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THREE-DIMENSIONAL DENSITY-DEPENDENT FLOW AND TRANSPORT MODELING OF SALTWATER INTRUSION IN THE SOUTHERN WATER USE CAUTION AREA

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ACRONYMS AND ABBREVIATIONS

APT	Aquifer Performance Test
DSTRAM	Density-dependent Solute Transport Analysis
ETBWUCA	Eastern Tampa Bay Water Use Conservation Area
GHB	General Head Boundary
gpm	gallon/minute
LPZ	Lower Permeable Zone
mg/l	milligrams per liter
NGVD	National Geodetic Vertical Datum
ppm	parts per million
ROMP	Regional Observation and Monitor-well Program
SAS	Surficial aquifer system
SCU	Semi-Confining Unit
SWFWMD	Southwest Florida Water Management District
SWUCA	Southern Water Use Caution Area
TDS	total dissolved solids
UPZ	Upper Permeable Zone
USGS	U.S. Geological Survey
Waterstone	Waterstone Environmental Hydrology and Engineering, Inc.
WQMP	Water Quality and Monitoring Program
WUCA	Water Use Caution Area
WUP	Water Use Permit

1.0 INTRODUCTION

1.1 BACKGROUND

The Southwest Florida Water Management District (SWFWMD) is responsible for managing sensitive water resources within 16 counties in west-central Florida (Figure 1.1). Within this area, the SWFWMD is responsible for water supply, water quality, and the protection of natural systems related to water resources. The Floridan aquifer system is the primary source of potable groundwater within the southern portion of the SWFWMD. In this area, approximately 85% of groundwater supplies are derived from the Floridan aquifer system. Saltwater intrusion into the Floridan Aquifer along the coast of southern Hillsborough, Manatee, and Sarasota Counties is a principal constraint on the development of additional groundwater resources in the southern portion of the SWFWMD. Monitoring data collected by the SWFWMD indicates that saline water is slowly advancing further inland due to lowered water levels within the southern portion of the SWFWMD.

In response to this problem, the SWFWMD Governing Board designated the southern portion of the SWFWMD as the Southern Water Use Caution Area (SWUCA) (Figure 1.1). This area included all of the Eastern Tampa Bay and Lake Wales Ridge Water Use Caution Areas (WUCAs) and the areas within the SWFWMD that are south of Interstate 4. In total the SWUCA encompasses 5,100 square mile area including all of Manatee, Sarasota, Hardee, and DeSoto Counties and portions of Hillsborough, Charlotte, Polk, and Highlands Counties. In 1994, SWFWMD staff developed a resource management plan and a set of rules for water resources permitting aimed at limiting saltwater intrusion with the SWUCA. A principal objective of these rules was to protect freshwater resources within the Floridan aquifer system. For the past several years, the SWFWMD has revisited its options for managing groundwater within the SWUCA in an effort to develop additional sources of water for the growing population of the region while continuing to protect existing supplies. Physically based, numerical groundwater flow models of the region have provided an important component to the decision making process.

1.2 PROJECT OBJECTIVES

In October 2001, HydroGeoLogic, Inc. was retained by the SWFWMD to develop a density-dependent groundwater flow and solute transport numerical model to simulate the position and movement of saline water in the Upper Floridan aquifer along the coastal area of the SWUCA (Figure 1.2). The primary objective of this effort was to predict the long-term impact of proposed water use options on saltwater intrusion within the Upper Floridan aquifer. The saltwater intrusion model may be further used to establish minimum water levels or maximum pumping levels for groundwater extraction wells within the Upper Floridan aquifer or for developing a refined understanding of the stress response of chlorides to various regional management scenarios. The density-dependent model was constructed and calibrated to simulate conditions in the Upper Floridan aquifer that existed from the pre-development period (approximately 1900) to present conditions (through 2000). The model was then used to predict the long-term impacts associated with different usage rates for water within the area.

1.3 METHODOLOGY

The modeling investigation was completed in four phases including:

- Phase 1: Background literature review, conceptual model development, and model setup;
- Phase 2: Model calibration;
- Phase 3: Predictive scenarios; and
- Phase 4: Governing board meetings/presentations.

During Phase 1, historical reports and previous modeling investigations were reviewed to understand the hydrogeologic conceptual model, identify model calibration targets, and construct the framework for the saltwater intrusion model. Particular emphasis was placed on reviewing the Southern District Groundwater Flow model developed by the SWFWMD (2001) and an uncalibrated, saltwater intrusion model that was initiated by Waterstone Environmental Hydrology and Engineering, Inc. (Waterstone). These models will henceforth be referred to as the Southern District Model (SWFWMD, 2001) and the Waterstone Model (Waterstone 2001), respectively. Both of these models were provided to HydroGeoLogic in electronic form *via* Groundwater Vistas (Environmental Simulations, Inc.) project files. At the end of Phase 1, the framework for the saltwater intrusion model was established, and preliminary simulations were performed to ensure that all data was correctly entered into the density-dependent model, before proceeding to the Phase II calibration activities.

During Phase 2, the saltwater intrusion model was calibrated to simulate hydraulic heads and chloride concentrations in the Upper Floridan aquifer. The model was calibrated to steady-state pre-development (approximately 1900) conditions and transient conditions from approximately 1900 to 2000. A sensitivity analysis was also conducted, to identify the parameters that have the greatest impact on calibration and conclusions of the model.

Predictive simulations were completed as part of Phase 3 activities. The model was used to predict hydraulic heads and saltwater intrusion (i.e., saline water concentrations) for 20- to 50-year time periods. Four different water use scenarios proposed by the SWFWMD were evaluated. These comprise of withdrawing 400, 600, 800 and 1,000 million gallons per day (MGD) from the Southern District Model (SWFWMD, 2001) area. A predictive sensitivity analysis was also conducted to evaluate the uncertainty associated with the modeling results.

1.4 REPORT ORGANIZATION

This report documents the development of the conceptual and numerical model for saltwater intrusion in the SWUCA. Section 2 documents the hydrogeologic conceptual model, and Section 3 summarizes the previous modeling analyses that provide information and insights that will be utilized during the current modeling effort. Section 4 describes construction of the preliminary model, and Section 5 describes the model calibration effort and results. Section 6 details the sensitivity analysis that was conducted and Section 7 discusses the predictive analysis and predictive sensitivity studies. Finally, Section 8 provides a brief summary of the modeling activities and presents the major conclusions.

2.0 HYDROGEOLOGIC CONCEPTUAL MODEL

2.1 PHYSIOGRAPHY AND TOPOGRAPHY

The physiography of the Eastern Tampa Bay Water Use Caution Area (ETBWUCA) includes three provinces described by White (1970): Gulf Coastal Lowlands, the DeSoto Plain and the Polk Upland. These provinces reflect a series of marine sand terraces formed by the advance and retreat of shallow seas during ice age events. Elevations of these terraces correspond to changes in sea level. Additional physiographic features that lie within the SWUCA include a series of north-northwesterly trending sand ridges found along the eastern boundary of the SWFWMD. The elevation in the study area ranges from sea level along the coast to approximately 150 ft National Geodetic Vertical Datum (NGVD) along the ridges (SWFWMD 1993).

2.2 RAINFALL, EVAPOTRANSPIRATION AND RECHARGE

The climate in the southern SWFWMD is humid, subtropical and is characterized by warm, wet summers and mild, dry winters (SWFWMD, 1993). Based on records since 1911, the mean annual rainfall is about 54 inches per year at Bradenton in Manatee County. During the summer months of June through September, monthly rainfall averaging between 7 and 9 inches accounts for approximately 60 percent of the annual total. The mean evapotranspiration rate estimated for the ETBWUCA is 39 inches per year (Dohrenwend, 1977). According to SWFWMD (1993), nearly 60 percent of the annual evapotranspiration occurs between May and September with the greatest rates usually observed in May and June.

Recharge to the surficial aquifer occurs by infiltration of rainfall and irrigation water. Figure 2.1 depicts areas of recharge and discharge to the Upper Floridan aquifer for pre-development hydrologic conditions (Aucott, 1988).

2.3 HYDROGEOLOGY

Various geologic formations characterized by unconsolidated and consolidated sediments comprise the three principal aquifer systems that underlie the study area as shown in Table 2.1. These include: the surficial aquifer system; intermediate aquifer system; and the Floridan aquifer system. Undifferentiated near-surface deposits of sands, clayey sands and silts with some peat and shell comprise the surficial aquifer system. The intermediate aquifer system corresponds to the Hawthorn Group and generally consists of phosphatic clay and limestone. These near-surface materials in turn overlie the massive marine carbonates, limestones and dolomites of the Floridan aquifer system. Each of the three principal aquifer systems consists of higher permeability aquifer layers that are separated by lower permeability semi-confining layers, which restrict the vertical movement of groundwater between the aquifers.

Four major units comprise the Floridan aquifer system: the Upper Floridan aquifer, the middle confining unit, the Lower Floridan aquifer and the lower confining unit (Figure 2.2). Due to its large thickness and low permeability, the middle confining unit is generally considered as a barrier to flow. The Lower Floridan aquifer in the region is salty, and not a source of potable water.

Consequently, for the purposes of this study, the following discussion of the hydrogeology of the study area will focus on the surficial aquifer system, the intermediate aquifer system, the Upper Floridan aquifer and the middle confining units of the Floridan aquifer system.

2.3.1 Surficial Aquifer

The unconfined surficial aquifer system consists primarily of fine-to-medium grained quartz sands of the Holocene and Pleistocene epochs that range in thickness from 77 feet in south-central Hillsborough County to 19 feet in northern Sarasota County (Basso, 2001). The surficial aquifer generally produces only small quantities of water suitable for domestic purposes. The water table varies seasonally and has depths ranging from near land surface to depths of perhaps tens of feet beneath some sand ridges. Groundwater flow in the surficial aquifer system typically follows local topography and occurs in an east to west direction on a regional scale. Seasonal fluctuation of the water levels is generally less than 5 ft (SWFWMD, 1993). The base of the surficial aquifer system consists of Pliocene age clays and clayey sands that form the top of the intermediate aquifer system.

Basso (2001) cites various studies for the hydraulic properties of the surficial aquifer system. Two aquifer tests conducted in southeast Hillsborough County yielded hydraulic conductivity estimates of 6 and 18 ft/day. A hydraulic conductivity value of 9 ft/day was determined from a pumping test in Hardee County. An aquifer test in northeast Sarasota County resulted in an estimated hydraulic conductivity of 13 ft/day. The specific yield values from these tests ranged from 0.05 to 0.12.

2.3.2 Intermediate Aquifer System

The Peace River and Arcadia Formations of the Miocene age Hawthorn Group comprise the intermediate aquifer system. In general, the interbedded phosphatic clays, sands, gravels, dolomite and thin limestone beds of this system function as a confining unit that separates the surficial aquifer from the Upper Floridan aquifer; however, permeable units are found to exist within the clay matrix. In the ETBWUCA (Figure 1.1), the thickness of the intermediate aquifer system increases to the southwest (the direction of dip) from 230 to over 500 ft (Basso, 2001). While there is no clear pattern of decreasing vertical hydraulic conductivity southward, the increasing thickness acts to restrict vertical flow to the southwest (Waterstone, 2001a).

Three separate flow zones, identified as PZ1, PZ2 and PZ3 (in descending order), and three confining units, designated as UICU, MICU and LICU, occur within the intermediate aquifer system in Sarasota County (Barr, 1996). The lateral continuity of these zones is typically limited. The PZ1 zone is generally absent from the ETBWUCA. The PZ2 zone is more extensive than PZ1, but it is not very productive. The most productive aquifer unit is PZ3 which is mostly represented by the Tampa Member of the Hawthorn Group. In some areas, clays found at the base of the Tampa Member act as a confining unit between the intermediate aquifer system and the Upper Floridan aquifer; in others, the carbonate units of the Tampa Member appear to be in direct hydraulic communication with the Upper Floridan aquifer.

Basso (2001) presents a summary of hydraulic properties for the intermediate aquifer system. Based on the results of 10 falling-head tests conducted on core samples, the mean vertical hydraulic conductivity of the confining units in the system is $5x10^{-4}$ ft/day. The properties of the aquifer units in the system are available from pumping tests. For the PZ2 zone, the estimates of horizontal hydraulic conductivity from three tests showed large variability. Two of the tests yielded values of 0.01 ft/day while the other produced a value of 36 ft/day. Hydraulic conductivities determined from four tests conducted in the more productive PZ3 zone averaged 9 ft/day and varied from 0.3 to 19 ft/day. The groundwater flow direction is generally west to southwest. Seasonal fluctuations of the potentiometric surface may reach 30 ft (SWFWMD, 1993).

Figures 2.3, 2.4 and 2.5 show the leakance distributions of the various confining units of the intermediate aquifer system, as estimated during the calibration of the Southern District Model (SWFWMD, 2001). These leakance values are pertinent to development of the density-dependent, saltwater intrusion model (Section 4).

2.3.3 Upper Floridan Aquifer

Massive carbonates of the Suwannee Limestone, Ocala Limestone and part of the Avon Park Formation comprise the Upper Floridan aquifer in the study area. Each of these stratigraphic units corresponds to distinct hydrogeologic units. The Suwannee Limestone, a cream to tan, sandy, vuggy and fossiliferous limestone, functions as an aquifer unit designated as the upper permeable zone (UPZ). The Ocala Limestone is a white to tan, fine-grained calcavenitic limestone that behaves as a confining unit known as the semi-confining unit (SCU). The upper portion of the Avon Park Formation or lower permeable zone (LPZ) is a brown, sucrosic and fractured dolomite. The direction of groundwater flow in the Upper Floridan aquifer varies seasonally.

According to Basso (2001), the permeability of the UPZ is primarily intergranular. Secondary porosity such as fractures or solution conduits appear to be mostly absent from this unit. The top of the UPZ, which corresponds to the top of the Suwannee Limestone, ranges from about -250 to -450 ft NGVD in the Eastern Tampa Bay WUCA and exhibits a south to southwest dip direction. Figure 2.6 depicts the top of the Suwannee Limestone as assigned in the Waterstone Model (Waterstone, 2001b). The total thickness of this unit varies from 200 to 300 ft. Horizontal hydraulic conductivities estimated for this moderately permeable aquifer are generally uniform. Based on the results of 11 pumping tests, the mean horizontal hydraulic conductivity is 61 ft/day and ranges from 6 to 143 ft/day. Figure 2.7 provides the transmissivity distribution of the Suwannee Limestone over the study area, as assigned in the Southern District Model (SWFWMD, 2001). Transmissivities range from as high as 100,000 ft^2/d under Pinellas County to 16,250 ft^2/d in Sarasota County. Storativity values for this unit vary between $1.0x10^{-5}$ and $6.5x10^{-4}$.

The SCU of the Upper Floridan aquifer is characterized by a fine-grained calcarenitic limestone that typically corresponds to the Ocala Limestone (Basso, 2001). The base of this hydrogeologic unit is defined as the contact with highly permeable fractured dolomites that comprise the LPZ. Because the lower part of the Ocala Limestone may contain a sucrosic dolomitic limestone, the transition from the SCU to the LPZ may occur within the Ocala Limestone or the Avon Park

Formation. The top elevation of the SCU ranges from -500 to -800 ft NGVD in the Eastern Tampa Bay WUCA and dips to the southwest. Figure 2.8 depicts the top of the Semi-Confining Unit as provided by the Waterstone Model (Waterstone, 2001b). The total thickness of the unit is variable, ranging from 200 to 500 ft. The horizontal hydraulic conductivity of the SCU estimated from 16 packer tests ranges of 0.01 to 2.4 ft/day with a mean of 0.53 ft/day. Vertical hydraulic conductivities for this unit have been determined from field and laboratory tests. The vertical hydraulic conductivity estimated from aquifer performance test (APT) at the Region Observation and Monitor-Well (ROMP) TR9-2 site is 0.03 ft/day (Basso, 2001). Vertical hydraulic conductivities determined from 56 falling-head tests conducted on core samples obtained at different depths from 10 different sites within the Eastern Tampa Bay WUCA ranged from 1.0×10^{-7} to 2.5 ft/day with a mean of 0.19 ft/day and median of 0.023 ft/day. The APT value probably provides a more realistic estimate of the mean vertical hydraulic conductivity for the entire thickness of the SCU. The leakance distribution of the SCU is uniform with a value of 0.01 day^{-1} in the Southern District Model (SWFWMD, 2001).

The LPZ of the Upper Floridan aquifer is a regionally extensive, highly transmissive, sucrosic and fractured dolomite (Basso, 2001). Conceptually, the top of the LPZ corresponds to the top of the Avon Park Formation, but occasionally the lower portion of the Ocala Limestone also contributes to this unit. Within the Eastern Tampa Bay WUCA, the top of this unit occurs between -700 and -1400 ft NGVD. Figure 2.9 depicts the top of the LPZ as assigned in the Waterstone model (Waterstone, 2001b). The total thickness of this zone varies from 500 to 700 ft. According to Basso (2001), secondary porosity accounts for the permeability of the LPZ, the most productive unit in the Upper Floridan aquifer. Although multiple discrete flow zones are typical with perhaps 100 ft or more of relatively tight sections between individual flow zones, conceptual models of this unit tend to treat it as an equivalent porous medium. Based on eight APTs, the horizontal hydraulic conductivity of this unit varies from 96 to 475 ft/day with a mean of 308 ft/day. Figure 2.10 provides the transmissivity distribution of the Avon Park Formation over the study area, as used by the Southern District Model (SWFWMD, 2001). This transmissivity distribution is subsequently used for developing areal conductivity distributions for the Avon Park Formation in the density-dependent saltwater intrusion model.

2.3.4 Middle Confining Unit

The middle confining unit, composed of interbedded dolostones and evaporites, separates the Upper Floridan aquifer and Lower Floridan aquifer in the Floridan aquifer system (Basso, 2001). The top of this unit ranges from -1,200 to more than -1,700 ft NGVD in the Eastern Tampa Bay WUCA and forms the bottom of the model domain. Figure 2.11 depicts the top of the Middle Confining Unit as provided by the Waterstone Model (Waterstone, 2001). The horizontal hydraulic conductivity determined from five packer tests in the Middle Confining Unit ranges from 0.002 to 0.04 ft/day. No explicit vertical hydraulic conductivity measurements are available for this unit.

2.4 GROUNDWATER SOURCES AND SINKS

Over the past ten years (1989-1998), groundwater withdrawals from the SWUCA fluctuated between 562 MGD (1994) and 832 MGD (1989). Approximately 65 percent of this water is withdrawn for permitted agricultural use. The second largest demand is for public supply, approximately 21 percent. The surficial aquifer system produces only small quantities of water for lawn irrigation and domestic water supply. The intermediate aquifer system is primarily a source of domestic water supply, but occasionally supplements the Upper Floridan aquifer for both irrigation and public supply. Well yields in the intermediate aquifer system generally range from 20 to 200 gallons per minute (gpm). The Upper Floridan aquifer is the principal source of groundwater for water supply. Well yields in the UPZ range from 500 to 1,500 gpm. Wells completed in the highly transmissive LPZ can yield from 1,500 to 5,000 gpm (SWFWMD, 1993).

The Upper Floridan aquifer was once under artesian conditions along the coast, with at least 20 ft of pressure head at the coast. This implies that the Upper Floridan aquifer is well confined by the intermediate aquifer system, and that the intermediate aquifer system and Upper Floridan aquifer both extend a considerable distance offshore. The Upper Floridan aquifer likely subcrops about 120 miles offshore in the Gulf of Mexico where the sea bottom shelves abruptly. Offshore the Upper Floridan aquifer discharges into the Gulf of Mexico, probably mainly through diffuse leakage across the intermediate aquifer system. Potentiometric, water quality, and geologic data suggest that there is an enhanced discharge zone under Hillsborough Bay (Hutchinson, 1983).

In the coastal areas and southern portion of the basin, water levels in the Upper Floridan aquifer are usually higher than in the intermediate aquifer, creating areas of diffuse upward leakage. In these areas, groundwater discharge in the Floridan aquifer is on the order of zero to one inch per year (Barcelo and Basso, 1993).

2.5 GROUNDWATER FLOW DIRECTIONS

Pre-development groundwater flow patterns in the Upper Floridan aquifer are depicted in Figure 2.12 (Johnston, et. al, 1980). Regional groundwater flow is from the Green Swamp potentiometric high located near Polk City, Florida, toward the west/southwest. Major features of the potentiometric surface are the Green Swamp regional potentiometric high and the tendency for the potentiometric contours to wrap around the eastern portion of Tampa Bay, indicating discharge to the bay.

By the mid-1970s, pumping primarily for agricultural use, created a regionally extensive cone of depression at certain times of the year of over 40 feet in places in west-central Manatee County. Because all of the agricultural water use and a large portion of the public supply use are for supplemental irrigation, groundwater withdrawals are inversely correlated with rainfall. Consequently, maximum withdrawals occur near the end of the dry season, sometime in May or June. The potentiometric surface for May 2000 conditions is shown in Figure 2.13. The groundwater flow direction during this time is from the Gulf of Mexico inland. Since the transmissivity of the Upper Florida aquifer is high and the storativity low, most of the head recovery from pumping during the wet period occurs within a few months, resulting in groundwater flow resuming its coastward flow direction. However, recovery to pre-development conditions does not occur. The potentiometric surface for September 2000 conditions is shown in Figure 2.14. The strong seasonal nature of demand causes considerable variability in the annual demand cycle and produces large fluctuations in groundwater levels during the year.

Barcelo and Basso (1993) provide a comparison of pre- and post-development potentiometric surface conditions. The major changes are that the 20- and 30-foot contours in Hillsborough and Manatee Counties have shifted significantly inland since pre-development, and the 50 to 100 foot potentiometric contours are closely spaced in the high-recharge region of northern Polk County.

2.6 GROUNDWATER QUALITY

2.6.1 General Water Quality Characteristics

The major threat to groundwater quality within the study area is considered to be the intrusion of saline waters, particularly seawater. Water quality in the area is generally good in all the aquifers above the middle confining unit ("evaporites") separating the Upper and Lower Floridan aquifers. In general, water quality degrades with depth and becomes more mineralized as the water flows from east to west along natural flow paths. The water quality also deteriorates from the north to the south as the thickness and depth of the Floridan and intermediate aquifer system increases (SWFWMD, 1993).

Water is generally considered fresh if it contains less than 1,000 mg/l (milligrams per liter) total dissolved solids (TDS), while brackish water ranges from 1,000 to 35,000 mg/l TDS (Clark and others, 1971). The SWFWMD defines saline water as water that is characterized by TDS concentration greater than 500 mg/l (SWFWMD, 1989). A concentration of 35,000 mg/l is considered equivalent to seawater. The State of Florida Drinking Water Standards requires that TDS concentrations for finished water be less than 500 mg/l (FDER, 1989).

There is considerable areal variation in the groundwater quality of the surficial aquifer system within the study area. Generally, the quality of the water in the surficial aquifer system is good except in the tidally influenced areas along the coast (Brown, 1983). Surficial aquifer system water along the coast and rivers is also influenced by lower quality water discharging from below (AGWQMP, 1991). AGWQMP (1991) also reports that chloride and sulfate concentrations in the study area are highest along the coastal reaches of the rivers.

The problem of assessing the water quality of the intermediate aquifer system is complicated by the hydrogeology of the aquifer. The existence of multiple, permeable zones, in poor hydraulic connection, complicates the analysis of water quality distributions (Ambient Ground-water Quality Monitoring Program [AGWQMP, 1990]). There is a lack of water quality data for this system, both spatially and temporally (SWFWMD, 1993). Overall water quality of the intermediate aquifer system is good (SWFWMD, 1993). Major ion concentrations in groundwater of the intermediate aquifer system are generally higher than ion concentrations observed in the surficial aquifer but lower than ion concentrations observed in the Floridan aquifer system (AGWQMP, 1990). The exception to this general observation is along the coast where chloride concentrations are frequently elevated (AGWQMP, 1990).

In the east and northeast areas of the study area, Upper Floridan aquifer water is principally of a calcium-magnesium-bicarbonate-sulfate type water of good quality (SWFWMD, 1993). Down gradient, to the west and southwest, the water changes to a sodium magnesium chloride type, similar to seawater. This down-gradient water of the Upper Floridan aquifer is of variable to poor quality (Steinkampf, 1982).

2.6.2 Saltwater Intrusion

In the coastal aquifers within the study area, lower density freshwater overlies denser seawater. The seawater and freshwater meet and blend in the aquifer to form a transition zone. The transition zone in the Upper Floridan aquifer ranges in thickness from about one hundred feet to several hundred feet (Beach and Kelley, 1998). The thickness depends on the conductivity of the subsurface matrix and the flow rate through the system. Chloride concentrations are the usual indicator of the transition zone existence. Chloride concentrations on the freshwater side (east) are often less the 50 mg/l and approach 19,000 mg/l on the seaward side (west) (Beach and Kelley, 1998). The ROMP wells located in Figure 2.15 provide the best quality information on chloride values at various depths within the study area. In general, the saltwater interface gets deeper from north to south. These depths generally coincide with a highly permeable zone within the Avon Park Formation. In addition, north of the Manatee River the transition zone is relatively sharp; while south of the river, the transition zone becomes more diffuse. This comparison is illustrated by the following discussion of water quality near Apollo Beach and Osprey, Florida (SWFWMD, 1993).

Near Apollo Beach an exploratory well (ROMP TR9-2) was cored to 819 feet and completed 1,254 feet below land surface (Figure 2.15). Based upon the observed relationship between chloride concentration and depth, the transition zone begins at a depth of 740 feet below land surface, and seawater is encountered at about 840 feet below land surface. The concentration of chloride is approximately 100 mg/l, or less, until the interface is contacted. This is slightly above the upper limit for ambient chlorides in Eastern Tampa Bay area from non-marine sources (Steinkampf, 1982). Above the interface, sulfate is the predominant anion. However, chloride replaces sulfate as the predominant anion below the transition zone.

Exploratory drilling near the city of Osprey began in 1991 (i.e., ROMP 20 site) (SWFWMD, 1993). Beginning at depths of 650 feet below land surface, the chloride concentrations began to increase above 100 mg/1. Chlorides increased gradually to a concentration of 2,230 mg/l at a depth of 1,439 feet below land surface where coring was discontinued. Subsequent thief sampling from the bottom of the well produced samples with chloride concentrations equivalent to seawater.

In 1991, AGWQMP conducted mapping exercises to delineate the chloride interface. More recently, Beach and Kelley (1998) projected the freshwater-seawater interface onto hydrogeologic cross sections at six locations along the coast (Figure 2.16). The cross section locations were selected where the SWFWMD has completed water quality explorations during drilling of ROMP wells (Figure 2.15). Detailed water quality data, often based on packer tests and thief samples, are available from these locations.

Based on exploratory drilling in the coastal regions of the SWUCA, the transition zone usually occurs in the upper portions of the Avon Park Formation within the Upper Florida aquifer. This represents the deepest production zone of the aquifer. In coastal Sarasota and Charlotte counties, the transition zone may occur within the Suwannee Limestone of the Upper Florida aquifer (Beach and Kelley, 1998). The transition zone may occur in the intermediate aquifer system when wells are drilled on the barrier islands or very near the coast. Exploratory wells completed in the surficial aquifer system (SAS) rarely encounter the transition zone although the transition zone may be present where such wells are adjacent to coastal surface water bodies (e.g., bays and estuaries) (Beach and Kelley, 1998).

The locations where multiple sites exist near the cross section were pivotal in this analysis. Multiple explorations along a transect permit estimates to be made as to the slope of the interface. Where a cross section had only one well to reference, the slope was interpolated from adjacent cross sections (Beach and Kelley, 1998). The interface line for each section was extended to the middle confining unit. The plane of the interface has a slight slope (0.5 to 3 degrees) downward as the interface dips landward (Beach and Kelley, 1998). The location where the interface intersects the bottom of an aquifer is known as the toe and defines the landward extent of seawater in the aquifer.

The distance along each cross section to the toe was superimposed onto a map. A smooth line through each toe was drawn delineating the 1,000 mg/l chloride concentration defining the areal extent of the interface between the freshwater and saltwater (Figure 2.16). This approach was later updated (Beach and Schultz, 2000) by delineating the top and bottom of the "highly permeable zone" within the Avon Park Formation from exploratory drilling data and adding this information to each cross section. Where exploratory drilling data was inadequate, the top of the "highly permeable zone" was derived from Miller (1986). The point on the cross sections where the interface exits the bottom of the "highly permeable" zone of the Avon Park was determined to be the toe of the interface.

Beach and Schultz (2000) determined that the current position of the interface toe in the Avon Park Formation is only two to three miles inland in south Hillsborough County. In Sarasota County, the interface toe in the Avon Park may be as much as ten miles inland. Beach and Schultz (2000) also provide estimates for future positions of the toe after 50 years of pumping at different levels (Figure 2.17). The estimates indicate that future movement will be greater in south Hillsborough County than in northern Sarasota County. Application of the Ghyben-Herzberg principal indicates that ultimately Sarasota County would be affected to a greater extent than Hillsborough or Manatee Counties (Beach and Schultz, 2000).

Appendix A shows the variation of chlorides with depth for various ROMP wells within the study area. Due to the high quality of spatial chloride distributions provided by this data, it is used for calibrating the density-dependent saltwater intrusion model.

2.6.3 Saltwater Intrusion Potential Risk

The risk of a well to saltwater intrusion is a function of at least four factors: (1) the completed depth of the well; (2) the proximity of the well to the coast; (3) the amount of water withdrawn in the vicinity of the well; and (4) the local and regional properties of the aquifers and confining units (Beach and Kelley, 1998). Typically, deeper wells are closer to the transition zone and saline water. The closer a well is located to the coast, the thinner the freshwater zone. The greater the withdrawal quantity, the more likely wells are to induce local saltwater upconing from the transition zone. The distribution of hydraulic conductivity is the most important local and regional property of the aquifers and confining units, which affects the potential for saltwater intrusion. Sediments characterized by higher hydraulic conductivity values allow the interface to move more quickly under a given change in potential. Hydraulic conductivity heterogeneity is the variation in hydraulic conductivity that occurs from place to place in the aquifer and confining units. Frequently, hydraulic conductivity heterogeneity is caused by spatial or vertical variations in fracture density and/or distribution; lithologic properties; or distribution and magnitude of secondary dissolution features (i.e., karst conduits). Heterogeneity is the principal factor that accounts for multiple wells being affected to different extents by saltwater intrusion when all the wells are completed to the same depth, are located the same distance from the coast, and are located in similar withdrawal environments (Beach and Kelley, 1998).

Based on the four risk factors above, wells completed in the Avon Park Formation are generally at the greatest risk of experiencing saltwater intrusion. The Avon Park Formation of the Upper Floridan aquifer is a highly prolific water-producing unit due to its very high hydraulic conductivity. The high hydraulic conductivity results from a horizontal interval, about 100 to 400 feet thick, characterized by considerable fracturing and secondary porosity. This interval is frequently referred to as the "highly permeable" or "fractured" zone of the Avon Park Formation. Although this highly permeable zone comprises only 10 to 25 percent of the Avon Park thickness, as much as 95 percent of the Avon Park water production may be derived from this zone (Beach and Schultz, 2000). The remainder of the formation is characterized by relatively low permeability and limited groundwater production. For this reason, the Avon Park Formation wells are usually completed in the highly permeable zone.

Most exploratory drilling in coastal areas of Hillsborough, Manatee and Sarasota counties have located the seawater transition zone in the upper portions of the Avon Park. Increasing temporal trends in chloride concentration data from dedicated monitoring wells occur most frequently in wells completed in the Avon Park Formation. Based on that data, Beach and Kelley (1998) conclude that wells in Hillsborough and Manatee counties, completed in the Avon Park Formation and located within four to five miles to the coast, are most likely to experience saltwater intrusion in the near future. For the purposes of their discussion, the "near future" is considered to be within the next five or ten years (from 1998). On the other hand, wells completed above the toe of the interface would probably not experience saltwater intrusion within present long-term planning periods, generally out to 2025 (Beach and Kelley, 1998). These estimates assume no change in current withdrawal rates and patterns.

Avon Park Formation wells in Charlotte and DeSoto Counties already withdraw very poor quality water. The transition zone is more diffuse in these counties than in Hillsborough and Manatee Counties (Beach and Kelley, 1998). Data from exploratory wells in the area show the influence of seawater well into the Suwannee Limestone although chloride concentrations are somewhat less than 1,000 mg/l.

Based on the four risk factors, coastal Suwannee Limestone wells are at much less risk of saltwater intrusion than similarly located wells completed in the Avon Park Formation (Beach and Kelley, 1998). Generally, the lower hydraulic conductivity of the Suwannee Limestone is less susceptible to saltwater intrusion. Wells that appear to be a greatest risk are those located within several miles of the coast in Charlotte and southern Sarasota Counties (Beach and Kelley, 1998). Relatively high chloride concentrations, 570 to 1,800 mg/l were encountered in the Suwannee Limestone during exploratory drilling in those counties (i.e., ROMP 5, ROMP 9, and ROMP TR 4-1). In Hillsborough and Manatee Counties, there are a large number of Suwannee Limestone production wells located within several miles from the coast (Beach and Kelley, 1998). Based on water quality data from dedicated monitoring wells in the area, chloride concentrations range from 200 to 500 mg/l (ROMP TR 9-2, ROMP TR 9-3). However, there are no increasing trends in these data, unlike similar data from the Avon Park Formation dedicated monitoring wells at the same locations (Beach and Kelley, 1998). It has been demonstrated that such concentrated pumping from the Suwannee Limestone, as occurs in the area, could cause the interface to be pulled up into the Suwannee Limestone from the Avon Park Formation over the next 50 years (HydroGeoLogic, Inc, 1994a).

Regionally, the intermediate aquifer system and surficial aquifer system wells are at little risk of saltwater intrusion. However, there are local problems for intermediate aquifer system and surficial aquifer system wells in Manatee, Sarasota and Charlotte Counties that are located less than a mile from the coast or barrier islands (Beach and Kelley, 1998). The transition zone on the barrier islands is usually located in the intermediate aquifer system. The Water Use Permit (WUP) wells located on the barrier islands of northern Sarasota County are known to have experienced considerable degradation from saltwater intrusion for many years (Beach and Kelley, 1998). This is also true for many of the shallow intermediate and surficial aquifer system wells along the southwest coast of the area.

2.7 IMPLICATIONS OF CONCEPTUAL MODEL COMPONENTS AND UNCERTAINTY ON THE NUMERICAL MODEL

One primary goal of mathematical modeling is to synthesize the conceptual model into numerical terms from which flow and transport processes may be investigated under specified conditions. This process entails several discrete steps: (1) partitioning the conceptual model into units of time and space; (2) assignment of boundary conditions; and (3) specification of the parameter values. There are always uncertainties in predictions derived from modeling. These uncertainties are frequently divided into two main categories: 1) conceptual model uncertainty; and 2) parameter uncertainty. This section briefly describes these uncertainties and the approach that will be applied to address these uncertainties in the model calibration process.

The conceptual model is based on the modeler's experience and technical judgment and represents the modeler's understanding of the system framework and behavior, from all available data and information of a site. The conceptual model will naturally become more complex as more processes are identified and interrelationships of important components within the systems are considered. The transformation of the conceptual model into a mathematical model, is a further extrapolation of the basic understanding of the system, resulting in intrinsic simplifications of the system. For example, the mathematical model assumes that there is a direct scaling between the model simulations and the scale at which the data are collected. The lack of knowledge about the system resulting from limited information also contributes to inevitable simplifications in the conceptual and mathematical models. Based upon the data and model review a number of conceptual model uncertainties have been identified and are presented in Table 2.2. This table also describes the methods that will be applied to address the primary uncertainties during the model calibration.

In addition to the conceptual model uncertainties, there are always uncertainties in the parameter values that are assigned in the model. As specified in the Work Order agreement between the SWFWMD and HydroGeoLogic, sensitivity analyses will be conducted to address parameter uncertainties during the model calibration. Sensitivity analyses will be conducted for key parameters (which may be performed on the pre-development or post-development model depending upon significance). Parameter sensitivities will be determined by varying a specific parameter and evaluating the change in hydraulic heads and/or chloride concentrations thus simulated. Depending upon the results of this initial sensitivity analyses, multiple parameters may be simultaneously perturbed during subsequent sensitivity analyses. Based on the results of the sensitivity analysis, the parameters will be categorized following the protocol developed by the American Society of Civil Engineers (ASCE) to determine the parameters of greatest concern. This approach will serve to provide recommendations for future data collection, as well as to design sensitivity simulations that will be conducted during the next phase of the project to evaluate prediction uncertainties.

3.0 SUMMARY OF PREVIOUS MODELING STUDIES

Over the last 15 years, a number of models have been constructed in the SWFWMD to address the problem of deteriorating groundwater quality due to lateral intrusion of seawater or the upconing of highly mineralized water from deeper stratigraphic units. One of the first documented studies is by Hutchinson (1983) in which a two-dimensional areal freshwater model was used to study the effects of the channelization in Tampa Bay and the effects of pumping in the vicinity. Wilson (1982) also used an areal freshwater model to predict the effect of pumping on the potentiometric surface in the west-central Florida area. Both investigators estimated the current location of the seawater-freshwater interface and estimated the rate of advancement using the freshwater flow velocity at the interface.

Mahon (1988) performed a cross-sectional analysis to evaluate the potential for saltwater intrusion in Hernando and Manatee Counties. Mahon conceptualized the Upper Floridan aquifer as having an upper permeable zone, semiconfining unit, and a lower permeable zone. Each hydrostratigraphic layer was divided into several computational layers for solute transport. The top of the middle confining unit was assumed to be impermeable, the intermediate aquifer system was explicitly simulated, and the surficial aquifer system was set as a constant pressure to provide a source for downward leakage to the intermediate aquifer system. The lateral freshwater flux on the landward model edge had to be lowered relative to the initial estimates in order to bring the approximate location of the interface to a reasonable location from its initial location somewhere in Tampa Bay.

HydroGeoLogic (1991a, b, and c) performed variable density flow and transport cross-sectional analyses (Figure 3.1) for three representative cross-sections in the Manatee-South Hillsborough Water Resources Assessment area where a large, groundwater depression was observed (Figure 2.9). The numerical code DSTRAM (Density-dependent Solute TRansport Analysis finite-element Model) was applied. For each cross-section, the model was first calibrated against steady-state pre-development conditions. Flow boundaries for the cross-sectional models were defined as a combination of flux and prescribed head boundaries based on the pre-development potentiometric surface map of the Upper Floridan aquifer. The middle confining unit at the bottom of the Avon Park were considered a no-flow boundary. Both Sinclair (1979) and Guyton and Associates 1976 report that highly mineralized water was found in this evaporites zone. Thus, along the bottom boundary, chloride concentrations were normalized to seawater (i.e., set equal to 1, which is representative of a chloride concentration of 18,000 mg/l). Hutchinson (1983) found that the water samples taken at Hillsborough Bay are slightly less saline than seawater (approximately, 14,400 mg/l). Therefore, the seaward boundary of the B-W cross-sectional model (HydroGeoLogic, 1991a) was assigned a concentration of 14,000 mg/l. Sensitivity analyses were subsequently performed to determine relative influences of changes in key parameters on system responses. Two post-development scenarios were simulated in a transient manner and are representative of the most pessimistic and optimistic conditions over a 100-year simulation period.

Model predicted chloride concentrations associated with pre-development conditions are shown on Figure 3.1 for the intermediate aquifer system. Modeling results along cross section B-W indicate that the length of the transition zone at the top of the Avon Park Formation is about 4 miles while at the bottom it is about 1 mile. The model predicted that chloride concentrations in wells constructed at the shoreline would range from 900 ppm to 17,000 mg/l over a depth of 250 feet in the Avon Park Formation. The vertical transition zone predicted by the model is more gradual than suggested by earlier field investigations. The authors note that the simulated transition zone can be made thinner by reducing the dispersivities and the element size further.

The second cross section, section M-S, passes through the city of Sarasota in Sarasota County, and terminates in the Gulf of Mexico (Figure 3.1). As shown in the figure, the pre-development 1,000 mg/l chloride isochlor in the Tampa/Suwannee layer is located somewhat west of the city of Sarasota. In the Avon Park, however, the 1,000 mg/l chloride is located approximately 6 miles east of Sarasota.

The third cross section, section H-M, is located along the Hillsborough-Manatee County border and lies in the middle of a large potentiometric depression during the dry season (Figure 2.9). Chloride concentration isochlors indicate that the chloride transition zone is very narrow which is consistent with field data indicating that wells located further inland and tapping the Tampa/Suwannee and Avon Park Formations depict very small chloride concentrations values, as reported by Brown (1983).

During post-development simulations, the transition zones advanced landward in all three cross sections, however, with varying degrees. In the worst case scenarios the maximum advancement of 3 to 5 miles was observed in the southernmost section (S-M) while at most 2 miles of advancement was observed in the northernmost section (B-W).

In all three cross sections, the response of the saltwater-freshwater transition zone to the imposed conditions was more significant in the lower producing zone (the Avon Park Formation) of the Upper Floridan than in the upper producing zone (the Tampa/Suwannee Formation). Sensitivity analyses indicated that the results are very sensitive to vertical hydraulic conductivities of the confining units, particularly the Intermediate aquifer system.

Barcelo and Basso (1993) implemented a quasi-three dimensional MODFLOW modeling effort to assess regional groundwater flow in the eastern Tampa Bay WUCA. The flow model consisted of three layers to simulate groundwater flow within the Intermediate and Upper Floridan Aquifers and the vertical exchange of water between the surficial, intermediate and Upper Floridan Aquifers.

Although the Upper Floridan Aquifer has two major production zones (i.e., Suwannee Limestone, Avon Park Formation), the aquifer is conceptualized as a single hydrologic unit. Referring to the Upper Floridan Aquifer, Ryder (1982) noted that "despite the large permeability contrasts, aquifer-test results indicate that there is enough vertical interconnection between each formation to consider the Floridan Aquifer a single hydrologic unit." Menke (1961) noted that in Hillsborough County, the connection between the upper and lower production zones is such that "...when the time of interchange of water is great and the amount of water interchanged is small..." the system behaves as a single aquifer. The concept of treating the Upper Florida aquifer as a single hydrologic unit was further investigated by Guyton and Associates (1976). During an aquifer test of the Avon Park Formation that was performed in Manatee County, measured water levels in two wells that were open to the different production zones were nearly identical. This conceptualization will be revisited for the saltwater intrusion model because it may not be adequate to investigate chloride intrusion.

Barcelo and Basso (1993) calibrated their model to steady-state, annual-average hydrologic conditions for calendar year 1989. Following the steady-state calibration, a transient calibration/ verification was performed to evaluate the response of the model to changes in hydrologic stress. The transient calibration was conducted for the period from October 1988 through September 1989.

As a means of evaluating the steady-state calibration effort during the calibration phase, the investigators periodically removed pumping from the model and the model was used to simulate pre-development hydrologic conditions. Because the original parameter estimates were based in part on a groundwater flow model that had been calibrated to pre-development conditions (Ryder, 1985), it was decided that emphasis should be placed on calibrating the model to more recent stressed conditions rather than calibrating to pre-development conditions. Calibration to pre-development conditions enables a determination of the areal distribution of the aquifer parameters without incurring the error associated with estimating water use; however, the authors believed that the pre-development target heads are not sufficiently well known. Although there is some degree of confidence in the pre-development potentiometric surface of the Upper Floridan aquifer (Johnston and others, 1980) there is no published map on the pre-development head distribution of the Intermediate Aquifer (Barcelo, and Basso, 1993).

In 1992, HydroGeoLogic developed a computer code called SIMLAS for the SWFWMD to simulate saltwater intrusion using a sharp-interface technique. The sharp interface technique assumes that the freshwater and the saltwater are immiscible and that the transition between the two liquids is abrupt. This assumption along with the Dupuit-Forchheimer approximation replaces the density-dependent flow and transport equations with a pair of flow equations for freshwater and saltwater. The two flow equations are still coupled, but are less prone to numerical difficulties than the variable density flow and transport equations for large scale simulations.

Two sharp-interface models were subsequently developed using SIMLAS (HydroGeoLogic, 1993; 1994b) to extend the work of Barcelo and Basso (1993) to include the dynamics of saltwater. One of HydroGeoLogic's objectives was to compare the sharp interface formulation in SIMLAS to the fully coupled density-dependent approach in DSTRAM. In order to make this comparison, the southernmost cross section (M-S) from HydroGeoLogic's 1991 study was selected. This southern cross-section was chosen, primarily because a well defined narrow transition zone exists in both lower and upper aquifer layers. Results indicated that the two numerical solutions are in good agreement when the effects of dispersion in the DSTRAM model are negligible. For zero dispersion, the only major difference between the two modeling approaches is the Dupuit-Forchheimer assumption employed in the sharp-interface formulation.

The saltwater-freshwater interface in the Upper Floridan aquifer was predicted by the SIMLAS model to occur over a large area. As shown in Figure 3.1, the predicted toe location is considerably further inland than in the Intermediate Aquifer System. The modeling results also indicted that when the leakance of the lower confining bed of the Intermediate System is reduced (by a factor of 3), both the tip and the toe positions are pushed toward the coastline (west). However, the shift is much more pronounced for the tip than for the toe. Similar behavior was observed between the cross-sectional and areal simulations; the toe moved toward the coastline roughly five miles whereas the tip moved all the way to the offshore boundary.

Post-development simulations were also performed which concluded that after 500 years of pumping under post-development conditions, little change was observed on the position of the interface in the intermediate aquifer system. The toe of the interface in the Upper Floridan Aquifer, however, moved inland up to six miles in the northern half of the model domain. The tip of the interface hardly moved revealing the tightness of the overlying confining layer. The interface in the southern half of the model domain showed little change to the applied stress.

Major conclusions of these studies were that the Upper Floridan aquifer may need to be divided into major producing and confining zones, and that the leakance of the intermediate aquifer system should be adjusted to move the tip inland. In particular, the 1994 study showed that the MODFLOW-derived leakances offshore needed to be increased by a factor of 10 in order to avoid simulating the interface too far offshore.

In another variable density flow and transport analysis, HydroGeoLogic (1994c) performed two extensive cross sectional investigations of long-term pumping effects on chloride levels in the northern and southern regions of the ETBWUCA. The location of the toe of the pre-development interface at both cross sections is shown in Figure 3.1. With respect to the boundary conditions, Hillsborough Bay seawater was assigned a slightly lower (14,400 mg/l) chloride concentration than seawater (18,000 mg/l). The bottom of the model was placed at the top of the middle confining unit and assigned a concentration of seawater. However, no fluid flow was allowed along this bottom boundary. The system was found to be most sensitive to the vertical hydraulic conductivity of the evaporite zone and the horizontal hydraulic conductivity of the Avon Park formation. Recharge to the top of the Upper Floridan aquifer mainly affected heads with minor effects on chloride distributions, but both heads and chlorides were sensitive to the middle confining unit hydraulic conductivity.

All of the above models assumed that the fractured LPZ may be represented as an equivalent porous medium. Waterstone (Waterstone, 2001a), however, provides a discussion on alternative conceptualizations involving dual porosity, discrete fracture and dual permeability conceptualizations and their potential affects on groundwater flow and chloride migration. Waterstone concludes that an equivalent porous medium approach will adequately describe flow and transport through the LPZ.

4.0 NUMERICAL MODEL CONSTRUCTION

4.1 MODELING APPROACH

The following section describes the approach used to construct a density-dependent groundwater flow and solute transport model to simulate saltwater intrusion in coastal portions of the SWUCA. The framework for the saltwater intrusion model has been developed based on the conceptual model presented in Section 2.0. In addition, information derived from other modeling investigations has provided valuable information for the development of the current model. In particular, the regional groundwater flow model developed by the SWFWMD (2001) and an uncalibrated, local-scale, saltwater intrusion model developed by Waterstone (2001a, 2001b) have provided significant data that have been used for the preliminary construction of the current model.

As discussed in Section 3.3, the computer code MODFLOW (MacDonald and Harbaugh, 1988) has been applied by several models in the SWFWMD for simulating groundwater flow within the SWUCA. These models have culminated into the Southern District Groundwater Flow Model (SWFWMD, 2001), a regional MODFLOW model that integrates and updates previous models. This regional groundwater flow model, transmitted electronically (via Groundwater Vistas project files) to HydroGeoLogic, Inc. by the SWFWMD (SWFWMD, 2001), forms the basis for the current study. The primary objective of the Southern District Model was to provide a groundwater management tool to the SWFWMD. Currently, the SWFWMD is further updating the calibration of the regional groundwater flow model, but large changes to the model are not anticipated (Beach, pers. comm., 2001). Therefore, the Southern District Model of June 11, 2001 provided by the SWFWMD has been used to construct the current saltwater intrusion model. Since a report documenting the regional modeling effort is not completed, critical information related to the Southern District Model and its uncertainties have been acquired through numerous conversations with the SWFWMD and a thorough review of model input and output files.

Groundwater Vistas project files associated with an uncalibrated saltwater intrusion model developed by Waterstone (Waterstone, 2001b) have also been used to a certain extent in the current modeling effort. Specifically, the grid employed for their study, including hydrostratigraphic elevations and layering geometry, was also adopted for the current modeling investigation.

As will be discussed in greater detail in the sections that follow, both the Waterstone Model (Waterstone, 2001b) and the Southern District Model (SWFWMD, 2001) electronic data files were used to construct and initialize the density-dependent saltwater intrusion model. The regional MODFLOW model files were used primarily to assign hydraulic properties and boundary conditions, since the density-dependent model is conceptually based on the regional study. Alternatively, the Waterstone (Waterstone, 2001b) model files provided by the SWFWMD were used to assign the model domain, grid spacings and layer thicknesses to the density-dependent model, since these were acceptable to the SWFWMD for the previous study, and were reasonable for the goals and scale of the current study.

When the density-dependent model was constructed, it was first used to simulate groundwater flow only, to establish that the translation from regional to local grids was appropriate and that the simulated pre-development conditions for both models are the same. Once these "basecase" conditions were established (Section 5.1), the saltwater effects were incorporated into the density-dependent model. Parameter values (e.g., hydraulic conductivities) were, to a certain extent, adjusted from the basecase conditions during calibration of the density-dependent, saltwater intrusion model (Section 5.0), because the regional flow model does not include the affects of chloride concentration which affect groundwater flow.

4.2 COMPUTER CODE SELECTION AND OVERVIEW

The computer code MODHMS was selected for construction of the flow and solute transport model (HydroGeoLogic, 2000). MODHMS is a MODFLOW-based code developed by HydroGeoLogic for evaluating complex hydrologic and hydrogeologic settings. The density-dependent transport capabilities of MODHMS have been incorporated from DSTRAM, which is a well established and applied saltwater intrusion model developed by Huyakorn and Panday (1991). The MODFLOW structure of MODHMS provides several features that are attractive for use in this study. First, it makes the code fully compatible (in terms of numerical approximations, grid structure as well as input/output data structures) with the other MODFLOW- based models (regional as well as local) developed by the SWFWMD. Further, the MODFLOW framework of MODHMS allows for use of any of the pre- and post-processing tools developed for use with MODFLOW. Specifically, Groundwater Vistas (Environmental Simulations, Inc.) provides support to the additional modules of MODHMS used for density-dependent modeling. This is advantageous because the SWFWMD has developed the Southern District Model in Groundwater Vistas, and that model can be directly translated to MODHMS framework. In addition, all the MODFLOW features are available for use within MODHMS including a wide range of boundary conditions such as drains, streams, general-head conditions, and those involving water table conditions, infiltration, aquitard leakages, and pumping and injection wells. For contaminant transport simulation, MODHMS accounts for advection, anisotropic hydrodynamic dispersion (with separate areal and vertical components for the longitudinal and transverse dispersivities essential in such groundwater systems as encountered by the SWFWMD), linear equilibrium sorption, and first-order degradation.

The MODHMS code was selected for this study because of the following reasons:

- The code is fully documented and has been successfully applied to problems of similar complexity. For instance, the DSTRAM models for the Seminole County and East Orange County saltwater intrusion studies (Panday et al., 1994, HydroGeoLogic, 1998) were translated to MODHMS and transient as well as steady-state results were demonstrated to be accurate. MODHMS has also been verified against problems with known solutions.

- MODHMS employs the most advanced solution and matrix computation techniques available. The transport equation uses advanced flux-limiting Total Variation Diminishing (TVD) schemes to control unphysical oscillations and minimize numerical diffusion. The code has robust (Preconditioned Conjugate Gradient and Orthomin) matrix solvers unavailable in other standard codes which make it more efficient and versatile.

- MODHMS can quickly extend the Southern District Model developed by the SWFWMD under Groundwater Vistas, to include the density-dependent saltwater transport regime. Conversely, changes made within the calibrated saltwater intrusion model may be quickly and easily incorporated into the Southern District Model. Compatibility among all SWFWMD models allows for consistency and defensibility of results across models.

MODHMS is an extension to the USGS three-dimensional finite difference groundwater flow code, MODFLOW (McDonnald and Harbaugh, 1988), and is capable of simulating density-dependent, single-phase fluid flow and solute transport in saturated porous media. The code is applicable for complex situations where the flow of fluid (groundwater) is influenced significantly by variations in solute concentration. MODHMS can perform steady-state and transient simulations, and a wide range of boundary conditions can be accommodated. For contaminant transport simulation, MODHMS accounts for advection, hydrodynamic dispersion, linear equilibrium sorption, and first-order degradation. When MODHMS is used to simulate the combined processes of density-dependent groundwater flow and solute transport, the code solves two coupled partial differential equations: one for density-dependent fluid flow and one for the transport of dissolved solutes (e.g. chloride).

The governing equation for three-dimensional flow of a mixture fluid (i.e., water and salt) of a variable density in an aquifer system can be written in the form

$$\frac{\partial}{\partial x_i}\left[\rho\frac{k_{ij}}{\mu}\left(\frac{\partial p}{\partial x_i} + \rho g e_j\right)\right] = \frac{\partial}{\partial t}(\phi\rho), \qquad (4.1)$$

$$i,j = 1,2,3$$

where p is fluid pressure, k_{ij} is the intrinsic permeability tensor, ρ and μ are the fluid density and dynamic viscosity, respectively, g is the gravitational acceleration, e_j is the unit vector in the upward vertical direction, and Φ is the porosity of the porous medium. In working with the above flow equation, it is convenient to replace pressure by a reference hydraulic head defined as

$$h = \frac{p}{\rho_0 g} + z \qquad (4.2)$$

where ρ_0 is a reference (freshwater) density and z is the elevation above a reference datum plane. The reference hydraulic head is often referred to as the equivalent freshwater head. The reference hydraulic head is directly related to the true hydraulic head, H, by the relationship

$$H = \frac{h + z\eta c}{1 + \eta c} \qquad (4.3)$$

where H is defined as

$$H = \frac{p}{\rho g} + z \tag{4.4}$$

and

$$\eta = \frac{\rho_s - \rho_o}{\rho_o c_s} \tag{4.5}$$

where c_s is the solute concentration that corresponds to the maximum density, ρ_s. In practice, the term ηc is usually much less than 1 and thus equation (4.3) can be approximated by

$$H = h + \eta c z \tag{4.6}$$

In MODHMS, therefore, two types of boundary conditions must be entered: those that describe the reference (equivalent freshwater) head or fluid fluxes, and those that pertain to solute concentration or solute mass fluxes.

