribution of grain sizes, the sphericity and roundness of the grains, and the nature of their packing (Freeze and Cherry 1979).

Leakance. Leakance (K'/b'[1/t]) is the ratio of the vertical hydraulic conductivity (K') of a confining unit and its thickness (b') (Lohman 1972).

Specific storage. The specific storage (S_s[1/L]) of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. The release of water from storage under conditions of declining hydraulic head is attributed to the expansion of water in the aquifer in response to declining pressure, and to compaction of the aquifer material in response to increasing intergranular stress (Freeze and Cherry 1979).

Specific yield. Specific yield (S_y[Dimensionless]) is applied to unconfined aquifers and is analogous to storativity for confined aquifers. Specific yield is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table (Freeze and Cherry 1979).

Storativity. Storativity (S[Dimensionless]) is applied to confined aquifers. Storativity is the product of the specific storage of a confined aquifer and its thickness. Therefore, it is the volume of water released from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface (Freeze and Cherry 1979).

Transmissivity. Transmissivity ($T[L^2/t]$) is most often applied to confined aquifers, but it can be applied to unconfined aquifers as well. For a confined aquifer, transmissivity is the product of hydraulic conductivity and the thickness of the aquifer. For an unconfined aquifer, transmissivity is the product of the hydraulic conductivity and the saturated thickness of the aquifer (Freeze and Cherry 1979).

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