There is a third type of hydraulic head, referred to as environmental head (or potential head), which is defined as

$$\psi = h - \int_{z_1}^{z_2} \eta c \, dz \tag{4.7}$$

where z_1 is the elevation above datum at which the environmental head (ψ) is to be determined, and z_2 is the elevation above datum of the top of the model domain. The environmental head may be conceptualized as the head value that would be measured in a well that had open hole construction from the top of the aquifer system where solute concentrations are small or negligible (z_2) to a total depth of z_1.

The groundwater flow equation can be coupled with the solute transport equation, which may be written in the form

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right) - V_i\frac{\partial c}{\partial x_i} = \phi R\left(\frac{\partial c}{\partial t}\right) + \lambda\phi Rc, \qquad i,j = 1,2,3 \tag{4.8}$$

where D_{ij} is the apparent hydrodynamic dispersion tensor, V_i is the Darcy velocity of fluid, R is the retardation coefficient, and λ is the decay or degradation constant of the solute. For a conservative solute species, such as chloride, there is no adsorption R = 1) and no decay (λ = 0). Equations (4.1) and (4.8) are coupled through the concentration variable and the Darcy velocity.

The hydrodynamic dispersion for three-dimensional anisotropic systems maybe computed from relations provided by Guvanasen (2002), as

$$D_{xx} = \alpha_{Lh}\frac{v_x^2}{|v|} + \alpha_{Th}\frac{v_y^2}{|v|} + \alpha_{Tv}\frac{v_z^2}{|v|} + \beta D_o \tag{4.9a}$$

$$D_{yy} = \alpha_{Th}\frac{v_x^2}{|v|} + \alpha_{Lh}\frac{v_y^2}{|v|} + \alpha_{Tv}\frac{v_z^2}{|v|} + \beta D_o \tag{4.9b}$$

$$D_{xz} = D_{zx} = \left(\frac{\alpha_{Lh} + \alpha_{Lv}}{2} - \alpha_{Tv}\right)\frac{v_x v_z}{|v|} \tag{4.9c}$$

$$D_{zz} = \alpha_{Tv}\frac{v_x^2}{|v|} + \alpha_{Tv}\frac{v_y^2}{|v|} + \alpha_{Lv}\frac{v_z^2}{|v|} + \beta D_o \tag{4.9d}$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_T)\frac{v_x v_y}{|v|} \tag{4.9e}$$

$$D_{yz} = D_{zy} = \left(\frac{\alpha_{Lh} + \alpha_{Lv}}{2} - \alpha_{Tv}\right)\frac{v_y v_z}{|v|} \tag{4.9f}$$

where $|v|$ is the magnitude of the velocity vector, $|v| = (v_1^2 + v_2^2 + v_3^2)^{1/2}$, α_L and α_T are longitudinal and transverse dispersivities, respectively, δ_{ij} is the Kronecker delta, D^o is the free-water molecular diffusion coefficient, and β is the tortuosity given by the Millington-Quirk (1961) equation as $\beta = S_w^{10/3}\phi^{4/3}$. The subscripts *Lh*, *Th*, *Lv*, and *Tv* are indices for horizontal longitudinal, horizontal transverse, vertical longitudinal and vertical transverse directions respectively. Note that equations above collapse to equations for isotropic media when *Lv*=*Lh* and *Tv*=*Th*. The set of equations (4.9) is typically used to calculate dispersivities in a three dimensional system where vertical flow components are significant. In such cases, the vertical and horizontal components of dispersion can be an order of magnitude apart for their respective longitudinal and transverse components. For three-dimensional systems with mainly horizontal flows, the longitudinal dispersivities in vertical and horizontal directions may be treated as equal, to produce a 3-component dispersivity tensor. In such cases, the vertical transverse dispersivity is typically an order of magnitude less than the horizontal transverse dispersivity for areally extensive systems. Finally, for isotropic systems or two-dimensional analyses, the vertical and horizontal components of the transverse dispersivity may also be treated as equal, to produce the Scheidegger (1961) dispersivity equation.

The major assumptions and limitations incorporated into MODHMS that are relevant to this project are as follows:

- Fluid flow and salt transport occurs in a fully saturated porous medium. Flow and transport within individual fractures and solution cavities is not simulated explicitly.

- Flow of the fluid considered is isothermal and is governed by Darcy's Law.

- The fluid considered is slightly compressible and homogeneous.

- Dispersive transport in the porous medium system is governed by Fick's Law. The hydrodynamic dispersion is defined as the sum of the coefficients of mechanical dispersion and molecular diffusion. The medium dispersivity corresponds to that of an anisotropic porous medium and may be related to four constants, α_L and α_T, in the areal and vertical directions, which are the longitudinal and transverse dispersivities, respectively. This four component dispersivity tensor reduces to the two-component isotropic dispersivity tensor when the areal and vertical components for the dispersivities are equal.

One final comment is appropriate concerning the MODHMS code, and that is that it solves a mathematical problem that is "nonlinear". In the case of variable density flow, the nonlinearity of the system arises because the density of groundwater at some point depends upon the concentration of solute at that point, but the solute concentration is dependent upon the groundwater flow, which in turn depends upon the density, and so on. Nonlinear systems may be solved mathematically using iterative procedures. Iterative procedures require that some tolerance be specified for the dependent variables being solved for (in our case reference heads and concentrations at nodal points). When the differences between the dependent variable values calculated between successive iterations is less than the tolerance, the nonlinear solution is said to "converge" to within that tolerance. If the differences between the values calculated during successive iterates never become smaller than the tolerance, the solution is said to be non-convergent. In many practical cases, one-step steady-state solutions may not converge, and transient time-marching or parameter stepping may be required to achieve a steady-state system.

The parameter stepping scheme uses a series of steady analysis starting from a mildly nonlinear problem that can be solved readily (see for example Herbert et al., 1988). Each successive problem, presumably more nonlinear, can be solved using the latest solution as the initial guess. The time-march approach starts from an initial condition, and the problem is solved by marching through a long period of time until a quasi-steady state is reached. The time-marching method is preferable, since the storage term provides greater stability to the linear matrix solver, which is not achieved by the parameter stepping scheme. To examine how close the final solution was to the true steady-state solution, the final solution was compared with earlier time solutions to detect movement. The mass-balance components were also examined and steady-state was assumed when the storage terms of the mass-balance for flow and transport are small in comparison to the other flux terms.

4.3 MODEL DOMAIN AND DISCRETIZATION

The domain of the Southern District Model (SWFWMD, 2001) includes all of the SWUCA as shown in Figure 4.1. The density-dependent saltwater intrusion model domain is identical to that of Waterstone Model (Waterstone, 2001b), and is also shown superimposed over the Southern District Model domain in Figure 4.1. The regional grid is uniform with nodal spacings of 5,000 by 5,000 feet (Figure 4.2). Such spacings are rather coarse when used to predict the transient movement of chlorides. In view of this, the density-dependent model grid was finer and consists of 103 columns and 123 rows with spacings that range from 2,500 to 5,000 feet (Figure 4.3). The 2,500 foot spacing within the density-dependent model is over the primary area of interest. The grid is deformed in the vertical direction to conform with formation geometries and topography.

As previously discussed in Section 2.0, groundwater flow occurs in three principal aquifers; the unconfined surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer. The Upper Floridan aquifer contains two productive zones, the upper productive zone (corresponding to the Suwannee Limestone) and the lower productive zone (corresponding to the Avon Park Formation), separated by the confining units of the Ocala Limestone. Two intermediate confining beds restrict vertical movement of groundwater between the overlying surficial and underlying Floridan Aquifers. The upper intermediate confining bed limits flow between the surficial and Intermediate Aquifers. The lower intermediate confining bed restricts flow between the Intermediate and Upper Floridan aquifers. The intermediate aquifer itself is divided vertically into two water producing zones separated by confining beds. The Southern District Model (2001), divides this hydrogeologic system into 5 model layers as shown in Figure 4.4, to represent the surficial, the two intermediate aquifer productive units, and the upper and lower productive zones of the Upper Floridan aquifer respectively.

To accurately simulate the migration of saltwater using MODHMS, the thickness of aquifers and aquitards must be explicitly assigned in the model, and hydraulic conductivity values must be assigned to each hydrostratigraphic unit. Because transmissivities (i.e., hydraulic conductivity multiplied by thickness), rather than hydraulic conductivities and thicknesses are assigned in the Southern District Model, the thicknesses of the aquifers and confining units could not be obtained from the Southern District Model data files for input into the density-dependent model. The Waterstone Model (Waterstone, 2001b) includes generalized thicknesses and top/bottom elevations of the various hydrogeologic units. A comparison was made between the thicknesses provided in the Waterstone Model (Waterstone, 2001b) and several geologic cross sections constructed through the local model area. Barcelo and Basso (1993) present a series of cross sections and SWFWMD (1993) show similar cross sections. Basso (2001) also presents cross sections and isopach maps of the aquifers and confining units within the ETBWUCA. The hydrostratigraphy assigned in the Waterstone Model (Waterstone, 2001b) are consistent with the information provided in the cross sections and were used to construct the density-dependent model.

Vertical discretization of the density-dependent model is identical to that of the Waterstone Model (Waterstone, 2001b) and consists of 10 layers as shown in Figure 4.5. These layers conceptualize the Upper Floridan Aquifer system with explicit representation of the Suwannee Limestone, Ocala Limestone and Avon Park Formation, which are subdivided into 2, 3 and 5 finite-difference layers, respectively. The two upper units (i.e., Suwannee and Ocala) are equally divided and the Avon Park Formation has greater resolution in the uppermost layers (model layers 6 and 7) relative to the bottom model layers (8-10). The surficial aquifer system and intermediate confining units are incorporated into the density-dependent model via boundary conditions (Section 4.4).

The geometry of the hydrostratigraphic units assigned in the current model (i.e., top and bottom elevations) was adopted from the Waterstone Model (Waterstone, 2001b). During their modeling investigation, Waterstone estimated the top and bottom elevations for all of the hydrostratigraphic units based on lithologic data provided by the SWFWMD and information presented by Basso (2001). The uppermost formation in the current density-dependent model is the Suwannee Limestone. The Suwannee Limestone varies in thickness from less than 200 feet in central Hillsborough County to about 300 feet in northern Sarasota County (SWFWMD, 1993). The isopach map for the Suwannee Limestone as extracted from the Waterstone Model (Waterstone, 2001b) is shown in Figure 4.6. Figure 4.6 is essentially the difference between Figures 2.6 and 2.8. As shown in the figure, the Suwannee Limestone is thinnest in the east and thickens to approximately 465 feet along the western model boundary. Underlying the Suwannee Limestone are the Ocala Limestone and Avon Park Formation. Over the modeled area the Ocala thickens from approximately 200 feet in the northeast to approximately 800 feet thick in the southwest as shown in Figure 4.7. Figure 4.7 was created from the Waterstone Model (Waterstone, 2001b) files as a difference between Figures 2.8 and 2.9. Underlying the Ocala Formation is the soft to hard, chalky, cream to brown fossiliferous Avon Park Formation. The total thickness of the Avon Park Formation in the model area varies from approximately 400 to 710 feet as shown in Figure 4.8 which is the difference between the elevations of Figures 2.9 and 2.11. The evaporite zone within the Avon Park Formation is considered to be the bottom of the Upper Floridan aquifer, and the bottom of the model domain.

4.4 BOUNDARY CONDITIONS

4.4.1 Upper Boundary

As shown in Figure 4.4, the Southern District Model (SWFWMD, 2001) includes the unconfined surficial aquifer system (Layer 1) as well as two water-bearing zones in the intermediate aquifer system (Layers 2 and 3). Instead of assigning precipitation recharge rates throughout the Southern District Model (SWFWMD, 2001) a constant head boundary condition, representing the water table was assigned in the uppermost layer (i.e., corresponding to the surficial aquifer system) of the model. Rather than explicitly incorporating the surficial and intermediate aquifers system into the density-dependent model, vertical flow through these aquifers is simulated by specifying a general head boundary (GHB) condition at the top of the UPZ (Layer 1 of the density-dependent local model). This approach is justified because the hydraulic conductivities of these intermediate aquifer system units are much smaller than those of the underlying Floridan aquifer system. Therefore, the hydraulic heads for the surficial aquifer system in the Southern District Model (SWFWMD, 2001) were used in conjunction with the leakance values assigned in the Southern District Model to represent the intermediate aquifer system (including confining units within the surficial aquifer system and two intermediate confining beds) to specify the general head boundaries. Figure 4.9 shows the head and conductance values of the general head boundary. The head values represent surficial aquifer system heads (extracted from the Southern District Model (SWFWMD, 2001), while the conductances were computed on a cell-by-cell basis as follows:

$$GHB_{cond} = 1/(1/L_1 + 1/L_2 + 1/L_3) * A_{Cell}$$

where

GHB_{cond} (ft^2/d)	=	The GHB conductance term between the Surficial Aquifer and Suwannee Limestone.
L_1 (1/d)	=	Leakance for Layer 1 (surficial aquifer) in the Southern District Model (Figure 2.3).
L_2 (1/d)	=	Leakance for Layer 2 (intermediate aquifer and confining unit) in the Southern District Model (Figure 2.4).
L_3 (1/d)	=	Leakance for Layer 3 (intermediate aquifer and confining unit) in the Southern District Model (Figure 2.5).
A_{Cell} (ft^2)	=	corresponding cell area in density-dependent model (Figure 4.3).

The exclusion of the surficial and intermediate aquifer systems facilitate the calibration of the density-dependent model (Section 5.0) by increasing the computational efficiency of the model. The justification for this approach is based upon the insensitivity of the water table to stresses within the lower artesian aquifers as evidenced by the fact that long-term and annual variations in water levels in the surficial aquifer are small compared to water level fluctuations in the Upper Floridan aquifer (Barcelo and Basso, 1993).

4.4.2 Lateral Boundaries

The pre-development heads simulated by the Southern District Model (SWFWMD, 2001) were used to provide prescribed head boundaries along the northern, southern and eastern faces of the density-dependent model. Prescribed heads along these boundaries were assigned to the Suwannee Limestone (Southern District Model Layer 2), and to the model layers that comprise the Avon Park Formation (Southern District Model Layers 6 though 10). The Ocala Limestone acts as a semi-confining unit within the modeled area and flow is predominantly vertical through this unit.

Therefore, prescribed head boundaries along the northern, southern and eastern faces of the Ocala Limestone were deemed unnecessary.

The western boundary conditions are also specified as constant heads (prescribed heads) and are in hydrostatic equilibrium with the Gulf of Mexico. These heads were adjusted during the model calibration process (Section 5.0). Theoretically, either hydraulic heads or water fluxes could have been applied along the lateral boundaries. The appropriateness of the constant head boundaries, particularly for the transient post-development simulations, was further evaluated during the model calibration process.

4.4.3 Lower Boundary

The lower boundary was chosen as the top of the middle confining unit of the Floridan Aquifer system. This is generally associated with the first occurrence of intergranular evaporites near the base of the Avon Park Formation (Barcelo and Basso, 1993). Because of the very low permeability in this part of the flow system, the bottom boundary was simulated as a no-flow boundary. This is consistent with all other modeling studies that have been conducted within the SWUCA.

4.5 PRELIMINARY MODEL PARAMETERIZATION

Hydraulic Conductivity

As discussed above, the modeling approach which was used by SWFWMD to perform the regional groundwater flow simulations requires transmissivity values as input for each of the aquifers and confining units. To accurately predict chloride transport through the aquifer, however, the two components of transmissivity (i.e., aquifer or confining unit thickness and hydraulic conductivity) must be explicitly defined using the following equation:

$$K_h = T/b$$

Where

K_h = aquifer layer horizontal hydraulic conductivity (ft/day)
T = aquifer layer transmissivity derived from the Southern District Model (ft^2/day)
b = aquifer layer thickness

Initial values for hydraulic conductivity of the aquifer layers and confining units were derived from calibrated transmissivity and leakance values that were assigned to the Southern District Model. These values may be slightly altered, however, during the future model calibration (Section 5.0), to honor the chloride transport physics and chloride data as well as the head data which alone were used to calibrate the regional groundwater flow model.

It was assumed that horizontal hydraulic conductivity is isotropic in all model layers. That is, horizontal hydraulic conductivity was assumed to be equal in the row and column directions. No regional-scale data on horizontal anisotropy exists within the model area, and the assumption of isotropic conditions is consistent with previous models. A horizontal to vertical anisotropy of 100:1 is assumed for the aquifer units (i.e., the Suwannee Limestone and the Avon Park Formation). The vertical hydraulic conductivity of the Ocala Limestone was initially computed from the appropriate leakance of the Southern District Model, and Ocala Limestone thickness. However, since the leakance of the Southern District Model was a uniform value, its manipulation with non-uniform thickness provided spatially varying vertical hydraulic conductivities. This was deemed difficult to justify from sparse available measurements, therefore, a uniform vertical conductance of 0.2 ft/d was adopted early in the calibration process. It was noted that this conversion did not significantly affect simulated heads, flows or chlorides. A value of 2 ft/d was provided for the horizontal hydraulic conductivity of the Ocala Limestone. The horizontal conductance of the Ocala Limestone is much smaller than for the Avon Park Formation and the Suwannee Limestone with smaller total thickness, therefore the consequences of a uniform 2 ft/d horizontal hydraulic conductivity for the Ocala Limestone on horizontal flow through the system is minimal.

Suwannee Limestone

The transmissivity of the Suwannee Limestone assigned in the Southern District Model is shown in Figure 2.7. This transmissivity was divided by the thickness of the Suwannee Limestone (Figure 4.6) and input into the density-dependent model as horizontal hydraulic conductivity (Figure 4.10).

Ocala Limestone

In the Southern District Model the Ocala Limestone is treated in a quasi-three-dimensional manner, with leakance supplied across its thickness. A uniform leakance value of 10^{-2} ft/day was used throughout the domain. A uniform leakance value with varying thickness would produce a varying vertical conductivity for the Ocala Limestone, which would be difficult to justify based on available data. Therefore, a uniform value of hydraulic conductivity was used for the Ocala Limestone with horizontal conductivity of 2 ft/d and a vertical conductivity value of 0.2 ft/d. The vertical conductivity value is an average of available data. The horizontal conductivity value is not significant to the model because it is much smaller than the horizontal conductivity of the adjacent aquifer units of the Upper Floridan aquifer.

Avon Park Formation

The horizontal hydraulic conductivity of the Avon Park Formation (Figure 4.11) was derived by dividing the transmissivity of the Ocala Limestone/Avon Park Formation in the Southern District Model (Model Layer 5) (Figure 2.10) by the aquifer thickness of the Avon Park Formation in the Waterstone Model (Waterstone, 2001b) (Figure 4.8). This approach assumes that the Ocala Limestone does not contribute significantly to the transmissivity assigned to the Ocala Limestone/ Avon Park Limestone in the Southern District Model. Based upon the low hydraulic conductivity of the Ocala Limestone, this assumption is reasonable.

4.6 SOUTHERN DISTRICT MODEL TRANSLATION

The density-dependent saltwater intrusion study was initiated by first translating the regional model parameters and local model boundary conditions from the Southern District Model (SWFWMD,2001). A pre-development, steady-state groundwater flow simulation was then performed using MODHMS to evaluate the resultant hydraulic heads. This simulation was conducted in order to compare the hydraulic head distribution simulated using the local-scale MODHMS model to the hydraulic head distribution simulated using the regional MODFLOW model. The primary goals of this initial simulation were threefold: (1) to ensure that the input parameters and boundary conditions assigned in the local-scale model were consistent with the Southern District Model; (2) to detect errors in the model input files; and (3) develop the framework of the coupled flow and transport model, which will be calibrated to transient hydraulic heads and chloride distributions. For this simulation, pre-development steady-state conditions were evaluated by turning off all pumping and injection wells and the aquifer system was assumed to be free of saltwater. Parameter values and boundary conditions were derived from the regional groundwater flow model, of pre-development conditions. The pre-development modeling results (without saltwater) are shown for the Avon Park Formation (i.e., model layer 8) in Figure 4.12. The pre-development potentiometric surface for the Ocala Limestone/Avon Park Formation as predicted by the Southern District Model (SWFWMD, 2001) (i.e., model layer 5) is also presented in Figure 5.1. A comparison of the hydraulic heads simulated using both the regional and local-scale models indicates that the simulation results are in excellent overall agreement. The hydraulic head distributions calculated for the other model layers within the Upper Floridan aquifer also compare well with the Southern District Model.

4.7 SALTWATER TRANSPORT PROPERTIES

Since MODHMS simulates both freshwater and saltwater, additional data not contained in the Southern District Model files were required to complete simulations. The additional fluid and aquifer parameters required for this study are summarized in Table 4.1.

A key component in reliably evaluating density-dependent saltwater intrusion is the dispersivity of the various materials in the system. Due to large anisotropies between the horizontal and vertical directions, the dispersivities used in this system should reflect these anisotropies. The 4-component anisotropic dispersivity tensor of Guvanasen (2002) provides adequate control for such systems. The longitudinal and transverse dispersivities in the horizontal direction control dispersion due to horizontal flow in the longitudinal and horizontal transverse directions. The longitudinal and transverse dispersivities in the vertical direction control dispersion due to the vertical flow component, and vertical transverse dispersion due to horizontal flow, respectively. Typically, the vertical components of dispersivity are an order of magnitude lower than the corresponding horizontal components for three-dimensional anisotropic systems, since the mixing effects in the vertical direction are smaller than those of the horizontal direction. Using a 2- or 3-component dispersivity tensor for such systems tends to smear the transport species over the entire thickness of the modeled unit, and thus misrepresents the saltwater intrusion, causing further errors in the density-dependent flow term. Initial estimates of dispersivity coefficients for this study were taken from the Waterstone Model (Waterstone, 2001b) as shown in Table 4.2.

5.0 MODEL CALIBRATION

Model calibration is the process where model parameters and/or boundary conditions are adjusted to obtain a satisfactory match between observed and simulated conditions. Typically, the objective of model calibration is to develop a model that is capable of accurately predicting past, current, and/or future conditions. A model is calibrated by determining a set of parameters, boundary conditions, and hydraulic stresses that generate simulated potentiometric surfaces, fluxes and concentrations that match field-measured values to within an acceptable range of error. The end result of the process of model calibration is an optimal set of parameter values and boundary conditions that minimize the discrepancy between modeling results and the observed data.

The following sections detail the model calibration process that was completed as part of the current saltwater intrusion modeling investigation.

5.1 MODEL CALIBRATION STRATEGY

5.1.1 General Calibration Approach

At the beginning of the calibration process, model calibration goals were formulated in order to produce a model that accomplishes the project objectives outlined in Section 1.2, while recognizing the inherent uncertainties and limitations of the saltwater intrusion model. The primary limitations associated with the saltwater intrusion model are mainly caused by data uncertainties, resulting from the use of discrete borehole data to characterize subsurface conditions on a regional basis. Due to the size of the model domain and the spatial distribution of field data, hydraulic properties and boundary conditions are estimated over relatively large areas in the model, and small-scale heterogeneities cannot be represented. Therefore, the model is best suited to simulate groundwater flow patterns and chloride concentrations on a regional basis. This supports the primary objective of the model, which is to predict the large-scale impact of groundwater management options on saltwater intrusion.

The calibration strategy was designed to produce a model that is capable of simulating the general groundwater flow patterns and regional trends in chloride concentration. Consistent with this goal, model parameter values and boundary conditions were not adjusted beyond the limits of field measurements solely for the purpose of improving the calibration results. In addition, the principle of parameter parsimony was applied as a fundamental philosophy during the calibration. This rule dictates that the model should be calibrated with the fewest number of model parameters that are supported by field data or other supporting evidence. The use of excessive model parameters or parameter zones during model calibration creates a situation in which many combinations of model parameter values will produce equivalent calibration results. By following the principle of parameter parsimony, the goal is to reduce the degree of nonuniqueness and obtain a result which yields more reliable calibrated parameter values. The information gathered for the conceptual model guides any decision to add model parameters (e.g., zones of hydraulic conductivity) or change parameter values during the calibration process. Therefore, in the absence of hydrogeologic evidence that supports the inclusion of additional zones, the simpler model is preferred even at the expense of matching the calibration targets more closely. Although this approach may not result in the model that produces the best fit to the available data (i.e., calibration targets), it does, however, allow areas of greatest data uncertainty to be identified and targeted for future field work.

An iterative, two-phased approach was used to calibrate the local-scale, saltwater intrusion model. This involved the following:

- Pre-development Calibration (Phase 1): Calibration of the model to match hydraulic heads and chloride concentrations associated with pre-development conditions (i.e., year 1900); and

- Post-development Calibration (Phase 2): Transient calibration of the model to match hydraulic heads and chloride concentrations associated with post-development conditions (i.e., 1900 through 2000).

The first phase of the calibration process involved using MODHMS to simulate density-dependent groundwater flow and saltwater transport to reproduce pre-development conditions. During the calibration process, hydraulic parameters, transport parameters, and boundary conditions were adjusted, and the model results were compared to: (1) a map illustrating the development potentiometric surface in the Upper Floridan aquifer (Johnson et al., 1980); and (2) pre-development chloride concentrations simulated during previous saltwater intrusion modeling investigations (HydroGeoLogic, 1994a, 1994b, 1994c, 1993a, 1991a). Hydraulic head and chloride concentration data are not available for the pre-development period (i.e., approximately 1900); consequently, a rigorous, quantitative calibration was not performed during this phase of the calibration. However, estimates of the pre-development potentiometric surface was constructed by Johnston et al., (1980) and provided a qualitative means to check the pre-development calibration.

During the second phase of the calibration process, MODHMS was used to simulate transient, coupled groundwater flow and saltwater transport. These transient simulations were performed to simulate hydraulic heads and chloride concentrations from year 1900 (i.e., pre-development conditions) through December 2000. During the transient calibration, simulated hydraulic heads and chloride concentrations were compared to field data measured between 1993 and 2000. During the second phase, parameter values, model layering and boundary conditions were adjusted to allow the model to fit the calibration criterion discussed in detail in Section 5.1.2. The following sections describe the calibration process in greater detail.

5.1.2 Pre-Development Calibration

Prior to initiating the pre-development calibration, the local-scale model was revised to simulate coupled groundwater flow and saltwater transport. This involved the following:

- Assignment of constant chloride concentration boundary conditions along the lateral boundaries of the model:

- Specification of initial chloride concentrations throughout the model domain; and

- Assignment of transport properties within the model domain (e.g., porosity, dispersivities, fluid density, etc.).

The initial chloride concentrations that were assigned in the model were estimated based on observed chloride concentrations. Likewise, the preliminary chloride concentrations assigned to the constant concentration boundary conditions were also based on field data. These boundary conditions were adjusted along with transport properties, groundwater flow parameters, and constant head boundary conditions during the model calibration process described in Section 5.2.

Due to convergence problems that were encountered during preliminary simulations, the time-marching method described in Section 4.2 was applied during the pre-development simulations. To examine how close the final solution was to the true steady-state solution, chloride concentrations calculated for the last time step were compared to chloride concentrations calculated for earlier time steps. The solution was deemed to represent steady-state conditions when there were insignificant changes in chloride concentrations and when the storage terms of the mass-balance for flow and transport were small in comparison to the other flux terms.

The objective of the pre-development calibration was to simulate steady-state groundwater flow conditions and chloride concentrations for the period prior to the development of groundwater resources (i.e., approximately 1900). Because conditions that existed during this time are not known with certainty, a rigorous, quantitative calibration could not be completed. Instead, a qualitative calibration was completed, which involved the adjustment of model parameters and boundary conditions to match the following: 1) potentiometric surface contours estimated by Johnson et al., 1980; and 2) the lateral and vertical extent of chloride predicted for pre-development conditions during earlier investigations.

As discussed in Section 3.0, the distribution of chloride for pre-development conditions was estimated during several modeling investigations (HydroGeoLogic, 1994a,1993a,1991a). During the pre-development calibration, the chloride concentrations predicted by the current saltwater intrusion model were compared to the distribution of chloride presented in Figures 2.16 and 3.1. Because direct observations are not available for pre-development conditions, there is significant uncertainty in the distribution of chloride shown on these figures. Consequently, the goal of the pre-development calibration was to match the general pattern shown on the figures. A similar approach was adopted for calibrating the model to the inferred pre-development potentiometric surface contours developed by Johnson et al. (1980). The goal was simply to match the general shape of the contours.

5.1.3 Post-Development Calibration

During the second phase of the calibration process, the model was calibrated to post-development conditions (i.e., post-1900). To investigate the impact of groundwater withdrawals on the flow system, hydraulic heads and chloride concentrations were simulated for a period extending from approximately 1900 (i.e., pre-development conditions) to 2000. During these simulations, the hydraulic stresses associated with pumping were simulated by making two modifications to boundary conditions assigned in the model. First, the lateral boundaries of the model were modified to reflect the post-development hydraulic heads resulting from regional groundwater production. The post-development hydraulic heads that were assigned as lateral boundary conditions in the density-dependent model were derived from hydraulic heads simulated using the Southern District Model (SWFWMD, 2001). Secondly, groundwater extraction rates associated with production wells were assigned throughout the model. The groundwater extraction rates assigned in the model were based on the estimated water use for the area, and derived from the pumping/ injection well data compiled by the SWFWMD and represented in the Southern District Model (SWFWMD, 2001).

To complete the simulations, landward lateral boundary heads and well pumping rates were varied every 5 years for the first 60 years, with yearly variations for the next 15 years, followed by variations every 4 months up to December 2000. Boundary heads were obtained using the hydraulic head fields developed by performing parallel transient simulations using the Southern District Model (SWFWMD, 2001) constructed by the SWFWMD. The location and model layer of the groundwater extraction/injection wells within the density-dependent model domain are shown in Figure 5.1. These wells were represented in the local-scale saltwater intrusion model using an analytic element boundary condition. This type of boundary condition allows the water, entering the well from multiple model layers, to be proportioned based upon the hydraulic properties of the respective model layers.

Both quantitative and qualitative methods were employed to calibrate the local-scale saltwater intrusion model to post-development conditions. As part of this effort, the following data were used as the primary calibration targets:

- Chloride data collected as part of the Regional Observation Monitoring Well Program (ROMP);
- Chloride data collected as part of the Water Quality Monitor-Well Program (WQMP); and
- Potentiometric surface maps prepared by the USGS (2001) for the Upper Floridan aquifer.

Chloride data collected as part of the Regional Observation Monitoring Well Program (ROMP) provided the primary data set that was used to calibrate the saltwater intrusion model to post-development conditions. The ROMP data differs from other sources of chloride data in that it characterizes both the spatial and vertical distribution of chloride through a large number of exploratory wells (Figure 2.15). This data generally characterizes the distribution of water quality with depth at a single location during a single sampling event. The ROMP data is collected using a variety of sampling methods including bailers, thief samplers, and packer tests. The locations of the ROMP wells that were used for determining model calibration statistics are shown in Figure 5.2. These wells lie in the central portion of the model domain within the primary areas of interest. Since the data quality at a number of the ROMP wells is questionable, only the ROMP data identified by the SWFWMD as being of high quality were used for this investigation. Chloride concentrations with depth for each of these ROMP wells are presented in the Appendix B.

Chloride data collected as part of the WQMP were used to augment the ROMP data during the model calibration. Under the WQMP, the SWFWMD routinely samples and analyzes groundwater to monitor potential saltwater migration. This data is collected by the SWFWMD primarily from dedicated monitoring wells. The WQMP data is the best source of temporal chloride data within the coastal region of the SWUCA.

In addition to chloride data, the model was calibrated to hydraulic head data compiled by the USGS, which develops potentiometric surface maps for the Floridan Aquifer for September and May of each year. Typically, these represent the annual water-level low and high periods, respectively. During the post-development calibration, simulated hydraulic head distributions were compared to potentiometric surface maps developed for May and September 2000. This time period was selected, because it is the most recent time period in which hydraulic head data were available during this investigation.

Using the data described above, several measures were used to calibrate the saltwater intrusion model to post-development conditions including the following:

- Visual comparison of vertical profiles illustrating simulated chloride concentrations and chloride concentrations (using data from WQMP and ROMP wells);
- Statistical comparison of simulated chloride concentrations and chloride concentrations observed at the ROMP wells (using data from WQMP and ROMP wells);
- Plots illustrating the relationship between simulated chloride concentrations and chloride concentrations obtained from ROMP wells;
- Visual comparison of the predicted chloride distribution to maps illustrating the current extent of saltwater;
- Visual comparison of observed and temporal changes in chloride concentrations (using WQMP data); and
- Visual comparison of potentiometric surface maps developed using observed and simulated hydraulic head data (i.e., using potentiometric surface maps developed by the USGS for year 2000).

The vertical chloride profiles provided the most useful calibration measure to evaluate the model's ability to reproduce post-development conditions. The profiles that were used during the calibration are presented in Appendix A. The vertical profiles provided a mechanism to evaluate the slope, thickness, width, and depth of the saltwater interface. The ROMP wells provided the majority of the data that were used to develop the vertical profiles. However, the vertical profiles also included limited data that were collected as part of the WQMP.

A more quantitative assessment of the calibration was completed using statistical measures describing the relationship between simulated chloride concentrations and chloride concentrations observed at selected ROMP wells. The primary criterion for evaluating the calibration of a groundwater transport model is the difference between simulated and observed chloride concentrations at a set of calibration targets (typically monitoring wells). A residual or model error, e_i, is defined as the difference between the observed and simulated chloride concentrations measured at a target location:

$$e_i = c_i - \hat{c}_i$$

where c_i is the measured value of chloride concentration and $\hat{c}_i$ is the simulated value at the ith target location (i.e., at an individual ROMP wells). A residual with a negative sign indicates over-prediction by the model (i.e., the simulated chloride concentration is higher than the measured value). Conversely, a positive residual indicates under-prediction.

Several statistical measures were used to gauge the success of the model calibration. During the calibration process, an objective was to minimize the residual sum of squares (RSS) while still honoring the field data:

$$RSS = \sum_{i=1}^{n} (e_i)^2$$

where n is the total number of calibration targets. The RSS is a primary measure of model fit. The root mean squared (RMS) error, which normalizes the RSS by the number of calibration targets, is defined as follows:

$$RMS = \sqrt{\frac{RSS}{n-1}}$$

Another calibration measure that was used to evaluate the calibration is the residual mean:

$$\bar{e} = \frac{1}{n}\sum_{i=1}^{n} e_i$$

A mean residual significantly different from zero indicates that the model produces biased results (i.e., over-predicts or under-predicts chloride concentrations).

The chloride concentrations observed at the ROMP wells represent a small, discrete vertical interval within a given hydrostratigraphic unit. The groundwater samples taken from the ROMP wells represent a much smaller interval than the thickness of the finite-difference cells in which chloride concentrations are calculated using the saltwater intrusion model. In fact, for each finite-difference cell containing a ROMP well, there are typically multiple observed chloride concentrations associated with different depth intervals. In order to compare the observed and calculated chloride concentrations, average observed chloride concentrations were calculated for each model layer associated with a ROMP well location, and the residuals were calculated by subtracting the simulated chloride concentration at each finite-difference cell from the average chloride concentrations obtained from the ROMP wells. This averaging, however, produced inherent errors within the statistical analysis which are accentuated due to the sharp increases in chloride concentrations over short intervals. A vertical refinement of the numerical grid would probably result in better calibration statistics, although it would probably have little impact on the overall characteristics of the chloride distribution.

After a review of the existing data, and conversations with the SWFWMD regarding the quality of the well data, sixteen ROMP wells were selected for the statistical analysis. As shown in Figure 5.2, the majority of the wells are located over the primary area of interest, within the west central portion of the model domain within the chloride interface zone. Several of these wells are closely spaced, and aligned in an east-west orientation (e.g., TR AB-1, TR 9-2, TR AB-3). The data from these wells provided a means to evaluate the slope of the chloride interface during the model calibration.

In addition to the statistical evaluation of model residuals and the visual comparison of model results to vertical chloride profiles, maps were developed to evaluate the reliability of the calibration. A comparison between contour maps of measured and simulated values (i.e, hydraulic heads and chloride concentration) were prepared to provide a visual, qualitative measure of the similarity between patterns, thereby giving some idea of the spatial distribution of calibration errors. In addition, vertical and horizontal hydraulic heads and the fluid flux moving across the model boundaries were used as qualitative calibration criteria.

5.2 MODEL CALIBRATION IMPLEMENTATION

Section 4 describes in detail the approach used to construct the preliminary density-dependent groundwater flow and solute transport model to simulate saltwater intrusion in coastal portions of the SWUCA. The sections that follow primarily describe the changes and refinements that were made during the calibration process.

5.2.1 Evaluation of Alternative Conceptualizations and Uncertainty

One primary goal of mathematical modeling is to synthesize the conceptual model into numerical terms from which flow and transport processes may be investigated under specified conditions. This process entails several discrete steps: (1) partitioning the conceptual model into units of time and space; (2) assignment of boundary conditions; and (3) specification of the parameter values. There are always uncertainties in predictions derived from modeling. These uncertainties are frequently divided into two main categories: (1) conceptual model uncertainty; and (2) parameter uncertainty. This section briefly describes these uncertainties and the approach that was applied to address these uncertainties in the model calibration process.

The conceptual model is based on the modeler's knowledge, experience and technical judgment and represents the modeler's understanding of the system framework and behavior, from all available data and information at the site. The conceptual model will naturally become more complex as more processes are identified and interrelationships of important components within the system are considered. The transformation of the conceptual model into a mathematical model is a further extrapolation of the basic understanding of the system into a discretized numerical framework resulting in intrinsic simplifications of the system. The lack of knowledge about the system resulting from limited information also contributes to inevitable simplifications in the conceptual and mathematical models, in the sense that spatial correlations or zoning of material properties may not represent existing conditions.

As part of the model calibration process, a series of hypotheses were developed and numerical experiments were performed to address aspects of the conceptualization or parameterization that could improve model performance during the model calibration. Table 5.1 provides several significant results of these analyses.

5.2.2 Calibrated Model Domain and Discretization

As described in Section 4.0, the initial local-scale model consisted of 10 layers of finite-difference cells. During the model calibration process, an additional model layer was added to the base of the model to allow chloride transport through the Middle Confining Unit (i.e., evaporites) to be explicitly simulated. The vertical discretization of the calibrated density-dependent model consists of 11 layers as shown in Figure 5.3. This additional layer provides the necessary mechanism to more adequately simulate chlorides entering the Avon Park Formation from the evaporites below.

5.2.3 Calibrated Boundary Conditions

Upper Boundary

As presented in Section 4.4, rather than explicitly incorporating the surficial and intermediate aquifer system into the density-dependent model, vertical flow through these aquifers is simulated by specifying a general head boundary condition at the top of the Suwannee Limestone (model layer 1). This conceptualization was maintained throughout the model calibration and the upper boundary and its values were unchanged from those presented in Figure 4.9. The exclusion of the surficial and intermediate aquifer system facilitated the density-dependent model calibration by increasing the computational efficiency of the model, and is justified based upon the insensitivity of the water table to stresses within the lower artesian aquifers as evidenced by the fact that long-term and annual variations in water levels in the surficial aquifer are small compared to water level fluctuations in the Upper Floridan aquifer (Barcelo and Basso, 1993).

Lateral Boundaries

The pre-development and post-development heads simulated using the Southern District Model (SWFWMD, 2001) were used to develop prescribed head boundaries along the northern, southern and eastern faces of the density-dependent model (Section 4.4). Prescribed heads were assigned along these boundaries in model layers representing the Suwannee Limestone (model layers 1&2) and Avon Park Formation (model layers 8,9 and 10). The Ocala Limestone acts as a confining unit within the modeled area and flow is predominantly vertical through this unit. Therefore, prescribed head boundaries along the northern, southern and eastern faces of the Ocala Limestone were deemed unnecessary. The northern, southern, and eastern lateral boundary heads presented in Section 4.4 were unchanged for the final calibration simulation. Figure 5.4 shows the boundary conditions that were applied to the lateral boundaries of the density-dependent model.

The western boundary conditions are also specified as constant heads (prescribed heads) and were originally derived from the heads calculated in the Southern District Model (SWFWMD, 2001). These heads are based on assumptions pertaining to the relationship between the pressure head within the aquifers and the hydrostatic head within the ocean. Therefore, in the calibrated model the heads along the western boundary are set to zero in the uppermost layer and increase with depth to account for chloride density.

During the post-development calibration, the hydraulic stresses associated with pumping were simulated by making two modifications to boundary conditions assigned in the predevelopment model. First, the landward lateral boundaries of the model were modified to reflect the post-development, transient hydraulic heads resulting from regional groundwater production. These boundaries were modified based on the results of transient simulations performed using the Southern District Model (SWFWMD, 2001). These transient effects on the head boundaries are obtained from parallel transient simulations made with the Southern District Model (SWFWMD, 2001) by the SWFWMD and representative variations in the north and southeast corners of the model domain as illustrated in Figure 5.5. Second, transient groundwater extraction rates associated with production wells were assigned throughout the model.

A relative chloride concentration of one was applied along the western lateral boundary and along seaward portions of the northern and southern lateral boundaries. These boundaries for concentrations are prescribed for all inflow nodes. The option in enabled in MODHMS to provide flux boundaries at outflow nodes along this boundary.

Lower Boundary

The lower boundary for the calibrated model is located between 200 and 400 feet below the top of the middle confining unit of the Floridan Aquifer system. A general head boundary (GHB) condition was applied along this boundary. A uniform environmental head of 40 feet and a vertical conductance of 0.001 ft/day was assigned to all general head boundary conditions. Concentrations assigned to the general head boundary conditions are variable and range from 5,700 mg/l along the eastern boundary to 19,000 mg/l at the ocean (Figure 5.6). This concentration distribution does not significantly affect results as compared with applying a uniform 19,000 mg/L concentration, however, the distributed concentration boundary was adopted in the calibrated model to honor available data.

5.2.4 Calibrated Model Parameters

Groundwater Flow Parameters

As discussed in Section 4, initial values for hydraulic conductivity of the aquifer layers and confining units were derived from calibrated transmissivity and leakance values that were assigned to the Southern District Model (SWFWMD, 2001). This approach was adhered to during the model calibration process.

A uniform vertical conductivity of 0.02 ft/d was applied to the Ocala Limestone to conform with average measurements. It is assumed that horizontal hydraulic conductivity is isotropic in all model layers. That is, horizontal hydraulic conductivity was assumed to be equal in the row and column directions. Regional-scale data related to horizontal anisotropy was not available for the modeled area, and the assumption of isotropic conditions is consistent with previous models. A vertical to horizontal anisotropy ratio of 1:100 was applied to all units as discussed in Section 4.

Although the transmissivity assigned to the Avon Park Formation is the same in both the calibrated saltwater intrusion model and the Southern District Model (SWFWMD, 2001), the distribution of hydraulic conductivities among model layers within the Avon Park Formation was altered during model calibration. The Avon Park Formation is now conceptualized as having a highly permeable zone (in model layers 6 and 7) overlying the rest of the formation (model layers 8, 9 and 10). The hydraulic conductivities of these zones are presented in Figure 5.7 (for model layers 6 and 7) and Figure 5.8 (for model layers 8, 9, and 10). This hydraulic conductivity distribution provides an effective transmissivity for the Avon Park Formation that is identical to that used for the Southern District Model (SWFWMD, 2001), except for under Hillsborough Bay and Tampa Bay where the areal zones of transmissivity have been slightly modified by assigning a more gradational trend.

Saltwater Transport Properties

The values for effective porosity, dispersivity and storativity were adjusted during the model calibration in order to better match the measured field data. In general, lower effective porosities resulted in greater saltwater intrusion due to the increased velocities. Dispersivity values had a dominant effect on the spread and concentrations of the chlorides, with larger dispersivities causing a larger transition zone. The distribution of the post- development hydraulic heads are sensitive to the assigned storativity values. The transport properties that were assigned in the calibrated model are presented in Table 5.2.

5.3 MODEL CALIBRATION RESULTS

5.3.1 Pre-Development Calibration Analysis

As previously presented in Section 5.1.2, the calibration criteria for pre-development conditions are based primarily on the results of earlier modeling work that predicted the location of the saltwater interface shown in Figure 3.1. A comparison of the current modeling work with those earlier results is presented in Figure 5.9. As shown in that figure, the tip of the interface crisscrosses the tip location predicted by the HydroGeoLogic (1994) model. In the southwestern portion of the model the tip makes a sharp turn inland, due most likely to localized boundary effects. The toe of the plume follows the same general shape as that of the previous modeling investigations conducted by HydroGeoLogic, in 1993 and 1994. The most recent modeling, however, predicts greater saltwater intrusion in the northern part of the model domain than the other models and less intrusion from the center of the model southward. The toe location, in the cental portion of the model coincides reasonably well with the location predicted by the cross sectional model of HydroGeoLogic (1991).

Figure 5.10 presents calibrated pre-development potentiometric surface for the Suwannee Limestone (model layer 2) superimposed over the pre-development potentiometric surface prepared by Johnston et. al. (1980). The model is in very good agreement with the estimated hydraulic heads and typically differ by less than 5 feet except in the northeastern region of the model. In a similar comparison, the potentiometric surface prepared by Johnston et. al. (1980) was superimposed over the surface predicted by the model for Avon Park Formation (model layer 7) (Figure 5.11). Again the heads compare favorably and generally there is less than a 5-foot head difference.

5.3.2 Post-Development Calibration Results

After satisfactory pre-development, steady-state chloride concentrations were simulated using the local-scale model, the model was calibrated to conditions observed between 1993 and 2000 by performing transient simulations. The local-scale model was used to simulate conditions from 1900 (i.e., pre-development conditions) through 2000.

Chloride Interface Characteristics

Chloride concentrations with depth have been measured for each of these ROMP wells and are presented in the Appendix B. As discussed in Section 5.1.2, the chloride concentrations predicted by the model were superimposed over the actual field data to visually inspect the ability of the model to simulate the observed vertical and spatial distribution of chloride. A more quantitative assessment of the calibration was performed by computing an average error and a root mean square error for chloride concentrations observed at selected ROMP wells. Since the data quality at a number of the ROMP wells is questionable only the ROMP wells where the data is known to be of high quality were used for this analysis and are shown in Figure 5.12 along with the areal distribution of calibration errors (i.e., residuals). These errors are depicted in three distinct model layers to present the distribution of errors within different aquifer units. It is noted that the model errors are generally unbiased in space. However, the model overestimates chloride concentrations in the deeper layers in the southern coastal regions of the domain and underestimates chloride concentrations in the deeper layers in coastal Hillsborough County.

The calibration statistics are also summarized in Table 5.3 and a scatterplot of measured vs. simulated chlorides is shown in Figure 5.13. The scatterplot presented in Figure 5.13 illustrates that there is not a systematic bias (i.e., underestimation or overestimation) of chloride concentrations within the model domain. This observation is supported by the part that the residual mean (-0.00439) is close to zero. It may be noted from the chloride profiles (Appendix B) that concentrations change over several orders of magnitude within a few hundred feet. As shown in the scatter plot and Table 5.3, the residuals are generally unbiased and tend to be over- and under-estimated with approximately the same degree of frequency. Other observations with respect to the model comparison with the ROMP well data includes the following:

1. A good fit was obtained to the low chloride concentrations inland at ROMP 61, 49, 39, 33, and 22.

2. The model predicted chloride concentrations satisfactorily match observed chloride concentrations in the Ocala Limestone in the north for coastal wells TR AB-1, TR 9-2, TR 9-1, TR AB-3, TR 8-1.

3. Model predictions are low for chloride in the Avon Park Formation in the north at TR AB-1, TR 9-2.

4. The model provides a good fit to chloride concentrations in the Avon Park Formation at coastal well TR 8-1 (northern well south of TR 9-2).

5. A good fit for chloride was obtained in the Ocala Limestone and Avon Park Formation at coastal wells TR 7-2 and TR 7-4 (south of TR 8-1).

6. Model predictions are high in the Ocala Limestone and low in the Avon Park Formation at coastal wells TR SA-1, TR SA-3 (south of TR 7-2).

7. Model predictions for chloride are high in the Ocala Limestone at coastal wells 20, TR 4-1 (south of TR SA-3).

8. The model provides a good fit to chloride concentrations in the Ocala Limestone at inland well 9 near the southern model boundary.

The slope of the chloride interface, that can be calculated from the exploratory data at TR-SA-1 and TR-SA-3 was also used as a calibration measure which was evaluated against ROMP wells TR AB-1, TR 9-2 and TR AB-3 in coastal Hillsborough County. These wells are aligned perpendicular to the coastline and provide a good cross-sectional representation of the interface slope since the interface lies within the sampled interval in all three wells. As shown in Appendix B, the model provides a good depiction of the chloride profiles for these wells, and, hence, of the interface slope.

Another metric applied to the calibration effort was the thickness of the transition zone. It is noted from available data (see Appendix A for chloride data in ROMP wells) that the transition zone is fairly thin with rapid degradation of water quality from fresh to saltwater across the interface. This feature was duplicated by the model in addition to providing a good fit on average chloride data and depth to interface.

As previously discussed in Section 2, Beach and Kelley (1998) projected the freshwater-seawater interface onto hydrogeologic cross sections at six locations along the coast (Figure 2.16). The distance along each cross section to the toe was superimposed onto a map. A smooth line through each toe was drawn delineating the 1,000 mg/l chloride concentration defining the areal extent of the interface between the freshwater and saltwater. This approach was later updated (Beach and Schultz, 2000) by delineating the top and bottom of the highly permeable zone from exploratory drilling data and adding this information to each cross section. Beach and Schultz (2000) determined that the current position of the interface toe in the Avon Park Formation is only two to three miles inland in south Hillsborough County. In Sarasota County, the interface toe in the Avon Park Formation may be as much as ten miles inland. These estimates have been superimposed on the calibrated model results and presented in Figure 5.14. This figure indicates that the model predicts a similar overall shape to the saltwater interface but predicts that the saltwater interface is less inland in the northern and southern portions of the model domain.

The chloride interface in the Suwannee Limestone is shown on Figure 5.15. The calibrated model indicates that there has been almost no saltwater intrusion within the Suwannee Limestone except in the southern portion of the model domain south of Sarasota. Chloride interface for the Avon Park Formation layers 6, 8, and 10 are shown in Figures 5.16 through 5.18, respectively. These figures indicate that chloride intrusion roughly follows the coastal profile and increases with depth in the Avon Park Formation.

To illustrate the changes of chloride concentrations with time, a series of plots have been constructed comparing the model predictions to the actual field data. Figures 5.19 through 24, show the model predicted chloride concentrations versus time, superimposed on field data measured at selected ROMP wells.

The trend of the chloride data in TR-9-3 is relatively stable in the Suwannee Limestone, and sharply increases in the Avon Park (Figure 5.19). The model underpredicts the chloride concentrations in both layers. The trend of the data in the Avon Park illustrates the difficulty in matching the sharp increases in concentrations over short time periods. Although the trend in the model is upward it is not nearly as steep as that observed in the measured data. Some of this difference can be attributed to the fact that the model averages chloride concentrations over grid blocks and cannot simulate the sharp fluctuations in the chloride concentrations, which occur over short intervals. Again, a similar effect is observed in ROMP TR 9-2 (Figure 5.20). TR 8-1 provides a very good match to the data in both chloride concentrations as well as temporal trends (Figure 5.21). Observed chloride concentrations in ROMP 50, however, are significantly overestimated by the model (Figure 5.21), although the tends are similar. ROMP 22 provides a reasonable match to the data, but the increasing trend predicted by the model is not replicated by the field data. The model overestimates the chloride data collected from ROMP 20 (Figure 5.22) and predicts an slightly increasing trend which the data suggests that the chloride concentrations may be decreasing. The model underestimates the observed concentrations in both in ROMP 33 and 39 (Figure 5.23), although at the low chloride concentrations in these wells the differences could represent only minor differences. Figure 5.24 indicates that indicates that the model is slightly over predicts the data from TR SA-1, and significantly over-predicts the data from ROMP TR SA-3.

Although the model did not fit the transient chloride data particularly well, in general, the model provided a much better fit to the static ROMP well data. The greatest source of error aside from the unknown heterogeneities within the aquifer property values, is probably associated with the vertical discretization of the model not being at the same scale as the collected data. Chloride concentrations in the model are averaged over several hundred feet as compared with tens of feet in the field. This inconsistency in scale makes it difficult to precisely match the field data, particularly at high chloride concentrations, without introducing too much chloride to the model. This problem is aggravated because the interface transition zone is relatively thin and concentrations change dramatically over short vertical distances. The model does, however, provides a very good representation of the chloride intrusion characteristics and should provide an adequate means to meet the project objectives of the SWFWMD.

Post-Development Hydraulic Heads

To evaluate the hydraulic response of the calibrated model, a comparison of the calibrated model hydraulic heads was made against the potentiometric surfaces from September 2000 and May 2000 prepared by the U.S. Geological Survey (USGS). Typically, these represent the annual high water level period and the annual low water period, respectively. A comparison between the USGS potentiometric surface for May 2000 and the corresponding model predicted head distribution for the Suwannee Limestone is shown in Figure 5.25. The potentiometric surface constructed by the USGS indicates that the measured head values are lower than the predicted head values by approximately 35 feet in the northeastern portion of the model to about zero feet within the southeastern portion of the model. The measured heads are approximately 5 to 20 feet lower than predicted values in the central portion of the model. The general shape of both contour sets, however, is very similar throughout the model domain.

A similar comparison of May 2000 heads for the Avon Park Formation is presented in Figure 5.26. Again the heads predicted by the model are higher than measured values. The greatest discrepancies between the measured and predicted heads are located in the central and northeast portions of the model domain. The general shape of the potentiometric surface contours for the model versus field data is very similar over the entire model domain, with contours closing around a depression in the potentiometric surface in the central portion of the region.

A comparison between the measured and predicted head values for September 2000 for the Suwannee Limestone and Avon Park Formation are shown in Figures 5.27 and 5.28, respectively. Of particular relevance is that the measured values for May and September vary by about 30 feet over much of the model domain. The predicted heads for the Suwannee Limestone are in reasonably good agreement with measured head contours over most of the model area. As shown in Figure 5.28, the predicted heads in the Avon Park Formation are not as close to the field data but still capture the general shape of the measured potentiometric surface.

The most probable reason for the differences between measured and predicted head values is that there are significant transient hydraulic stresses within the hydrogeologic system which are not captured by the flow model, which uses applying 4-month averaged pumping and boundary conditions. It should be noted that the head responses of the saltwater intrusion model are very similar to that of the transient Southern District Model (SWFWMD, 2001) run with similarly time-averaged pumping conditions.

Another calibration criterion is the head difference between the Suwannee Limestone and the Avon Park Formation for which there is not expected to be an appreciable difference. This assumption is based upon an aquifer test conducted in Manatee County within the Avon Park Formation. During the pumping test, measured water levels in two wells that were open to the different production zones (i.e., Suwannee Limestone and Avon Park Formation) were nearly identical (Guyton and Associates,1976). Figure 5.29 shows the difference between the heads predicted in the Suwannee Limestone verses those in the Avon Park Formation. Over most of the model domain the difference in heads is less than 5 feet. The exceptions to this are along the northeastern and southern boundaries which are local boundary effects.

Mass Balance

The reliability of the model was also assessed during the calibration process by evaluating the computed water balance. The water balance calculated for pre-development conditions using the calibrated model is shown in Figure 5.30 and Table 5.4. The locations of the eastern, southern and northern freshwater boundaries are shown in Figure 5.4 as a series of blue dots. These boundaries were set to prescribed heads as determined from the Southern District Model (SWFWMD, 2001). The lateral saltwater boundaries are designated in Figure 5.4 as green dashes along the northern and southern boundaries and as a solid red line along the western boundary. Information for the drains (i.e., location, depth, conductivity, heads) was derived directly from the Southern District Model (SWFWMD, 2001). The bottom boundary represents the amount of fluid exchange between the Avon Park Formation and the middle confining unit (i.e., evaporites) (Figure 5.3). The top boundary represents the interface between the Tampa and Suwannee Limestone members of the Upper Floridan aquifer (Figure 4.4).

The water balance indicates that during pre-development conditions large volumes of water enter from the eastern freshwater and lateral saltwater boundaries. Appreciable amounts of water also leave the model domain from the lateral, saltwater and top boundaries. Although considerable volumes of water enter the model through the top and bottom boundaries, a significant amount of water leaves the model through the top boundary due to upward gradients over much of the model, particularly in the western portions of the model domain. The total volume of water entering the model domain is essentially equal to that leaving the model.

The computed water balance for post-development conditions (i.e., December 2000) is shown in Figure 5.31 and Table 5.5. The greatest differences between the pre- and post- development water balances are the large volume of water removed by wells during the post development (current) period, although a small amount of water is introduced to the model via injection wells. The stress imposed on the system by the pumping wells considerably alters the head gradients which induces water to flow downward through the upper boundary and laterally from the eastern and saltwater boundaries. Greater amounts of water also enter the domain from the lower boundary during the post development simulations. Water entering the model from the top and bottom boundaries are almost equal. Furthermore, almost no water exits the bottom boundary. The total inflow and outflow for post-development conditions are also in excellent agreement.

6.0 SENSITIVITY ANALYSES

6.1 GENERAL SENSITIVITY APPROACH

The purpose of sensitivity analyses are to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (Anderson and Woosner, 1992). Their significance and use is aptly summarized by ASTM (1994) as:

1. To identify which model inputs have the most impact on the degree of calibration and on the conclusions of the modeling analysis.

2. To categorize the parameter sensitivities in a manner that identifies the predictive capability of the calibrated model for its intended conclusions.

The ASTM (1994) procedures were applied to perform the sensitivity analysis for this study. Where applicable, this process was enhanced to provide a further understanding of system behavior in the presence of uncertainties (ASTM, 1994).

The sensitivity analysis was performed in two parts. The first part was a parameter sensitivity performed by systematically changing the values of the calibrated model parameters or boundary conditions within pre-established reasonable limits. The second part investigated the effects of alternative conceptualizations on the calibrated model. The first step in both parts was to identify the parameters or model inputs that need to be varied during the sensitivity analysis. Then for each parameter, the specified range of variation was determined based on the expected range of observed values (i.e., field data) or conceptual validity. Simulations were subsequently performed over this range for each parameter or conceptualization, for steady-state pre-development and transient post-development conditions. For the current study, the 'most probable high and low' values associated with each parameter or boundary condition were used to perform the sensitivity analyses.

For the parameter sensitivities, the calibration residuals and the results of model predictions of chloride intrusion were graphed as a function of parameter input value for each of the parameters investigated. In this study, the model conclusions were defined as the percentage of pumping wells impacted by chlorides at concentrations exceeding 500 ppm, and the total chloride mass that is contained within the model domain. The first conclusion was selected as a specific model outcome of interest to the SWFWMD, the second being a general conclusion on the state of chlorides within the entire simulation domain. From this set of graphs, the model input parameters that have the most impact on the degree of calibration and on the conclusions, were identified. This set of graphs is also used to categorize parameter sensitivities into four types, which are described below.

Type I sensitive parameters are those which cause insignificant changes in calibration residuals as well as model predictions. Type I sensitivity on a parameter is of no concern, because regardless of the parameter input value (within the predetermined range), the model predictions remain the same. Type II sensitive parameters cause significant changes in the calibration residuals but insignificant changes in the model predictions. Type II sensitivity on a parameter is of no concern because regardless of the value of the input, the model predictions remain the same. Type III sensitive parameters cause significant changes to both calibration residuals as well as the model predictions. Type III sensitivity on a parameter is of no concern because even though the model predictions change as a result of variation in input, the parameters used in those simulations cause the model to become uncalibrated with residuals increasing from the calibrated model that best represents the field conditions. Type IV sensitive parameters cause insignificant changes in calibration residuals but cause significant changes in the model predictions. Type IV sensitivities can have greater uncertainties because over the range of that parameter in which the model can be considered calibrated, the model predictions can change substantially. A Type IV sensitivity generally requires additional data collection to decrease the range of possible values of the parameter (ASTM, 1994).

For the conceptual sensitivities, the calibration residuals and model conclusions are noted along with a general description of notable or significant effects of the conceptual change, compared to the base case calibration simulation (Section 5.2.1). These conceptual changes from the base case correspond to uncertainties in the hydrogeologic system.

6.2 PARAMETER SENSITIVITY ANALYSIS AND RESULTS

A parameter sensitivity analysis was first conducted for the calibrated saltwater intrusion model to identify the model input groups that have the most impact on the model calibration and on the model predictions. The parameters and their range of variation were chosen in collaboration with SWFWMD staff, and are considered to be the important parameters that govern the behavior of saltwater intrusion in the domain. The parameter sensitivity study is summarized in Table 6.1. The first column of the table shows the parameters that were chosen for this sensitivity analysis followed by their selected variations in the second column. The remaining columns summarize calibration statistics and model predictions for the various parameters that were evaluated. The last column categorizes the various parameters into one of the four sensitivity analysis categories (i.e., Type I, II, III, or IV) as defined by ASTM (1994). The first row of Table 6.1 provides results for the calibrated model while subsequent rows discuss the various parameter sensitivities. Figure 6.1 provides significant calibration statistics and the results of model predictions of chloride intrusion for each of the parameter sensitivities. These calibration statistics include those that were evaluated during the model calibration process (i.e., residual mean error and root mean square error (RMS)).

Porosity (Parameter 1) is the most sensitive parameter in terms of the calibration statistics as well as on the conclusions of this study (Type III sensitivity). Since the effect of porosity is mainly to control the transient movement of chlorides, it is possible based on these statistics, to have an error in the pre-development location of chlorides with an associated error on porosity in the same region, to produce the same current conditions for chlorides. Therefore, the possibility of multiple solutions exists, to produce the same calibration, however, within the limits of the assumptions made in the model (uniform porosities of all materials), the calibrated model provides appropriate results for the noted transient behavior as discussed in Section 5.3.2. In fact, it may be noted that the multiplication factor of 2 (see Figure 6.1a) to the base-case porosity values provides a better "calibrated" model with a smaller average error and less spread in the results from observed chloride levels. However, these values are considered to be outside reasonable limits for porosities in the region, and the transient behavior is inferior to that of the calibrated model in terms of depth to chlorides (also used as a calibration measure) and its movement. Finally, on Figure 6.1a, the mass of chlorides in the domain is an inappropriate surrogate measure for the general intrusion of chlorides into the domain, since the porosity value affects volume and hence mass of chlorides within the domain, for the same amount of intrusion.

The second most sensitive parameter is the landward lateral boundary head (Parameter 12) in terms of the calibration statistics and the model predictions (Type III sensitivity). Figure 6.11 shows that the model is well calibrated to this parameter, with an increase in the average error and RMS error for an increase or a decrease in the lateral landward boundary head value.

The bottom GHB head value (Parameter 9) is the next most sensitive parameter in terms of the calibration statistics and the conclusions of this study (Type III sensitivity). As may be noted from Figure 6.1i, a 10 ft drop in the heads assigned to the GHB boundaries gives a substantially smaller average error, with not much effect on the spread of the error (RMS). However, lowering the head assigned to the bottom GHBs by 10 feet, degrades the ability of the model to match vertical chloride profiles observed in many of the ROMP wells.

The other parameters with a high degree of sensitivity, in terms of the model calibration and predictions (Type III sensitivity), include:

- the hydraulic conductivity associated with the entire Avon Park Formation (model layers 6 through 10) (Parameter 2);
- the hydraulic conductivity associated with the "highly permeable zone" within the Avon Park Formation (model layers 6 and 7) (Parameter 3); and
- the head value applied to the GHB condition along the bottom model boundary (Parameter 8).

Parameter sensitivities 2 and 3 are similar (the former being on the entire Avon Park Formation, the other on the "high-flow-zone" only) with a multiplying factor of 2.0 providing significantly reduced average errors (Figure 6.1b) and only a slight increase in the error spread. In fact, as noted in Table 6.1, the average change in December 2000 heads from the base case is significantly positive indicating lower heads than the base case for December 2000 conditions. However, this was a less desirable option for the calibrated model because measured values are considered to be more reliable than a factor of 2, and because it produced less accurate depth to chlorides than shown in Appendix B. Similarly, the +10 ft sensitivity simulation of parameter sensitivity 8 has a smaller residual with less spread, however, 10 ft is added to all top GHB nodes including those in Tampa Bay and Gulf of Mexico, which would be conceptually questionable. This exhibited sensitivity suggests that the GHB heads could be refined if more data become available.

Parameter sensitivities 6, 10, and 11 (for top GHB conductance values, Bottom GHB conductance values and the coastal lateral boundary head respectively) show a Type II sensitivity whereby the parameters are sensitive to the residuals, but not to the conclusions or requested prediction. The calibration sensitivity is considerable for these parameters, with a large change in the average chloride error for the range of parameters considered. Finally, parameter sensitivities 4, 5, 13, 14, and 15 (for vertical conductivity values of the modeled Ocala Limestone, hydraulic conductivity values of the modeled Suwannee Limestone, dispersion coefficients, diffusion coefficient, and Avon Park Formation's vertical anisotropy ratio, respectively) show Type I sensitivities whereby neither the residuals nor the conclusion are sensitive to changes in the parameter value. From Table 6.1, however, it may be noted that the Ocala Limestone's vertical conductivity value is most sensitive to the vertical head separation between the Suwannee Limestone and the Avon Park Formation. Conductivity values for the Avon Park Formation are the next most sensitive parameters for this head separation effect. Other parameters were not as sensitive.

Other model data that was evaluated during calibration included the overall bias of the model versus the data. It is noted in Table 6.1 that porosity, model layers 6 and 7 conductivity values, and bottom GHB head values can have the largest impact on chloride data fit among all the parameters. Fluxes through the top and bottom of the model were also evaluated during calibration and their sensitivity is also addressed. Flow in from the top GHB boundary was most sensitive (as much as 45% in volume) to top GHB conductance followed by top GHB heads (parameters 6 and 8 respectively). Flow out of the top GHB boundary was most sensitive (as much as 45% in volume) to top GHB conductance, top GHB heads and Coastal lateral boundary heads (6, 8, and 11 respectively) with a moderate sensitivity to the Avon Park conductivity values of sensitivities 2 and 3. Flow in and out of the bottom of the domain was most sensitive to bottom GHB head and bottom GHB conductance values. Aside from the porosity simulation, whereby chloride mass is not an indicator of intrusion into the domain as discussed earlier, the maximum chloride mass in the domain exists for the simulation with coastal lateral heads increased by +20 ft, and the minimum exists for the simulation with top GHB heads increased by +10 ft. In general, about two-thirds of the wells that are contaminated by chlorides greater than 500 ppm, also contain chlorides greater than 1,000 ppm. However, in general, the trends in parameter sensitivity of these conclusions are similar to those of the total chloride mass which may be used as an indicator here for the total chloride intrusion amount.

6.3 CONCEPTUAL SENSITIVITY ANALYSIS AND RESULTS

Conceptual uncertainties of the system, and their effect on saltwater intrusion have been investigated by the conceptual sensitivity analyses. Two primary conceptualizations are studied here, as an alternate to the calibrated model. First, it is unknown how the middle confining unit interacts with the overlying Upper Floridan aquifer, therefore, a sensitivity analysis was performed on this interaction. Second, the conceptualization of having a higher permeability zone within the Avon Park Formation was tested by performing a sensitivity simulation in which the higher permeable zone was removed from the model. Table 6.2 details these sensitivity analyses and provides calibration statistics and results.

For the first conceptual sensitivity simulation, the middle confining unit and its interaction with the Floridan Aquifer system under study exist only under the zone of high transmissivity in the Avon Park Formation under Pinellas County, Hillsborough Bay and Tampa Bay, to allow for saline water below the middle confining unit to interact with the Upper Floridan aquifer in this region only. The rest of the domain is unaffected by this interaction, as is the conceptualization used throughout the Southern District Model (SWFWMD, 2001). Two simulations were performed for this sensitivity analysis, to understand the behavior of this boundary in a systematic manner. The first simulation is designed from the calibrated model by cutting off the bottom GHB condition from portions of the domain not underlying the highly permeable zone under Pinellas County, Hillsborough Bay, and Tampa Bay. The second simulation further increases the GHB conductance under the highly permeable zone by an order of magnitude to increase the interaction with the middle confining unit in this region (i.e., the intrusion of chlorides from the MCV can be larger due to its larger vertical conductivity). This conceptualization is motivated by the fact that modeled chlorides have the tendency to be excessive in the southern portions of the domain, while they are less in the north, specifically in the area of TR AB-1, TR 9-2 and TR AB-3.

The calibration statistics associated with these simulations show much improvement over those of the base-case calibrated model with lower average errors and a similar RMS error to the base-case. Final heads are higher than those of the base-case, which is also a desirable feature. Flow in and out of the top GHB boundary is similar to that of the base-case, however net flow in/out of the bottom GHB boundary changes. For the first simulation, net flow in the bottom is less because of the smaller area of interaction with the middle confining unit than the base-case. For the second simulation, the net flow in the bottom is higher because of the higher GHB conductances which increase the interaction. For this sensitivity, only around half the pumping wells extract greater than 500 mg/l chloride than for the base-case. This conceptualization therefore, has the possibility of improving calibration. Thus, if a data collection program can validate the possibility of this conceptualization, further tuning on the parameters may be performed with investigations of depth to chlorides, slope of the interface, and thickness of the transition zone - all features that were examined in calibrating the model. A general inspection of the results indicates that chlorides are not affected by this calibration in the southern regions of the domain, chlorides intrude less than the base case in the middle portion of the domain, and chloride intrusion can be greater in northern parts of the domain if the bottom GHB interaction there is increased.

For the second conceptual sensitivity simulation, the Avon Park Formation is treated as a single unit vertically. The hydraulic conductivity of this unit is applied in a manner that provides an equivalent transmissivity to the base-case simulation. This conceptualization is examined as an alternative, to investigate the results of this simplification (always made in flow models), on chloride transport behavior. The average error for this simulation shows an improved fit than for the base case, with a similar RMS error (Table 6.2). Other flow statistics and model conclusions are similar to that of the base case. The model is quite insensitive to this alternative conceptualization which may be used instead without significant loss of accuracy or predictive capability. However, the nature of the calibration of such a model should be first examined with respect to depth to chlorides, width of transition zone, and slope of interface to determine if it would be adequate. A general inspection of the results indicates that the chlorides moved seaward in the entire domain from the base-case, and the interface slant became more vertical (not desirable) for this simulation.

6.4 QUALITY ASSURANCE REVIEW RESULTS

After calibrating the density-dependent model, the SWFWMD reviewed the wells and well depths assigned in the Southern District Model (SWFWMD, 2001) and in the local-scale, density-dependent model. The review was undertaken to reconcile differences between previous assessments of wells at risk of saltwater intrusion prepared by the SWFWMD and the current, preliminary estimates made with the local scale density-dependent model.

The review examined the total depth and/or casing depth assigned to wells for which no value is reported in the SWFWMD Water Use Permit (WUP) data base. The review determined that procedures used to assign these values to model layers in the Southern District Model (SWFWMD, 2001), which does not use elevations or depths, had incorrectly assigned total depth and casing depth elevations to wells in the local scale density-dependent model. After assessing the situation, a revised process assigned corrected total depth and casing elevations to the wells of the transport model.

This resulted in 512 of the 2,681 wells being eliminated from the model when the total depth elevations were above the top of the UPZ as configured in the transport model. A review of these wells indicated that most of these wells were located along the southwest coast and are known to be completed in the IAS, which is not simulated by the transport model. Although the number of wells removed is nearly 20 percent of the total, the total withdrawal rate is only 5.7 percent of the original 223.38 mgal/day. The result of this change on the calibrated model is minor as illustrated by the relative chloride concentration contours for model Layers 2 and 6 (Figures 6.2 and 6.3). The results of the comparison of the environmental head potentiometric surfaces for Layers 2 and 6 also indicate minor changes (Figures 6.4 and 6.5).

The total withdrawal rate associated with each predictive scenario is unchanged. The reported number of wells at risk of saltwater intrusion under each scenario in Section 7.0 reflects the revised pumping data set.

7.0 PREDICTIVE SIMULATIONS

The calibrated density-dependent saltwater-intrusion model was used to predict potential changes to the groundwater flow system and associated chloride conditions, which would result from changes in groundwater withdrawals in the Upper Floridan aquifer. Projected pumping conditions include withdrawals of 400, 600, 800 and 1,000 MGD within the SWUCA. Based on these pumping projections, the saltwater intrusion model was used to predict the distribution of chloride after 20 years and 50 years of pumping. December 2000 conditions provided the initial conditions for the predictive simulations. Most boundary conditions for the predictive simulations were kept the same as those used for the pre-development to post-development simulation. The only differences in model input were groundwater withdrawals and the lateral landward freshwater boundary heads which were provided by the District for the saltwater intrusion model by performing parallel simulations with the Southern District Model (SWFWMD, 2001). Since the saltwater intrusion model includes only a portion of the SWUCA individual well pumping within the saltwater intrusion model was scaled according to the ratio of total pumping of the various scenarios (i.e., 400, 600, 800 or 1,000 MGD), to total pumping for December 2000 conditions. In addition, a predictive sensitivity analysis was conducted on each of the four scenarios. For these simulations, selected input parameters were changed in order to provide a range of potential impacts. The parameters included for the predictive sensitivity study were selected from those found to be most sensitive during the sensitive analysis discussed in Chapter 6.

For the predictive scenarios, an analysis was performed to determine the number of wells contaminated by chloride concentrations either exceeding 500 mg/l or 1,000 mg/l, at 20 and 50 years of simulation (i.e., year 2020 and 2050). For production wells that arc completed across multiple hydrostratigraphic units, the chloride concentrations predicted by the model represent a homogeneous mixture of water that is contributed by each unit. This mixed concentration should approximate the actual concentration that is observed at the individual wells. The results of the predictive simulations are presented in Table 7.1. Also presented in the table is the 1995-1999 average annual usage from the contaminated wells and the associated 1999 permitted pumping from those wells. These columns of the table denote how much pumping (or permitted pumping) within the Upper Floridan aquifer would be at risk due to chloride intrusion, or moved to other locations. A total of 1,806 wells are included in the domain of the saltwater intrusion model. The saltwater intrusion model predicts that 154 of these wells (8.5%) are currently impacted by chloride at concentrations exceeding 500 mg/l. Furthermore, the model predicts that after 50 years of pumping, 224 of these wells (12.4%) will be impacted by chlorides at concentrations exceeding 500 mg/l. The model predicts that 63 wells (3.4%) are currently impacted by chlorides exceeding 1,000 mg/l, and chloride concentrations will exceed 1,000 mg/l in 147 wells (8.1%) after 50 years of continued pumping. Tables 7.2, 7.3 and 7.4 provide a detailed breakdown of this production well impact analysis for the Suwannee Limestone, the Ocala Limestone and the Avon Park Formation respectively. These tables illustrate that for the wells within the model domain, the wells completed in the Avon Park Formation are most likely to be impacted by saltwater.

Figure 7.1 shows the projected extraction well chloride concentration histogram for December 2000 of the post-development simulation. The histogram shows 1418 extraction wells with chloride concentration less than 100 mg/L and 1777 extraction wells with chloride concentration less than 2000 mg/L. Notice that the 136 wells between 200 mg/L and 500 mg/L are decreasing from left to right and the 91 wells between 500 mg/L and 1,000 mg/L are approximately uniformly distributed. This suggests that for the predictive simulations, the number of wells above 500 mg/L will increase along a non-linear trend and number of wells above 1,000 mg/L will increase along a linear trend. Figure 7.1 also shows the average pumping rate for the wells in each histogram bar. Notice that the wells between 200 mg/L and 500 mg/L have a lower average pumping rate than the wells between 500 mg/L and 1,000 mg/L. All of the predictive simulations have more extraction wells passing the 1,000 mg/L threshold than pass the 500 mg/L threshold (Table 7.1). Column 7 of Table 7.1 shows that the number of wells above 500 mg/L increased along a non-linear trend and the number of wells above 1,000 mg/L increased along a linear trend. Columns 8 of Table 7.1 indicates that the extraction wells passing the 1,000 mg/L threshold have a higher average pumping rate than the wells passing the 500 mg/L threshold.

Figures 7.2, 7.3, 7.4 and 7.5 show the areal distribution of chlorides within the highly permeable zone of the Avon Park Formation after 50 years of pumping for each of the four scenarios respectively. The largest intrusion in the highly permeable zone of the Avon Park Formation was for model layer 7 for each of the four simulations, which is shown in these figures. Chlorides move inland by about 2.5 miles from the current position within 50 years of pumping 400 MGD, about 5 miles for a pumping of 600 MGD, about 7 miles for a pumping of 800 MGD and about 9 miles for a pumping of 1,000 MGD within the highly transmissive zone of the Avon Park Formation. Movement of chlorides is less in the northern portion of the domain where the aquifer is thinner.

Figure 7.5 shows the 1,000 mg/l chloride isochlor in the highly permeable zone of the Avon Park Formation, after 50 years of pumping for the various scenarios. A comparison of this figure with estimates of Beach and Schultz (2000) provided in Figure 2.17 shows a reasonable comparison of the modeled saltwater front with their estimates, for pumping of 400, 600, 800, and 1,000 MGD. The 50-year movement from current conditions is also similar for the various pumping cases. Chlorides are however, more landward in the southern regions of the model, and slightly more seaward in the northern portions of coastal Hillsborough County than the estimates of Beach and Schultz (2000).

7.1 PREDICTIVE SENSITIVITY ANALYSIS

The possible effects of projected pumping within the Floridan Aquifer System upon chloride intrusion to wells, is of particular concern within the SWUCA. Therefore, a sensitivity analysis was conducted to estimate the potential ranges of the predicted number of wells contaminated by greater than 500 mg/l and 1,000 mg/l of chlorides. This analysis is further broken up into estimating potential ranges for the predicted number of wells contaminated by greater than 500 mg/l and 1,000 mg/l of chlorides in each of the aquifer units (i.e., the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation).

Sensitivity parameters selected for this analysis include the porosity of the aquifer and aquitard materials, the landward lateral freshwater boundary head, and the GHB head value applied to the bottom of the model. In terms of the model predictions, these were determined to be the most sensitive parameters (Section 6). For each sensitivity simulation set, the parameter value was raised and lowered by a predetermined amount that provides a reasonable range bounding that parameter value. This range of parameter sensitivity is identical to that used for the model sensitivity analysis in Chapter 6.

Table 7.5 shows the results of the predictive sensitivity study in the Floridan Aquifer system, and Tables 7.6, 7.7 and 7.8 provide a breakdown of these results for the Suwannee Limestone, the Ocala Limestone and the Avon Park Formation, respectively. The table presents the additional number of wells affected for each sensitivity study, from the respective base case scenario. It may be noted that multiplying the porosity value by 0.2 had greatest impact on the modeling results, in terms of increasing the number of wells that are affected by chlorides (both in the individual hydrostratigraphic units and within the entire Upper Floridan aquifer). The number of wells impacted by high chloride concentrations approximately double from the base case for this parameter perturbation, with wells completed in the Suwannee and Ocala Limestones being much more susceptible to contamination than wells completed in the Avon Park Formation. The decrease in the number of wells, affected by chlorides in the Suwannee Limestone and the Ocala Limestone, is most strongly influenced by the addition of 10 ft to the landward lateral boundary heads with the largest impact being in the Suwannee and Ocala Limestones. Alternatively, the most dominant factor for the decrease in the number of wells affected by chlorides in the Avon Park Formation is the lowering of the GHB boundary head value at the base of the model by 10 feet.

7.2 MODEL LIMITATIONS

The model described in this report is a numerical groundwater flow and solute transport model that uses the MODHMS computer code to approximate the groundwater flow and chloride transport system in the SWUCA. The model results are limited by the simplification of the conceptual model upon which the numerical model is based, by the grid scale, by the inaccuracies of measurement data and by incomplete knowledge of the spatial variability of input parameters.

The conceptual model used to construct the density-dependent saltwater intrusion model for the SWUCA is a simplified representation of the true groundwater flow and transport system. Due to its karstic nature, the Floridan aquifer system can be characterized as an extremely complex, heterogeneous aquifer system. These features may cause zones of preferential pathways caused by secondary porosity features and solution conduits. However, the secondary porosity features are believed to be so ubiquitous that the system behaves as an equivalent to a porous-medium at the scale of the modeled system.

The density-dependent saltwater intrusion model is based upon the Southern District Model (SWFWMD, 2001) for groundwater flow developed by the SWFWMD using the popular USGS MODFLOW code. Further, the calibrated saltwater intrusion model has almost the same conceptualization and parameter distribution as that of the Southern District Model (SWFWMD, 2001). Differences in conceptualizations are associated with the specifics of saltwater intrusion modeling. For instance, use of a transmissivity value for each aquifer unit is sufficient for groundwater flow modeling, however, saltwater intrusion simulations require the additional vertical resolution to capture the gradients in concentration resulting from saltwater intrusion within each aquifer unit. To address these issues, the density-dependent model was more finely discretized than the Southern District Model.

Averaging of boundary conditions and well pumping over 4-month intervals for the latter part of the transient simulations should not have much impact on chloride intrusion levels, since intrusion is an extremely slow process with time-scales that are orders of magnitude larger than four months. However, this averaging has a significant impact on the simulated head field within the aquifers, which do not exhibit the seasonal extremes noted in the field since the time-scales for head response to pumping can be much smaller than four months.

The model simulates conditions represented by the static chloride data from the ROMP wells better than the subsequent field data collected over some ten years as shown in Figures 5.19 through 5.24. The primary reason for this discrepancy in the model predictions is that greater reliance was placed on establishing the chloride interface position and vertical concentration gradients rather than attempting to match the transients in the chloride data. The justification for this approach is that chloride interface changes very slowly with time and the chloride profiles provide a better overall description of the chloride distribution within the modeled area. Local chloride vs. time data were obtained from relatively short monitoring intervals within respective monitoring wells. These local concentration data are governed by small-scale heterogeneity. The model's inability to mimic the magnitudes of local-scale time dependent chloride data may be attributable to the finite-difference grid size that is larger than the local heterogeneity scale. In addition, local changes in chloride concentrations with time could be affected by ephemeral processes (e.g. changes in recharge rates). These processes may be either too localized to be captured adequately by the model, or are of such short duration that the quarterly averaging by the model is insufficient to duplicate the temporal changes in the field data.

Horizontal and vertical discretization into model grid cells requires the assumption of average values of hydrologic properties and stresses for each grid block. The larger the range of the true values of a property or stress within a grid cell area, the greater the difference between the average value and the true value at any particular location within a cell. This difference is probably greatest for confining unit leakances which can vary greatly due to local changes in thicknesses and vertical hydraulic conductivity not represented in the model. The location of stresses is also somewhat distorted by the grid scale since all pumping in the model is accumulated at a grid-block center. This error should be small for the current simulations due to the distributed nature of pumping throughout the model domain which is applied to a reasonably fine grid. Another error source is that the resolution of results cannot be made finer than that of the grid. This is significant for representing chloride values within the model, since chloride data from ROMP wells is at a much finer vertical scale than the model's vertical resolution. This problem is compounded by the fact that chlorides can change dramatically within the domain with an extremely narrow transition zone between freshwater and seawater.

Model results are limited by incomplete knowledge of the true spatial variability of input parameters. However, sensitivity analysis conducted on the input arrays of parameters and stresses used for this model have indicated that the model's calibration and predictive results are sensitive to certain input parameters and stresses and insensitive to others. Model calibration and predictions are most sensitive to the value of porosity used for the aquifer units, followed by value of the lateral landward freshwater boundary head and the value of the bottom GHB head. Uncertainty of model results is therefore related primarily to the uncertainty in these input parameters. However, since the calibration is also sensitive to these parameters, a perturbation on the parameter value causes the model to be uncalibrated thereby restricting their values to those that provide a calibrated model. It may be noted that the model did not show a Type IV sensitivity to any parameter examined (A Type IV parameter is one which exhibits sensitivity to results but not to the calibration). Therefore, the reliability of the model is not compromised in this respect.

Results of the predictive sensitivity analyses indicate a range for the number of wells contaminated by 500 and 1,000 mg/l of chlorides after 50 years for the various scenarios examined. This range is greatest for the Avon Park Formation for all the cases examined, thereby providing a larger uncertainty of results for the Avon Park Formation than for the other units analyzed.

The density-dependent saltwater intrusion model was designed with grid-block scales of one-half mile. Material property zones were designed at a scale that is an order of magnitude larger. Temporal scales for varying pumping and boundary conditions for pre- to post-development simulations were initially large, reducing to an order of four months near the end of the simulation. Therefore, model results should be viewed at these space and time scales, and the model may be used to examine the general chloride intrusion trends for long-term average stress conditions.

8.0 SUMMARY AND CONCLUSIONS

HydroGeoLogic has completed the development of a numerical, coupled groundwater flow and density-dependent transport model for the coastal portions of the SWUCA. The primary objective of this effort was to predict the long-term impact of proposed water use options on saltwater intrusion within the Upper Floridan aquifer. The saltwater intrusion model may be further used to establish minimum water levels or maximum pumping levels for groundwater extraction wells within the Upper Floridan aquifer or for developing a refined understanding of the stress response of chlorides to various regional management scenarios.

Historical reports and previous modeling investigations were reviewed to understand the hydrogeologic conceptual model, identify model calibration targets, and construct the framework for the saltwater intrusion model. Once the density-dependent model was constructed, it was calibrated to simulate conditions in the Upper Floridan aquifer that existed from the pre-development period (approximately 1900) to present conditions (through 2000). The pre-development simulations were calibrated to the results of earlier modeling work that predicted the position of the tip and toe of the saltwater interface, and a historical reconstruction of pre-development hydraulic heads. The density-dependent model predicts greater saltwater intrusion in the northern part of the model domain than the earlier models, and less intrusion from the center of the model southward. Differences in the modeling results would be expected, however, since different approaches (e.g., two-vs. three-dimensional) and assumptions (e.g., sharp interface vs. fully coupled flow and transport) were made in the various models. A favorable comparison between the pre-development potentiometric surfaces predicted by the model and historical estimates were also obtained.

Following the calibration of the model to pre-development conditions, the hydraulic stresses associated with pumping were integrated into the model and the model was calibrated to post-development conditions (i.e., post-1900). During the post-development calibration process, the results of the model calibration were evaluated both qualitatively and quantitatively. In some instances, a comparison between contour maps of measured and simulated values (i.e, hydraulic heads and chloride concentration) was prepared to provide a visual, qualitative measure of the similarity between patterns, thereby giving qualification of the spatial distribution of calibration errors. In addition, vertical and horizontal hydraulic heads and the fluid flux moving across the model boundaries was used as qualitative calibration criteria. Quantitative statistical assessments were also performed on the model residuals to assess the reliability of the calibration.

A general observation, with respect to the model calibration, is that the model does not always provide a good match to the chloride data on a well-by-well basis. From a more regional perspective, however, the model does provide a reasonably good fit to chloride distribution maps that show the extent of the chloride interface. There are several explanations for this apparent discrepancy between the model predictions at the local and regional scales. One of the most significant of which is that the chloride interface is relatively thin vertically, and narrow in the east-west direction. This limited extent of the interface causes the chloride distribution to be controlled by heterogeneities at a scale that is considerably smaller than the horizontal discretization of the model elements (i.e., 2,500 feet). Similar issues arise with the vertical discretization of the model. Since the discretization is at a larger scale than the collected data, chloride concentrations in the model are averaged over several hundred feet as compared with tens of feet in the field. In fact, for each finite-difference cell containing a ROMP well, there are typically multiple observed chloride concentrations associated with different depth intervals. This inconsistency in scale makes it difficult to precisely match the field data, particularly at high chloride concentrations. This problem is aggravated by the fact that the interface transition zone is relatively thin and concentrations change dramatically over short vertical distances. Furthermore, since all of the calibration wells are located within the chloride interface, the models inability to capture the effects of the localized heterogeneities on the chloride distribution give the impression that the model predictions are unreliable. As noted above, however, the model does perform well when compared to the regional chloride maps. Although the model could be more finely discretized in both the horizontal and vertical dimensions to improve the localized calibration, the simulations times (which currently are on the order of 16-18 hrs at a 2.0 Ghz processing speed) would become excessively long. Furthermore, as described in greater detail in Section 5, the principle of parameter parsimony was applied as a fundamental philosophy during the calibration. This principle favors the use of uniform parameter zones unless there is hydrogeologic evidence indicating the presence of localized heterogeneous properties. Therefore, rather than attempting to precisely match the localized borehole data, by increasing the discretization and/or heterogeneities, the model was calibrated to provide a very good representation of the chloride intrusion characteristics on a more regional scale and should provide an adequate means to meet the objectives of the SWFWMD.

A comparison of simulated potentiometric surfaces to potentiometric surface maps developed by the USGS indicates that the model predicted head distributions for the Suwannee Limestone and Avon Park Formation tend to be lower than actual field data. The general shape of the potentiometric contour developed for simulated heads is very similar to the potentiometric surface developed using field data. The most probable reason for the differences between measured and predicted head values is that the model does not exactly simulate the transients within the flow system, in which hydraulic heads vary by about 30 feet from May to September.

A sensitivity analysis was also conducted, to identify the model input parameters and boundary conditions that have the most impact on the model calibration and on the model predictions. Porosity was found to be the most sensitive parameter, followed by the landward lateral boundary heads and the bottom GHB heads. The hydraulic conductivity associated with the entire Avon Park Formation (model layers 6 through 10), and with the "high-flow-zone" within the Avon Park Formation (model layers 6 and 7) also exhibited a high degree of sensitivity, in terms of the model calibration and predictions.

Predictive simulations were completed to estimate hydraulic heads and saltwater intrusion (i.e., saline water concentrations) for 20- to 50-year time periods. The possible effects of projected Floridan aquifer system pumping upon chloride intrusion to wells is of particular concern within the SWUCA. Therefore, four different water use scenarios proposed by the SWFWMD were evaluated. These comprise of withdrawing 400, 600, 800 and 1,000 MGD within the SWUCA. For the predictive scenarios, an analysis was performed on the number of wells contaminated by average chloride concentrations either exceeding 500 mg/l or greater than 1,000 mg/l, at 20 and 50 years of simulation (years 2020 and 2050, respectively). A total of 1,806 wells are included in the domain of the saltwater intrusion model. The saltwater intrusion model predicts that 154 of these wells (8.5%) are currently impacted by chloride at concentrations exceeding 500 mg/l. Furthermore, the model predicts that after 50 years of pumping, 224 of these wells (12.4%) will be impacted by chlorides at concentrations exceeding 500 mg/l. The model predicts that 63 wells (3.4%) are currently impacted by chlorides exceeding 1,000 mg/l, and chloride concentrations will exceed 1,000 mg/l in 147 wells (8.1%) after 50 years of continued pumping.

A predictive sensitivity analysis was also conducted to provide confidence limits on the results. Sensitivity parameters selected for this analysis include the porosity of the aquifer and aquitard materials, the landward lateral freshwater boundary head, and the GHB head value applied to the bottom of the model. Results of the predictive sensitivity analyses indicate a range for the number of wells contaminated by 500 and 1,000 mg/l of chlorides after 50 years for the various scenarios examined. This range is greatest for the Avon Park Formation for all the cases examined, thereby providing a larger uncertainty of results for the Avon Park Formation than for the other units analyzed.

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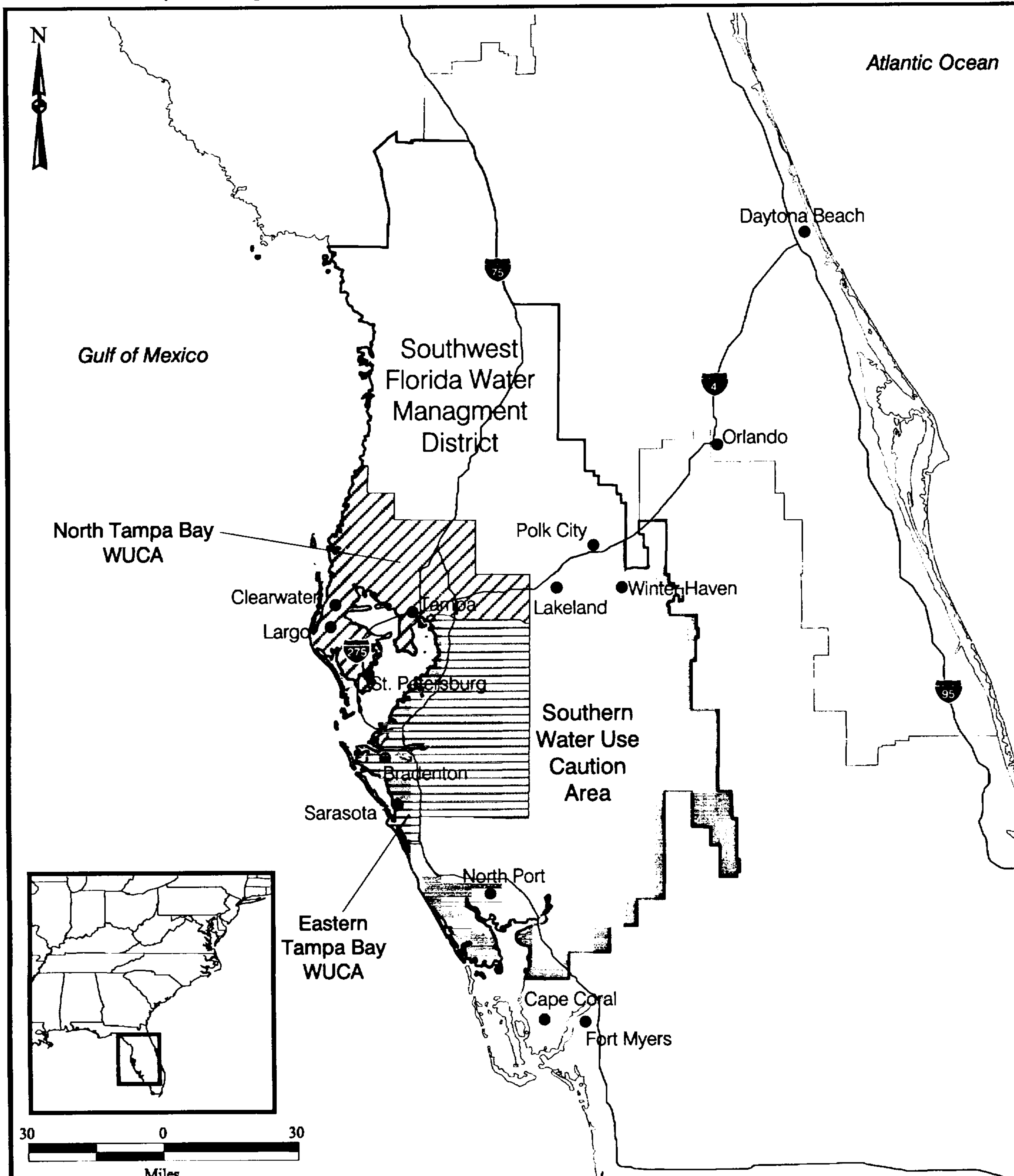
FIGURES



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Project: SWF024-001-01
Created: 11/28/01 TB
Revised: 5/31/02 TB

HYDRO GeoLogic Inc.

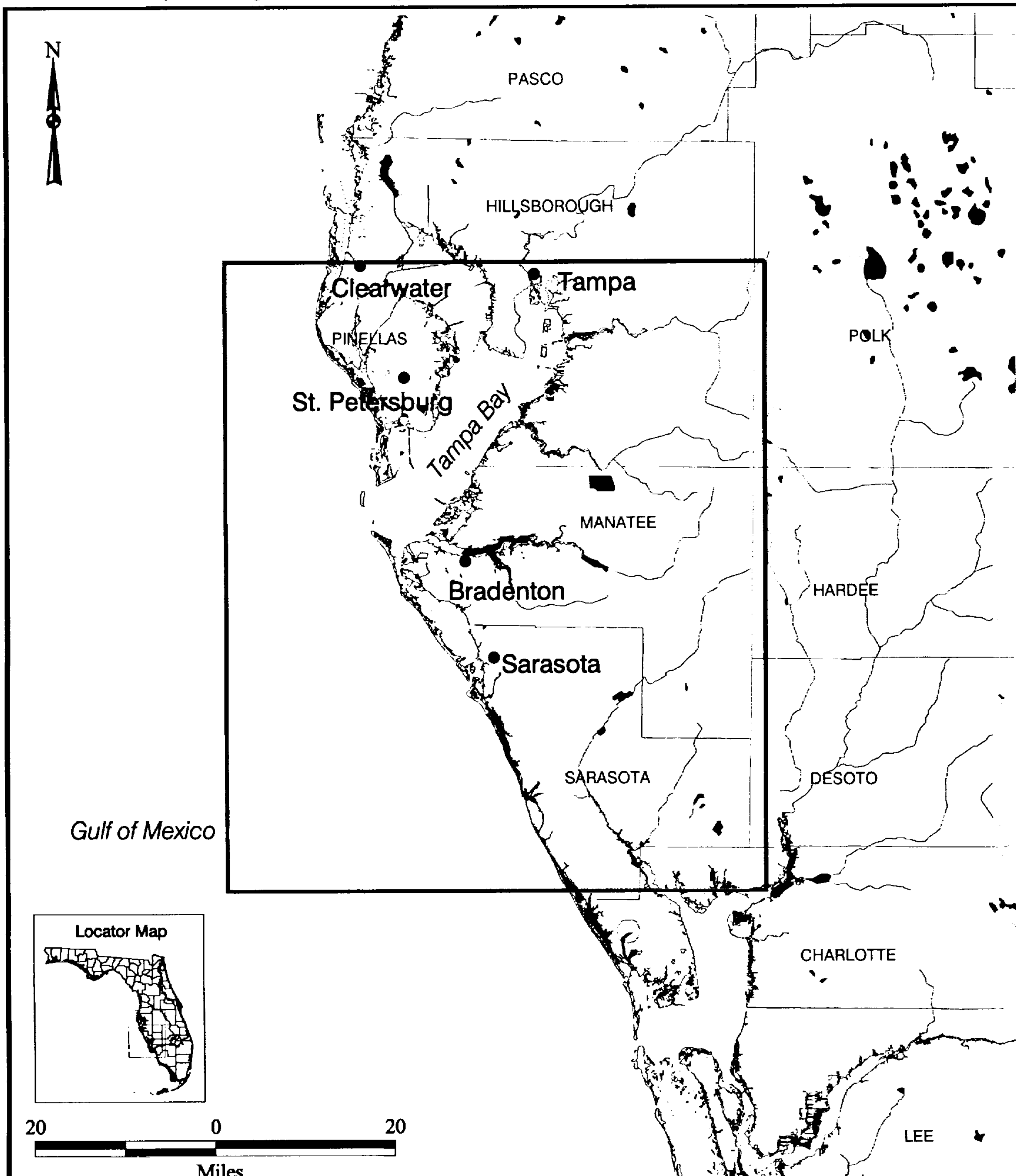
Legend

Southwest Florida Managment District Boundary

Interstate

Southern Water Use Caution Areas

Figure 1.1
Location of Southwest Florida Managment District and Southern Water Use Caution Area



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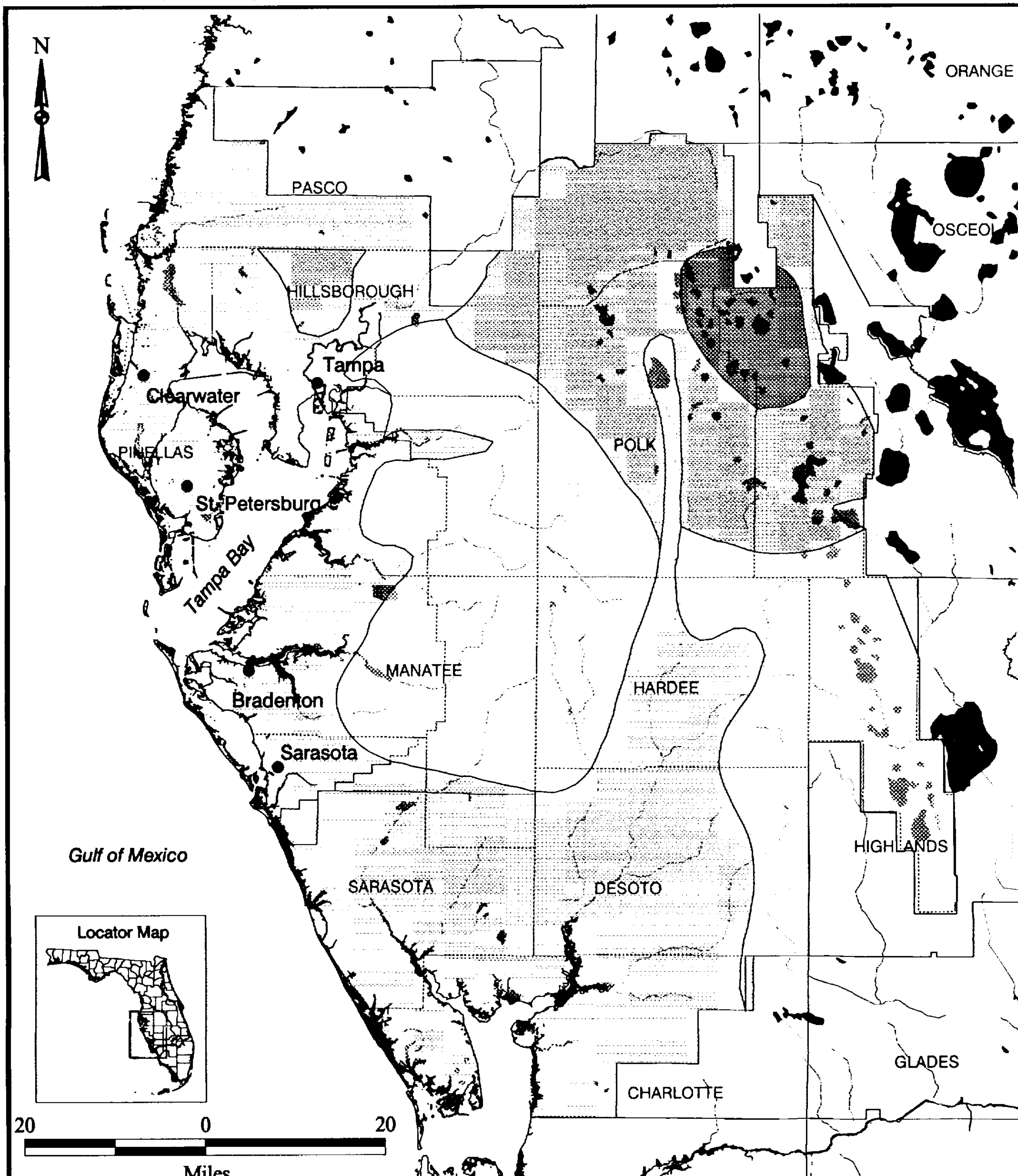
Created: 11/29/01 TH
Revised: 04/22/02 TB

Legend

- County Boundary
- Surface Drainage
- Study Area

Figure 1.2
Saltwater Intrusion Study Area



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Project: SWF024-001-01
Created: 11/29/01 TH
Revised: 04/22/02 TB

Legend

County Boundary
Surface Drainage
Recharge (inches / year)
Less than 1
1 to 10
Greater than 10
Discharge (less than 1)

Figure 2.1
Recharge / Discharge Zones of the Upper Floridan Aquifer for Pre-Development Conditions (Aucott, 1988)

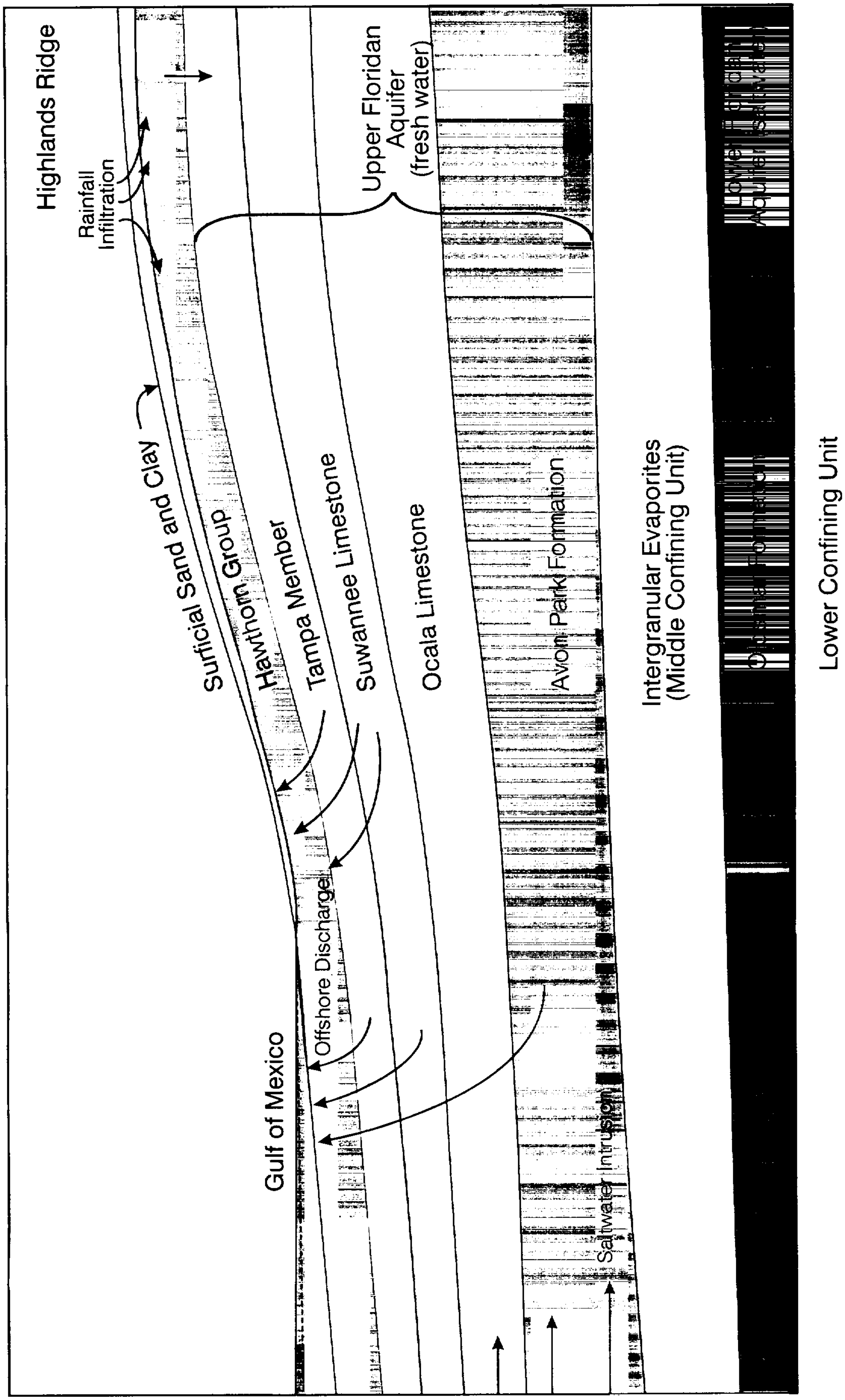

Figure 2.2

Generalized Conceptual Model

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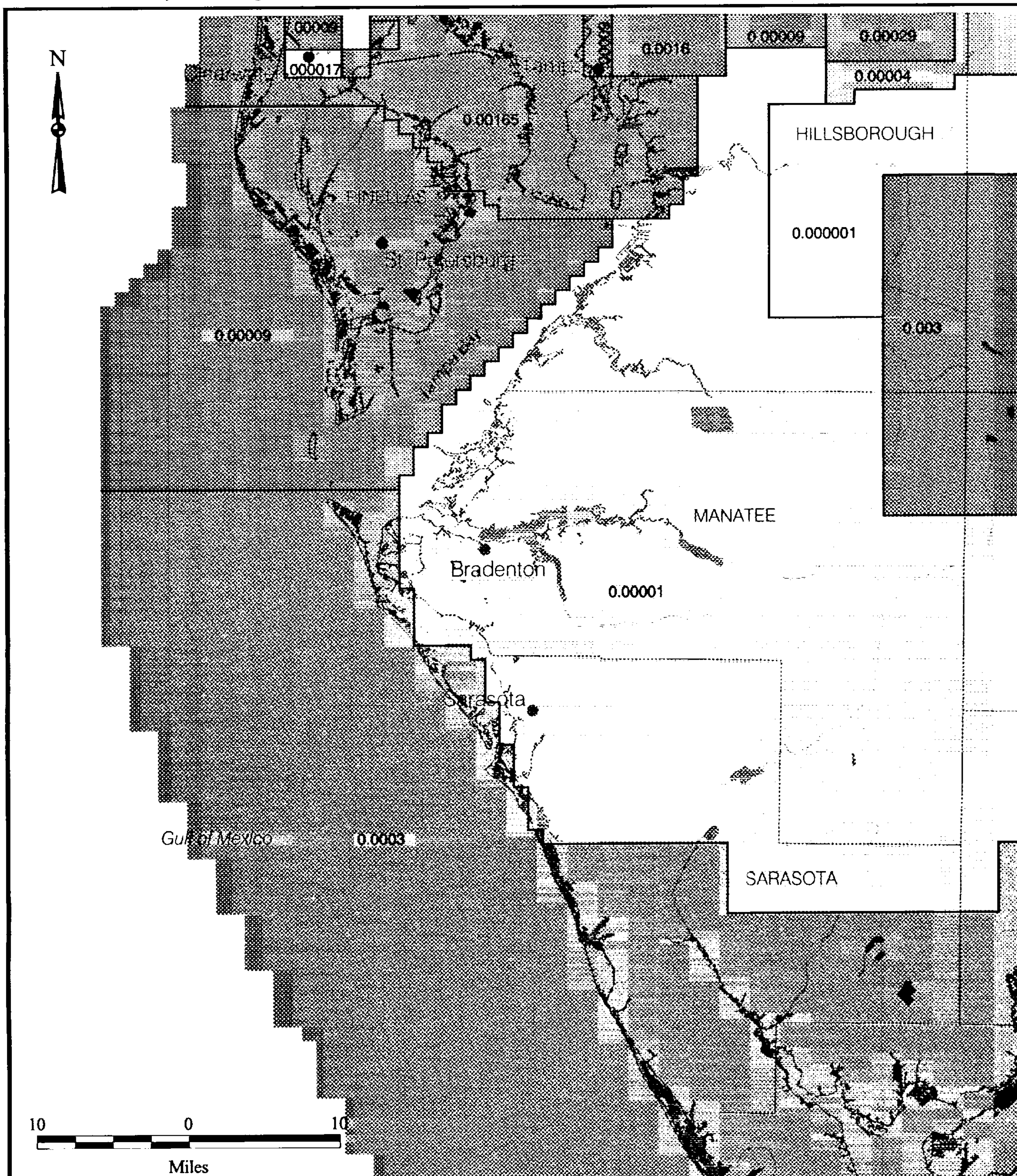
Created by: cfarmer 12/14/01
Revised: 05/30/02 cf
Source: Waterstone (2000)



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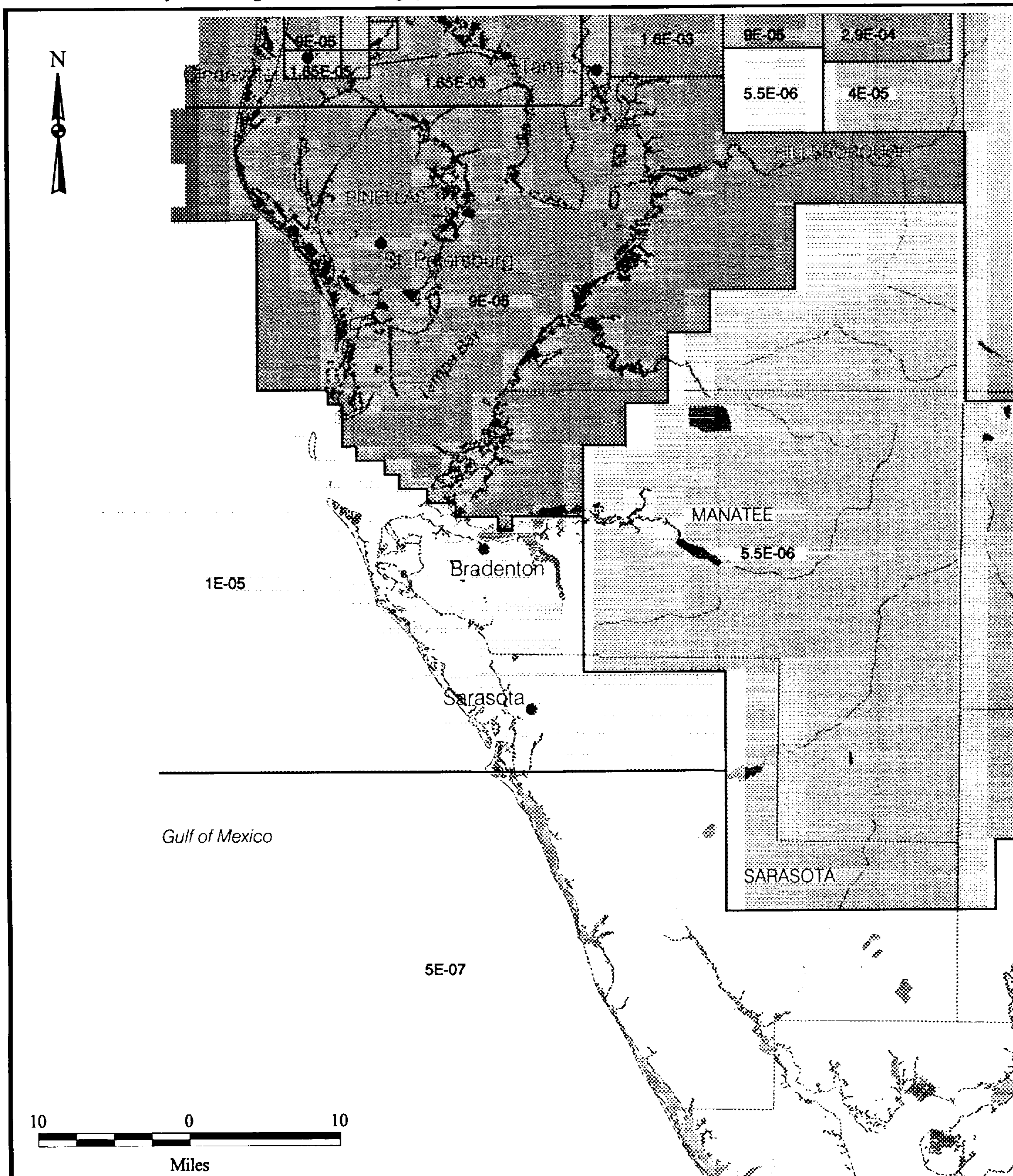
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 07/03/02 jb

Legend

County Boundary
Surface Drainage
Zone Boundary

Leakance (l/d)
0.000001
0.00001
0.000017
0.00004
0.00009
0.00029
0.0003
0.0016
0.00165
0.003

Figure 2.3
Leakance of Semi-Confining Unit Layer 1 of the Intermediate Aquifer System (Southern District Model, 2001)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 07/03/02 jb

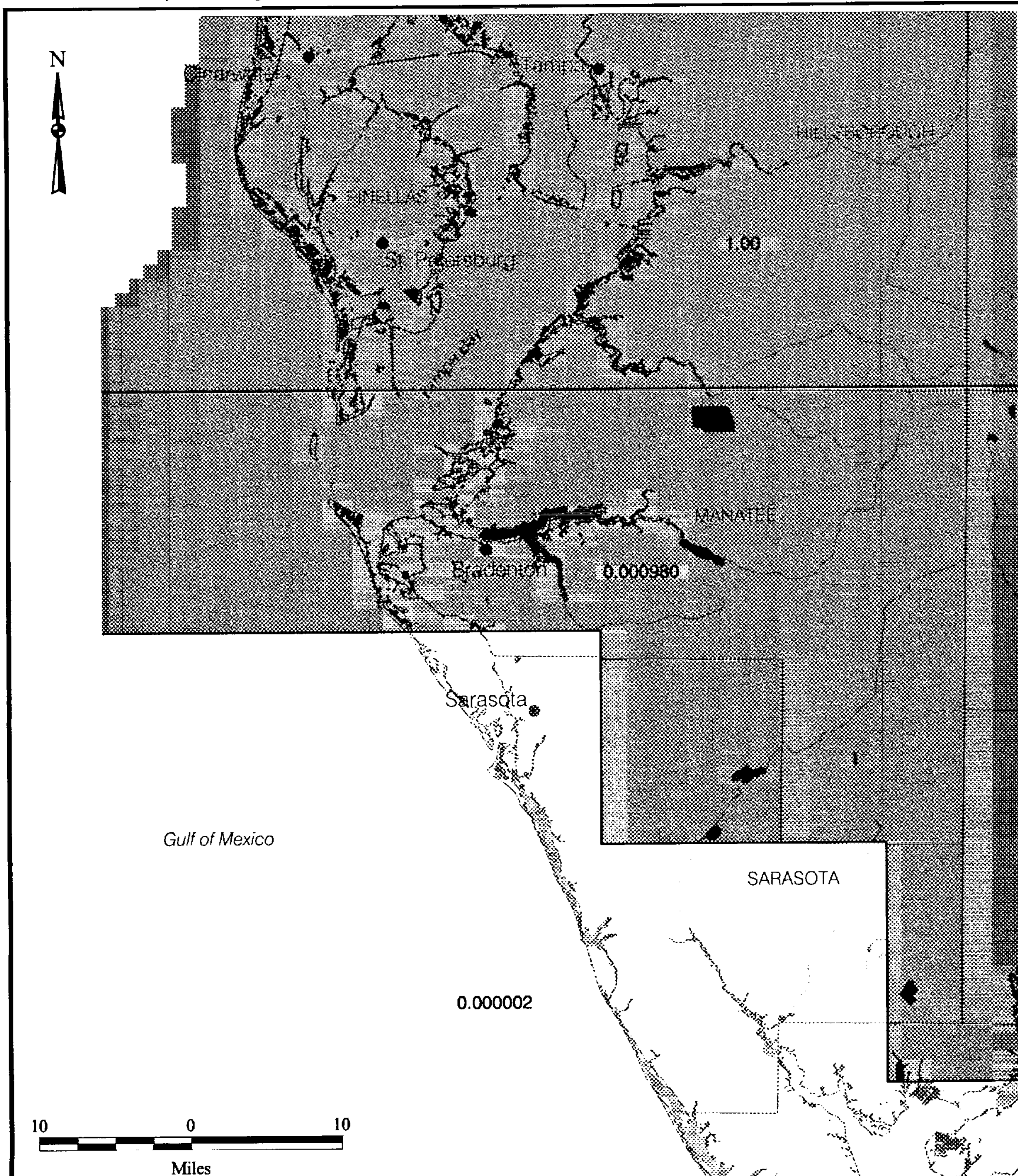
HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
Zone Boundary

Leakance (l/d)
5E-07
1E-05
5.5E-06
4E-05
9E-05
1.65E-05
2.9E-04
1.65E-03
1.6E-03

Figure 2.4
Leakance of Semi-Confining Unit Layer 2 of the Intermediate Aquifer System (Southern District Model, 2001)



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Created: 11/28/01 TH
Revised: 07/03/02 jb

HYDRO GeoLogic Inc.

Legend

County Boundary

Surface Drainage

1.00 Zone Boundary

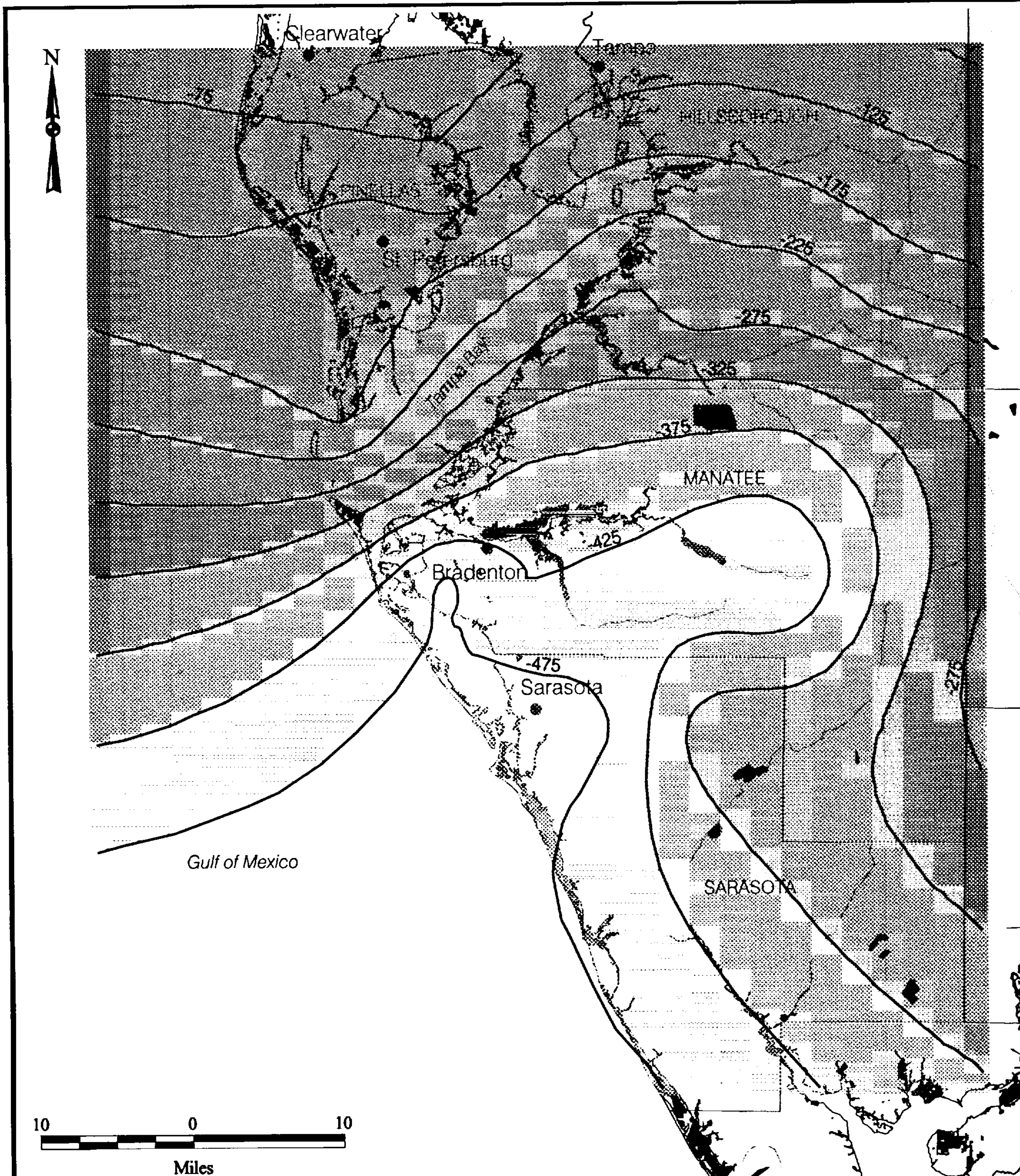
Leakance (l/d)

0.000002

0.00098

1

Figure 2.5
Leakance of Semi-Confining Unit Layer 3 of the Intermediate Aquifer System (Southern District Model, 2001)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic Inc.

Legend

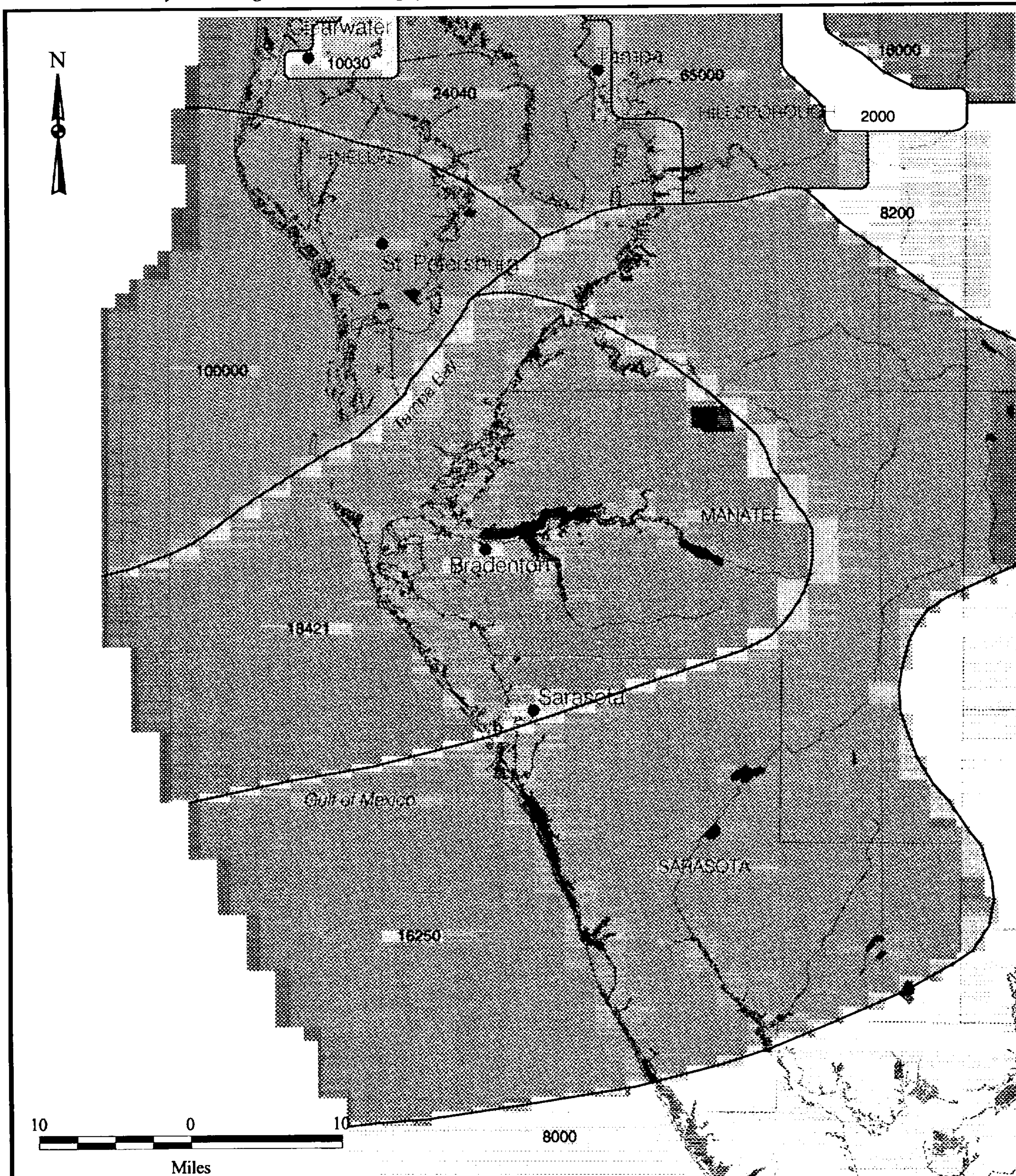
County Boundary

Surface Drainage

-275 Suwannee Top Elevation Contour (ft)

Suwannee Elevation (ft)
-560 - -475
-475 - -425
-425 - -375
-375 - -325
-325 - -275
-275 - -225
-225 - -175
-175 - -125
-125 - -75
-75 - -25

Figure 2.6
Top Elevation of the Suwannee Limestone (Waterstone Model, 2001)



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Created: 11/28/01 TH
Revised: 07/03/02 jb

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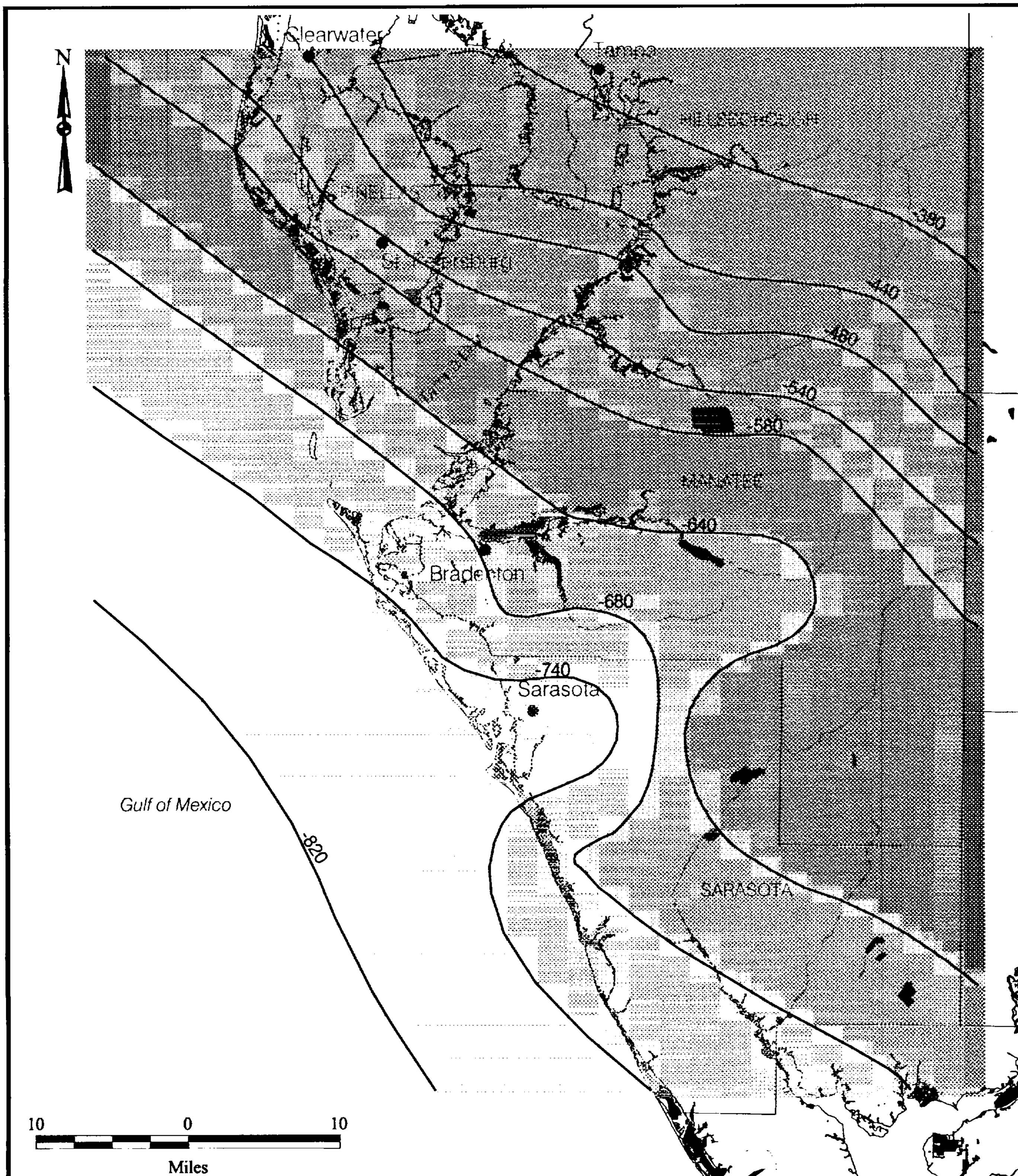
Legend

County Boundary
Surface Drainage
Zone Boundary

Suwannee Transmissivity (ft²/day)
2000
8000
8200
10030
16000
16250
18421
24040
65000
100000

Figure 2.7
Transmissivity of the Suwannee Limestone of the Southern District Model (SWFWMD, 2001)



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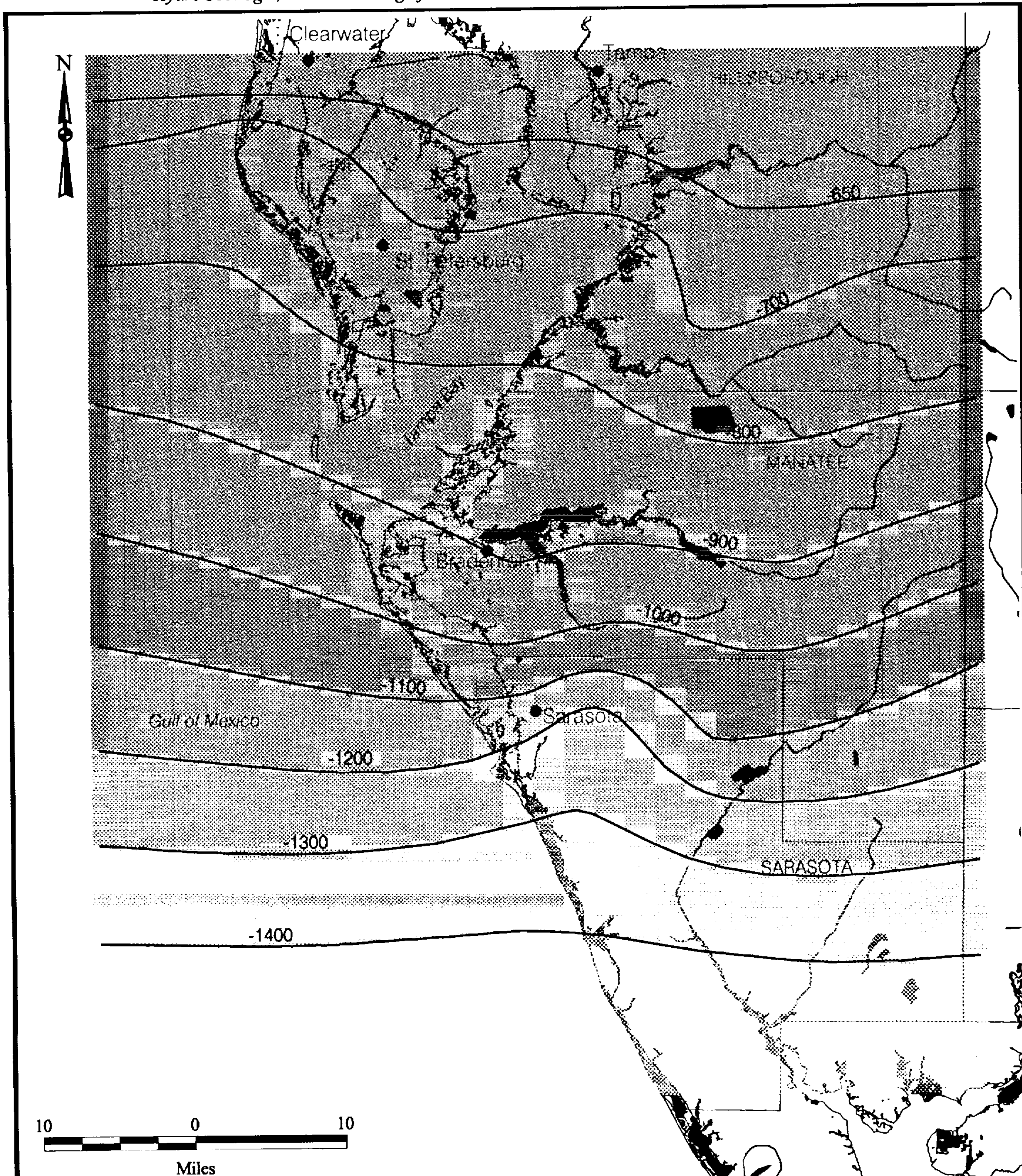
Created: 11/28/01 TH
Revised: 04/22/02 TB

Legend

		Ocala Elevation (ft)
County Boundary		-960 - -820
Surface Drainage		-820 - -740
-580	Ocala Top Elevation Contour (ft)	-740 - -680
		-680 - -640
		-640 - -580
		-580- -540
		-540 - -480
		-480 - -440
		-440 - -380
		-380 - -265

Figure 2.8
Top Elevation of the Ocala Limestone (Waterstone Model, 2001)



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Created: 11/28/01 TH
Revised: 04/22/02 TB

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Legend

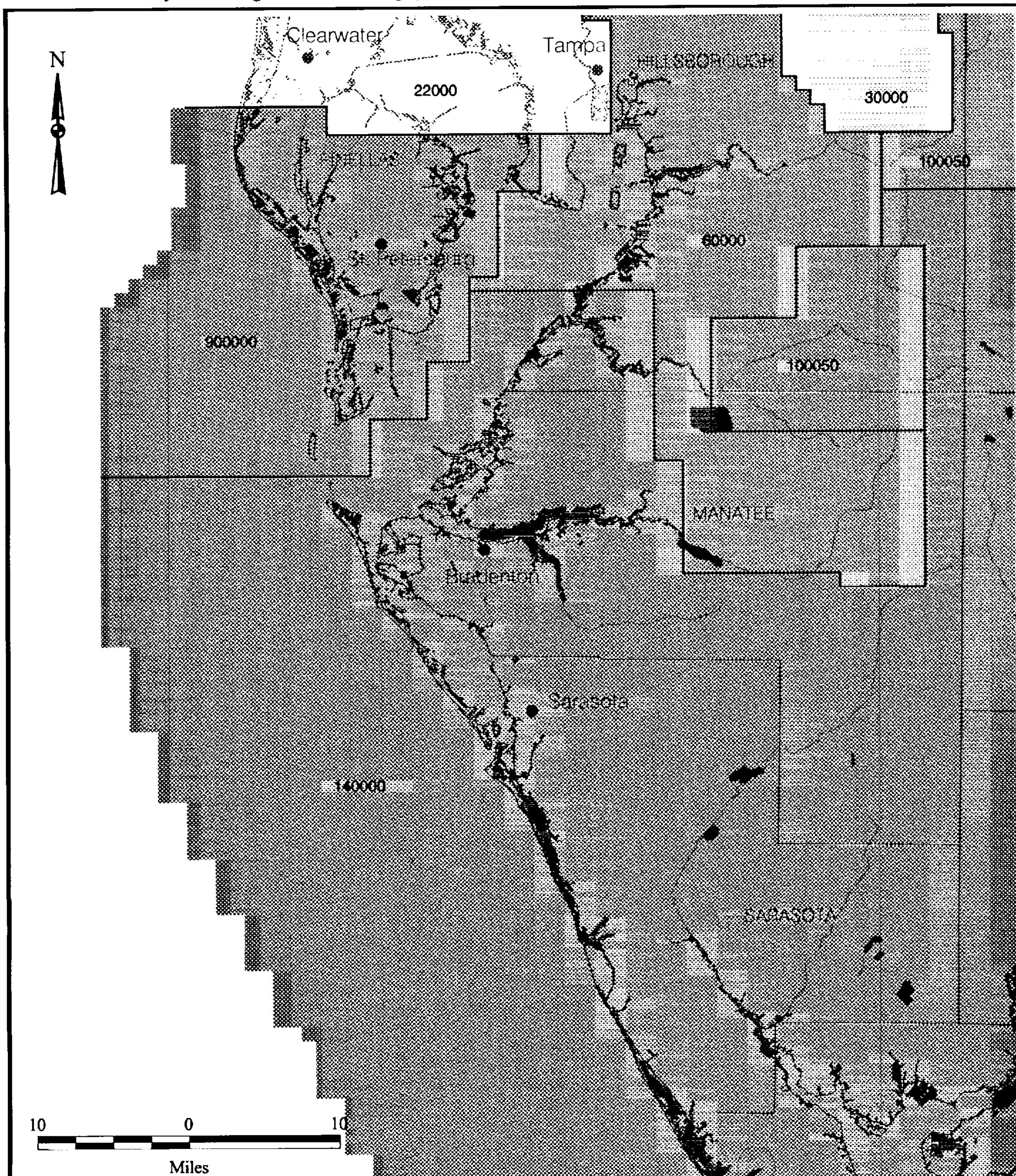
County Boundary

Surface Drainage

-700 Avon Park Formation Top Elevation Contour (ft)

Avon Park Elevation (ft)
-1550 - -1400
-1400 - -1300
-1300 - -1200
-1200 - -1100
-1100 - -1000
-1000 - -900
-900 - -800
-800 - -700
-700 - -650
-650 - -550

Figure 2.9
Top Elevation of the Avon Park Formation (Waterstone Model, 2001)



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Created: 11/28/01 TH
Revised: 07/03/02 jb

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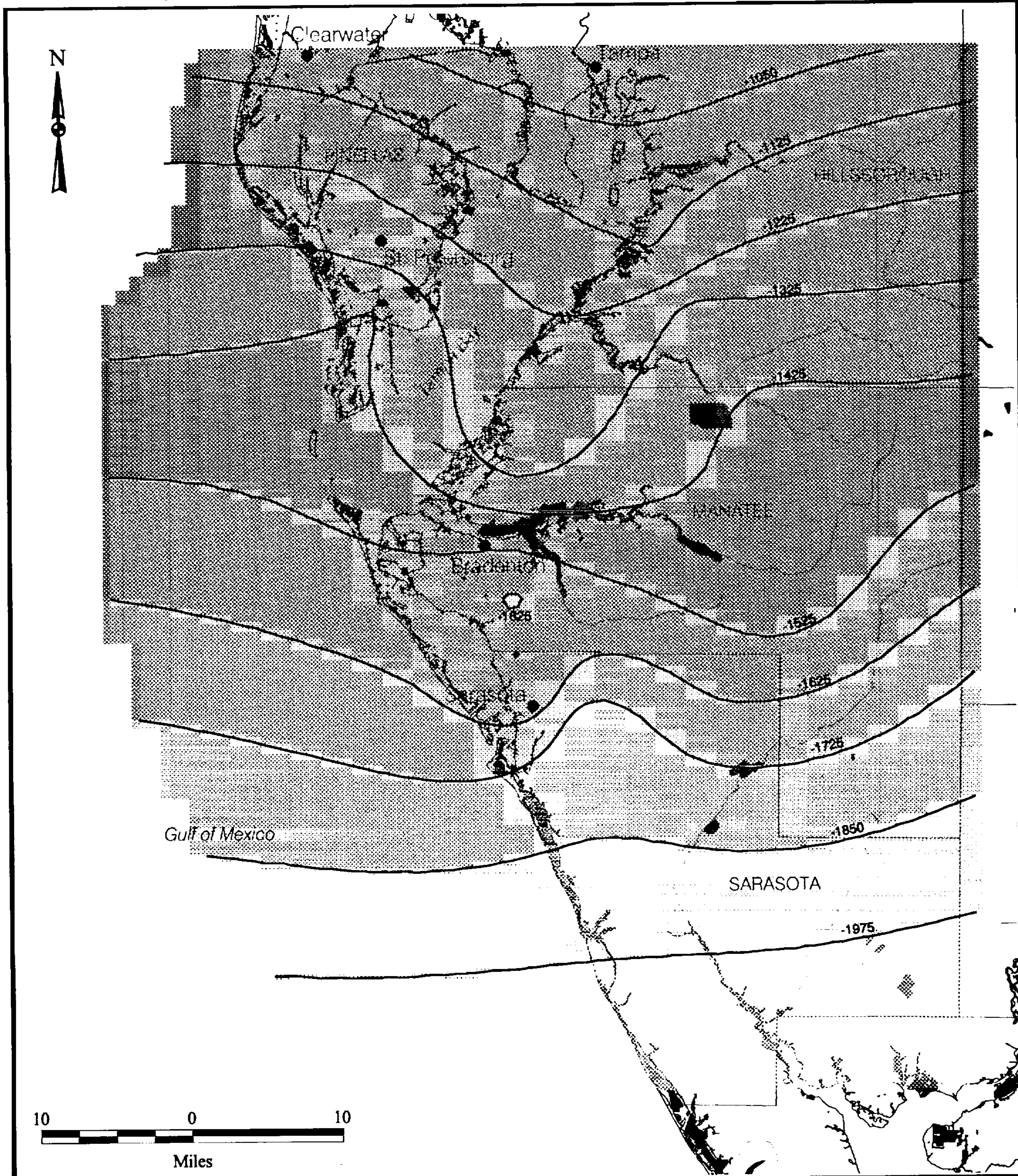
Legend

County Boundary
Surface Drainage
Zone Boundary

Ocala/Avon Park Transmissivity (ft²/day)
22000
30000
60000
100050
140000
900000

Figure 2.10
Transmissivity of the Avon Park Formation of the Southern District Model (2001)



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Created: 11/28/01 TH
Revised: 04/22/02 TB

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Legend

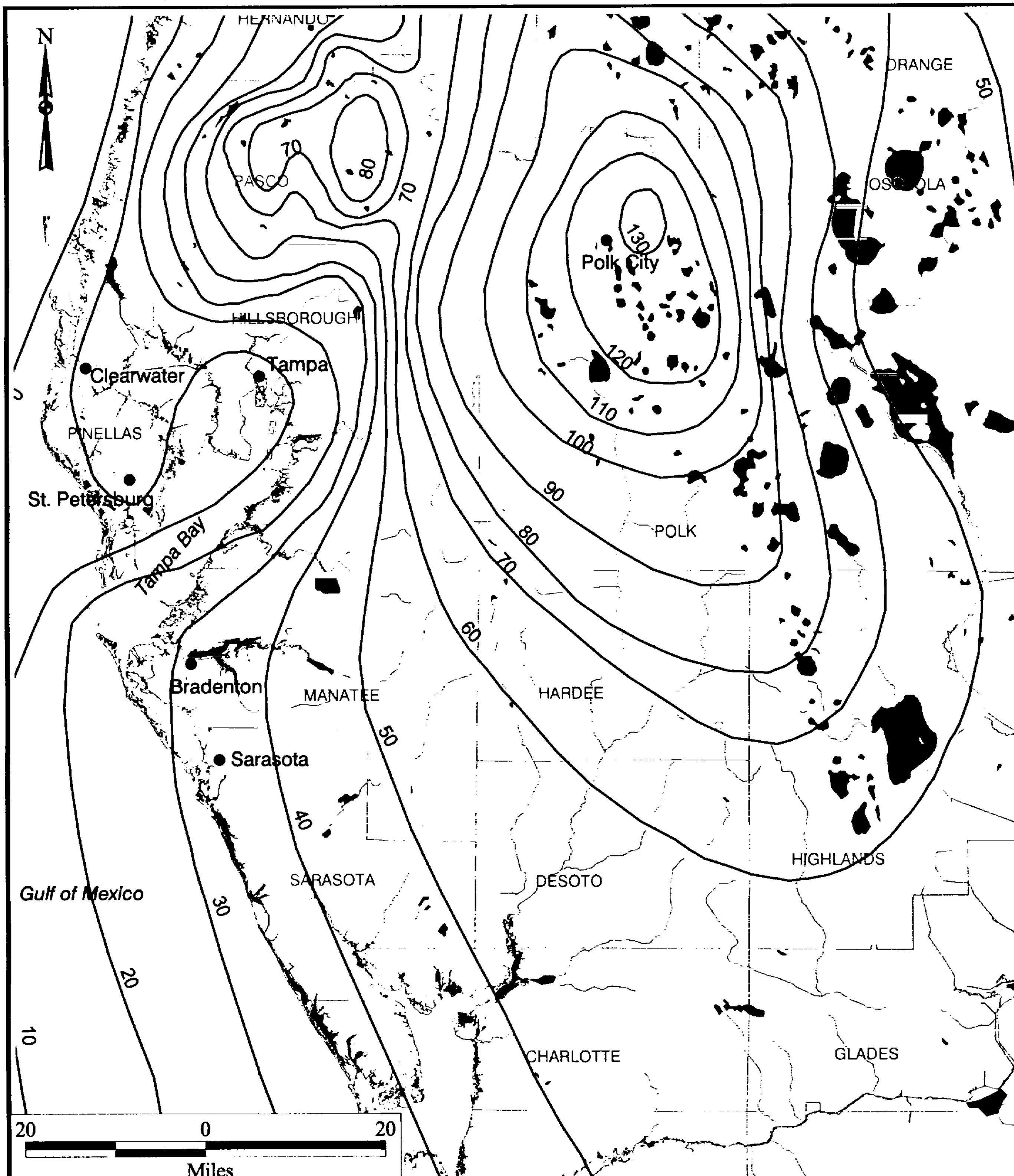
County Boundary

Surface Drainage

-1425 Middle Confining Unit Elevation Contour (ft)

Middle Confining Unit Elevation (ft)
-2150 - -1975
-1975 - -1850
-1850 - -1725
-1725 - -1625
-1625 - -1525
-1525 - -1425
-1425 - -1325
-1325 - -1225
-1225 - -1125
-1125 - -1050
-1050 - -975

Figure 2.11
Top Elevation of the Middle Confining Unit (Waterstone Model, 2001)



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Created: 11/29/01 TH
Revised: 06/05/02 TB

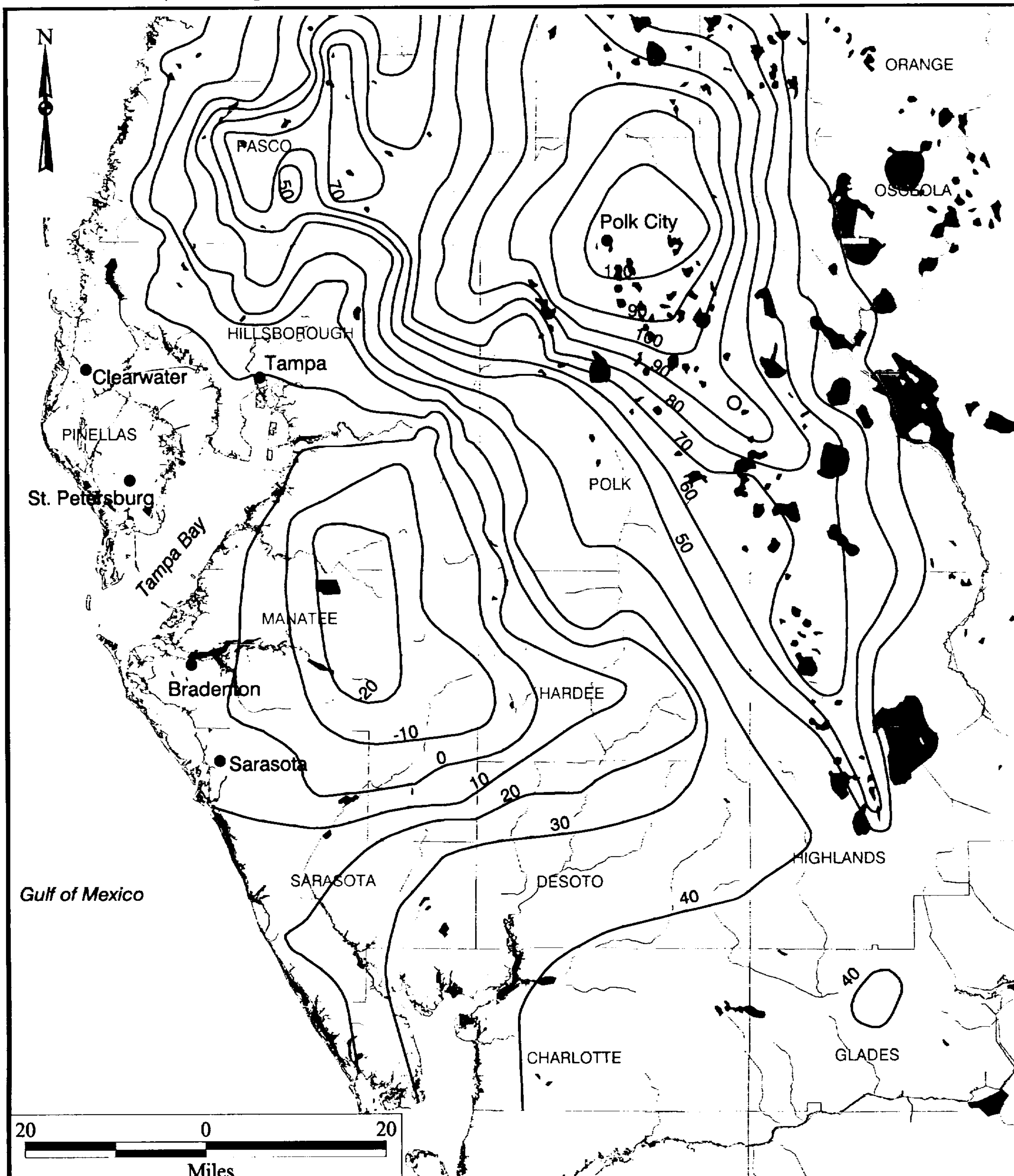
Legend

County Boundary

Surface Drainage

30 Potentiometric Surface Elevation (ft)

Figure 2.12
Upper Floridan Aquifer Potentiometric Surface for Predevelopment Conditions (from Johnston et.al., 1980)



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Created: 11/29/01 TH
Revised: 05/30/02 TB

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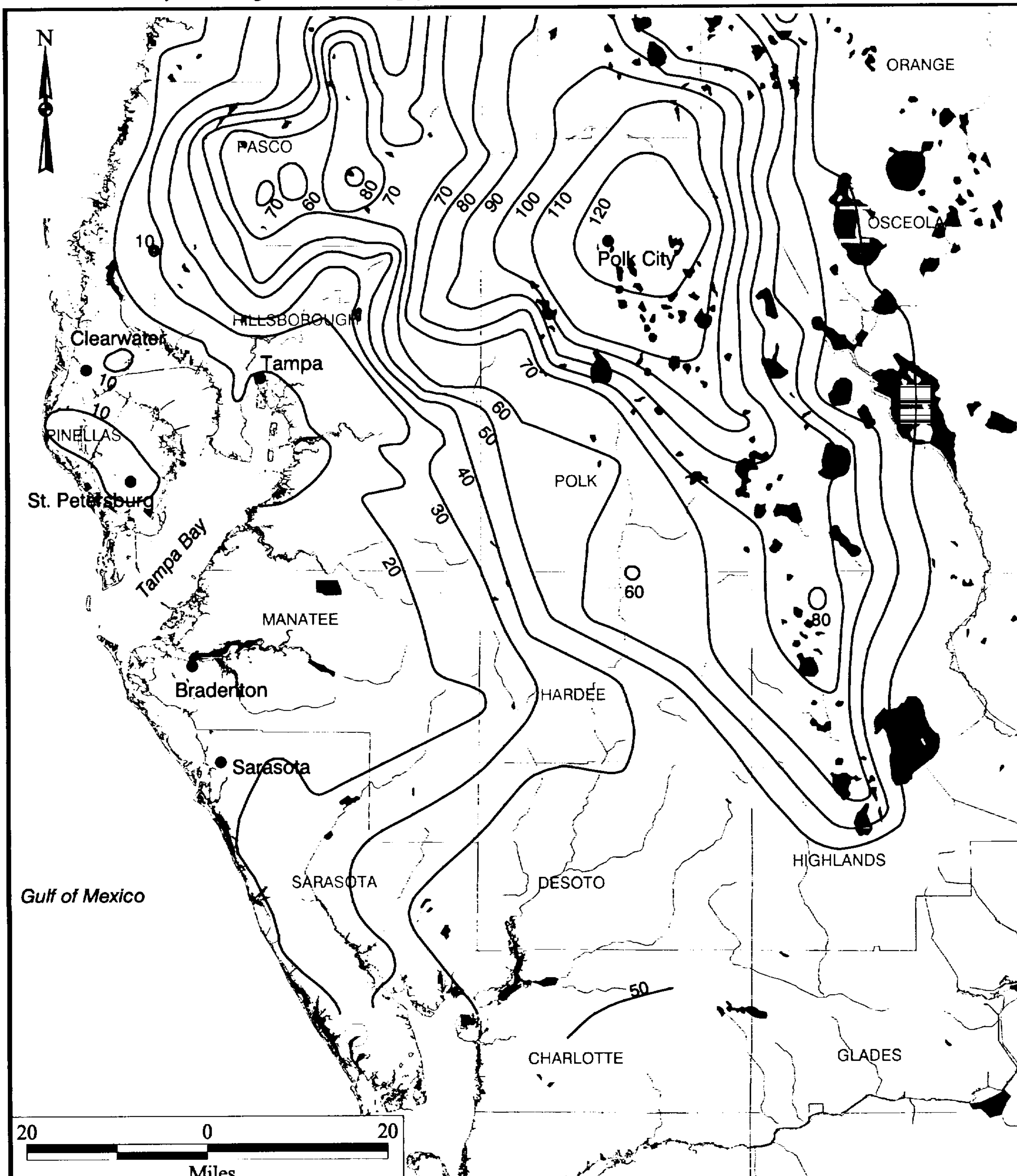
Legend

County Boundary

Surface Drainage

30 Potentiometric Surface Elevation (ft)

Figure 2.13
Floridan Aquifer Potentiometric Surface for May 2000 (USGS, 2001)



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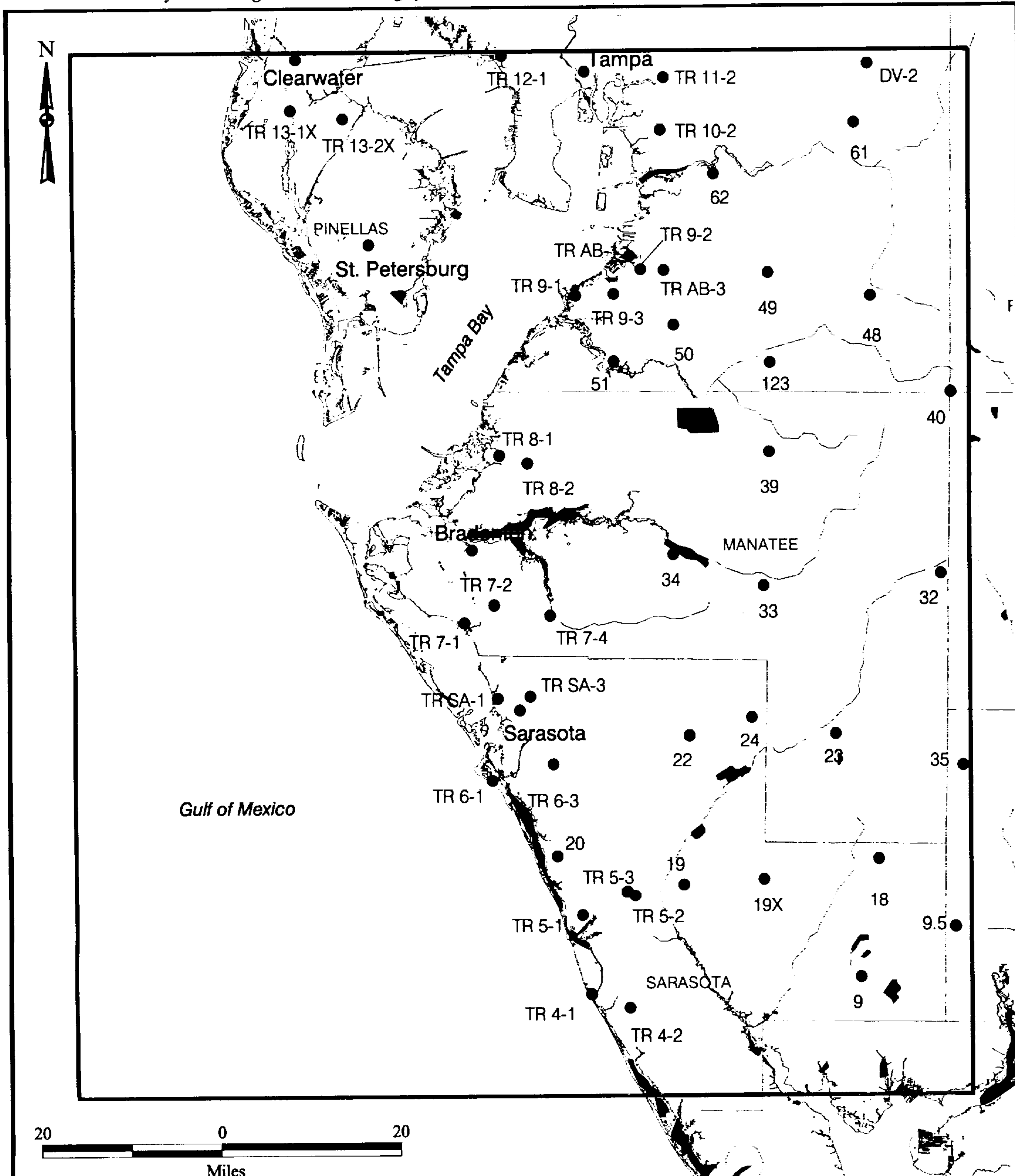
Revised: 05/30/02 TB

Legend

County Boundary
Surface Drainage
30 Potentiometric Surface Elevation (ft)

Figure 2.14
Floridan Aquifer Potentiometric Surface for September 2000 (USGS, 2001)



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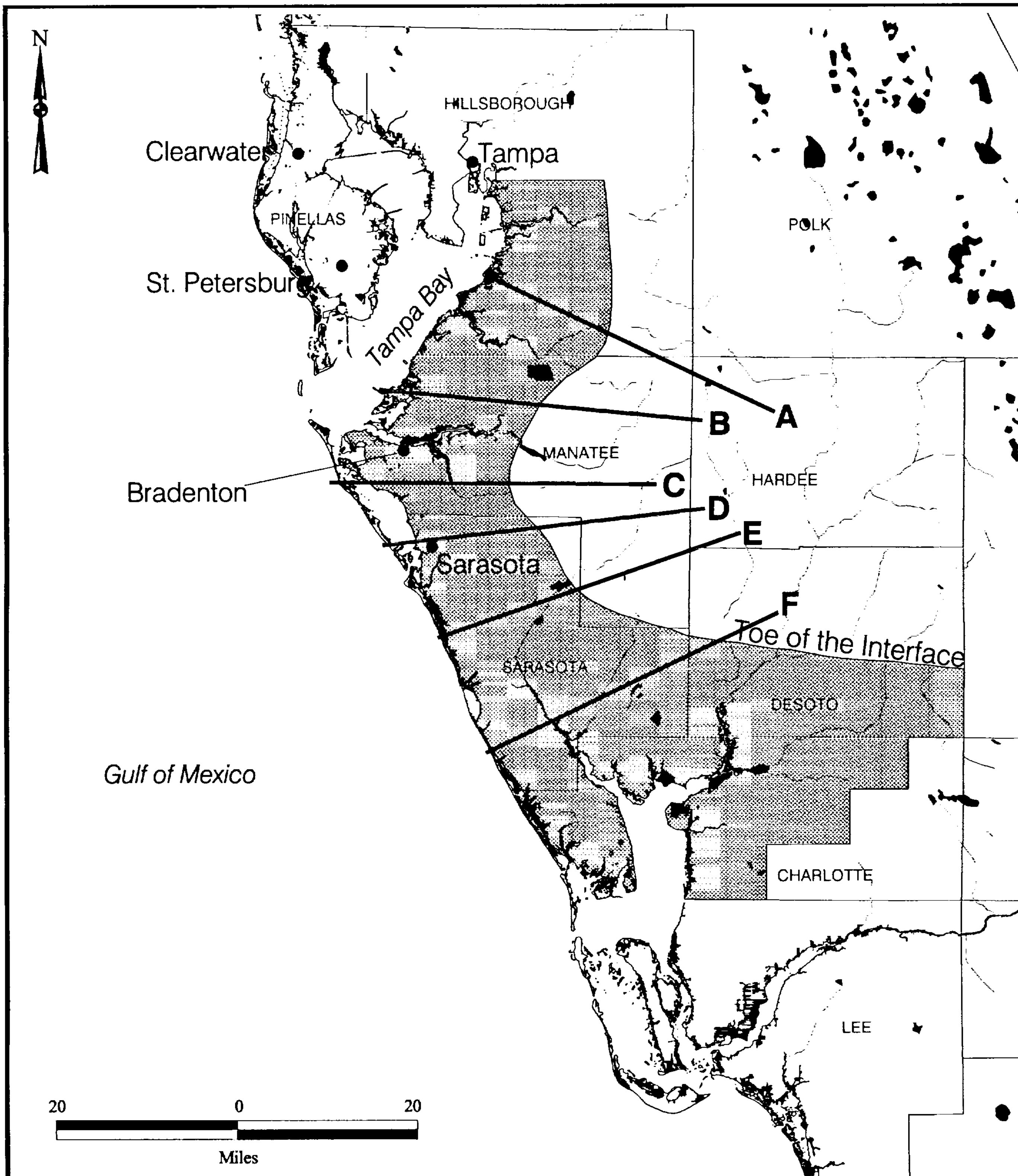
Created: 11/29/01 TH
Revised: 05/30/02 TB

Legend

County Boundary
Surface Drainage
Study Area
Well Location / ROMP ID (134)

Figure 2.15
Location of ROMP Wells within the Study Area



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Created: 11/29/01 TH
Revised: 06/05/02 TB

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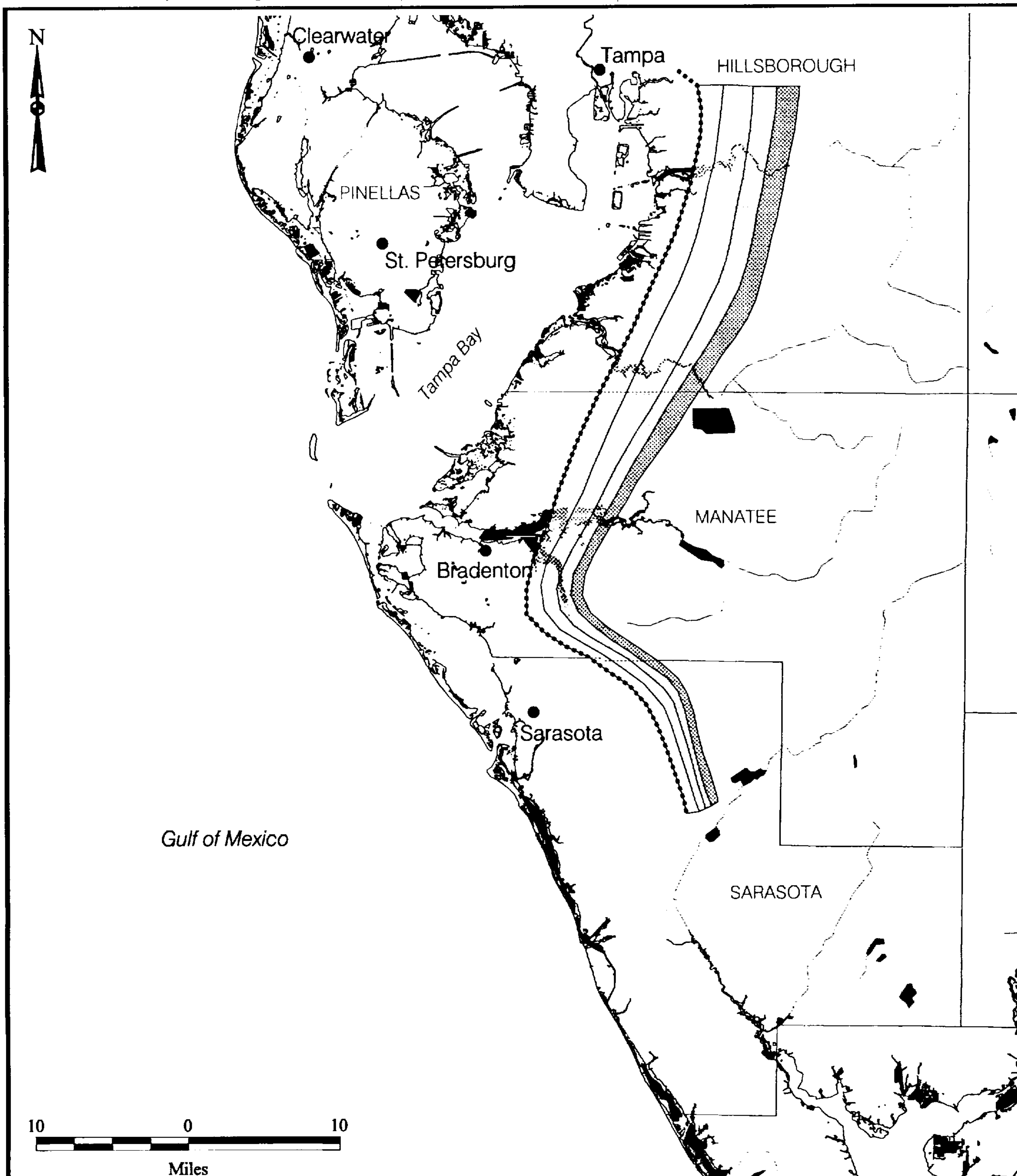
Legend
- County Boundary
- Surface Drainage
- A Cross-section Locations
- Chloride Transition Zone within the LPZ

Figure 2.16
Chloride Transition Zone within the Lower Permeable Zone of the Upper Floridan Aquifer (Beach and Kelley, 1998)



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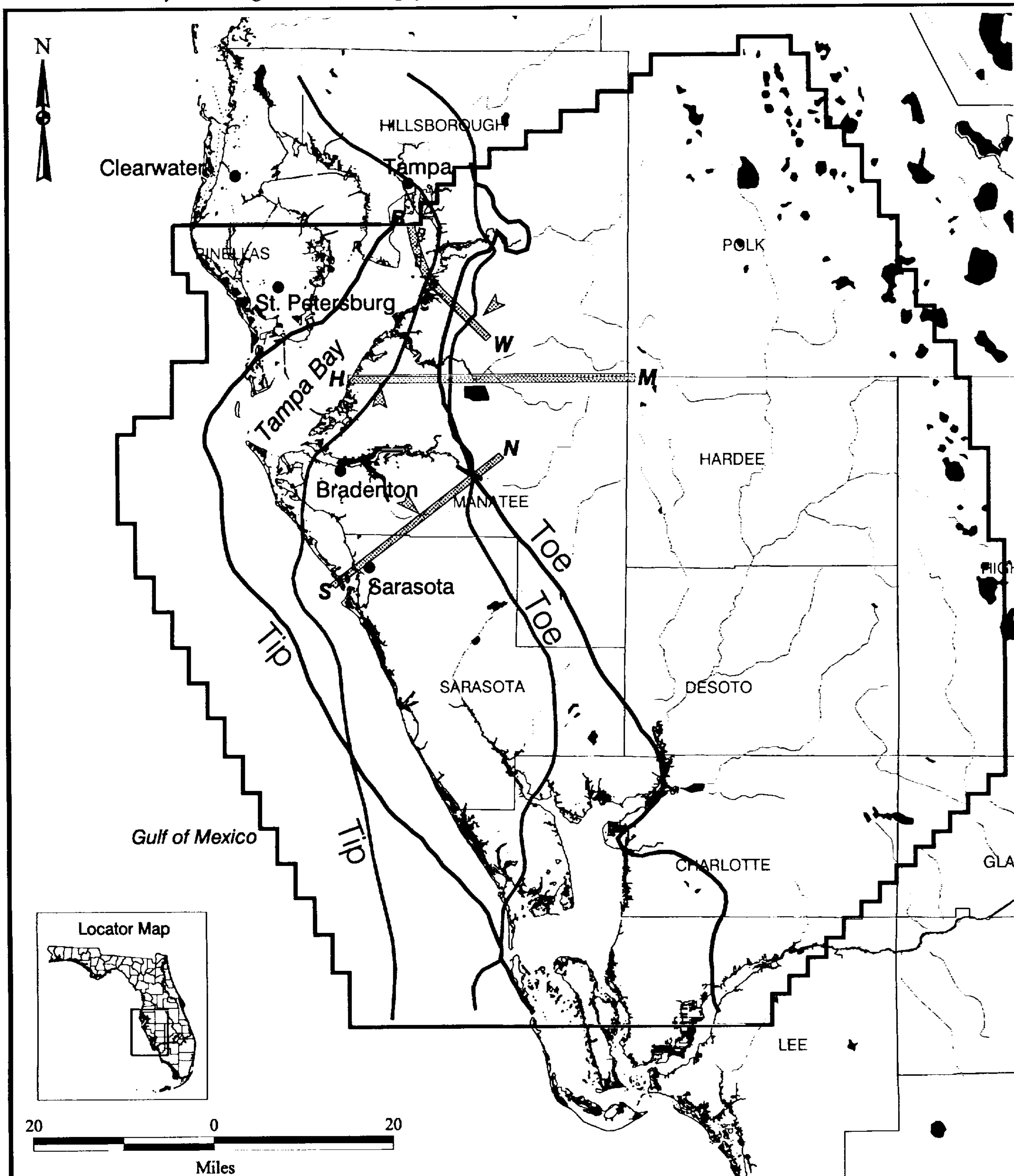
Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic

Legend

County Boundary
Surface Drainage
Present Postion (2000)
400 MGD
600 MGD
800 MGD
1000 MGD

Figure 2.17
Extent of the 1000 mg/l Chlorides in the Highly Permeable Zone of UFAS Fifty Year Position (Beach and Shultz, 2000)



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Revised: 06/05/02 TB

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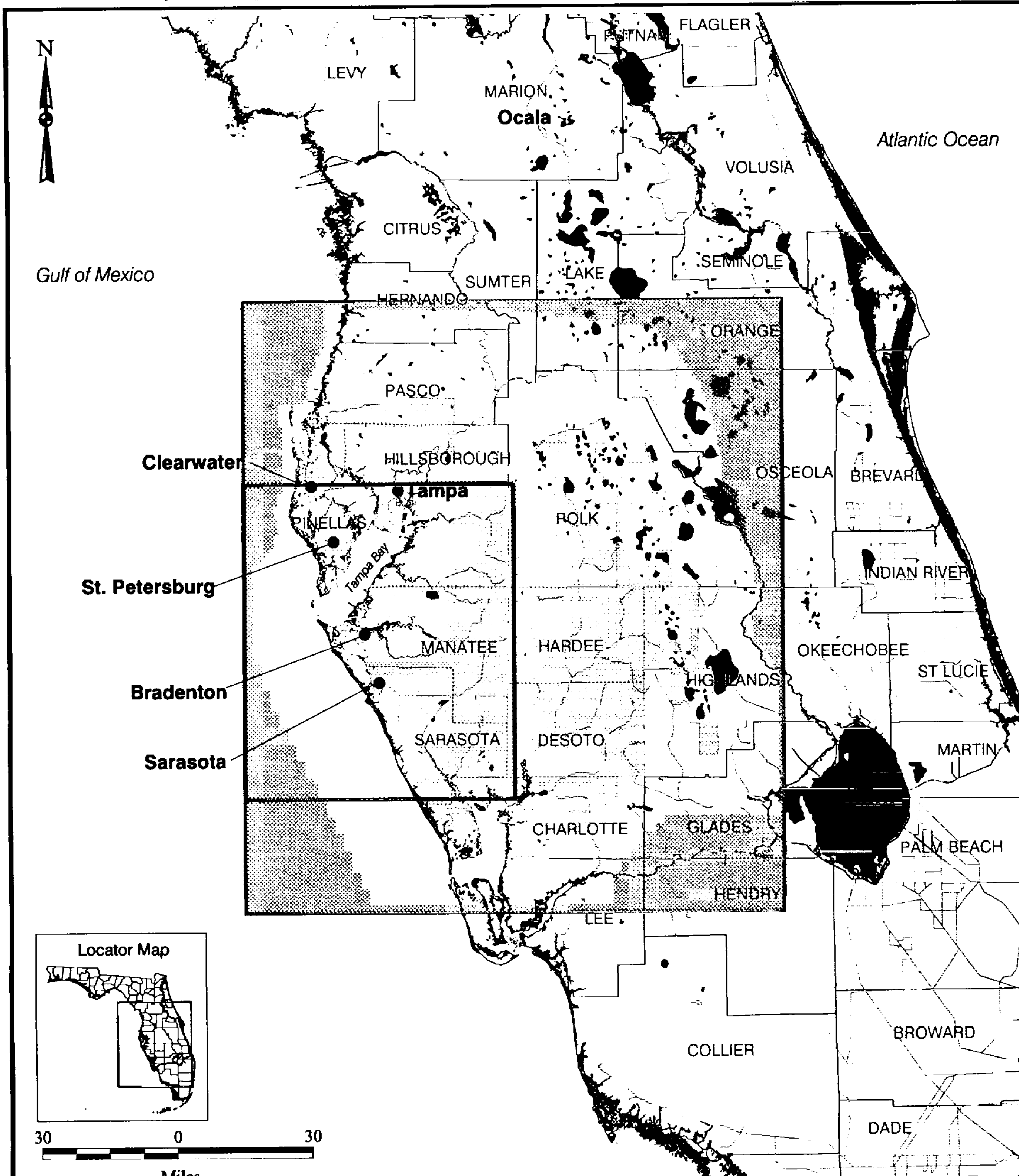
Legend

- County Boundary
- Surface Drainage
- Eastern Tampa Bay Model Grid Boundary
- Cross-section Locations (HGL, 1991a)
- Prediction of Toe of the Plume (HGL, 1991a)
- Predevelopment Interface Position (HGL, 1994a)
- Predevelopment Interface Position (HGL, 1993a)

Figure 3.1
Previous Model Domain and Simulated Predevelopment Interface Position of the Upper Floridan System



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Revised: 04/22/02 TB

Legend

- County Boundary
- Surface Drainage
- Regional Model Domain
- Local Density-Dependent Model Domain
- Inactive Model Cells
- Water Use Caution Areas

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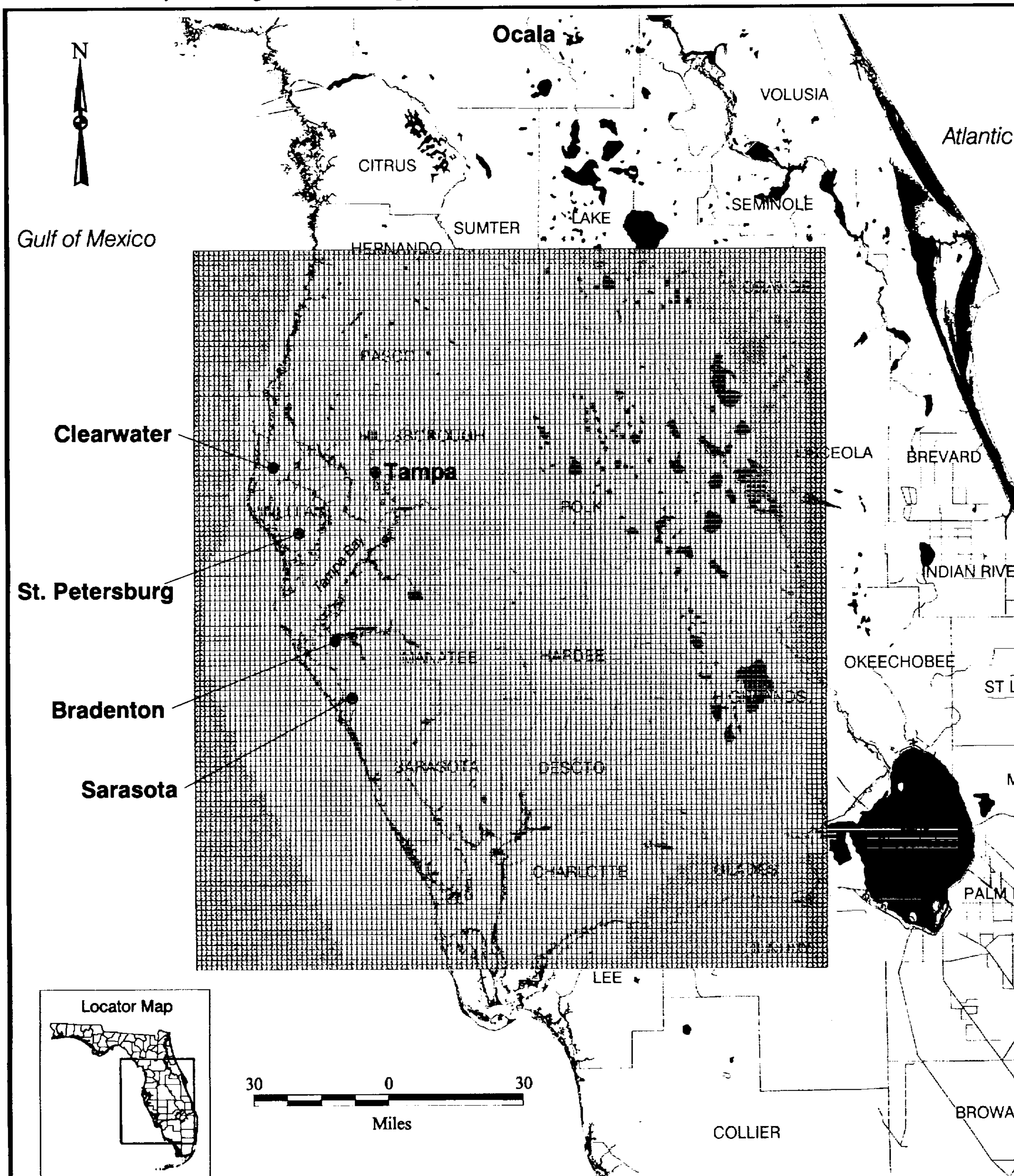
Figure 4.1
Regional and Density-Dependent Model Domains



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Project: SWF024-001-01
Created: 11/29/01 TH
Revised: 04/22/02 TB

Legend

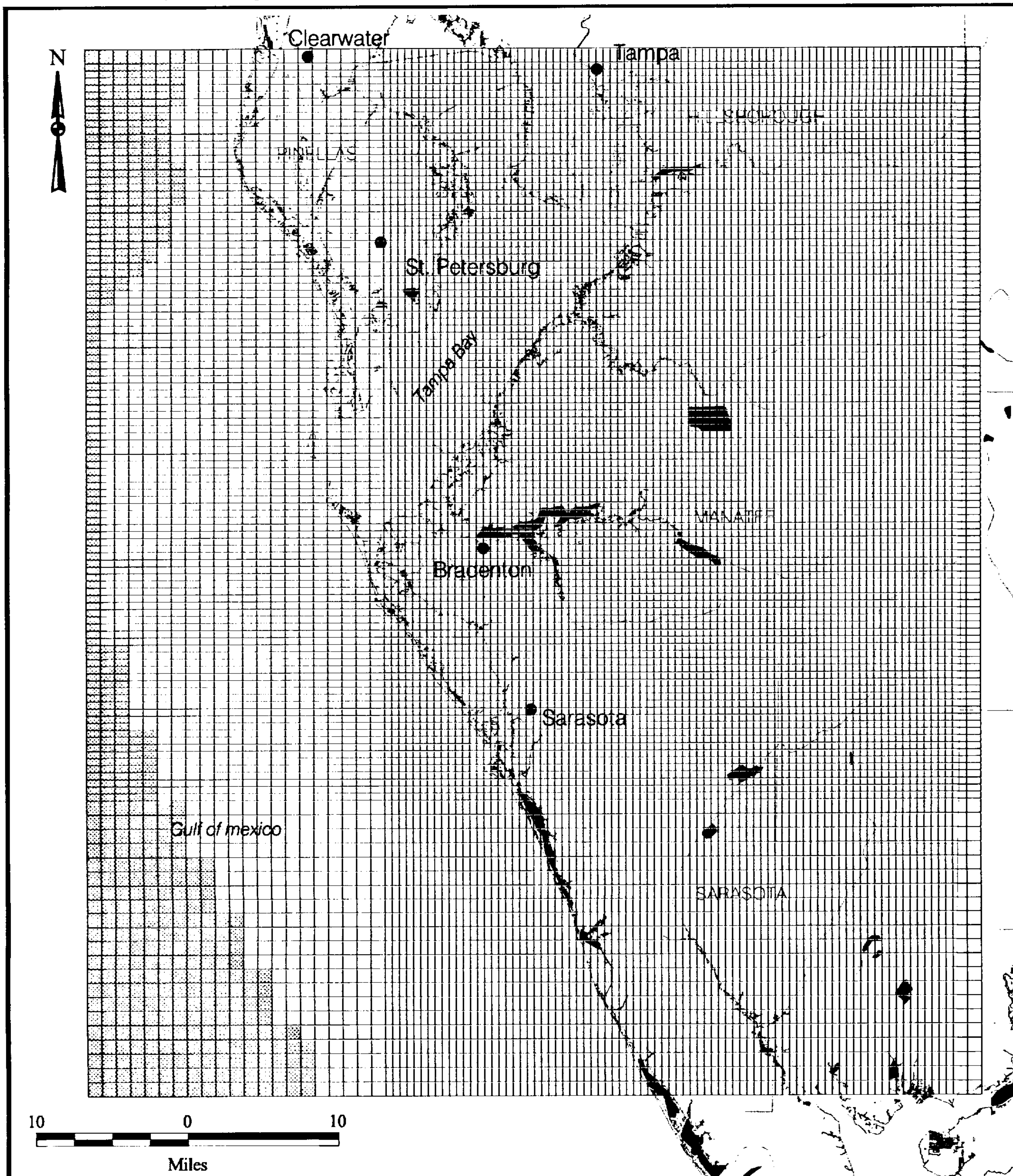
County Boundary

Surface Drainage

□ Active Grid Cell

⊡ Inactive Grid Cell

Figure 4.2
Regional Flow Model Finite-Difference Grid



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
Active Grid Cell
Inactive Grid Cell

Figure 4.3
Density-Dependent Model Finite-Difference Grid

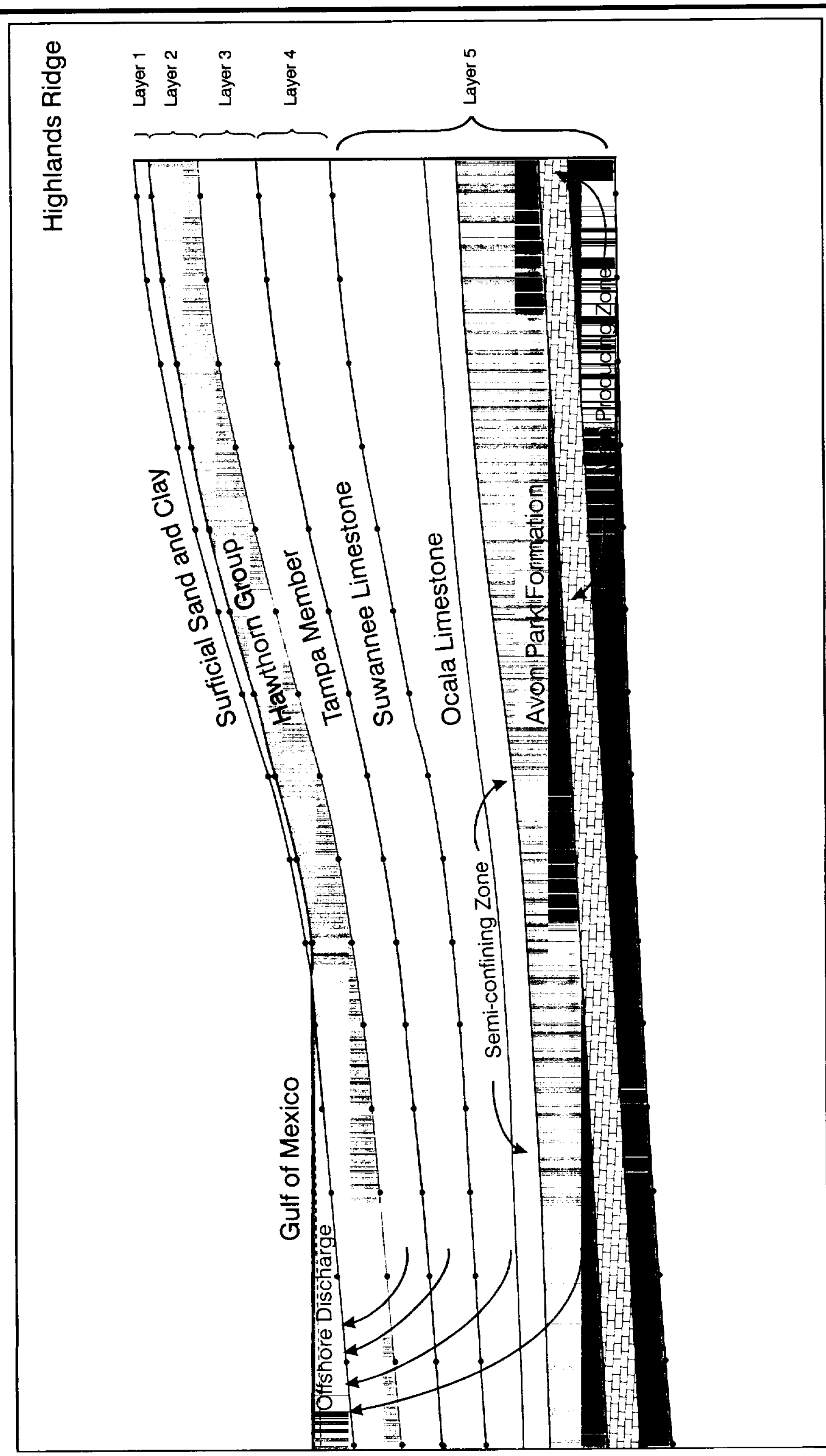

Figure 4.4

Vertical Discretization of Southern District Model

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Project: SWF024-0101
Created by: cfarmer 12/14/01
Revised: 07/03/02 cf
Source: Waterstone (2000)

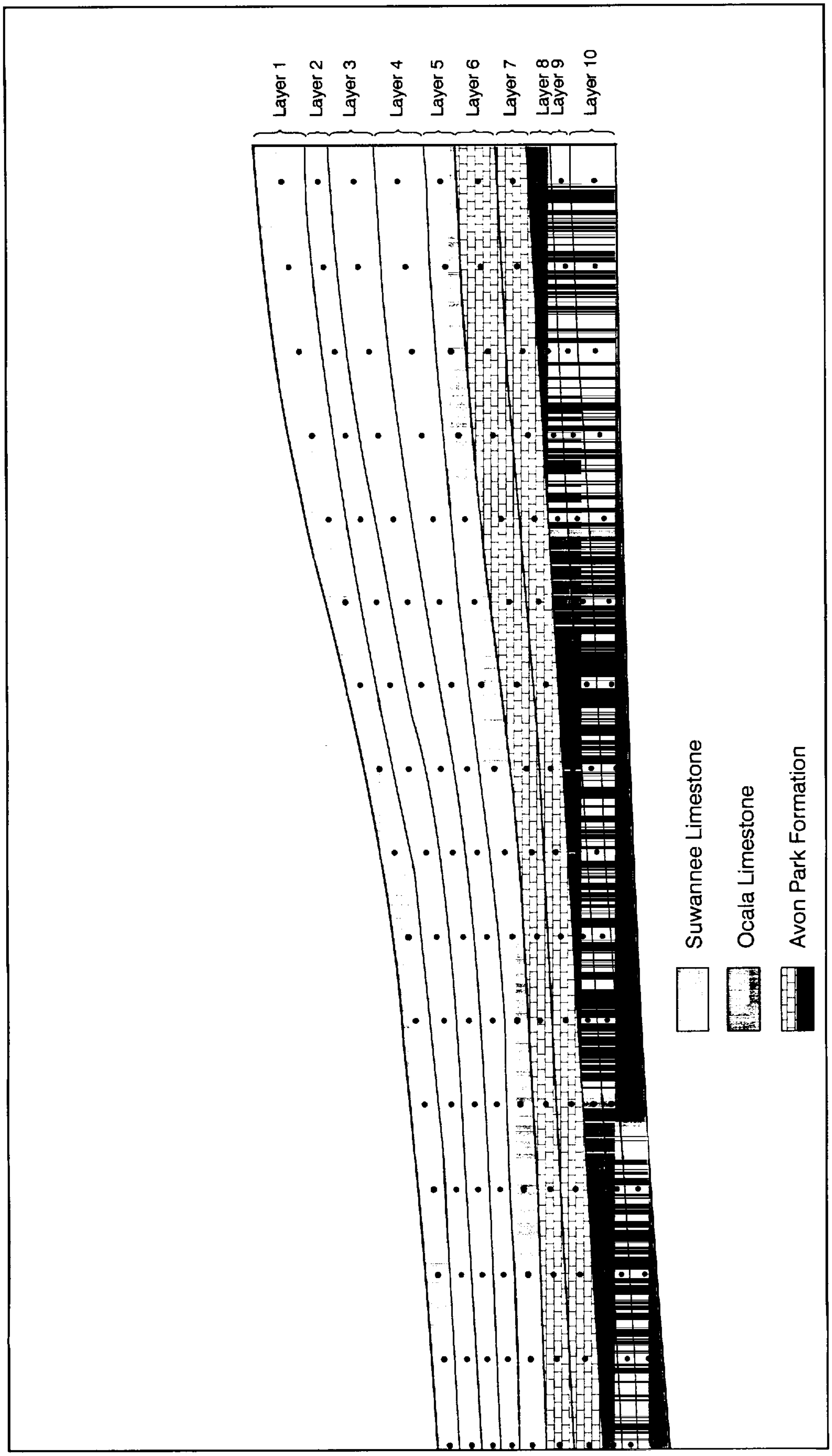

Figure 4.5

Initial Vertical Discretization of the Density-Dependent Model

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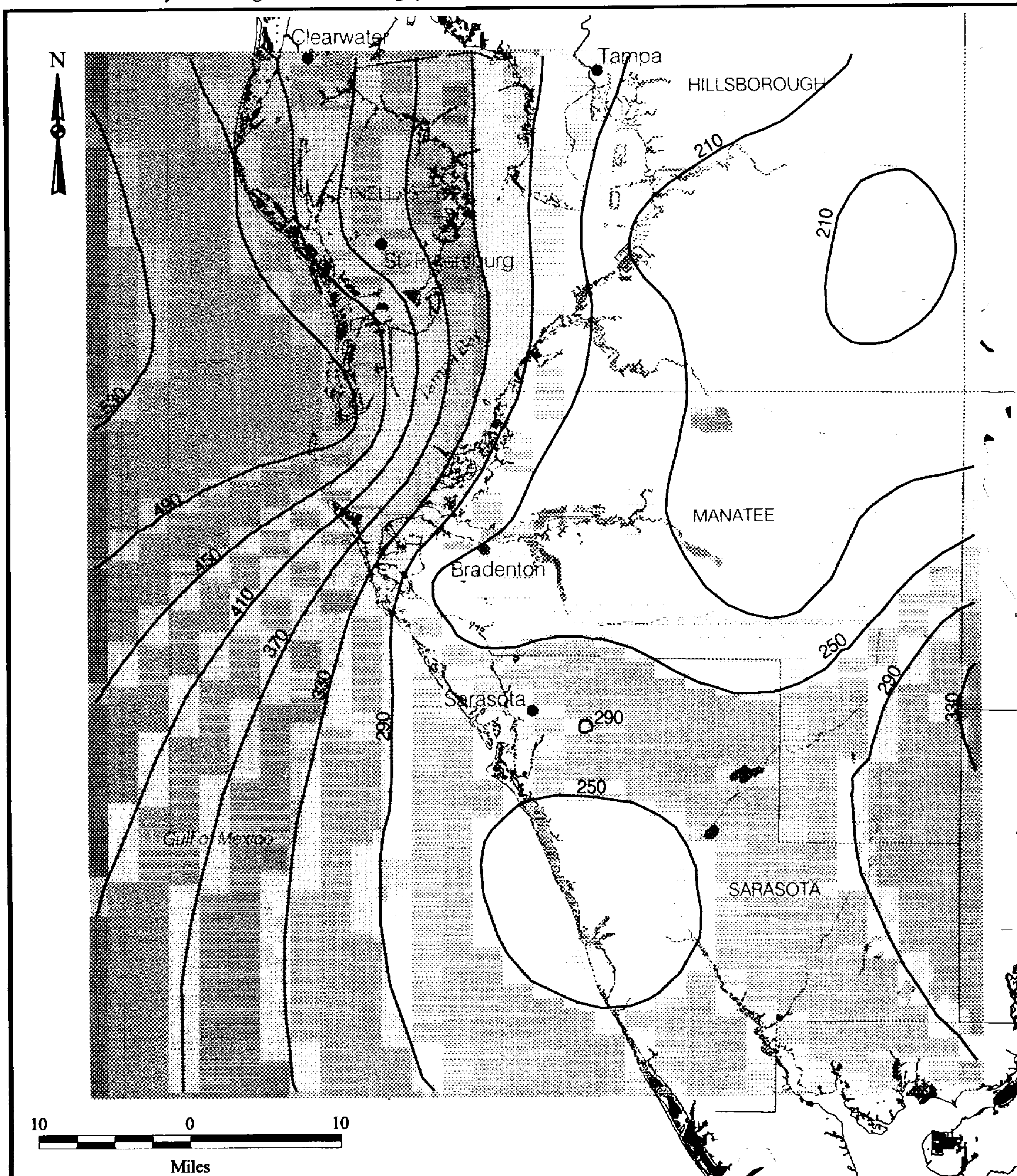
Source: Waterstone (2000)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

Legend

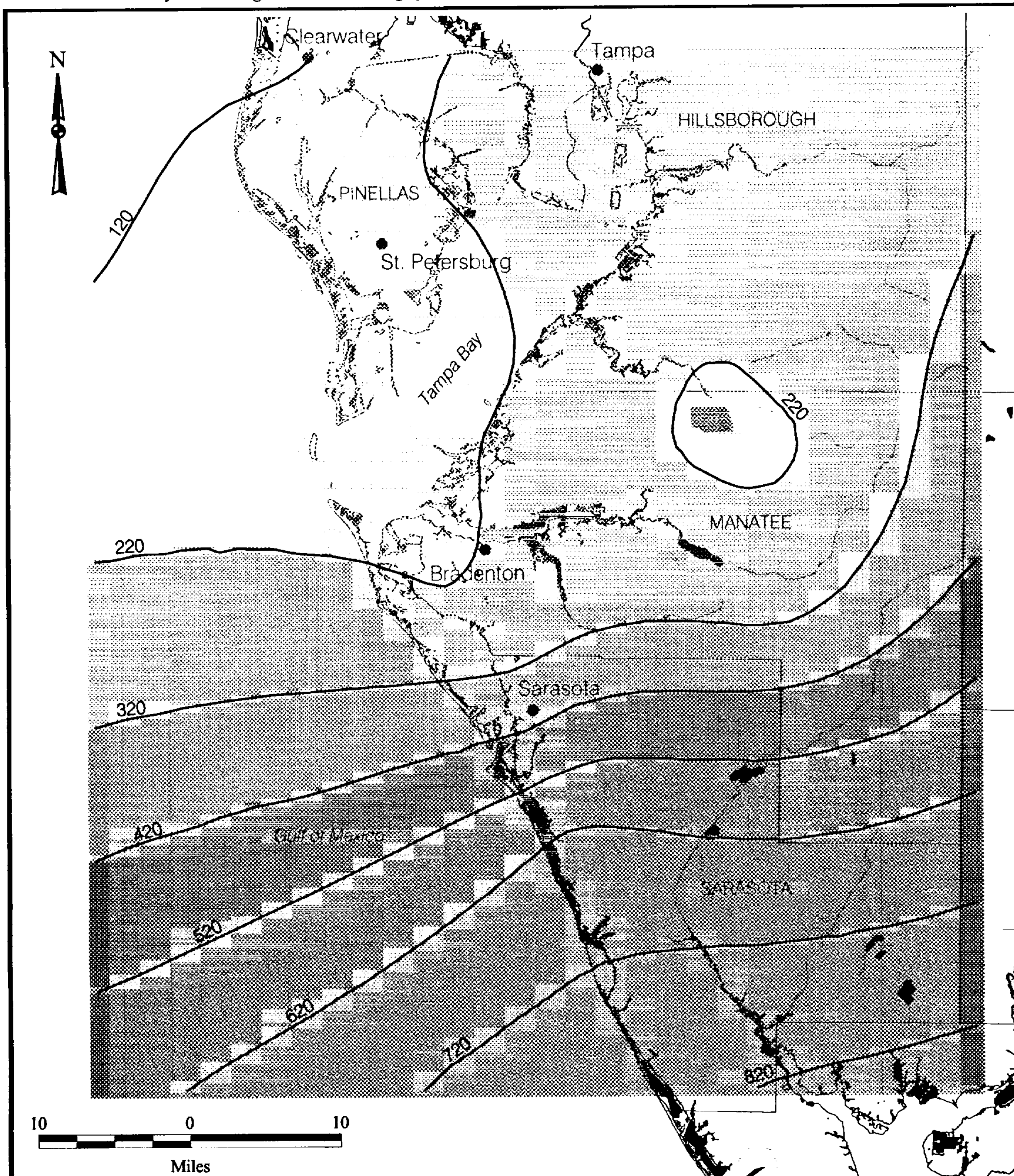
County Boundary

Surface Drainage

250 Suwannee Thickness Contour (ft)

Suwannee Thickness (ft)
170 - 210
210 - 250
250 - 290
290 - 330
330 - 370
370 - 410
410 - 450
450 - 490
490 - 530
530 - 570

Figure 4.6
Thickness of the Suwannee Limestone (Model Layers 1 and 2)



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Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic INC

Legend

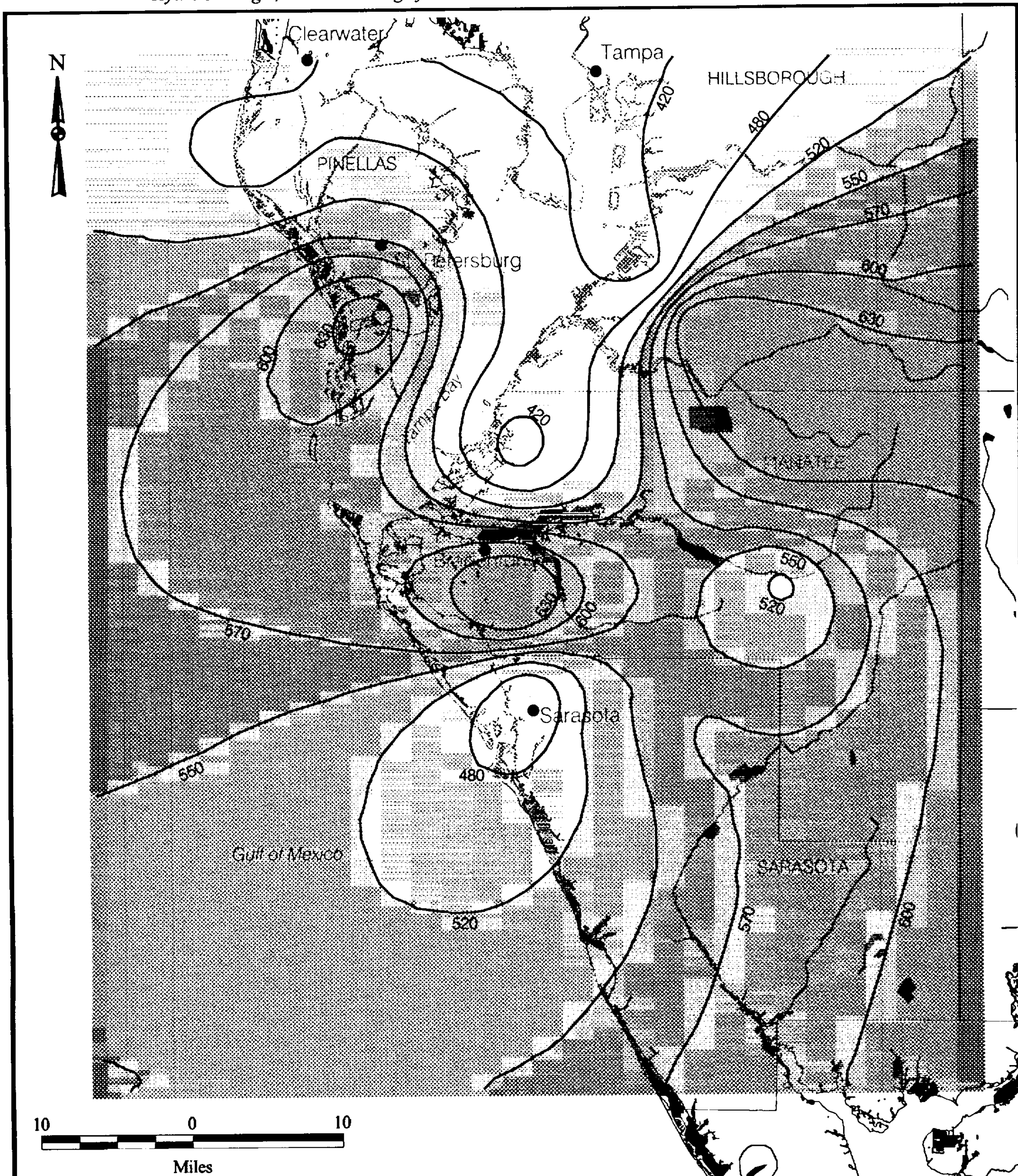
County Boundary

Surface Drainage

520 Ocala Thickness Contour (ft)

Ocala Thickness (ft)
1 - 120
120 - 220
220 - 320
320 - 420
420 - 520
520 - 620
620 - 720
720 - 820
820 - 920

Figure 4.7
Thickness of the Ocala Limestone (Model Layers 3, 4, and 5)



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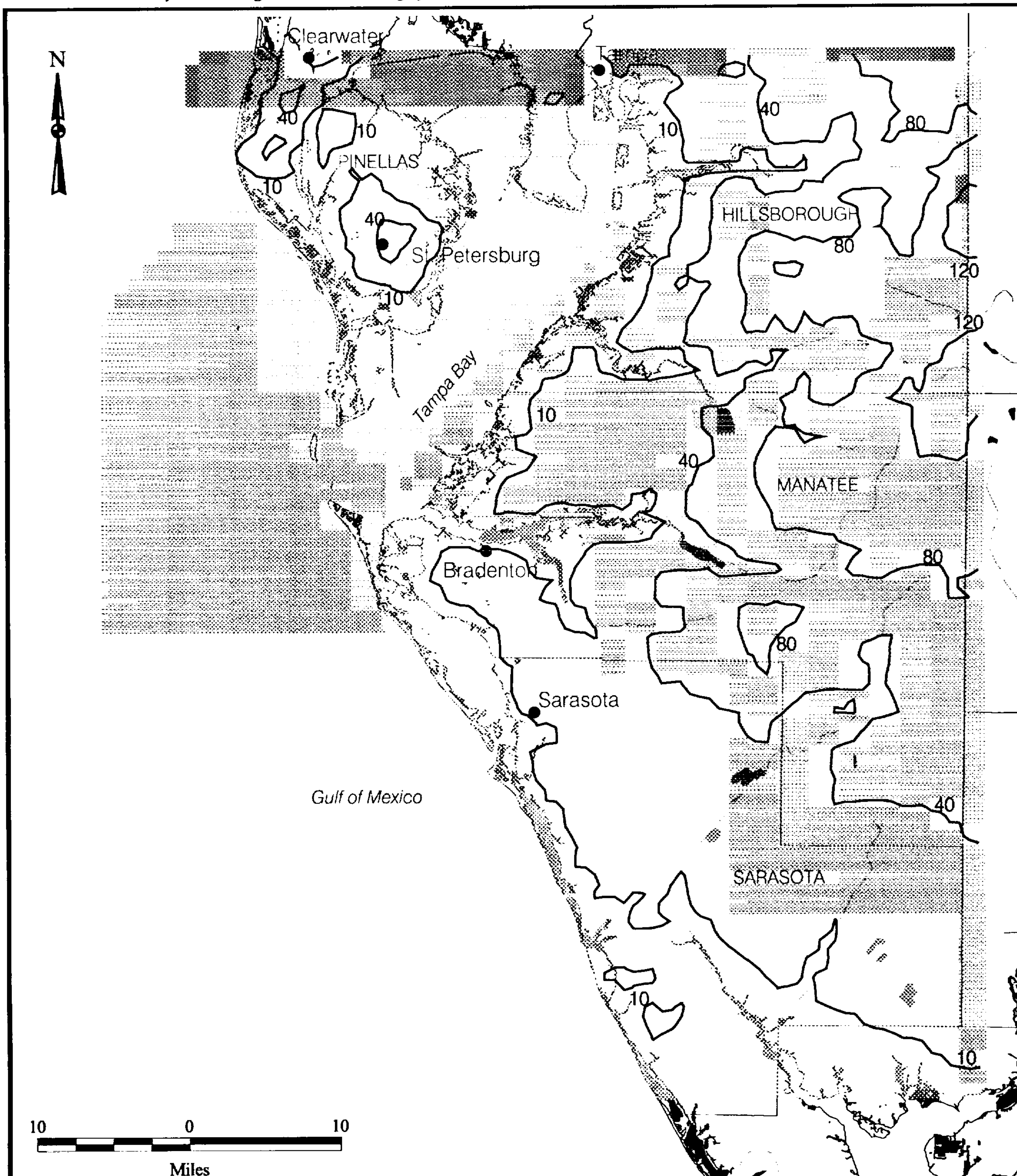
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/01 TB

Legend

County Boundary
Surface Drainage
570 Avon Park Thickness Contour (ft)

Avon Park Thickness (ft)
385 - 420
420 - 480
480 - 520
520 - 550
550 - 570
570 - 600
600 - 630
630 - 715

Figure 4.8
Thickness of the Avon Park Formation (Model Layers 6 through 10)



Filename: X:\SWF024\WO_01\saltwater_intrusion\fig 4-9.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

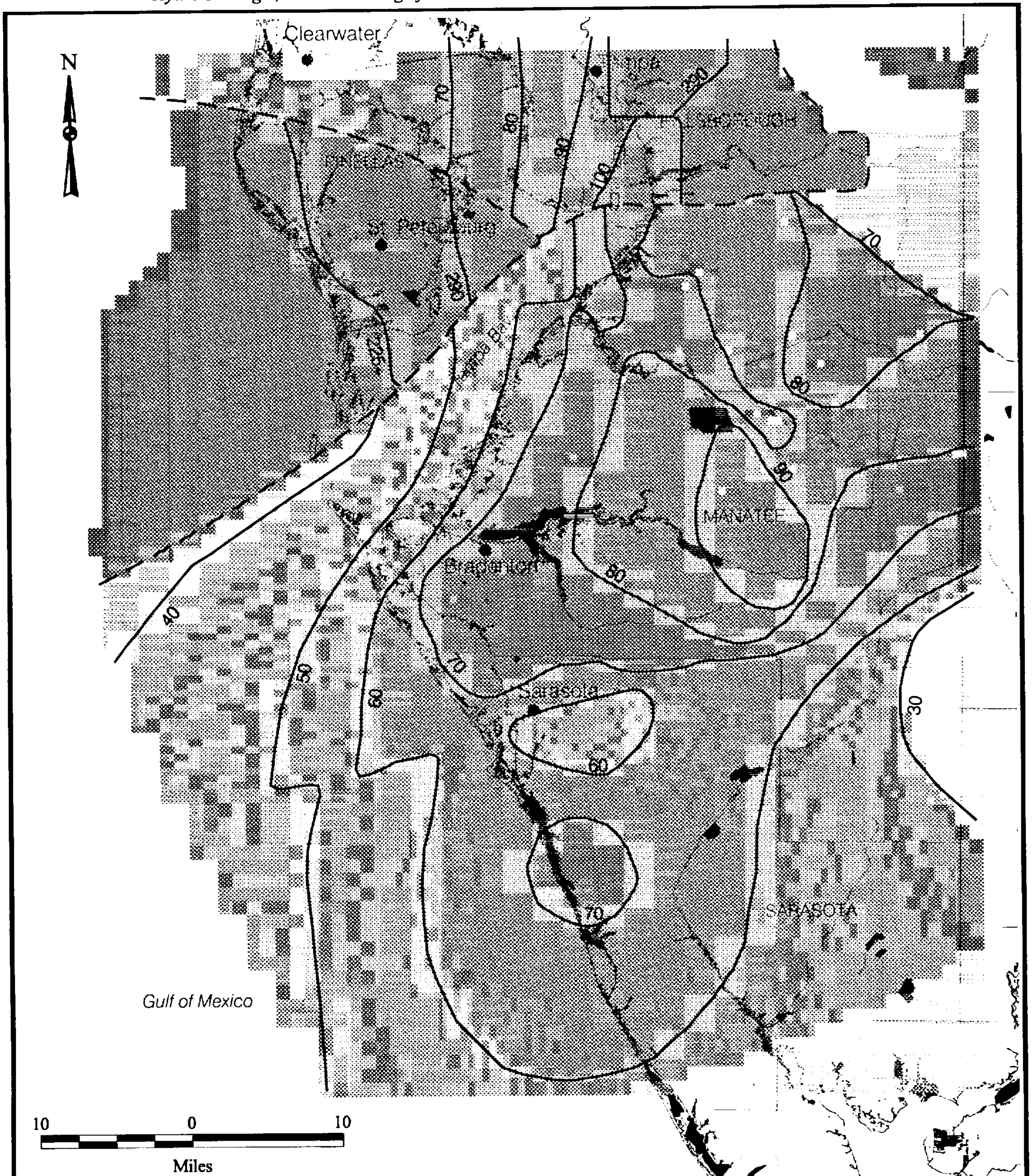
HYDRO GeoLogic Inc.

Legend

- County Boundary
- Surface Drainage
- 40 Hydraulic Head Assigned to General Head Boundaries (ft)

GHB Conductance - (1/Day)
- 1 - 10
- 10 - 100
- 100 - 1000
- 1000 - 10000
- 10000 - 100000

Figure 4.9
Head and Conductance Distribution of the General Head Boundaries Applied to the Top of the Suwannee Limestone (Model Layer 1)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/05/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary

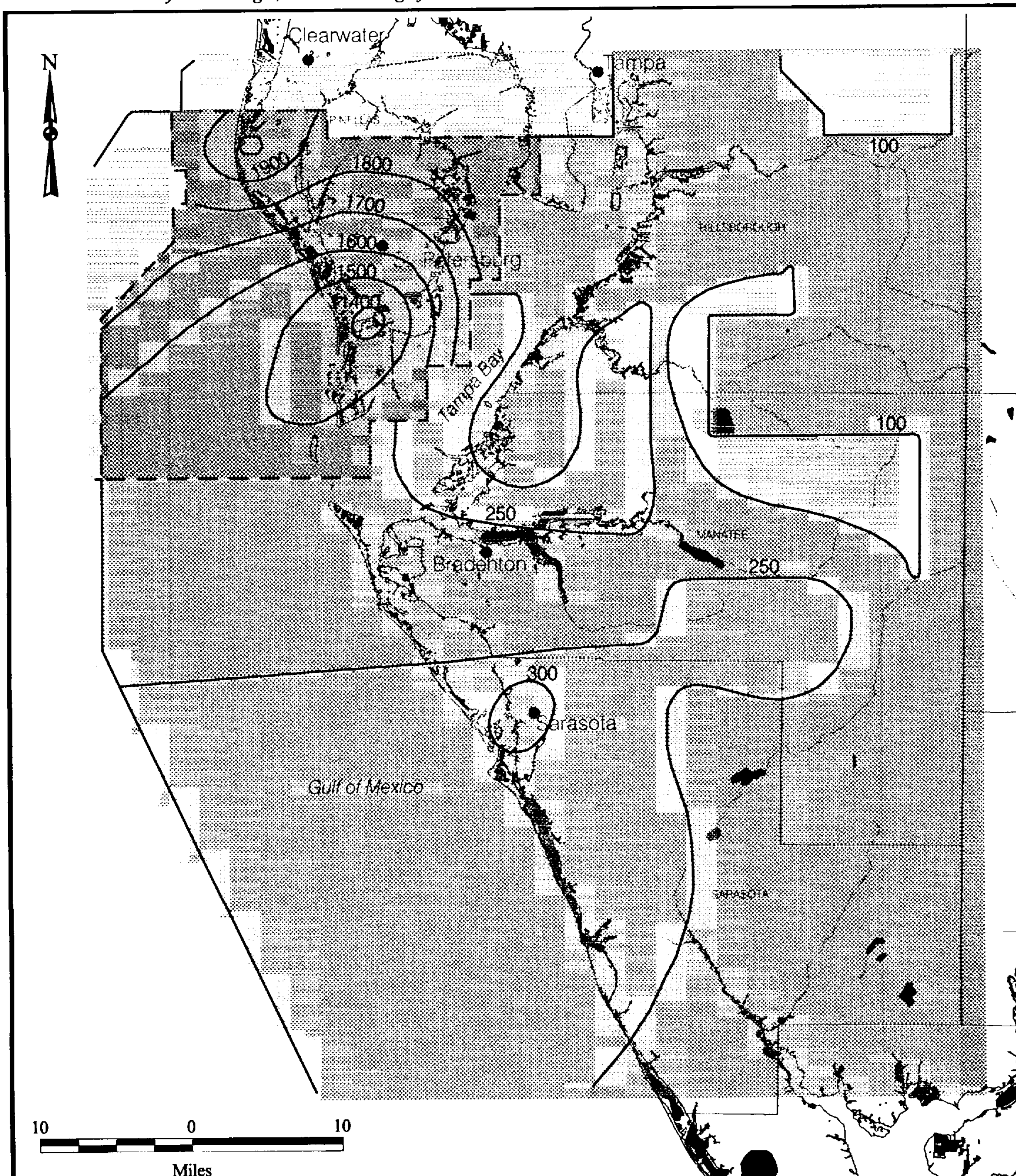
Surface Drainage

80 Suwannee Hydraulic Conductivity Contour (ft²/day)

Zone Boundaries

Suwannee Hydraulic Conductivity (ft²/day)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 225
225 - 290
290 - 420
420 - 600

Figure 4.10
Initial Hydraulic Conductivity of the Suwannee Limestone (Model Layers 1 and 2)



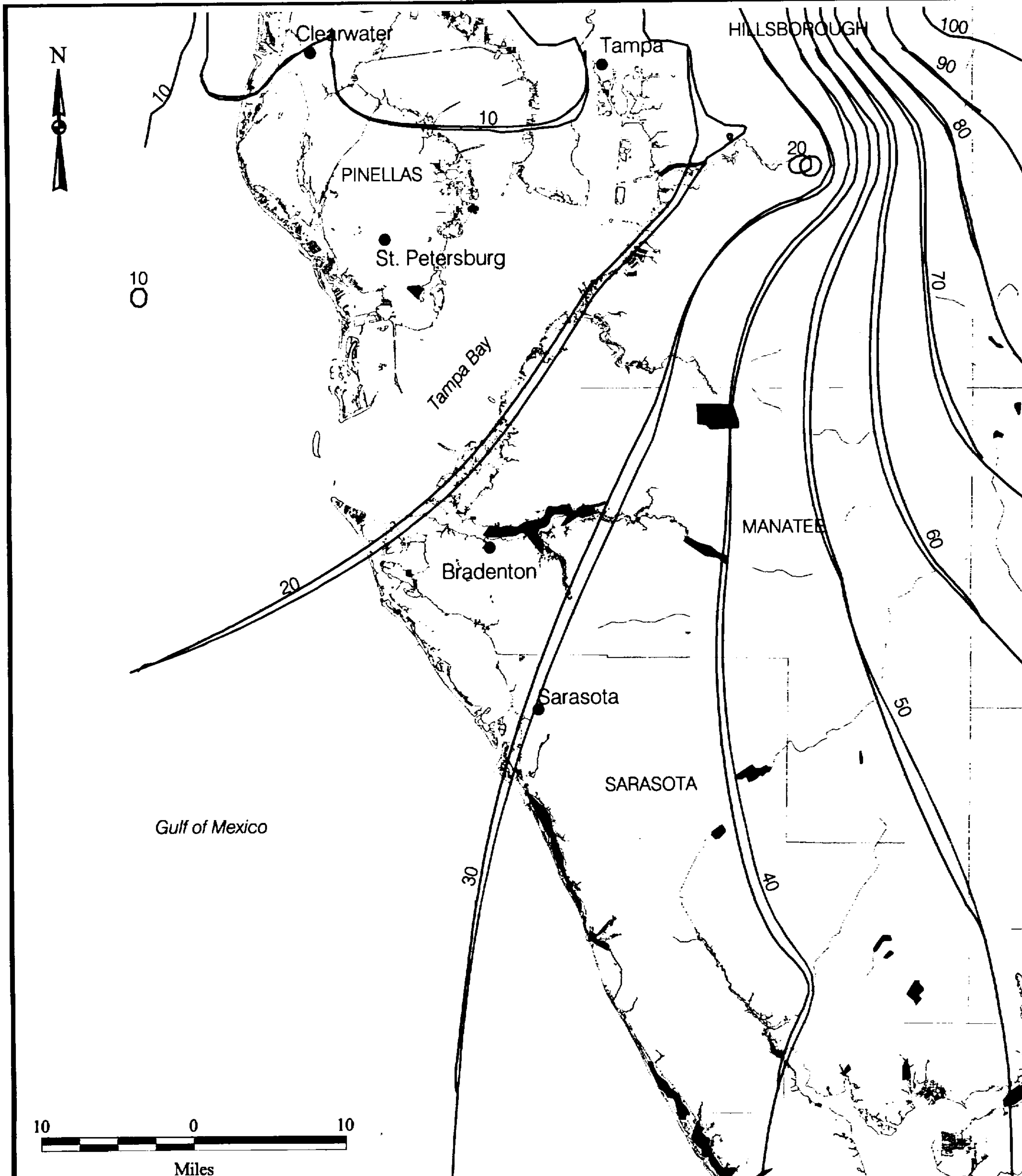
Filename: X:\SWF024\WO_01\saltwater_intrusion\fig4-11.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/05/02 TB

Legend

- County Boundary
- Surface Drainage
- 1600 — Avon Park Hydraulic Conductivity Contour (ft/day)
- Zone Boundary

Avon Park Hydraulic Conductivity (ft/day)
0 - 1
1 - 10
10 - 100
250 - 300
100 - 1000
1000 - 1400
1400 - 1500
1500 - 1600
1600 - 1700
1700 - 1800
1800 - 1900
1900 - 2000
2000 - 10000

Figure 4.11
Initial Hydraulic Conductivity of the Avon Park Formation (Model Layers 6 through 10)



Filename: X:\SWF024\WO_01\saltwater_intrusion\fig5-1.apr
Project: SWF024-001-01
Created: 11/28/01 TB
Revised: 04/22/02 TB

HYDRO GeoLogic Inc.

Legend

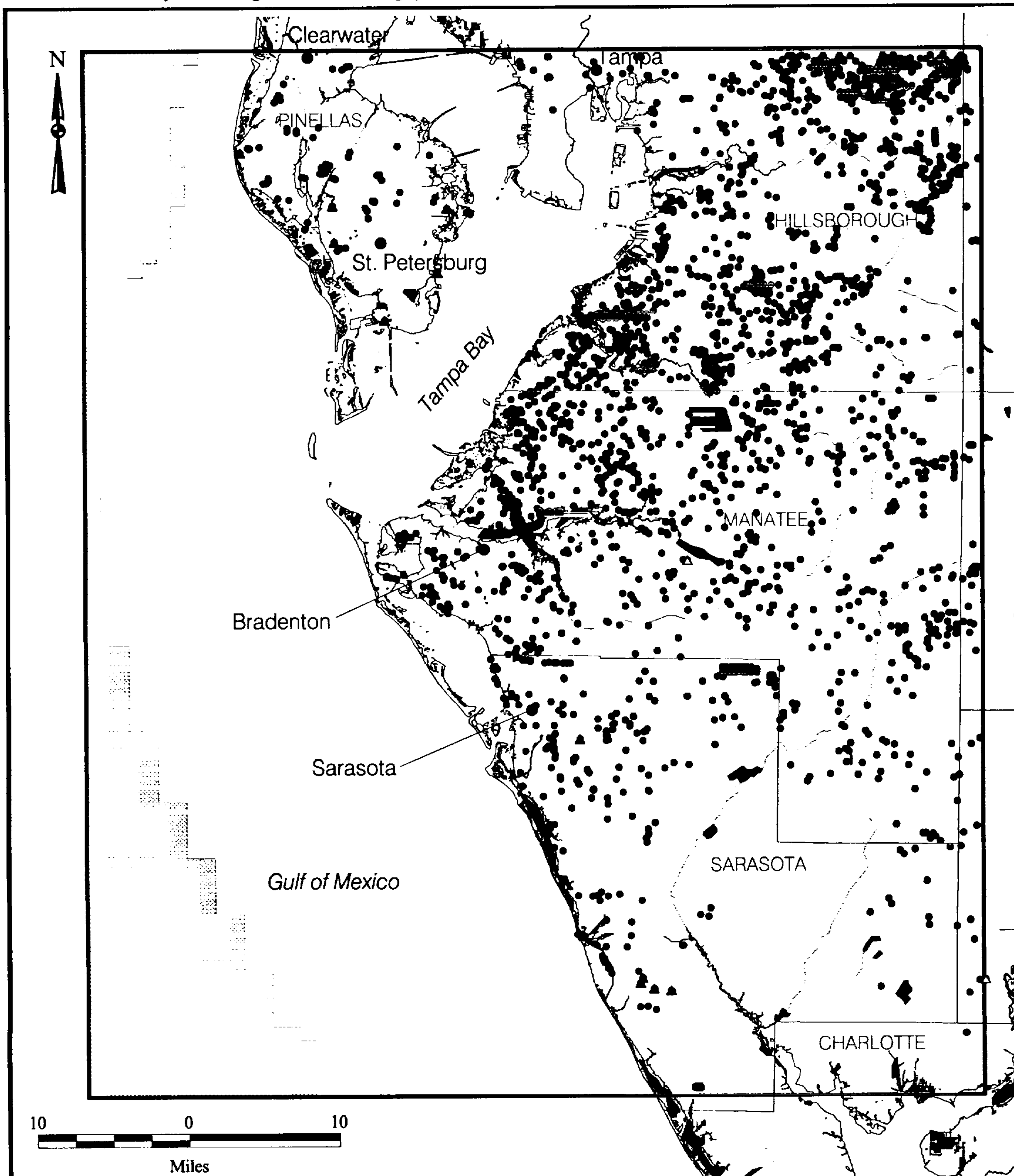
County Boundary

Surface Drainage

10 — Regional Model Contour Lines (ft)

10 — Local Model Contour Lines (ft)

Figure 4.12
Comparison of Predevelopment Heads Predicted by the Regional Flow and Density Dependent Models



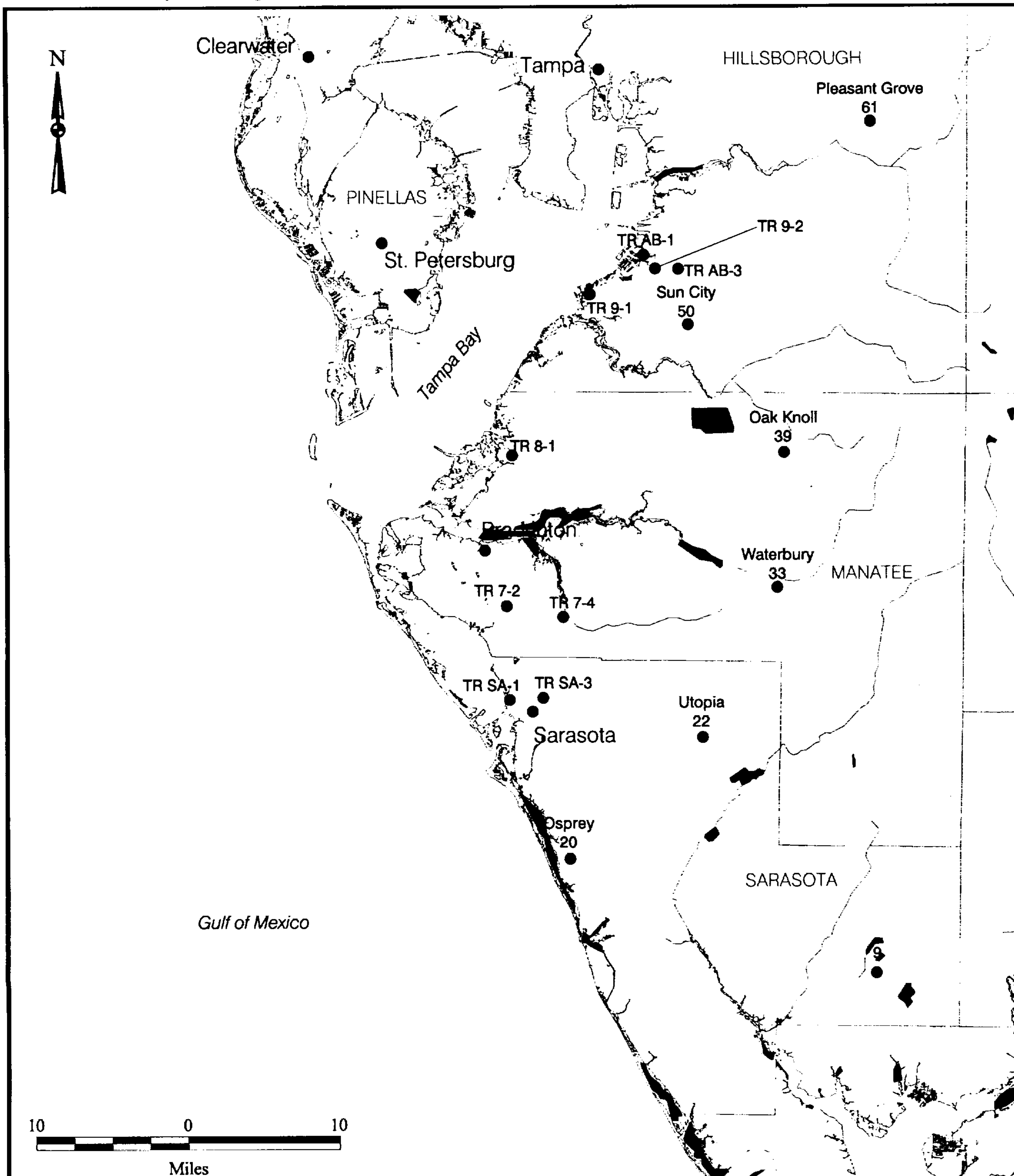
Filename: X:\SWF024\WO_01\saltwater_intrusion\well_loc_by_3area.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/05/02 TB

HYDRO GeoLogic INC.

Legend

- County Boundary
- Surface Drainage
- Model Domain
- Inactive Area
- ● Suwannee Well Locations
- ● Ocala Well Locations
- ● Avon Park Well Locations
- ▲ Avon Park Injection Well Locations
- △ Suwannee Injection Well Locations

Figure 5.1
Location of Groundwater Extraction/Injection Wells within the Study Area



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic Inc

Legend

County Boundary

Surface Drainage

TR 7-2 ROMP Well Name

● ROMP Well Location

Figure 5.2
ROMP Wells
Used for Determining
Model Calibration
Statistics

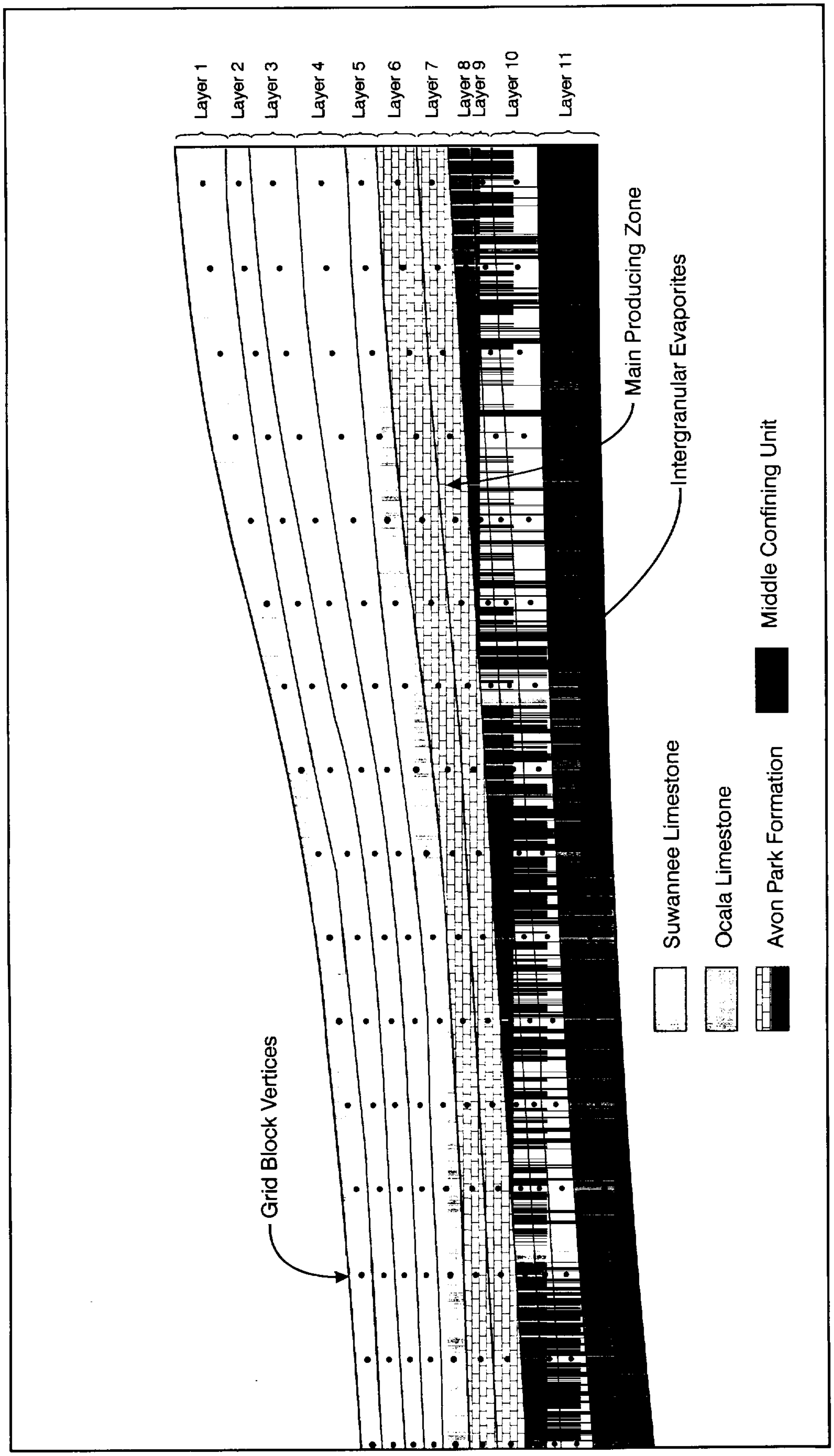
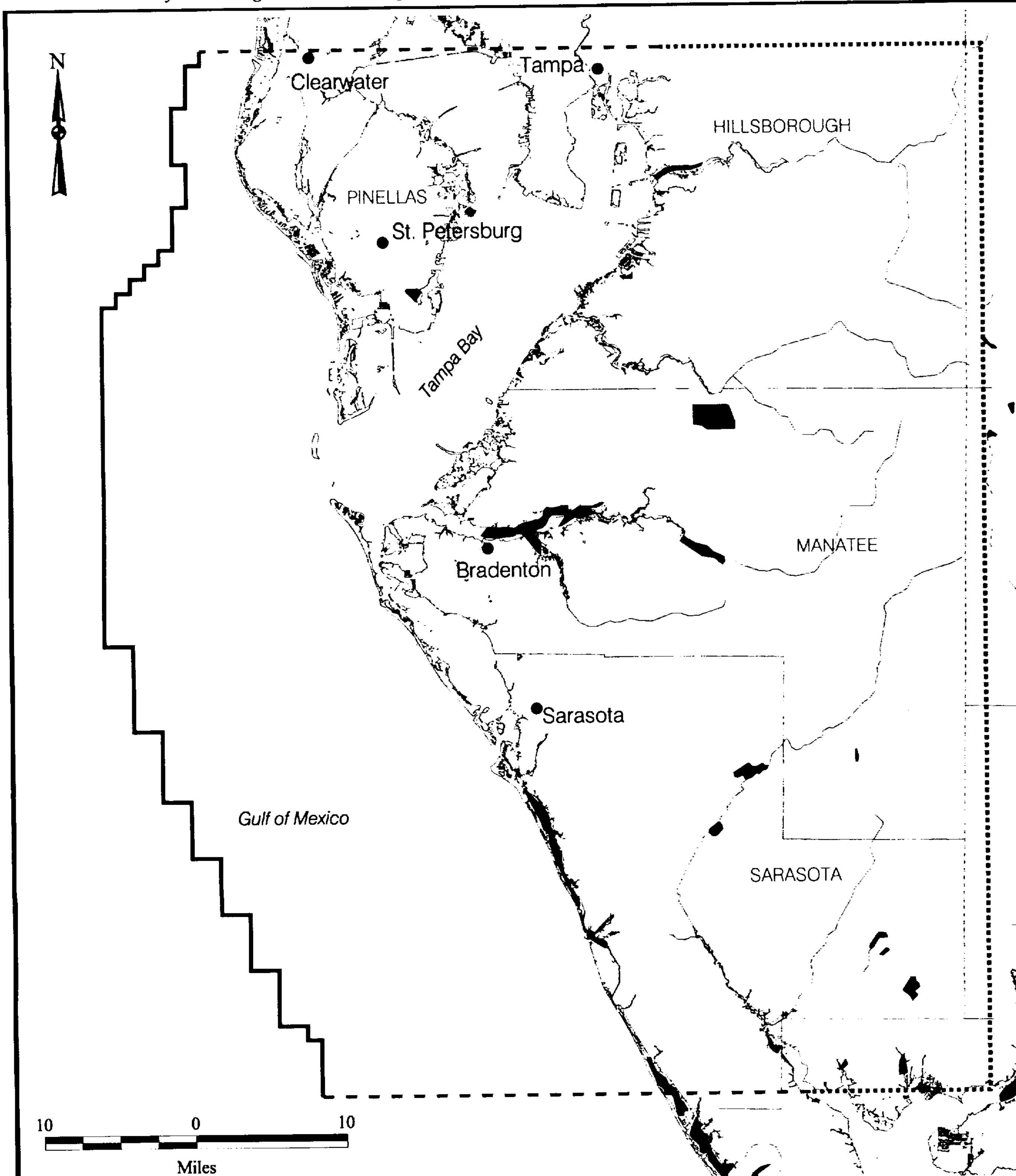


Figure 5.3

Vertical Discretization of the Calibrated Density-Dependent Model

HYDRO GEOLOGIC INC.

Filename: X:\SWF024\WO_01\vert_discret_calibrated_rev.cdr
Project: SWF024-001-03
Created by: cfarmer 04/03/02
Revised: 06/07/02 tbraswell
Source: Waterstone (2000)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
—— C = 1, h = 0
······ C = 0, h = prescribed from regional model (transient)
– – C = 1, h = constant, obtained from regional predevelopment model

Note: The Prescribed heads are converted to equivalent freshwater heads for use in the model.

Figure 5.4
Head and Chloride Lateral Boundary Conditions of the Density Dependent Model

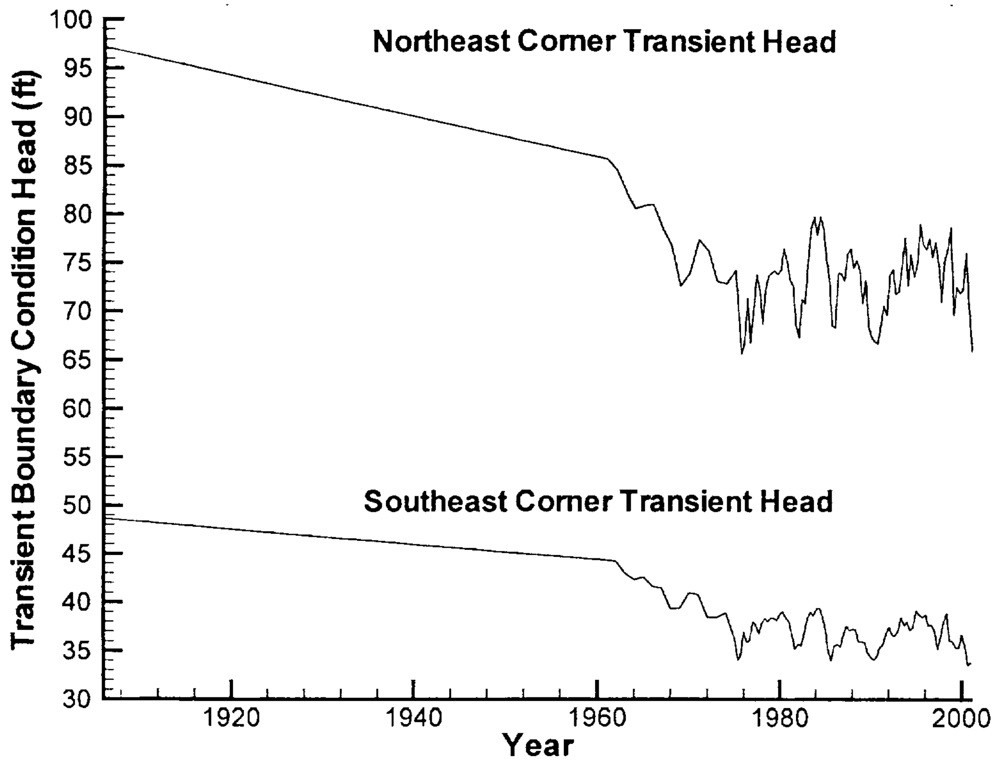
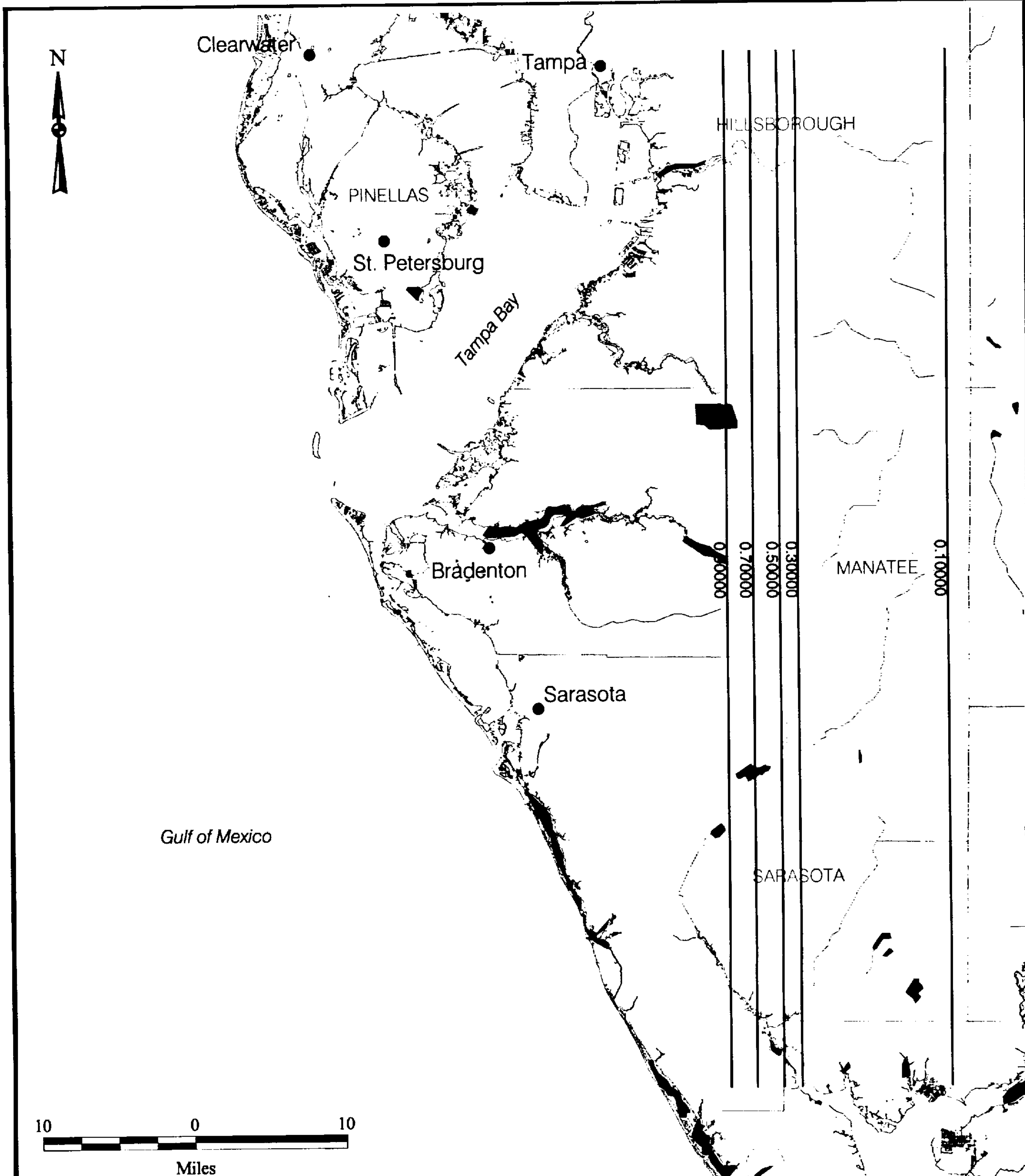


Figure 5.5 **Example of Transient Hydraulic Head Boundary Conditions Assigned to Cells Located in Northeast and Southeast Corners of Model Domain**



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 05/07/02 TB

HYDRO GeoLogic INC.

Legend

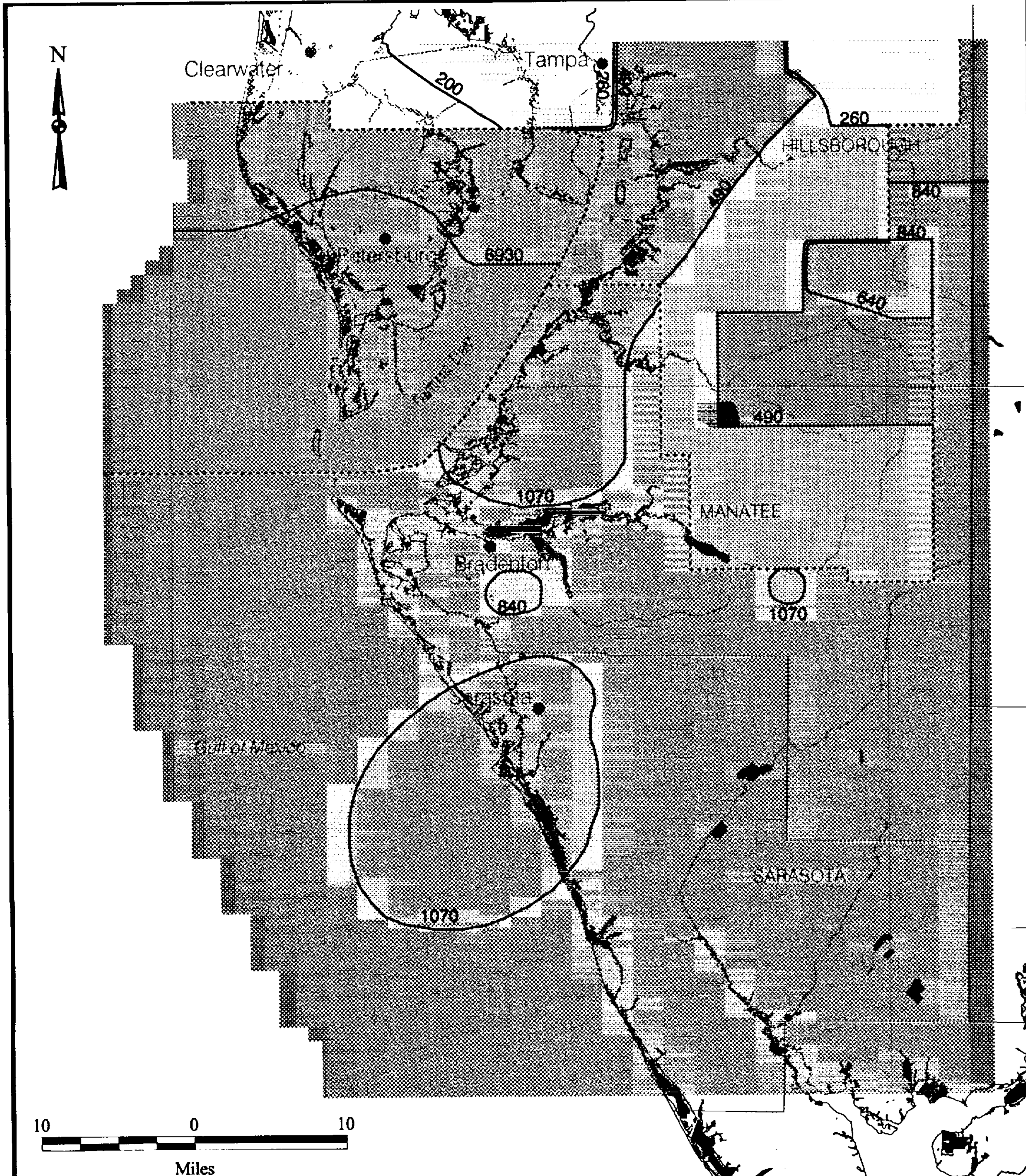
County Boundary

Surface Drainage

0.5 Bottom General Head Boundary's Relative Concentration Contour

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 5.6
Boundary Conditions at Base of Density Dependent Model



Filename: X:\SWF024\WO_01\saltwater_intrusion\conduct_highK.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 tbraswell

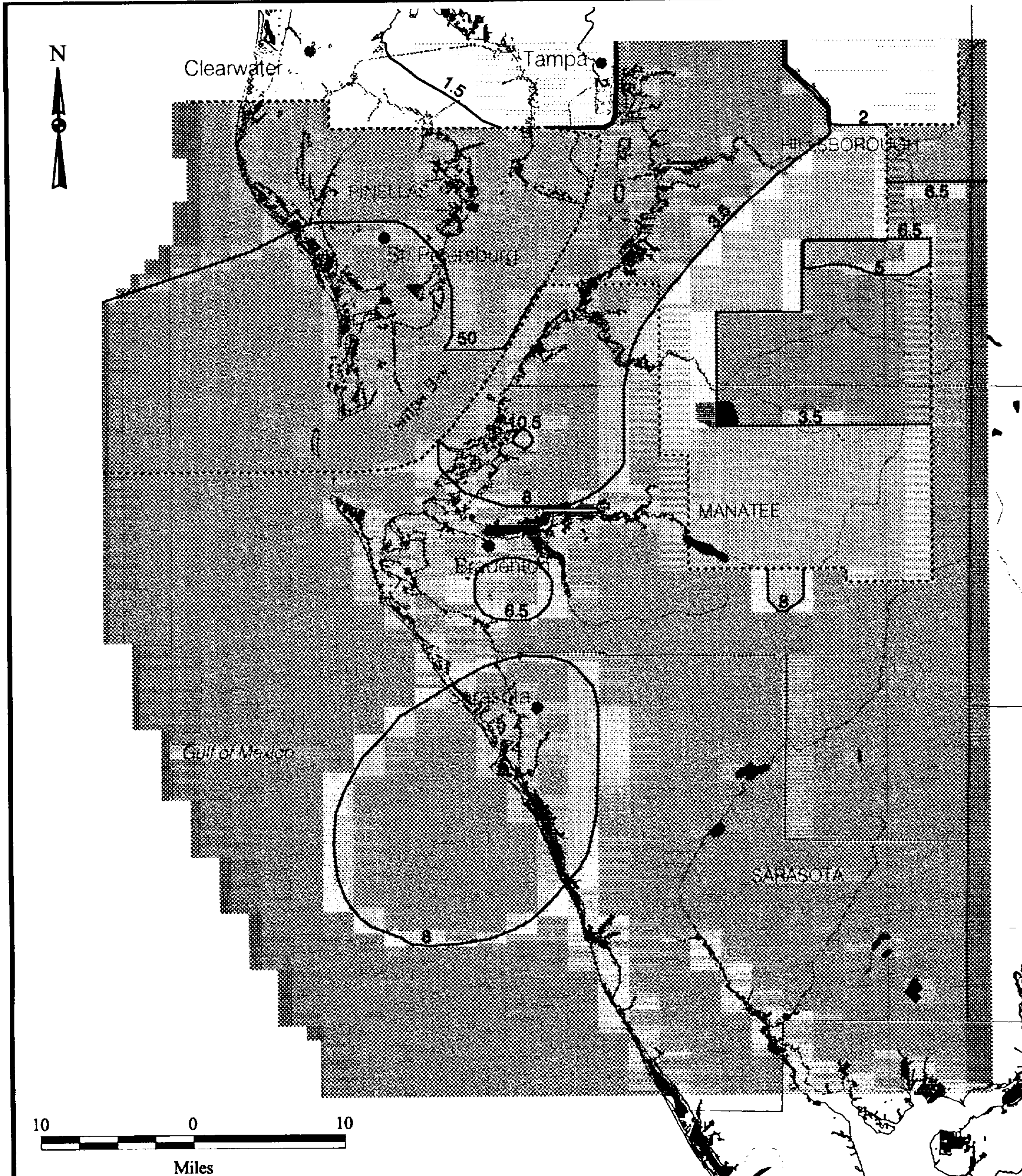
HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
Zone Boundary
840 Hydraulic Conductivity Contour (ft/d)

Hydraulic Conductivity (ft/d)
170 - 200
200 - 260
260 - 490
490 - 640
640 - 840
840 - 1070
1070 - 1430
1430 - 6930
6930 - 8480

Figure 5.7
Hydraulic Conductivity of the High K Zone in the Avon Park Formation (Model Layers 6 and 7)



Filename: X:\SWF024\WO_01\saltwater_intrusion\conduct_lowK.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary

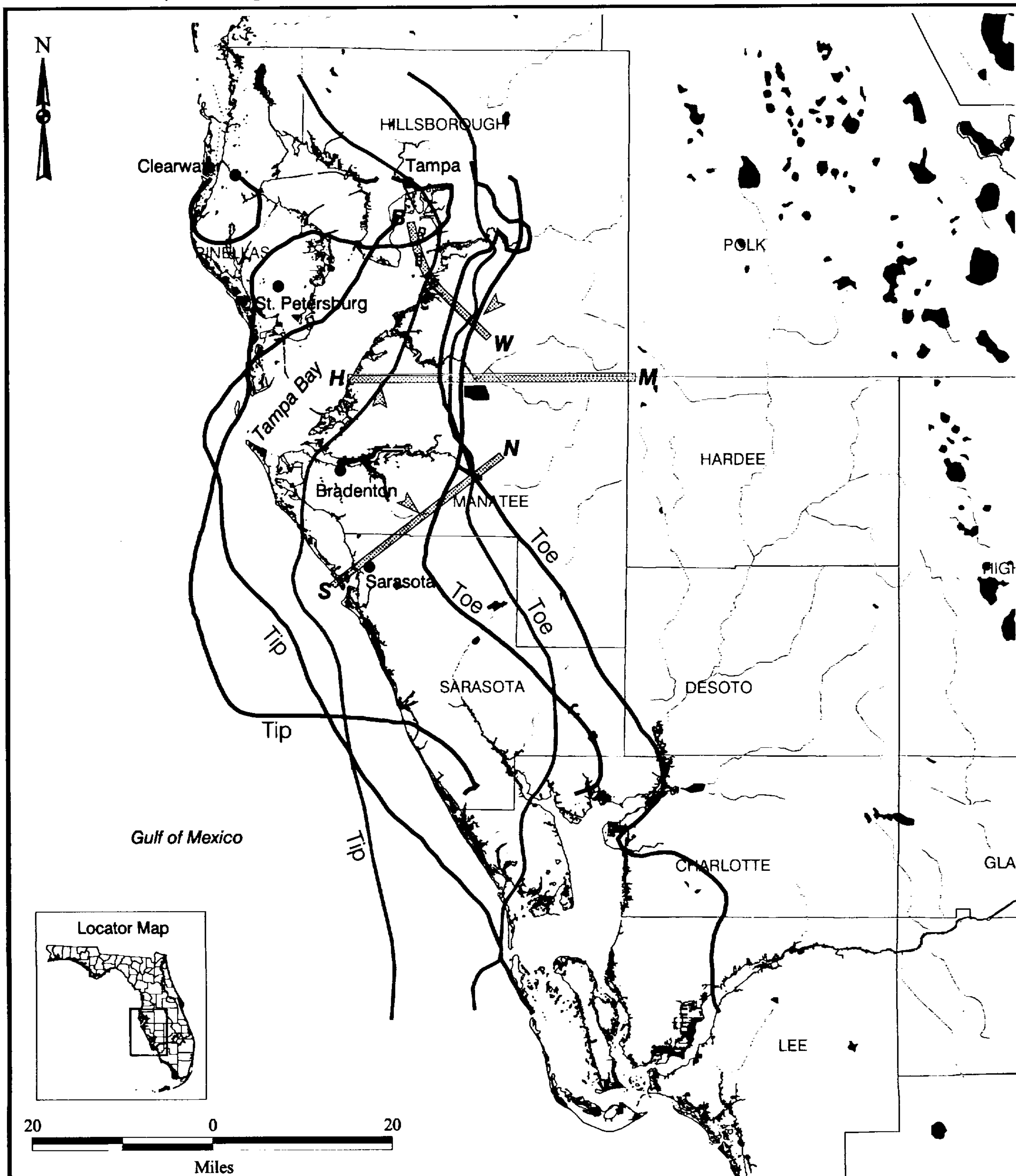
Surface Drainage

Zone Boundary

3.5 Hydraulic Conductivity Contour (ft/d)

Hydraulic Conductivity (ft/d)
- 1 - 1.5
- 1.5 - 2
- 2 - 3.5
- 3.5 - 5
- 5 - 6.5
- 6.5 - 8
- 8 - 10.5
- 10.5 - 50
- 50 - 64

Figure 5.8
Hydraulic Conductivity of the Lower K Zone in the Avon Park Formation (Model Layers 8, 9, and 10)



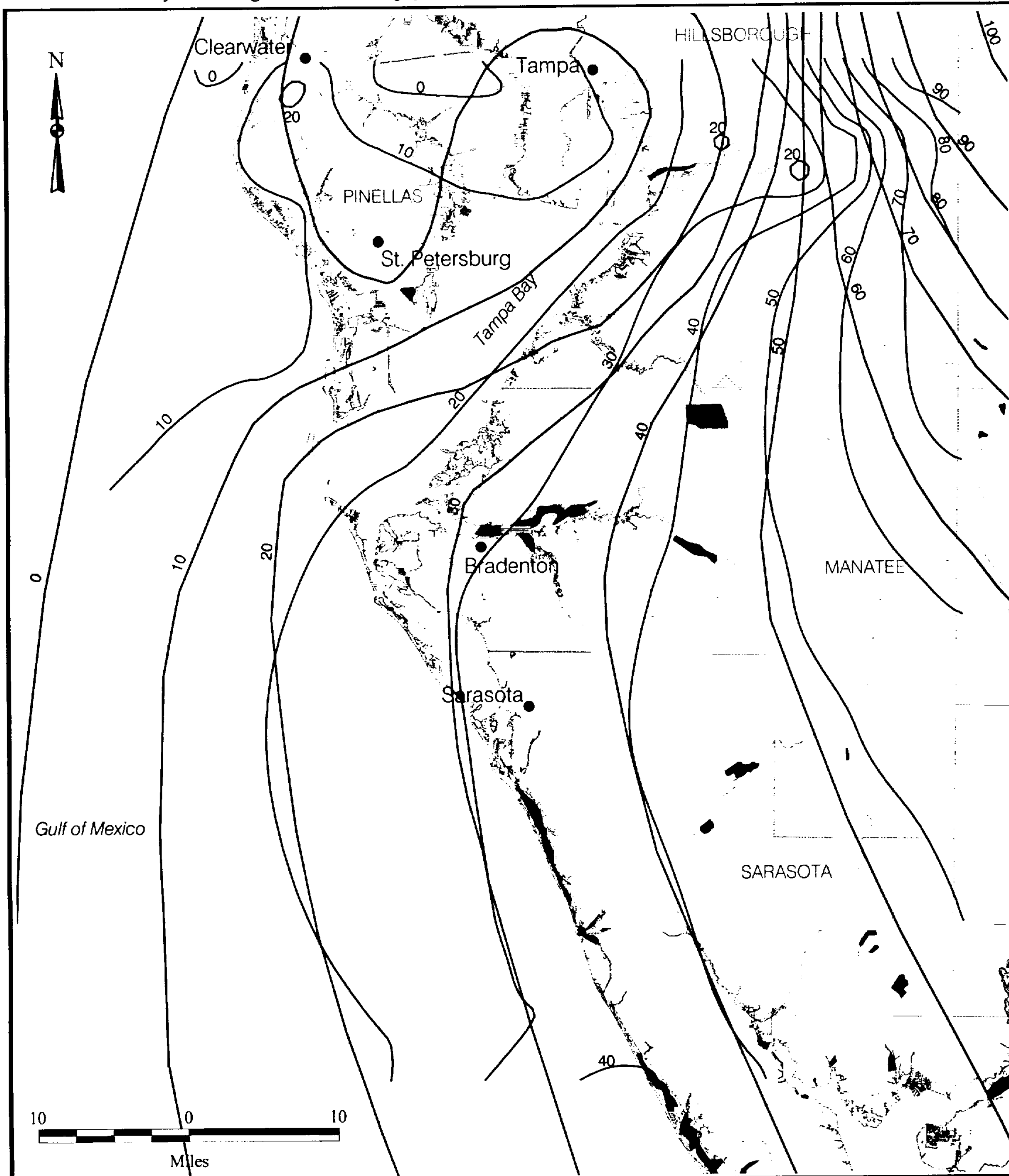
Filename: X:\SWF024\WO_01\saltwater_intrusion\tip-toe_dec2000-2.apr
Project: SWF024-001-01
Created: 11/29/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

- County Boundary
- Surface Drainage
- Cross-section Locations (HGL, 1991a)
- Prediction of Toe of the Interface (HGL, 1991a)
- Predevelopment Interface Position (HGL, 1993a)
- Predevelopment Interface Position (HGL, 1994a)
- Predevelopment Interface Position (Present Study)

Figure 5.9
Comparison of Predicted Saltwater Interface Positions (Upper Floridan System)



Filename: X:\SWF024\WO_01\saltwater_intrusion\head_dist_2_vs_PrePot.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

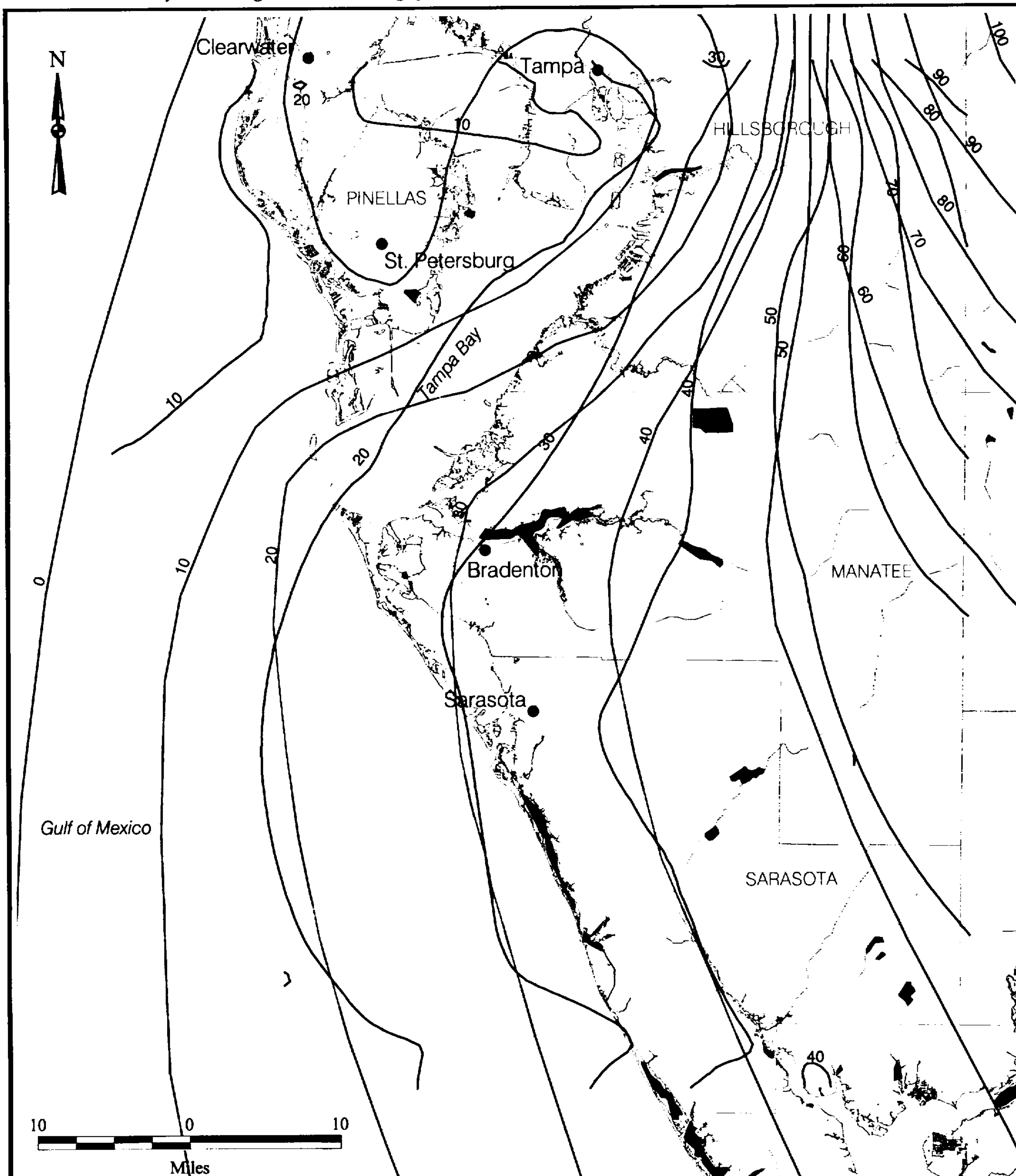
County Boundary

Surface Drainage

60 Head Distribution Contour (ft, msl) Predicted using Local Scale Model

60 Predevelopment Potentiometric Surface Elevation (ft) - (Johnston,1980)

Figure 5.10
Comparison of Calibrated Predevelopment Hydraulic Head Distribution in the Suwannee Limestone (Model Layer 2) to Johnston (1980)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

Legend

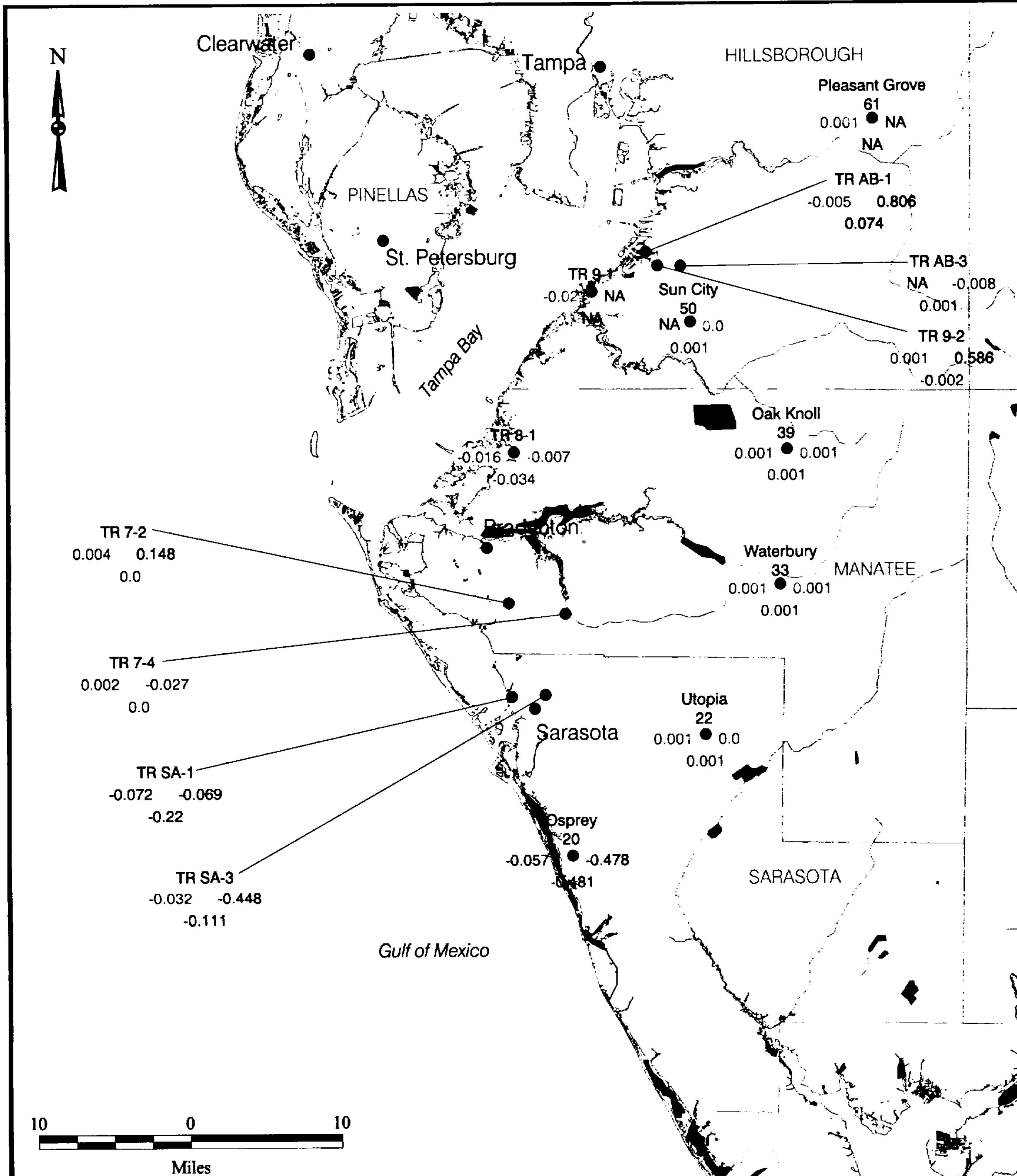
County Boundary

Surface Drainage

60 Head Distribution Contour (ft, msl) Predicted using Local Scale Model

60 Predevelopment Potentiometric Surface Elevation (ft) - (Johnston,1980)

Figure 5.11 Comparison of Calibrated Predevelopment Hydraulic Head Distribution in the Avon Park Formation (Model Layer 7) to Johnston (1980)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary — Surface Drainage
Well Name
Layer 2 ● Layer 7
Layer 4

-0.22	Residual Value < -0.05
0.001	Residual Value > -0.05 and < 0.05
0.148	Residual Value > 0.05
NA	No Measurements Available

Figure 5.12
Relative Concentration Residuals Calculated at Selected ROMP Wells Layers 2, 4, and 7

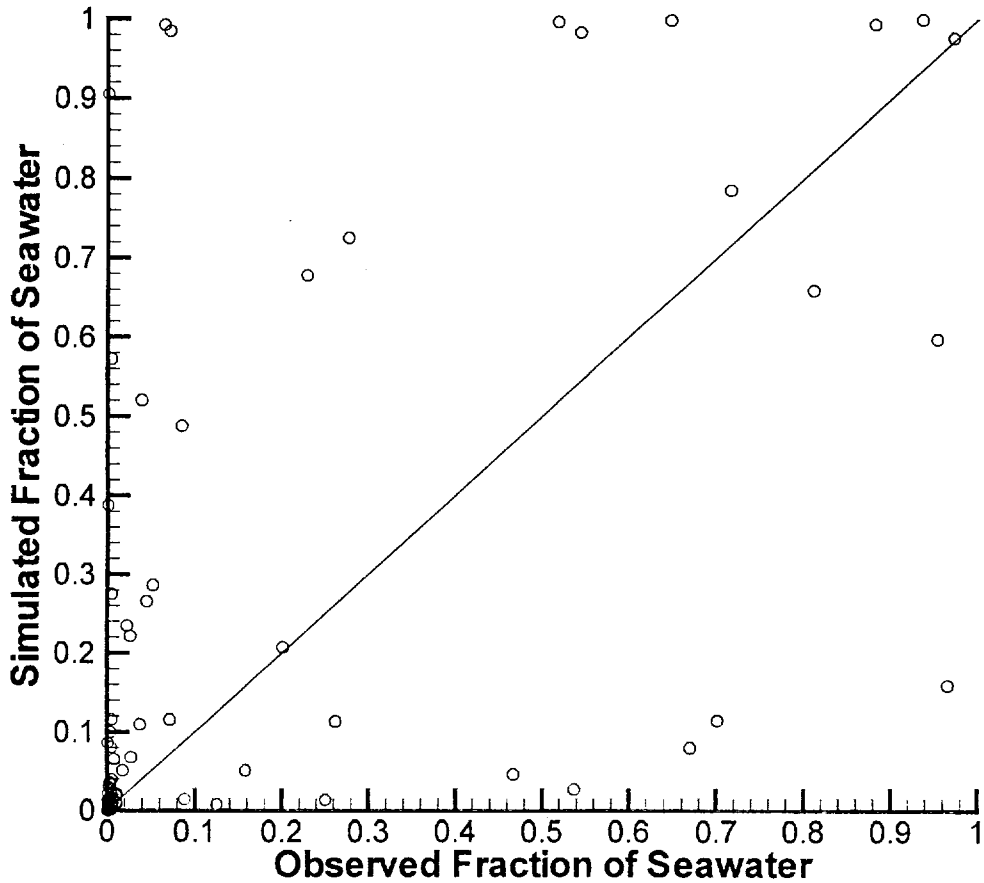
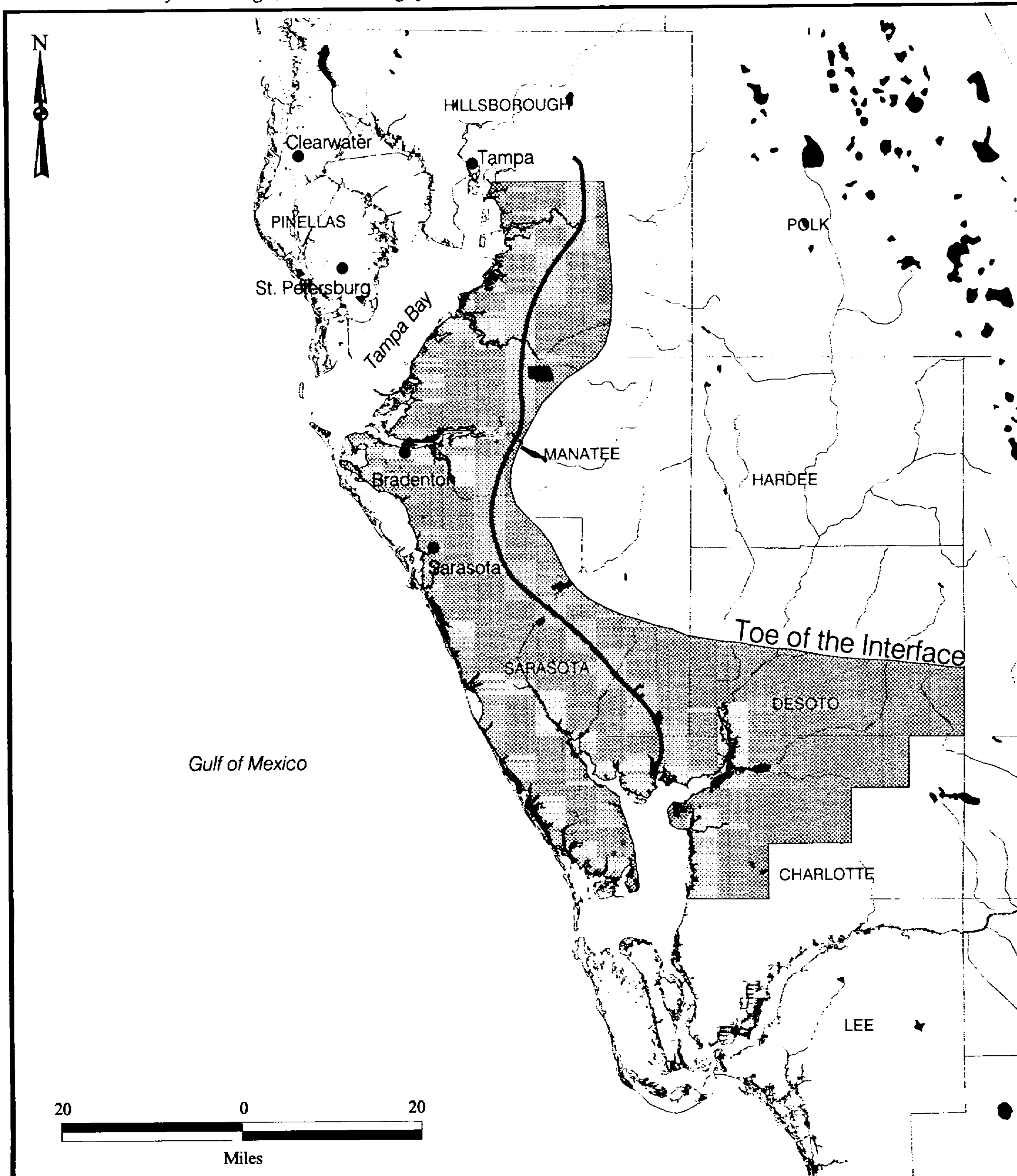


Figure 5.13 **Relationship between Simulated and Observed Relative Concentrations**



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Project: SWF024-001-01
Created: 11/29/01 TH
Revised: 06/05/02 TB

HYDRO GeoLogic Inc.

Legend

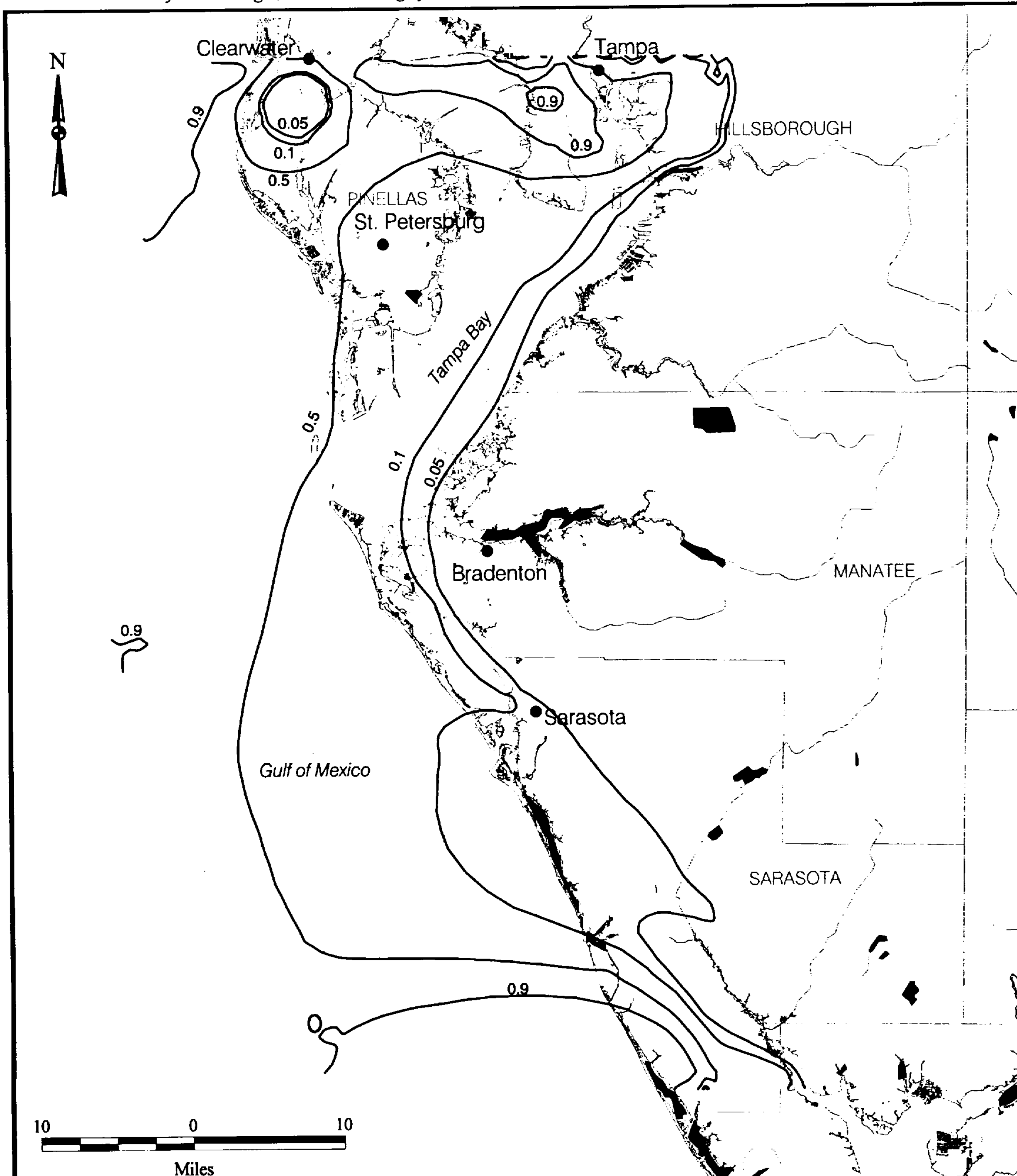
County Boundary

Surface Drainage

Extent of Chloride Concentration's exceeding 1000 mg/l (Calibrated Model)

Extent of Chloride Concentration's exceeding 1,000 mg/l (Beach and Shultz, 2000)

Figure 5.14
Comparison of Chloride Concentration in the LPZ Exceeding 1000 mg/l (Beach and Shultz) with Present Study for the Year 2000



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 4/22/02 TB

HYDRO GeoLogic INC.

Legend

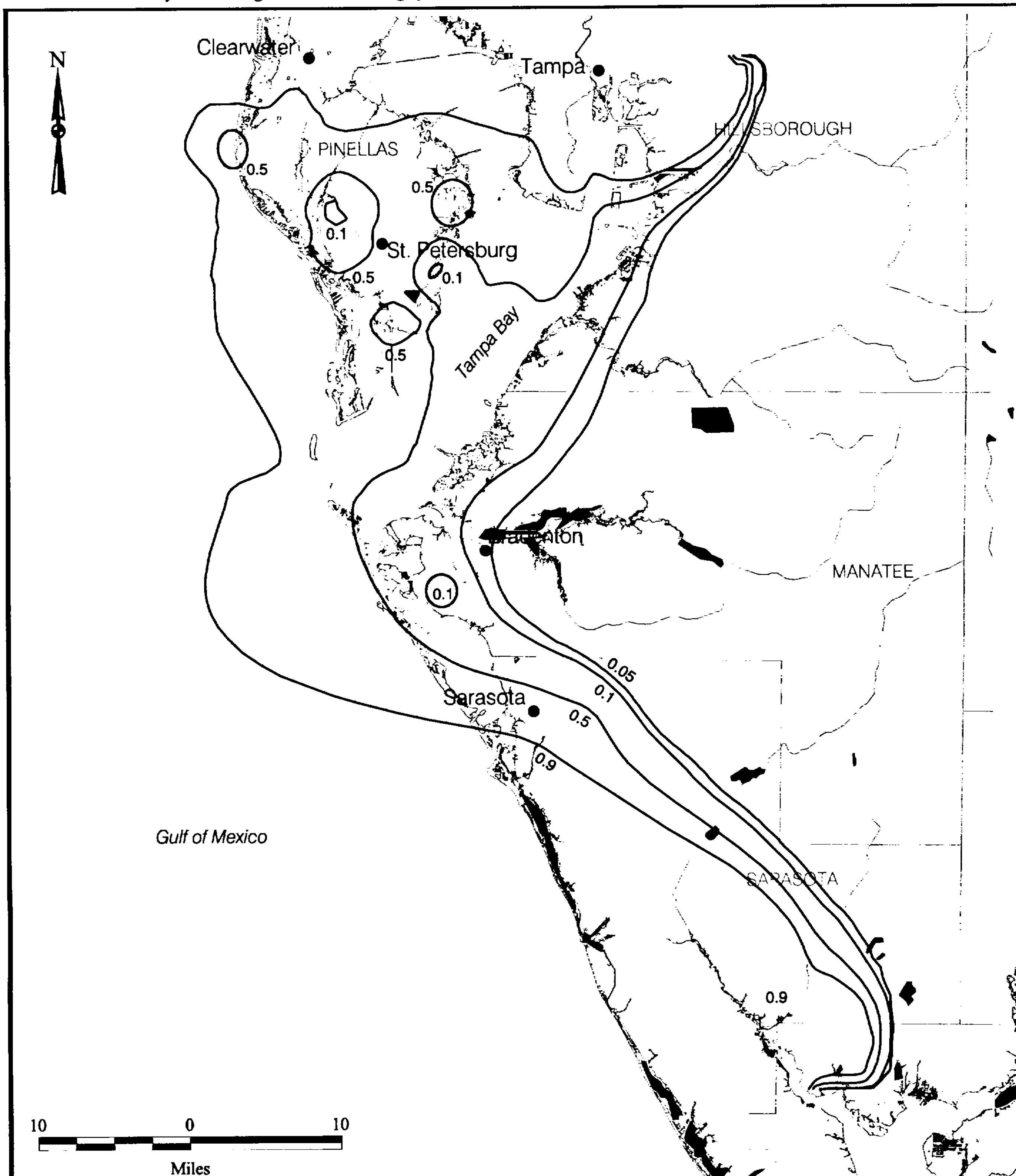
County Boundary

Surface Drainage

0.05 Relative Chloride Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 5.15
Relative Chloride Concentrations Predicted Using the Calibrated Model for the Suwannee Limestone (Model Layer 2)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 04/22/02 TB

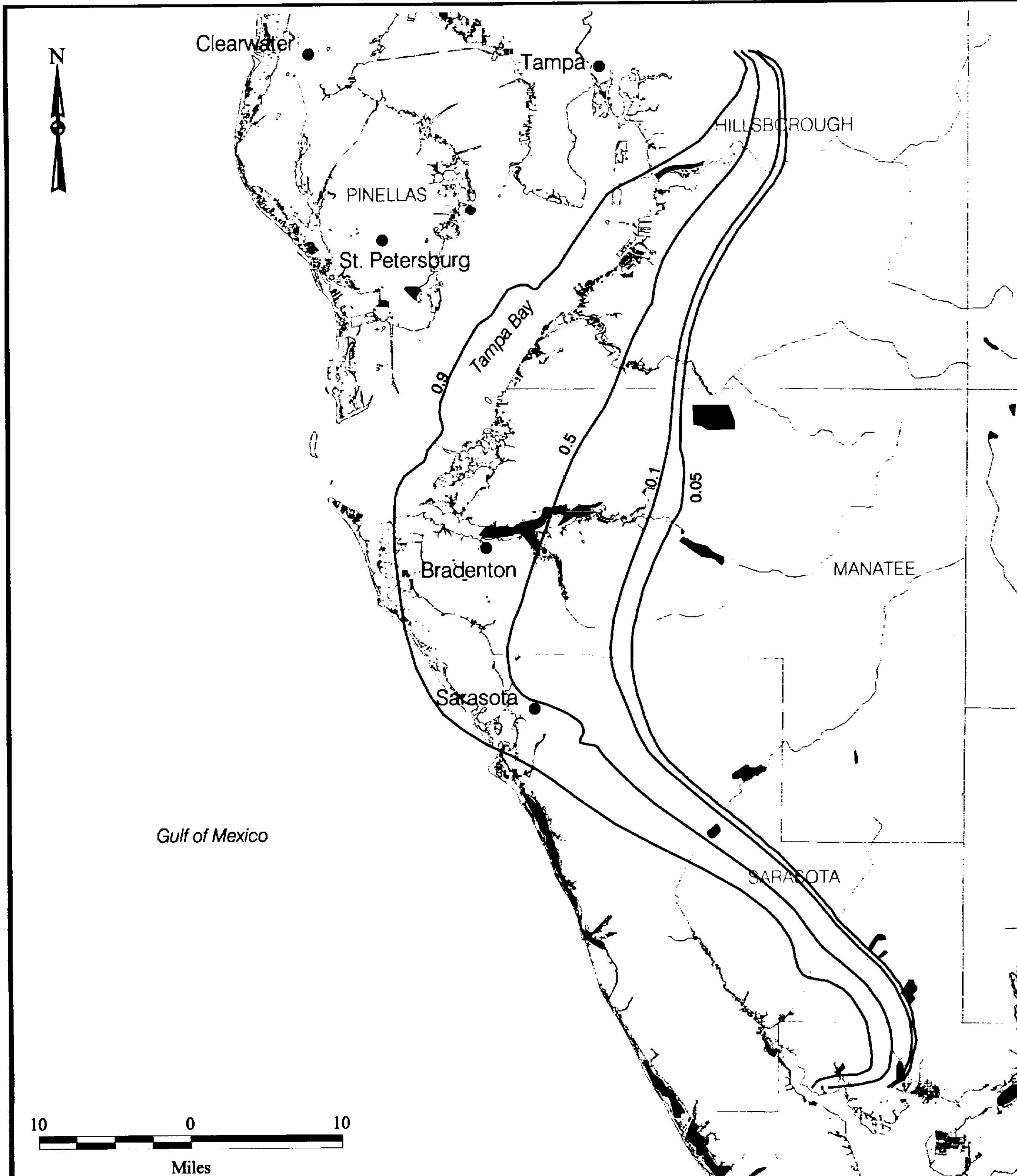
HYDRO GeoLogic Inc

Legend

County Boundary
Surface Drainage
0.05 Relative Chloride Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 5.16
Relative Chloride Concentrations Predicted Using the Calibrated Model for the Avon Park Formation (Model Layer 6)



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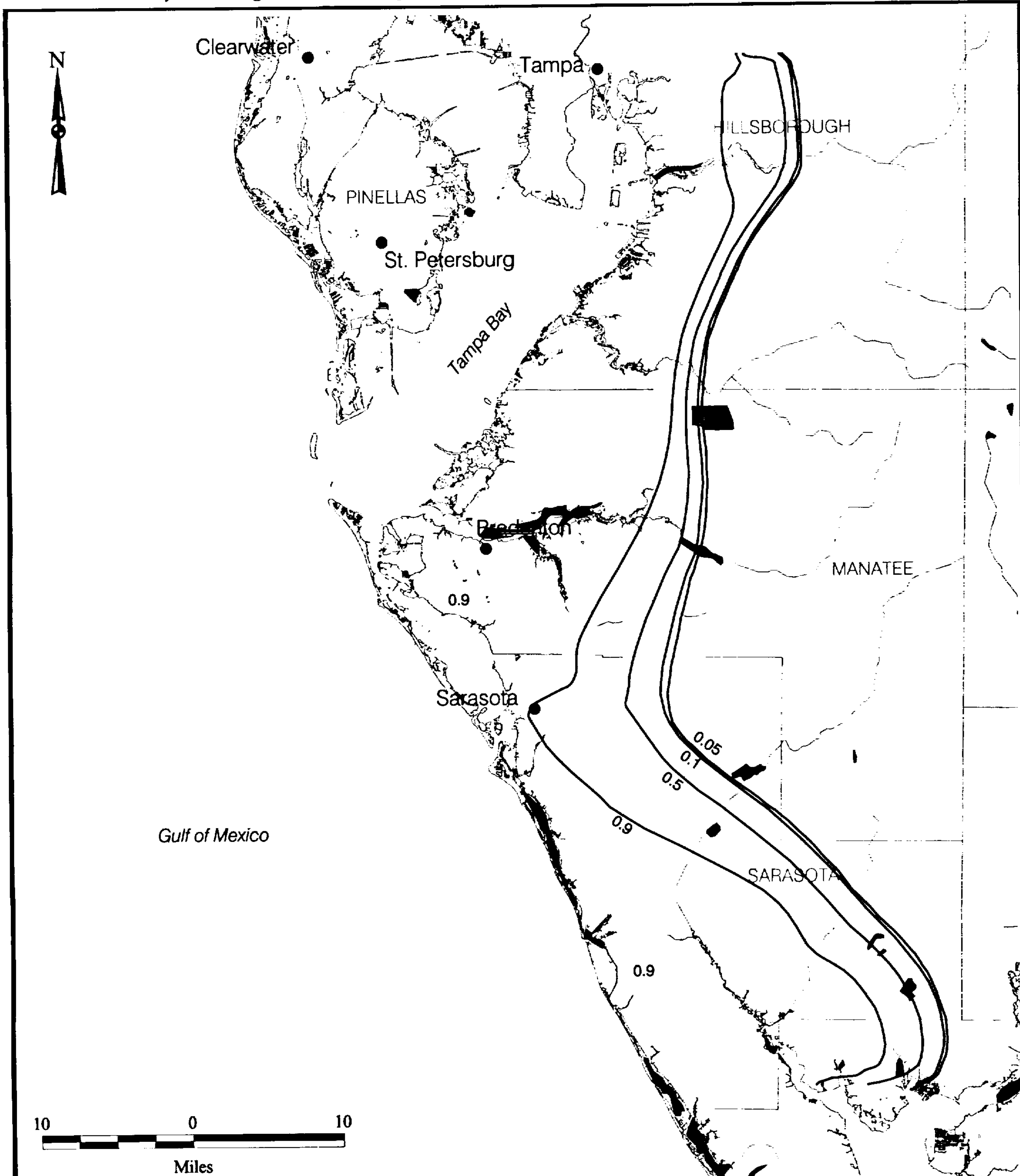
Created: 11/28/01 TH
Revised: 04/22/02 TB

Legend

County Boundary
Surface Drainage
0.05 Relative Chloride Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 5.17
Relative Chloride Concentrations Predicted Using the Calibrated Model for the Avon Park Formation (Model Layer 8)



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Created: 11/28/01 TH
Revised: 04/22/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary

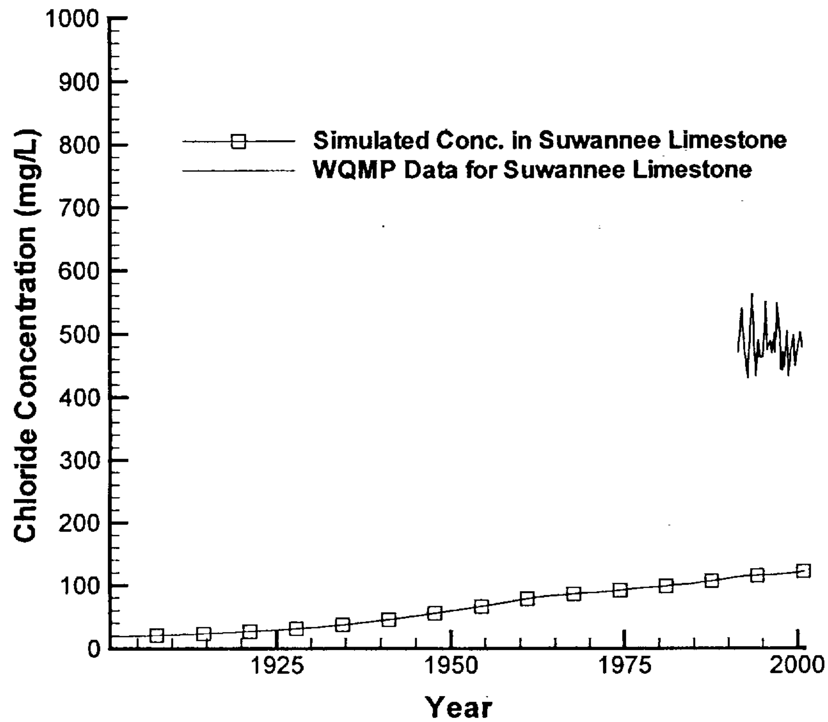
Surface Drainage

0.05 Relative Chloride Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 5.18
Relative Chloride Concentrations Predicted Using the Calibrated Model for the Avon Park Formation (Model Layer 10)

ROMP TR 9-3



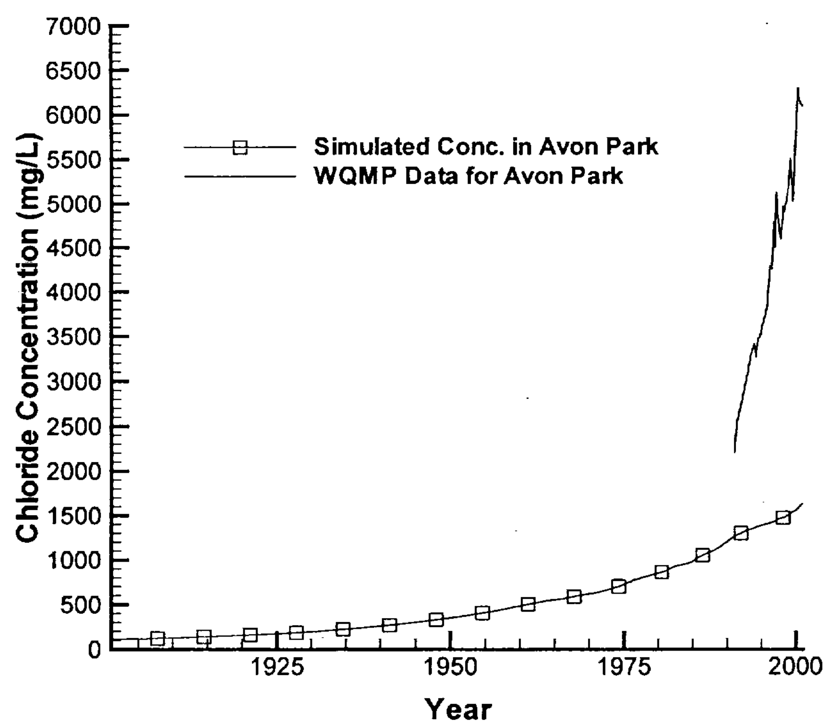
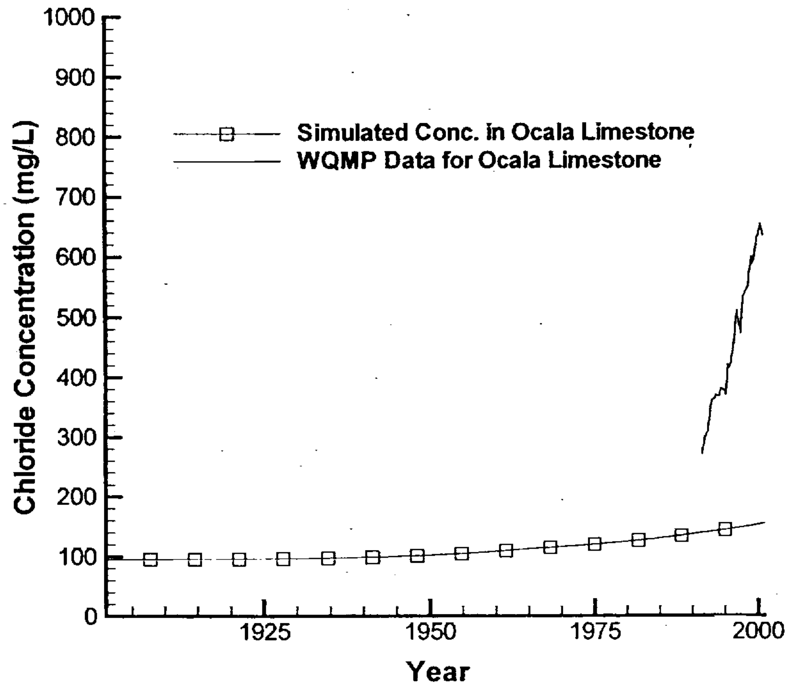


Figure 5.19 Model Predicted Verses Observed Chloride Concentrations with Time



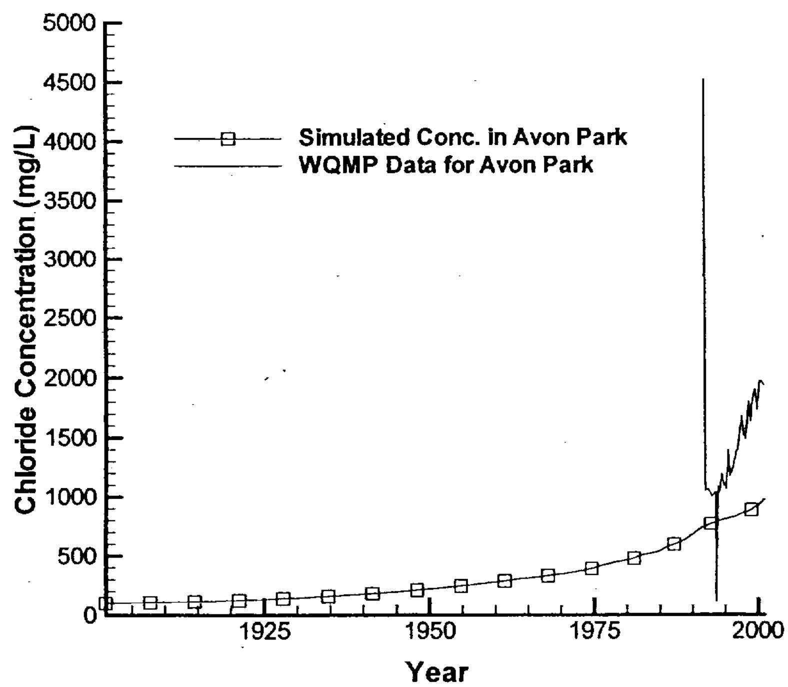
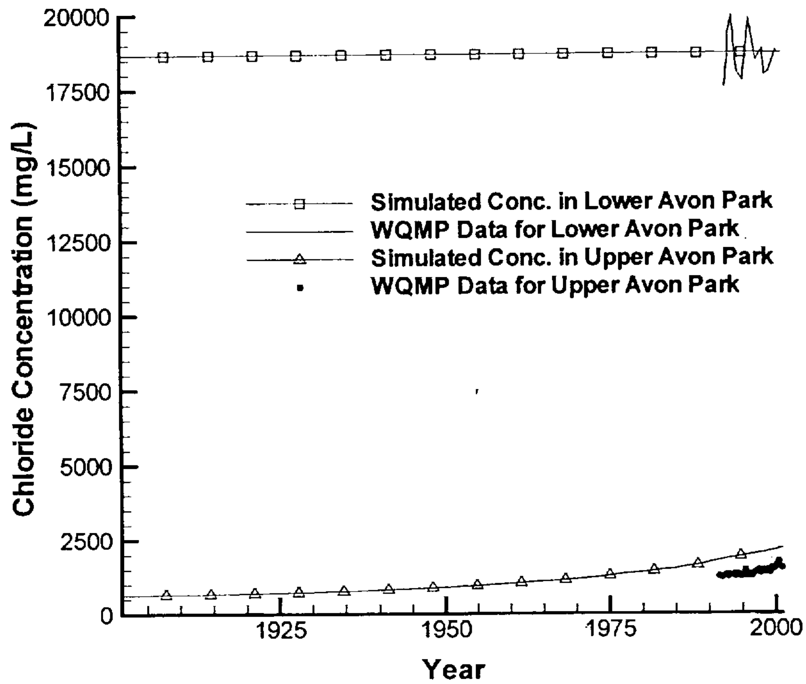


Figure 5.20 Model Predicted Verses Observed Chloride Concentrations with Time

ROMP TR 8-1



ROMP 50

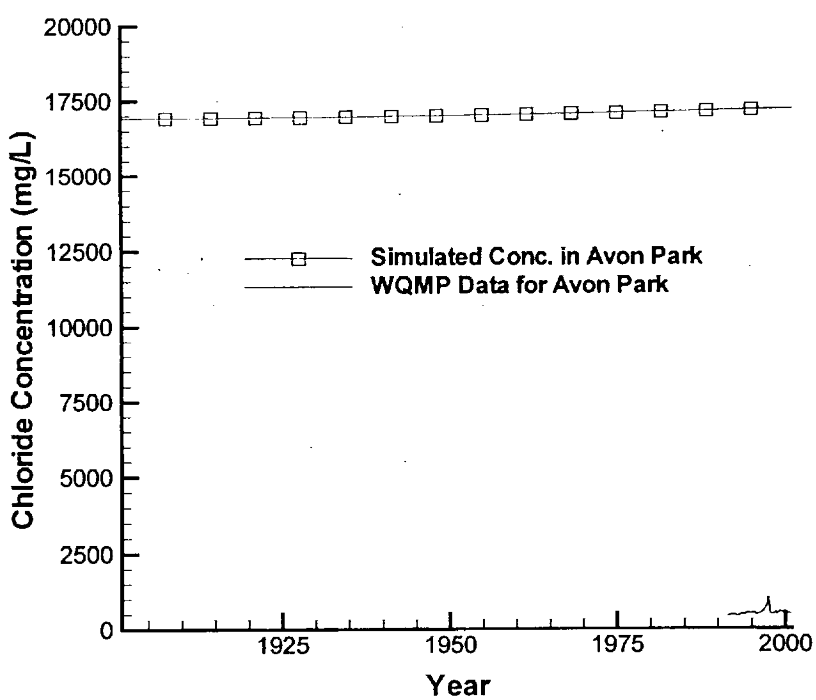
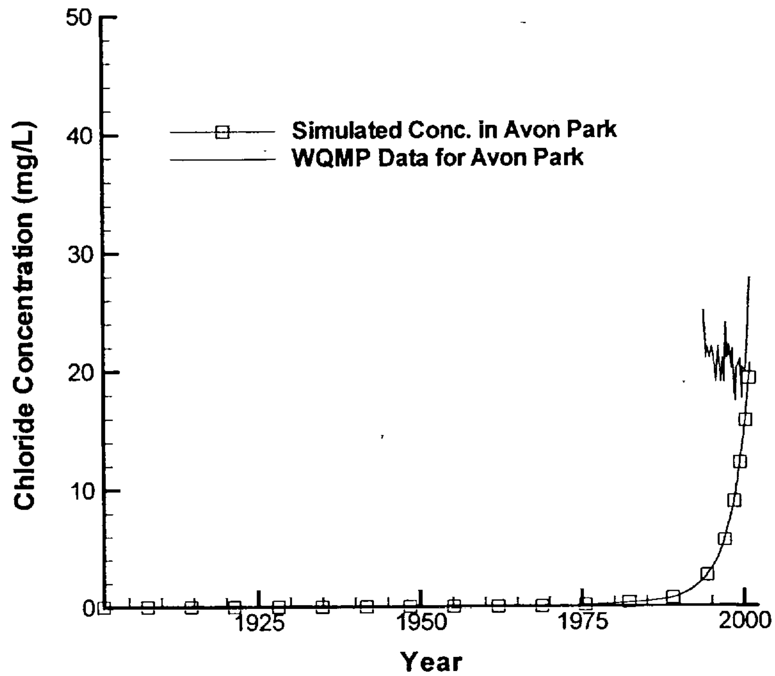


Figure 5.21 Model Predicted Verses Observed Chloride Concentrations with Time

ROMP 22



ROMP 20

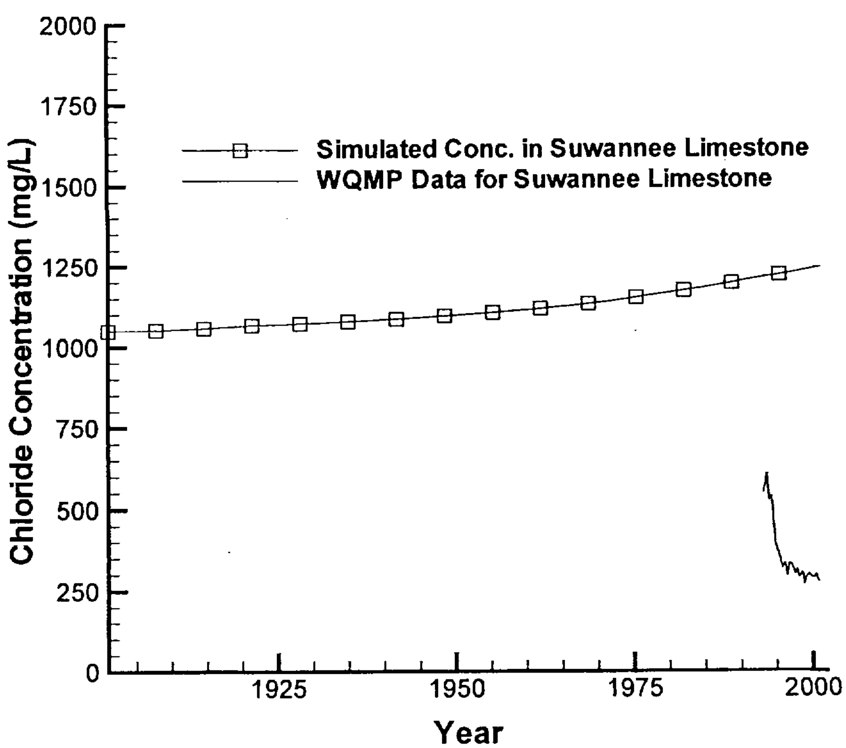
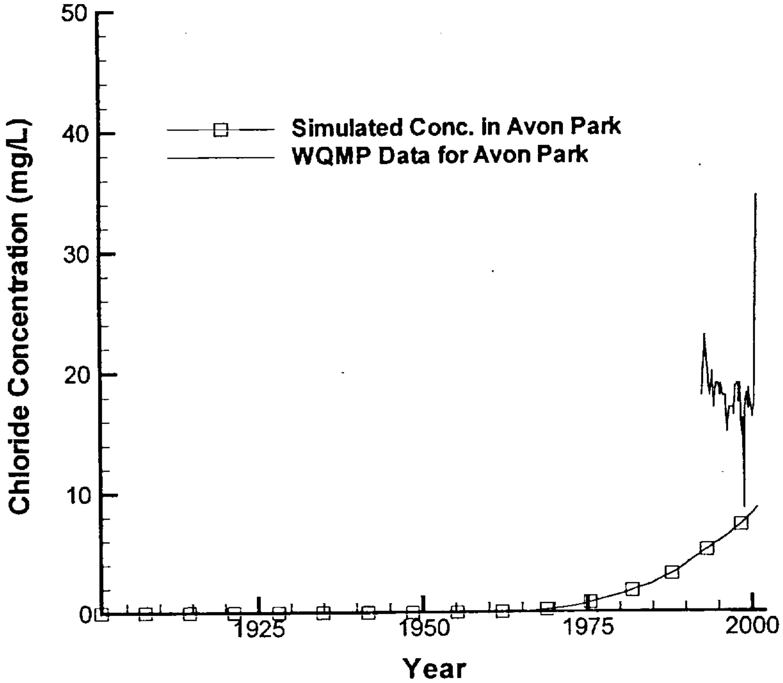


Figure 5.22 Model Predicted Verses Observed Chloride Concentrations with Time

ROMP 33



ROMP 39

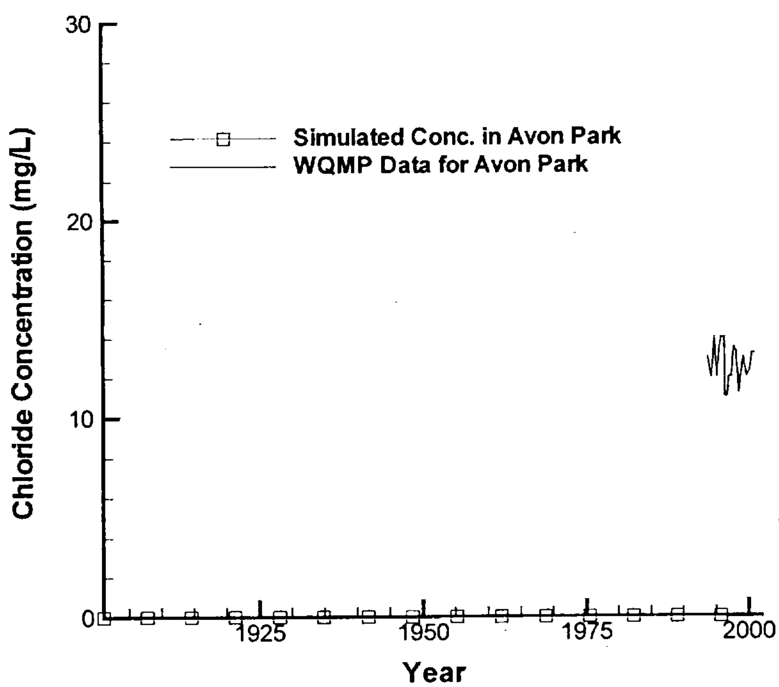
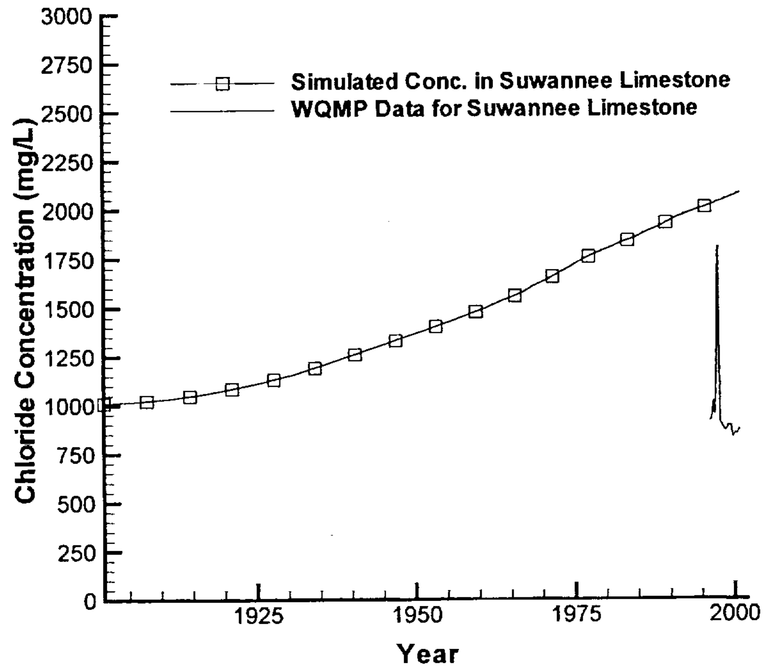


Figure 5.23 Model Predicted Verses Observed Chloride Concentrations with Time

ROMP TR SA-1



ROMP TR SA-3

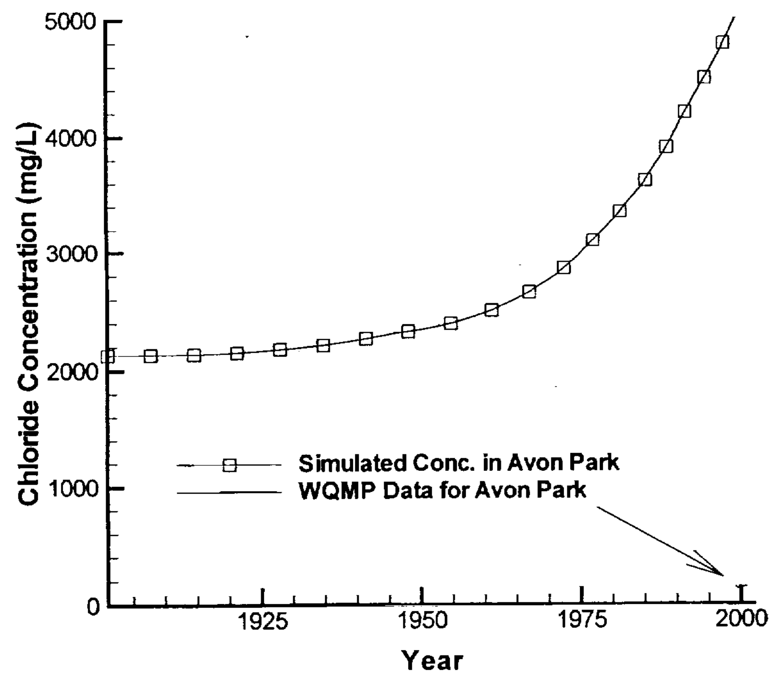
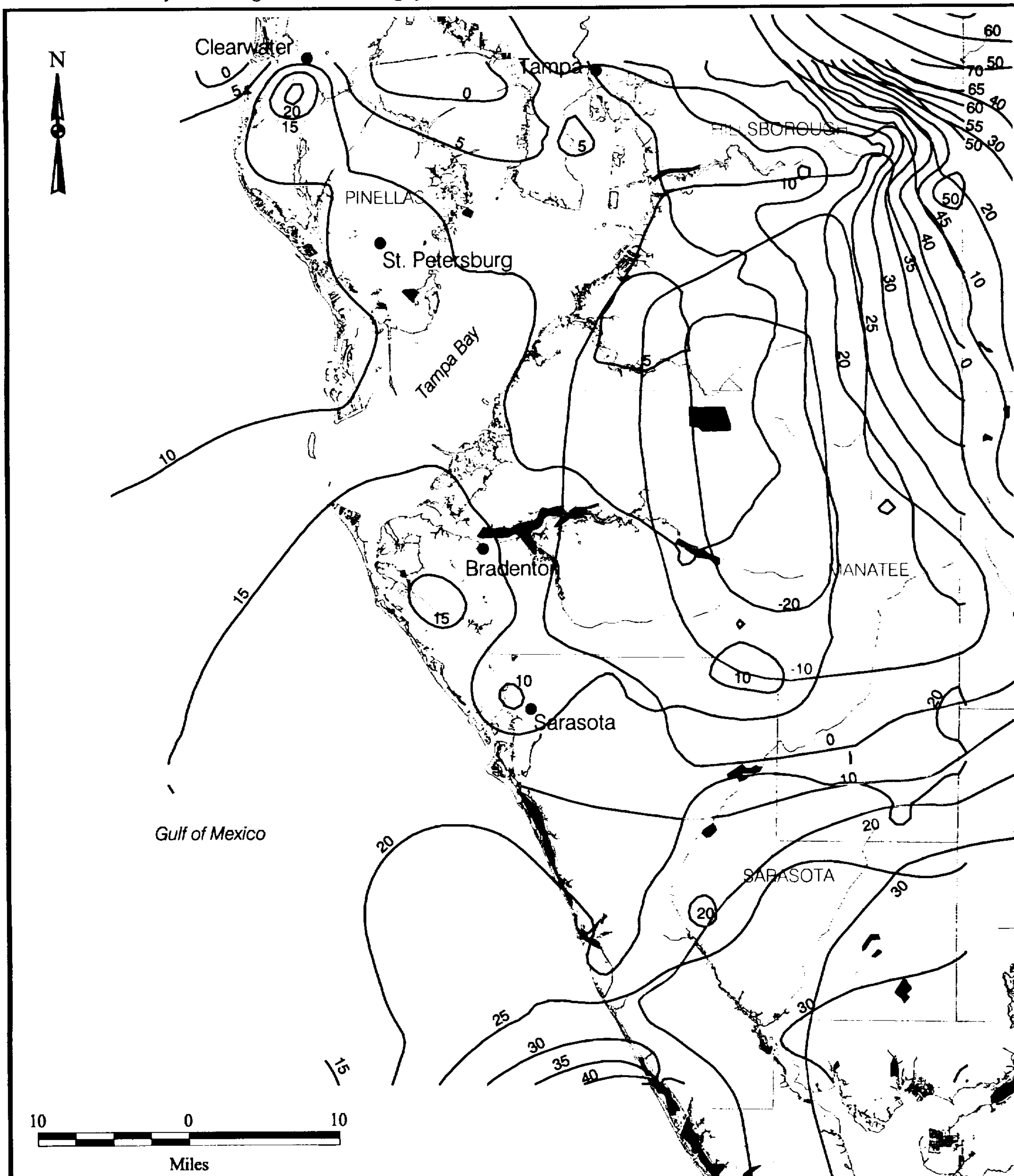


Figure 5.24 Model Predicted Verses Observed Chloride Concentrations with Time



Filename: X:\SWF024\WO_01\saltwater_intrusion\head_dist_may2000_2.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

Legend

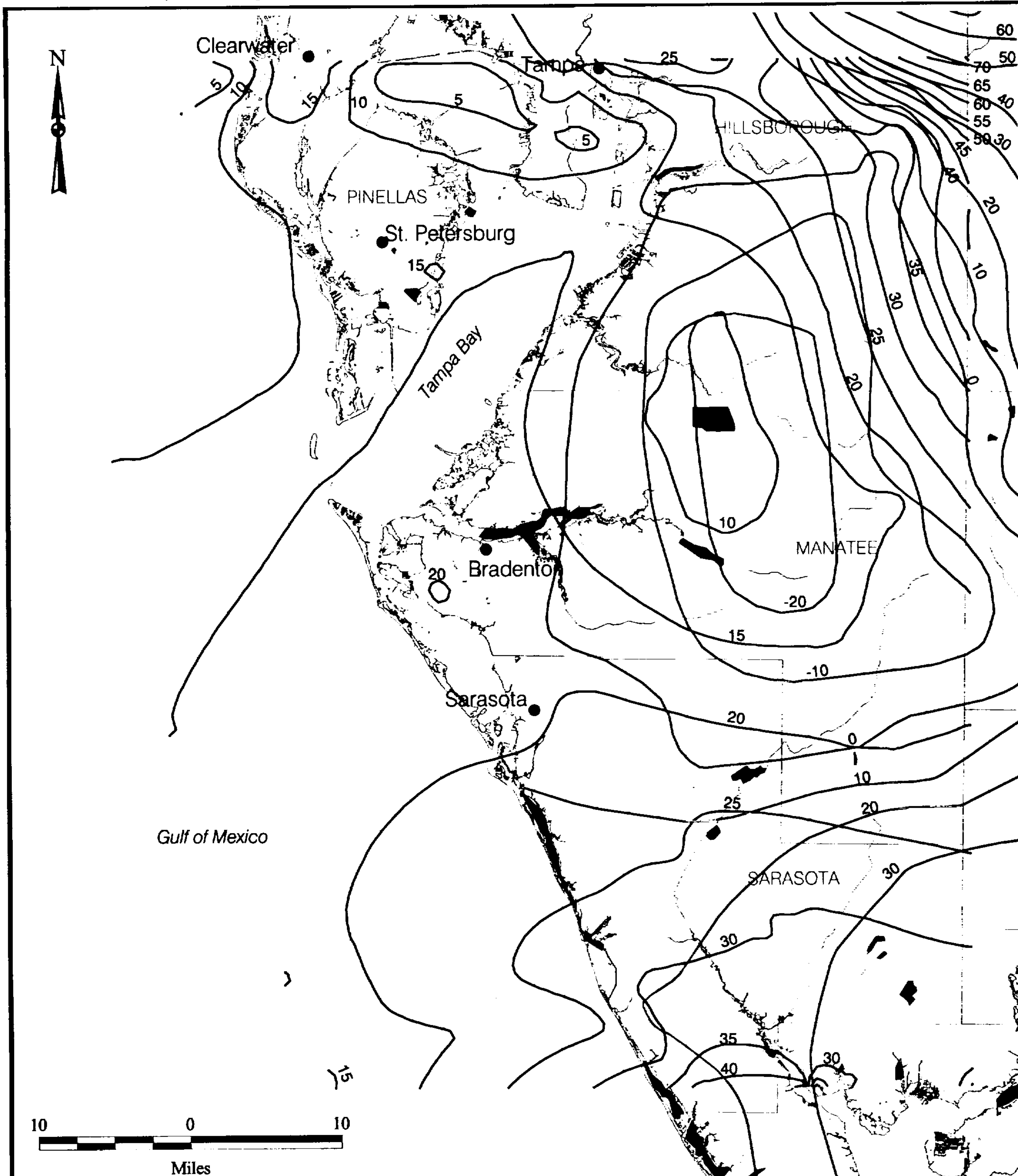
County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 2)

60 U.S.G.S. Potentiometric Surface Elevation (ft, msl)

Figure 5.25 Comparison of Observed and Predicted Potentiometric Surface - May 2000 (Suwannee Limestone, Model Layer 2)



Filename: X:\SWF024\WO_01\saltwater_intrusion\head_dist_may2000_7.apr
Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

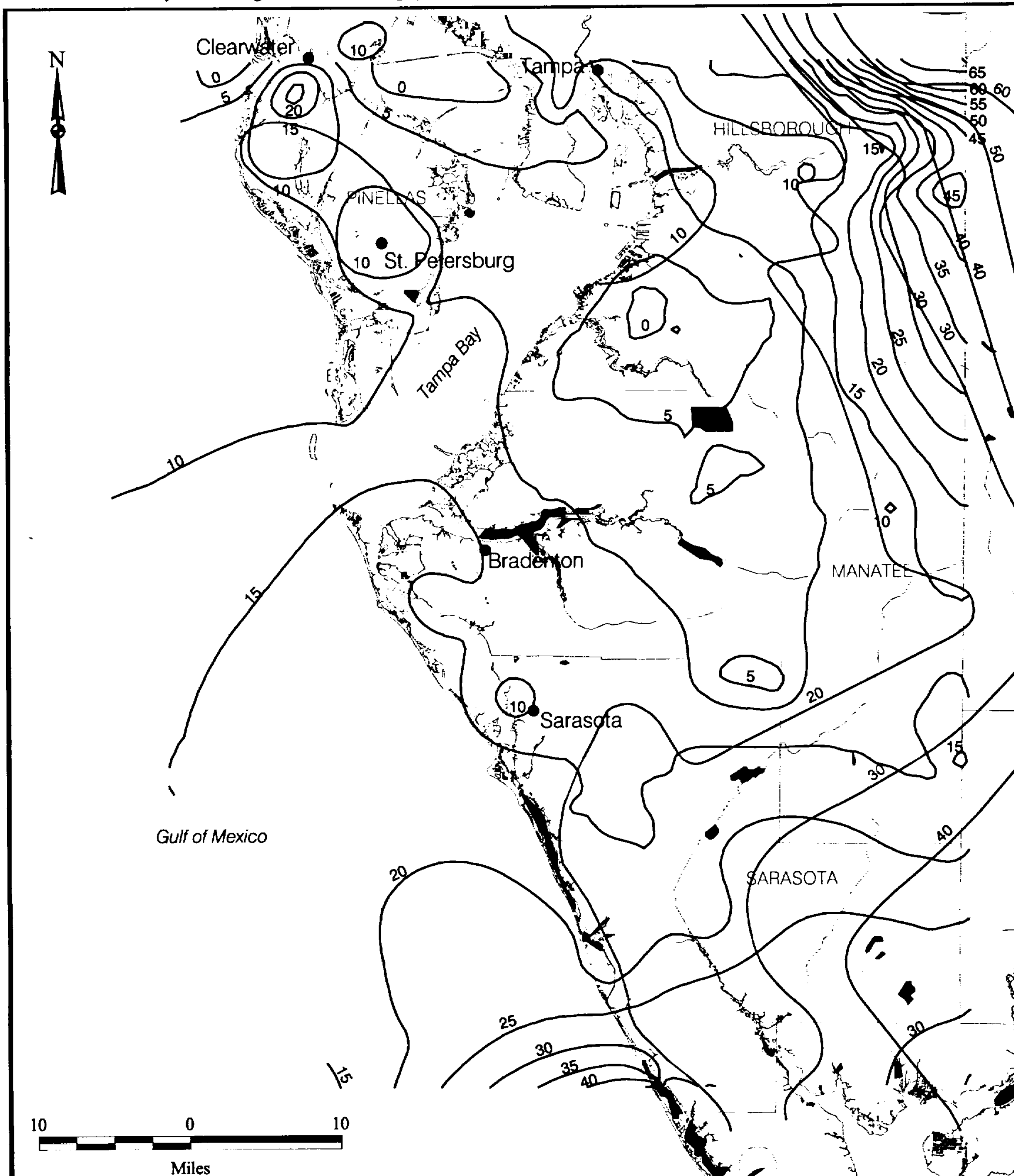
County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 7)

60 U.S.G.S. Potentiometric Surface Elevation (ft, msl)

Figure 5.26 Comparison of Observed and Predicted Potentiometric Surface - May 2000 (Avon Park Formation, Model Layer 7)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

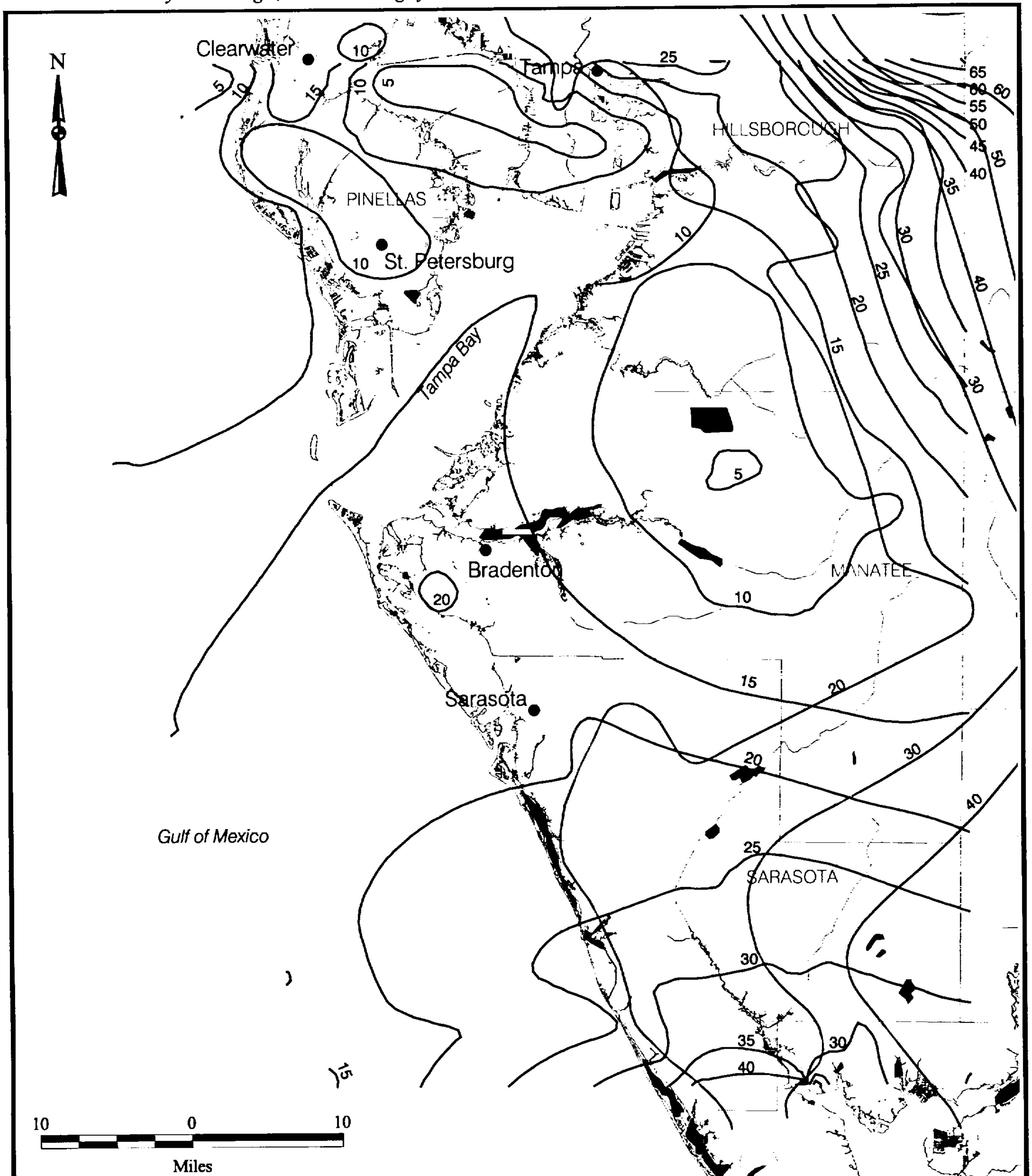
County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 2)

60 U.S.G.S. Potentiometric Surface Elevation (ft, msl)

Figure 5.27 Comparison of Observed and Predicted Potentiometric Surface - September 2000 (Suwannee Limestone, Model Layer 2)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic INC.

Legend

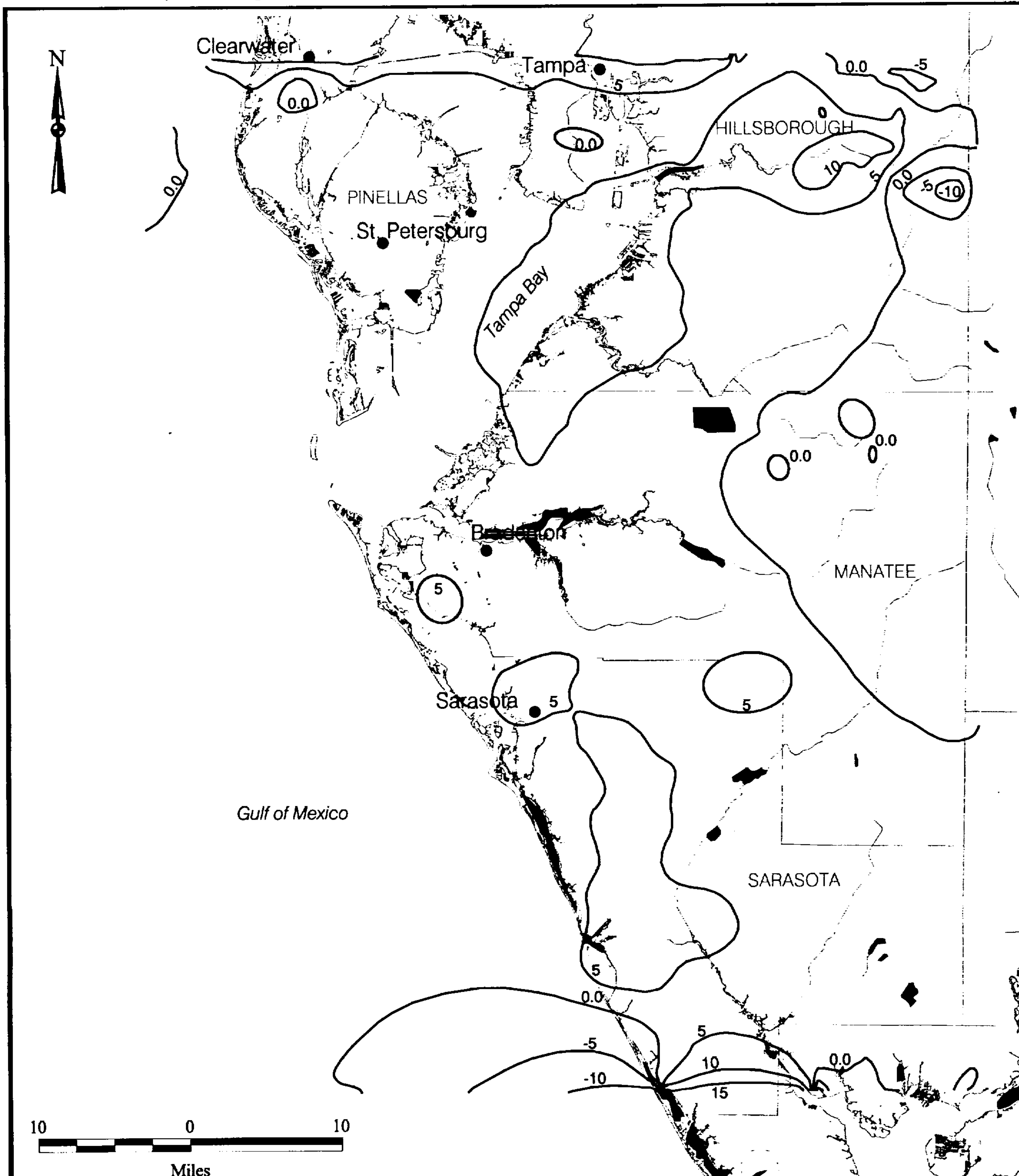
County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 7)

60 U.S.G.S. Potentiometric Surface Elevation (ft, mls)

Figure 5.28 Comparison of Observed and Predicted Potentiometric Surface - September 2000 (Avon Park Formation, Model Layer 7)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/07/02 TB

HYDRO GeoLogic Inc.

Legend

County Boundary

Surface Drainage

0.5 Head Difference Contour (ft, msl)

Figure 5.29
Simulated Head Difference Between the Suwannee Limestone and the Avon Park Formation for December 2000 Conditions

Figure 5.30. Global Mass/Water Budget for Pre-Development Conditions

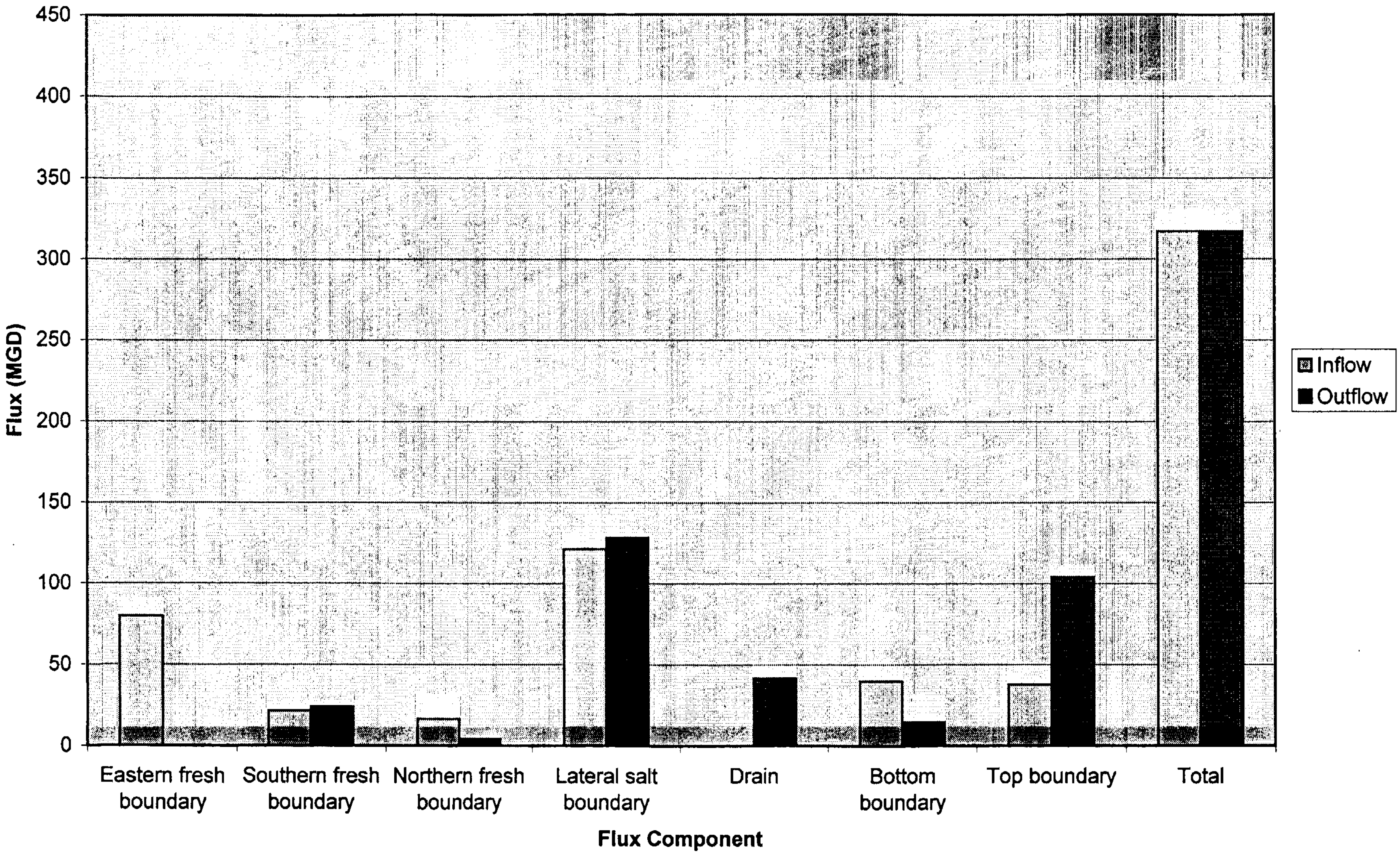
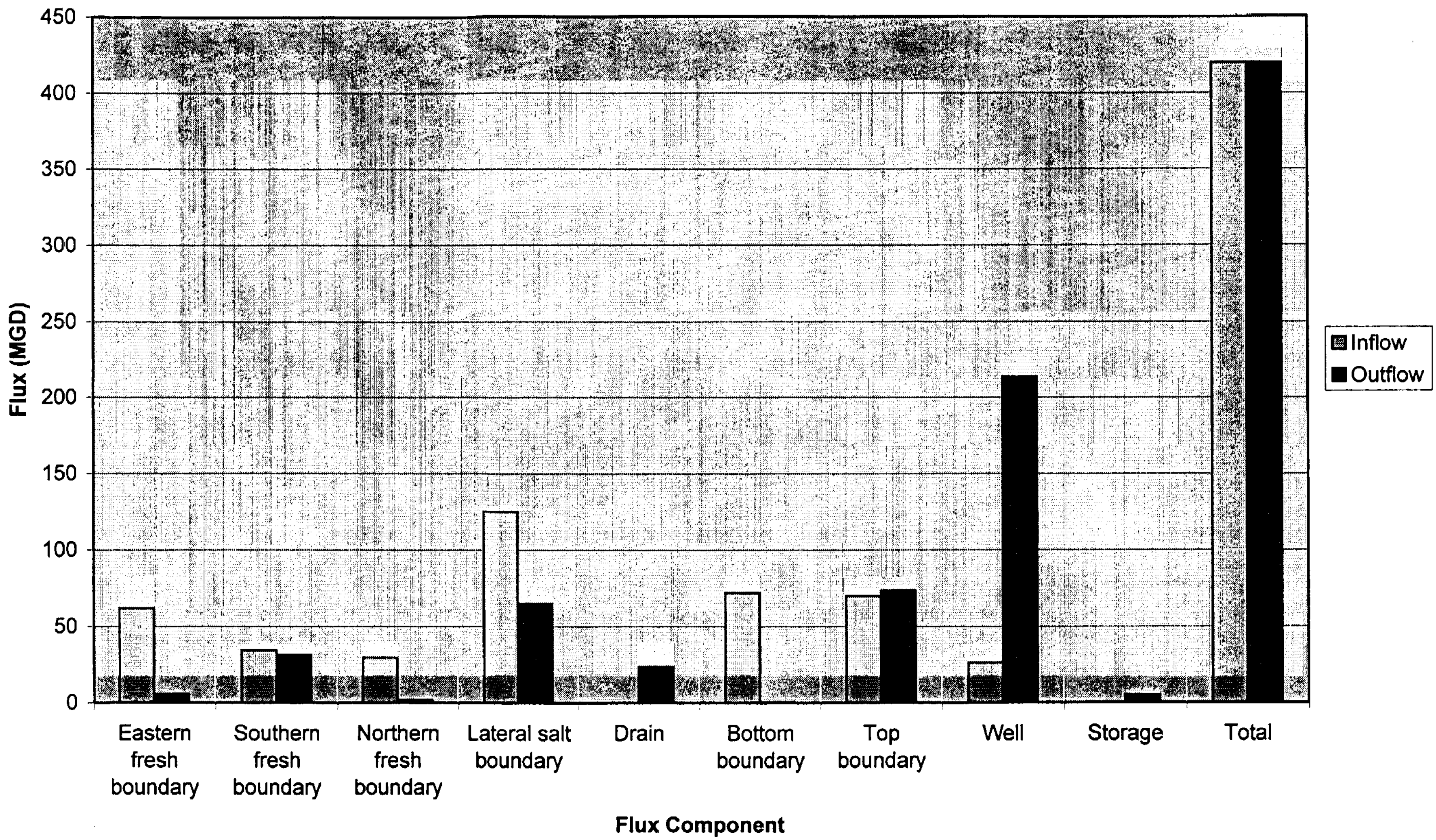
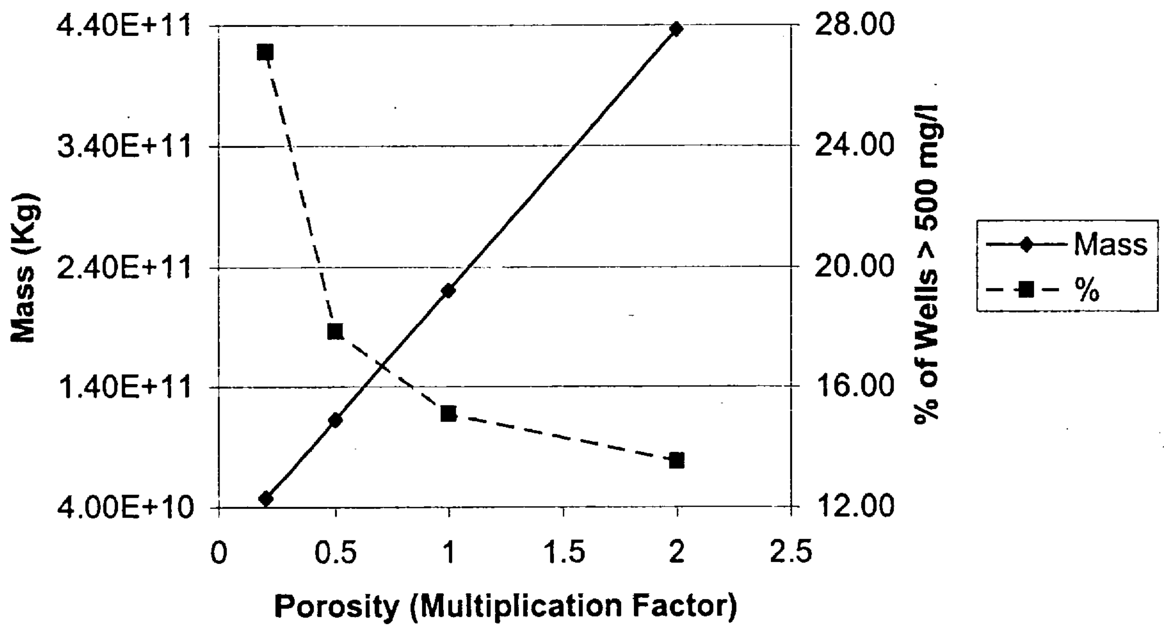


Figure 5.31. Global Mass/Water Budget For Post-Development (December 2000) Conditions





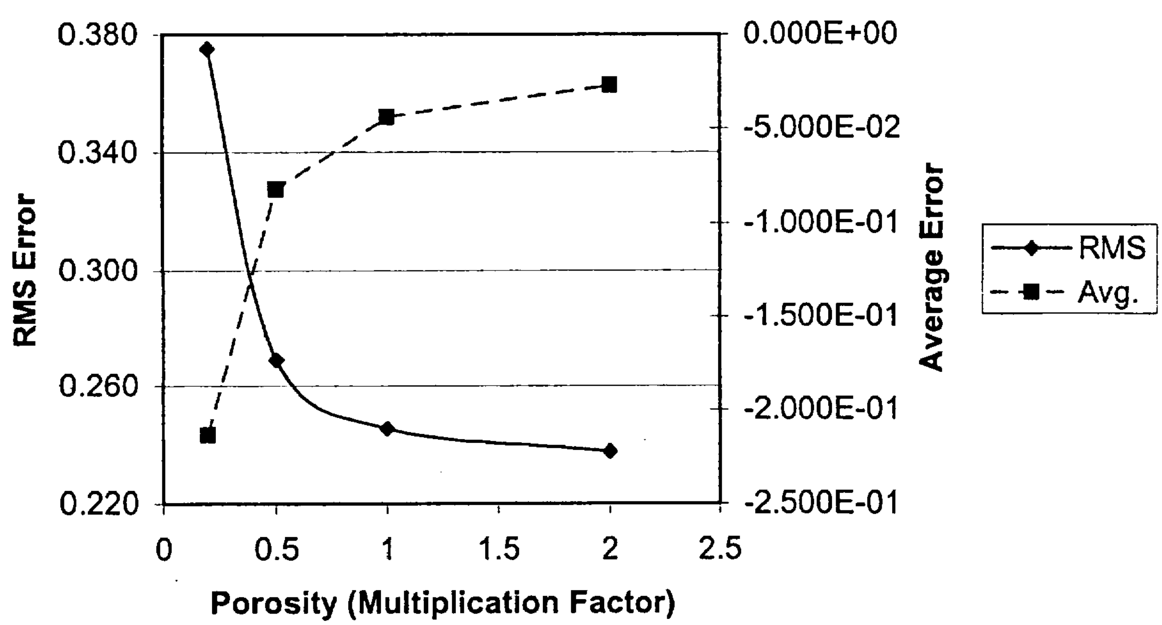


Figure 6.1 a. Sensitivity to Porosity

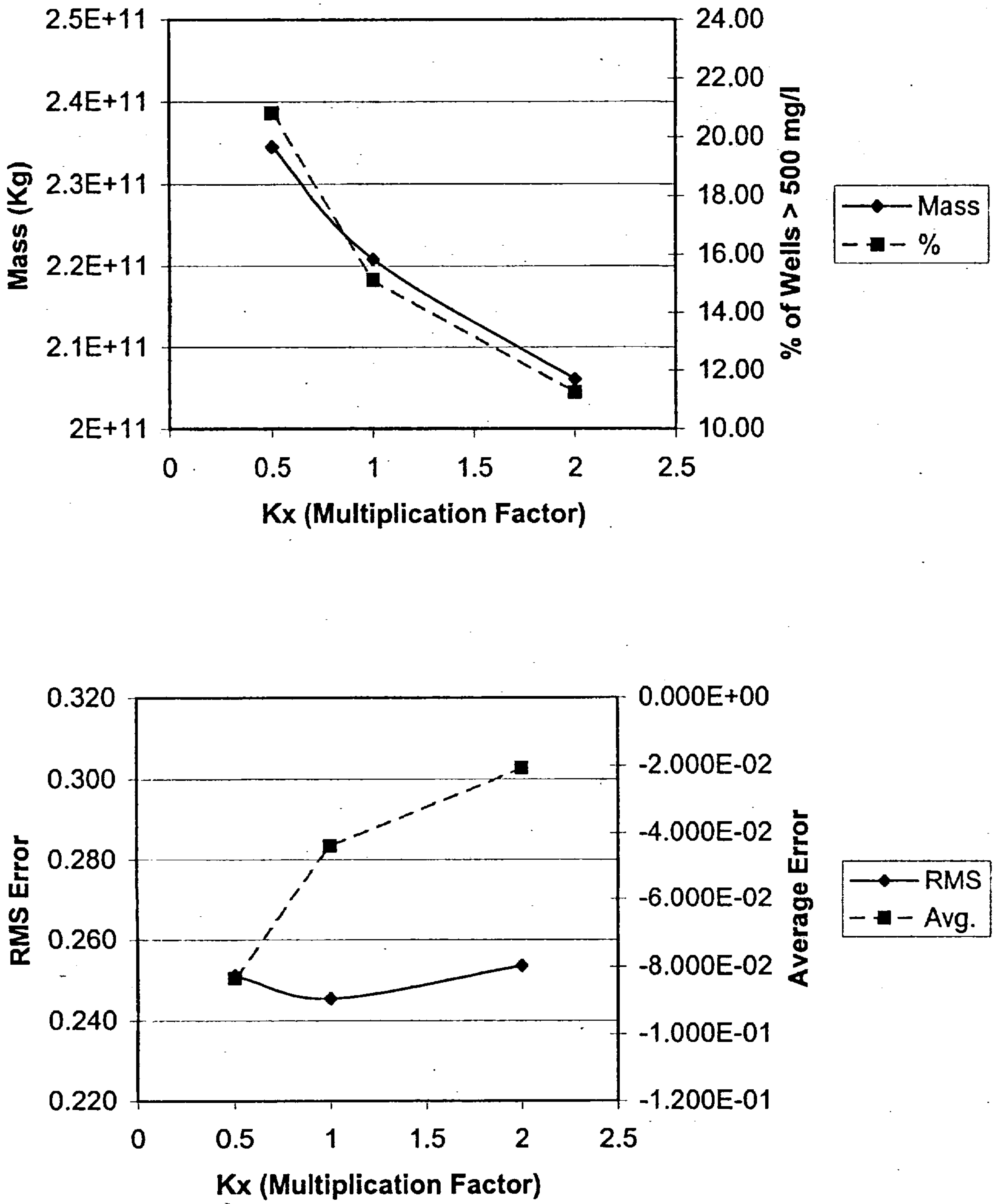


Figure 6.1b. Sensitivity to Avon Park Formation Hydraulic Conductivity Values (Model Layers 6 through 10)

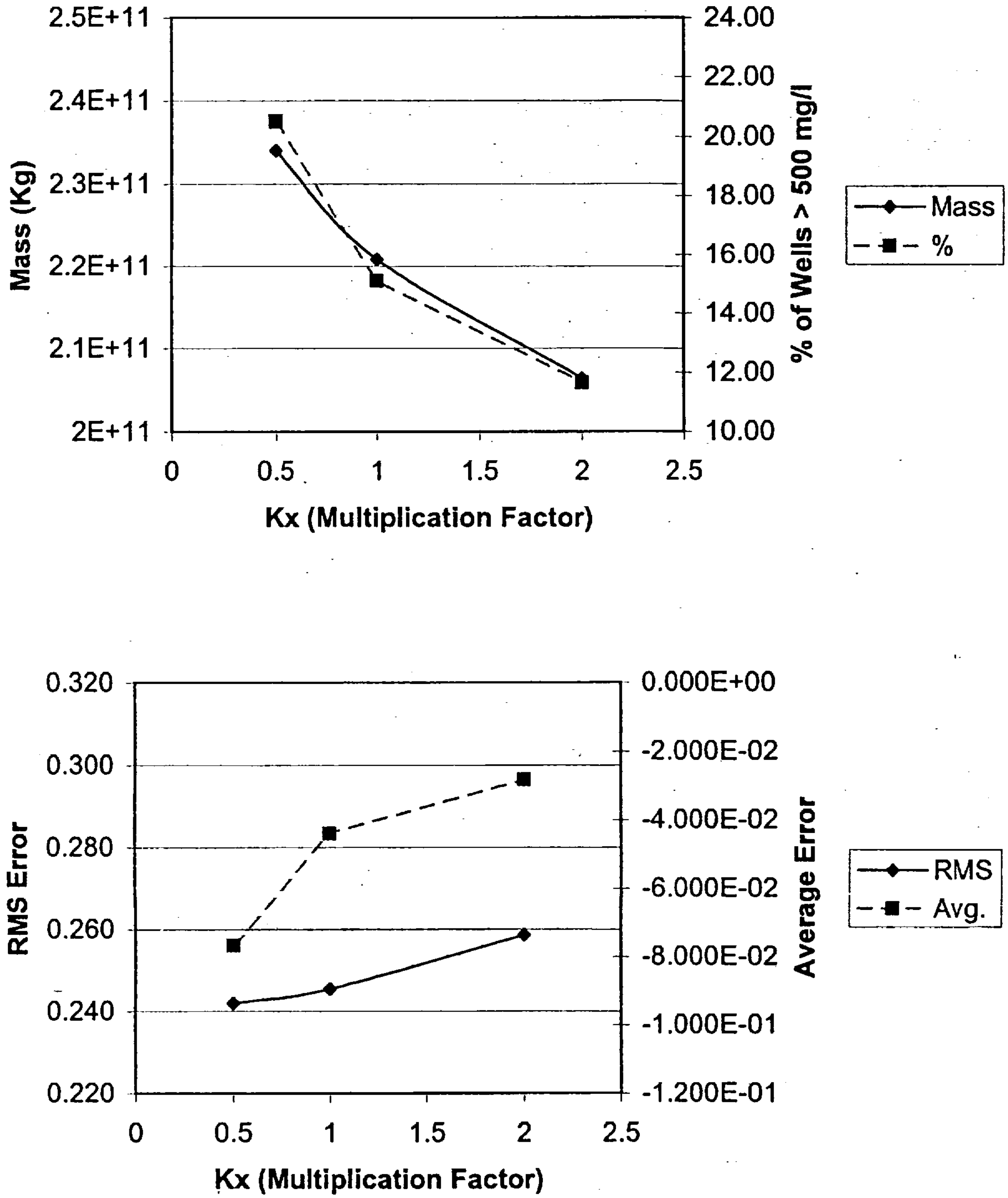
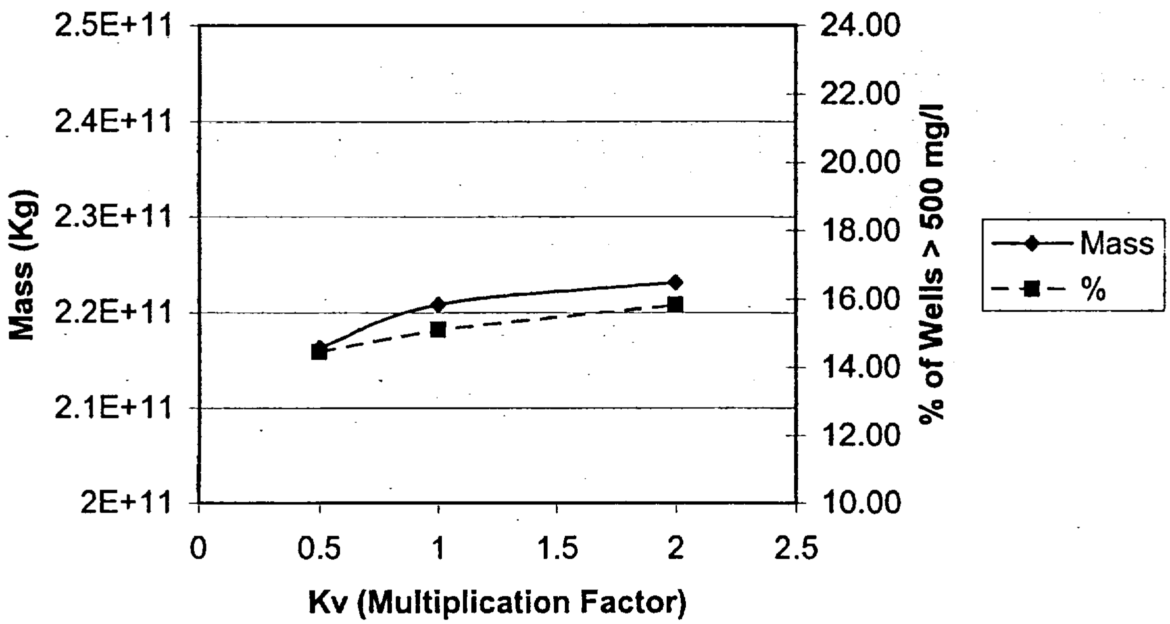


Figure 6.1c. Sensitivity to Conductivity Value of Highly Transmissive Zone in the Avon Park Formation (Model Layers 6 and 7)



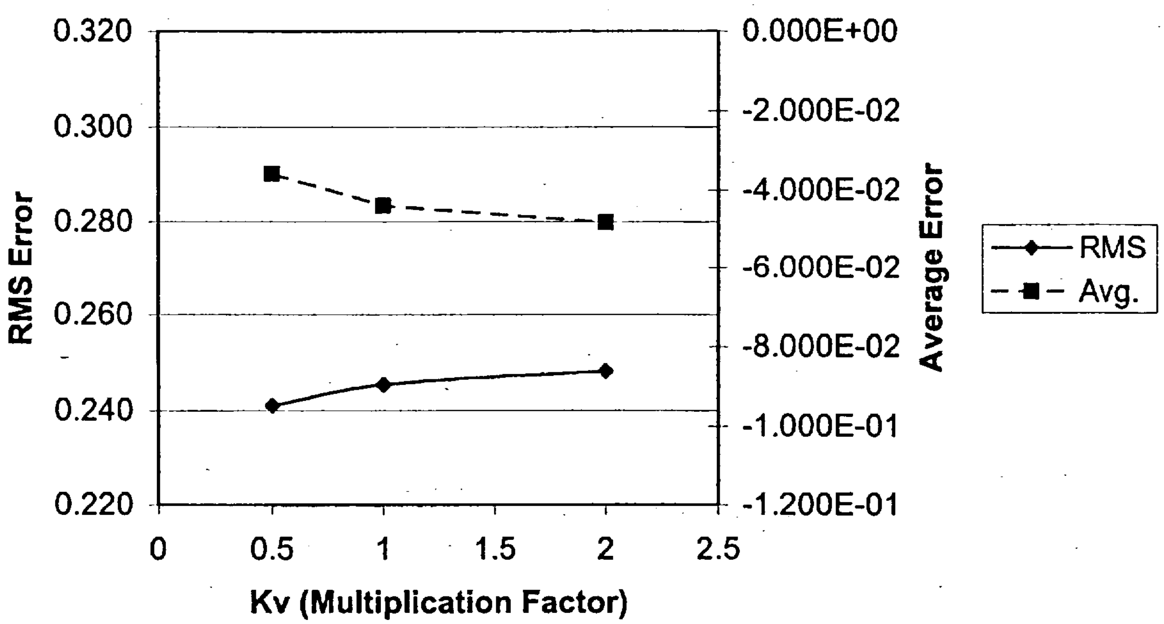
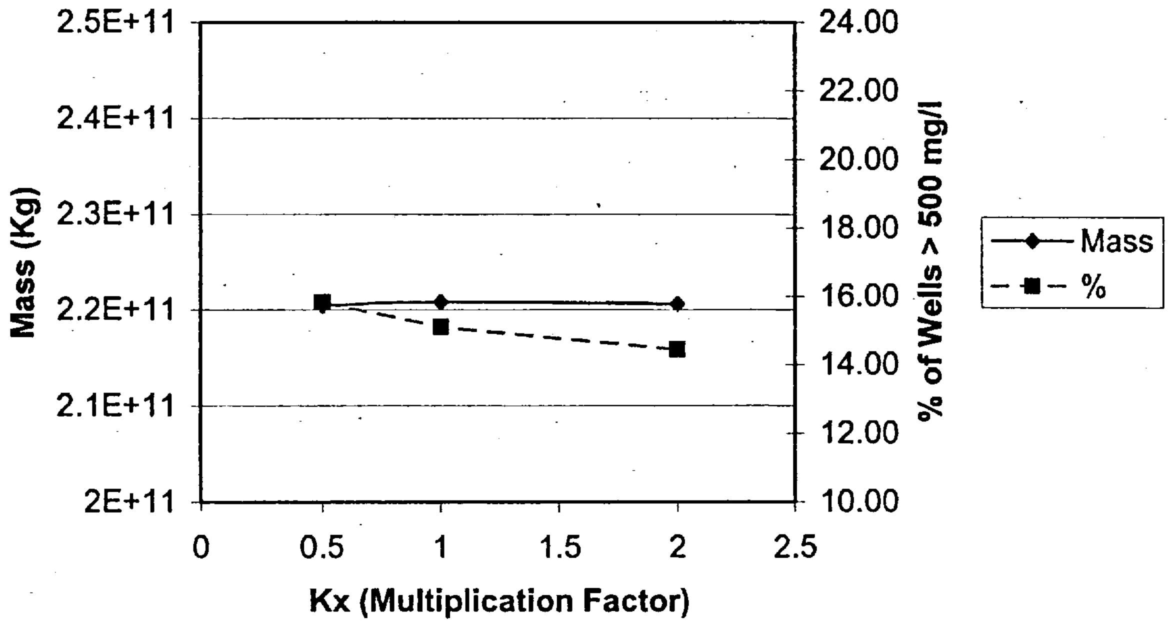


Figure 6.1 d. Sensitivity to Leakance in the Ocala Region (Model Layers 3 and 5)



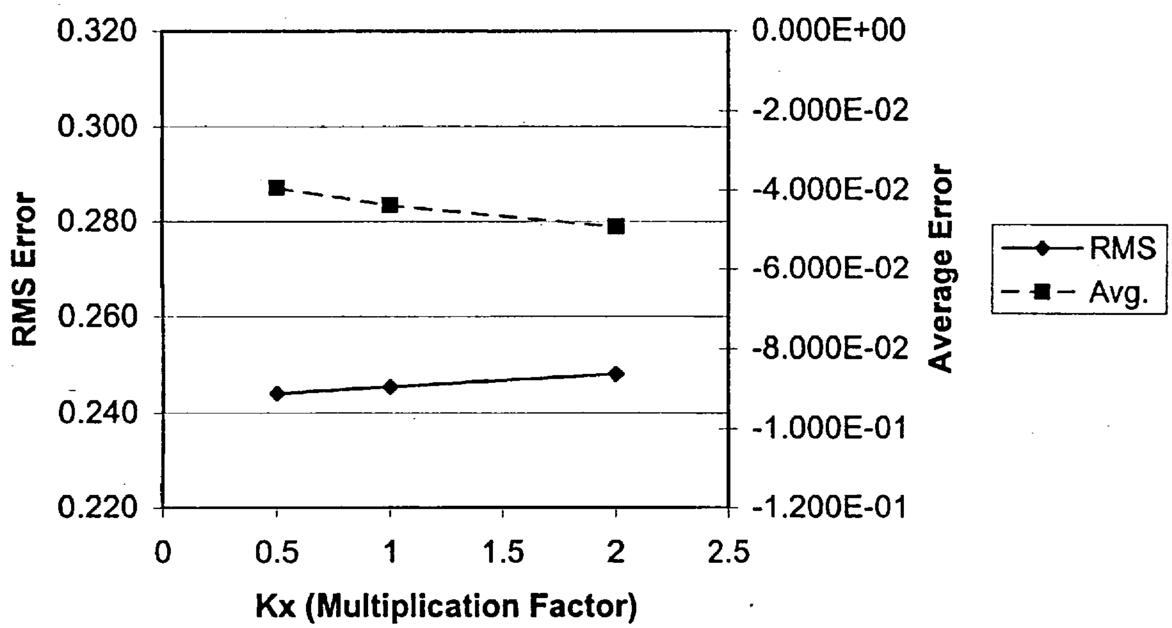


Figure 6.1 e. Sensitivity to Conductivity Value in the Suwannee Region (Model Layers 1 and 2)

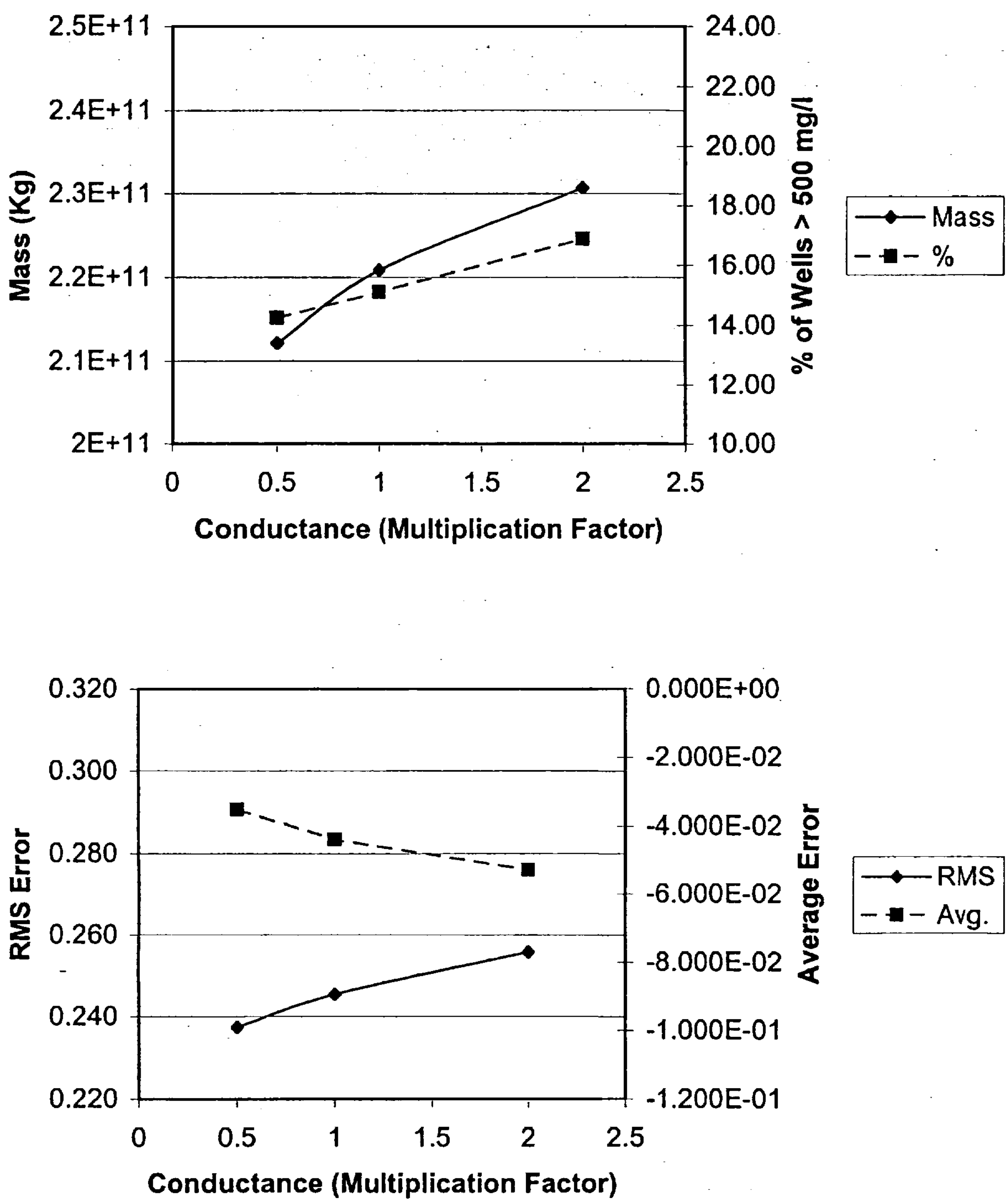
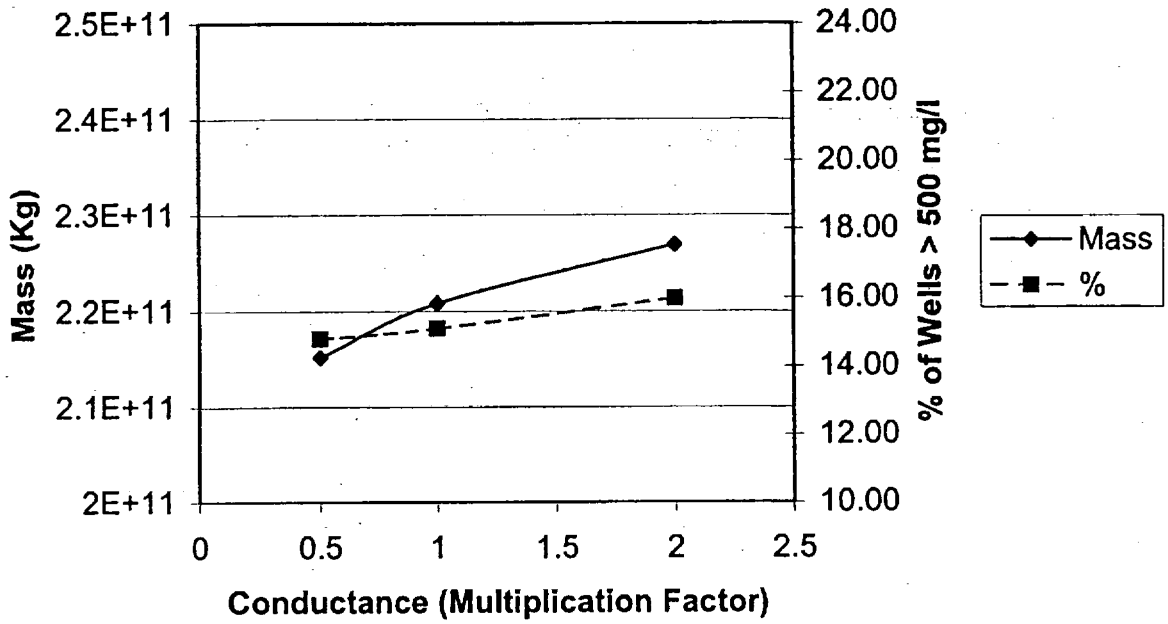


Figure 6.1 f. Sensitivity to GHB Conductance Values in the Top Layer



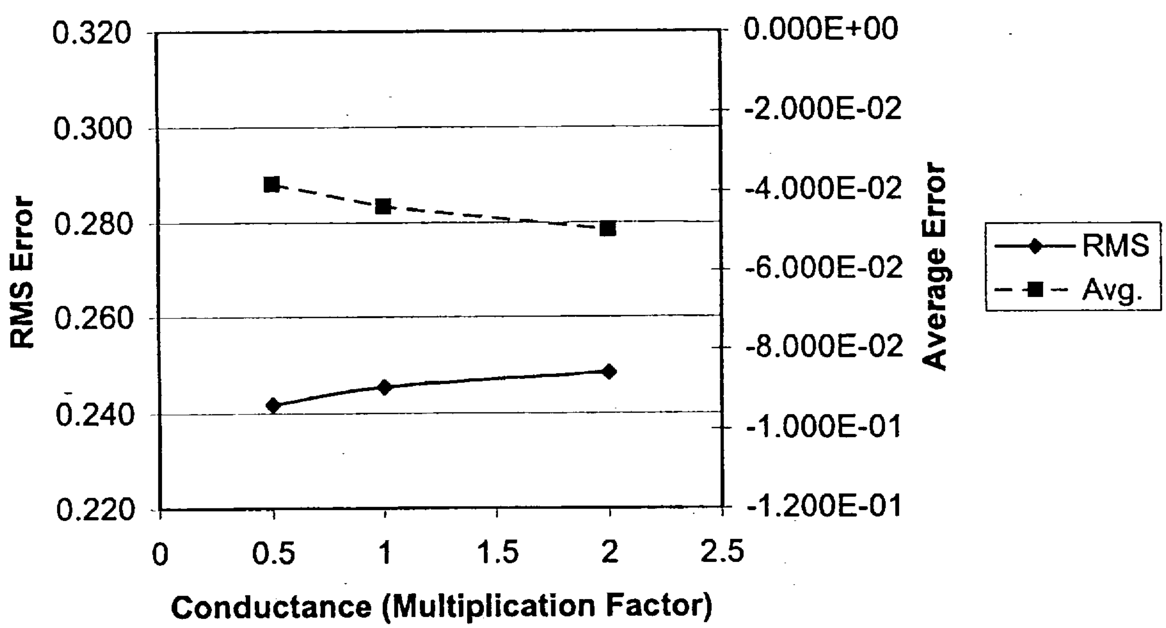
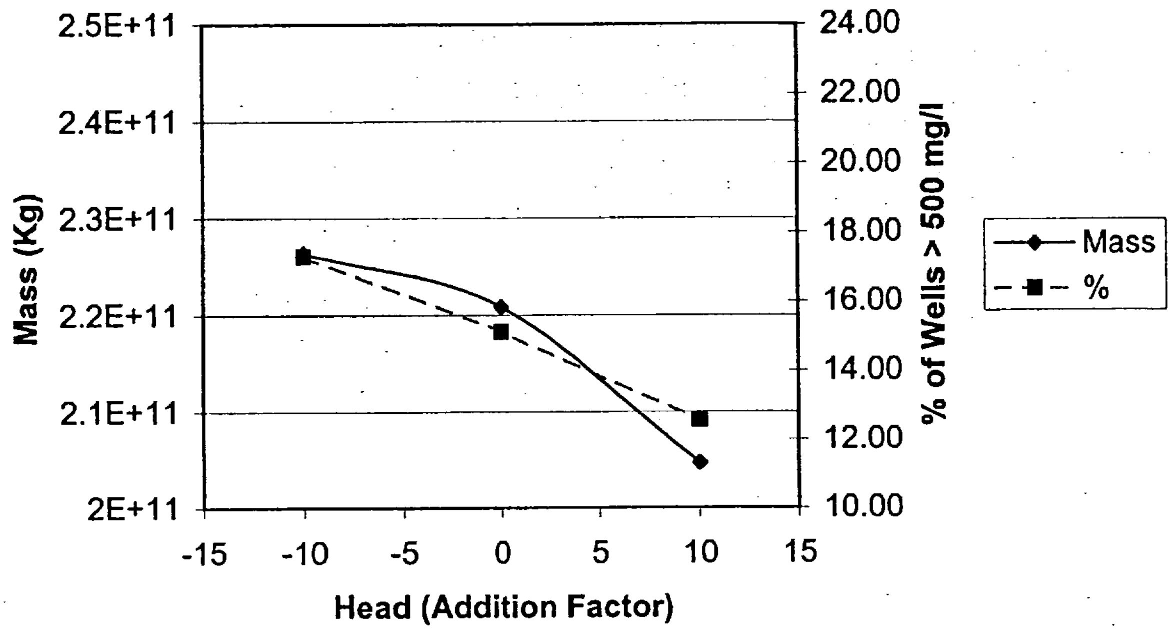


Figure 6.1 g. Sensitivity to GHB Conductance Values under Tampa Bay in the Top Layer



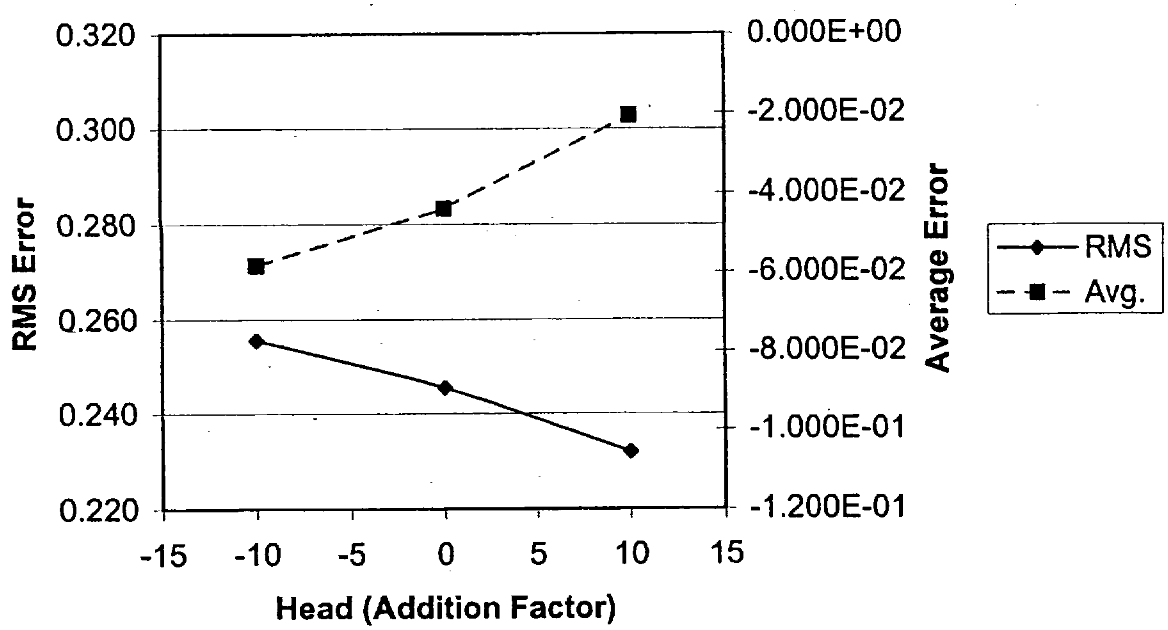


Figure 6.1 h. Sensitivity to GHB Head Values in the Top Layer

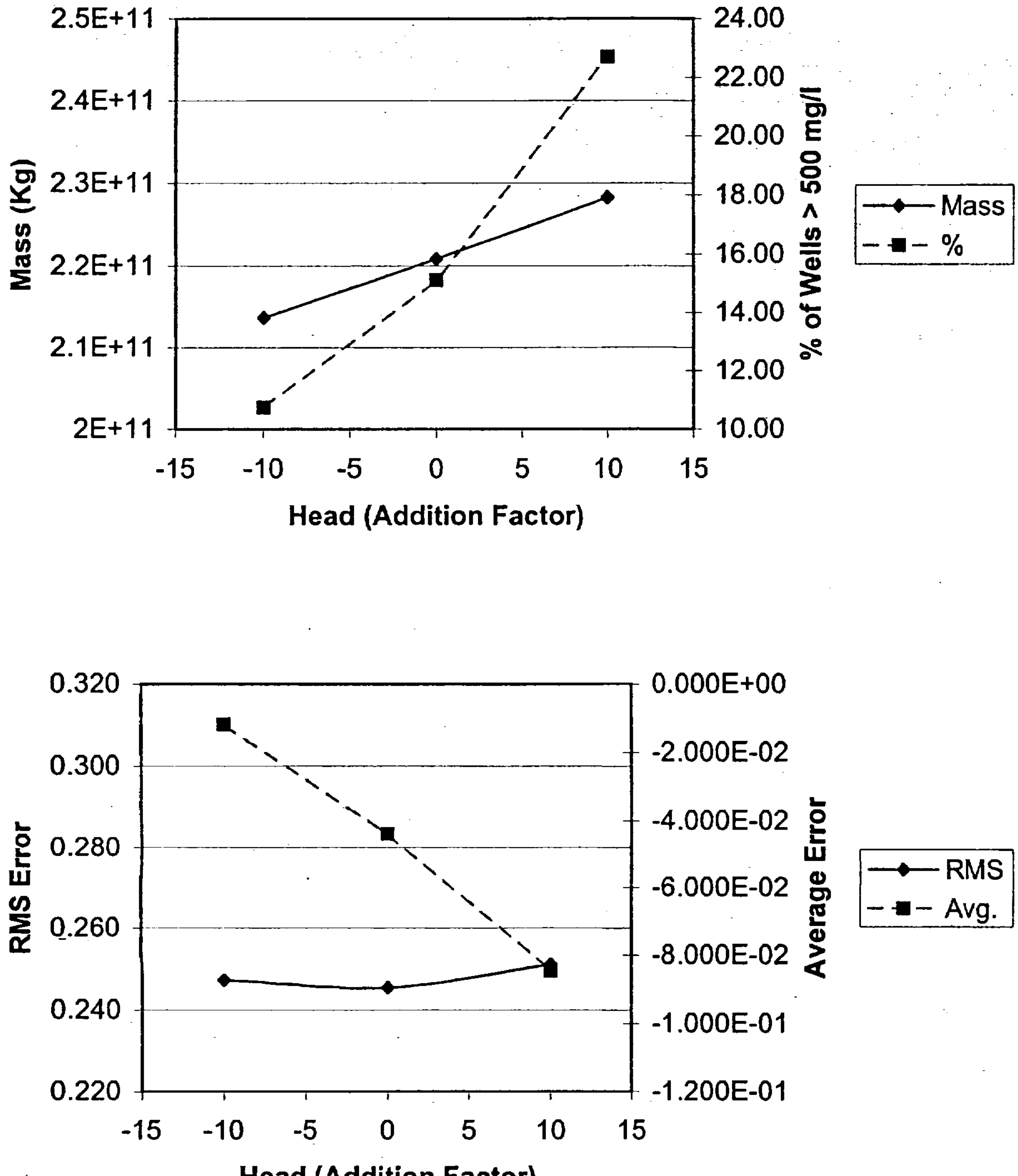
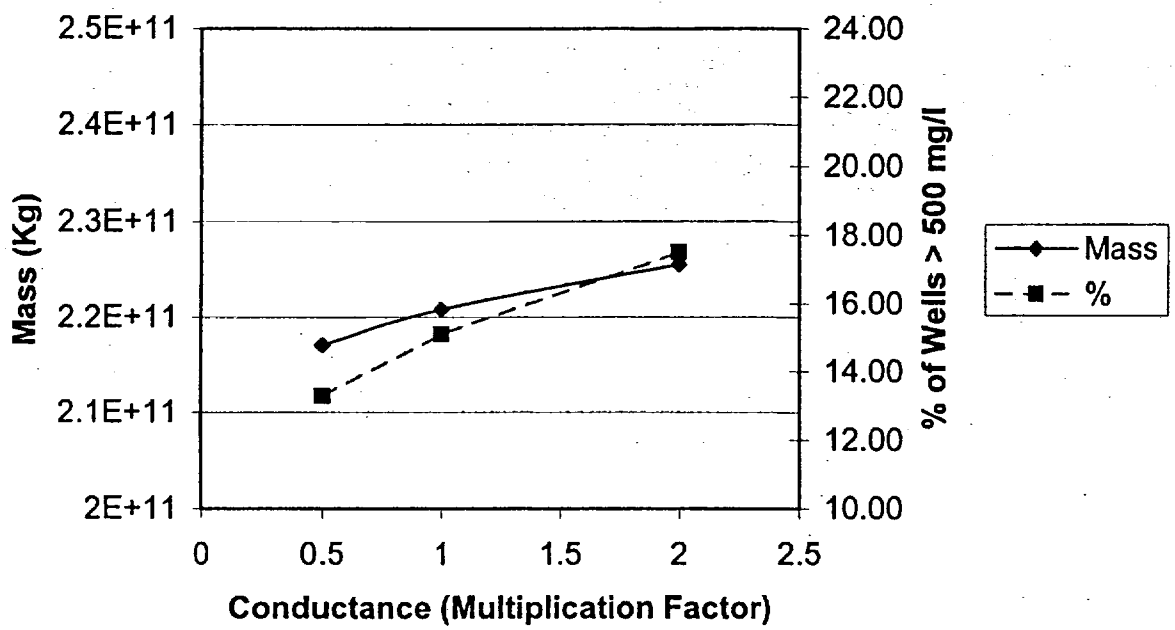


Figure 6.1 i. Sensitivity to GHB Head Values in the Bottom Layer



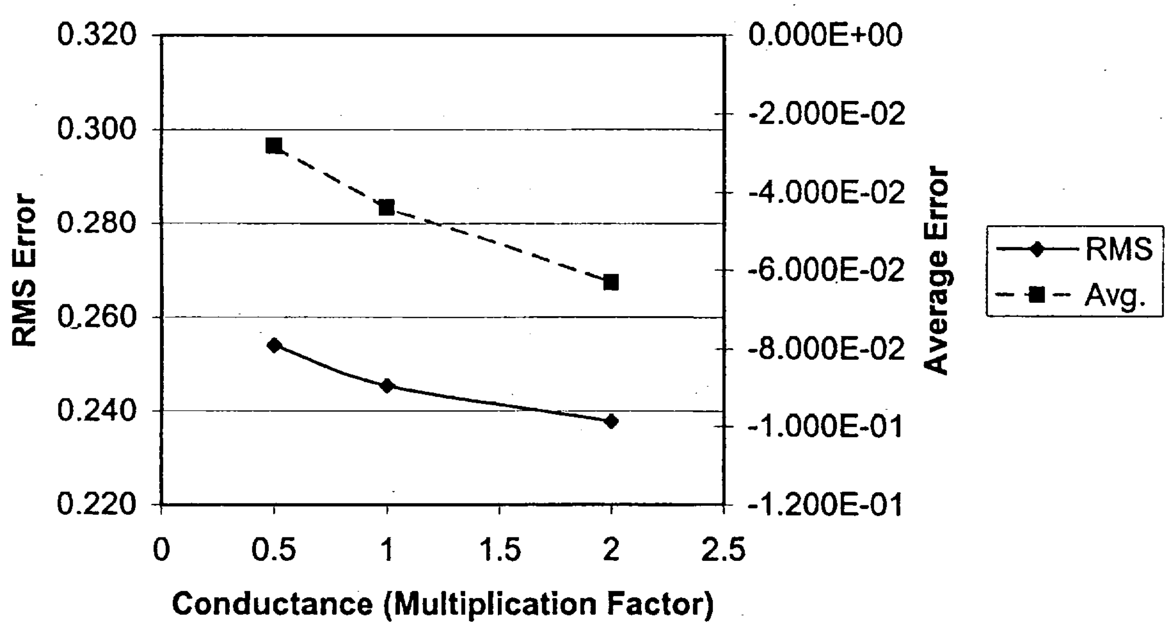


Figure 6.1 j. Sensitivity to GHB Conductance Values in the Bottom Layer

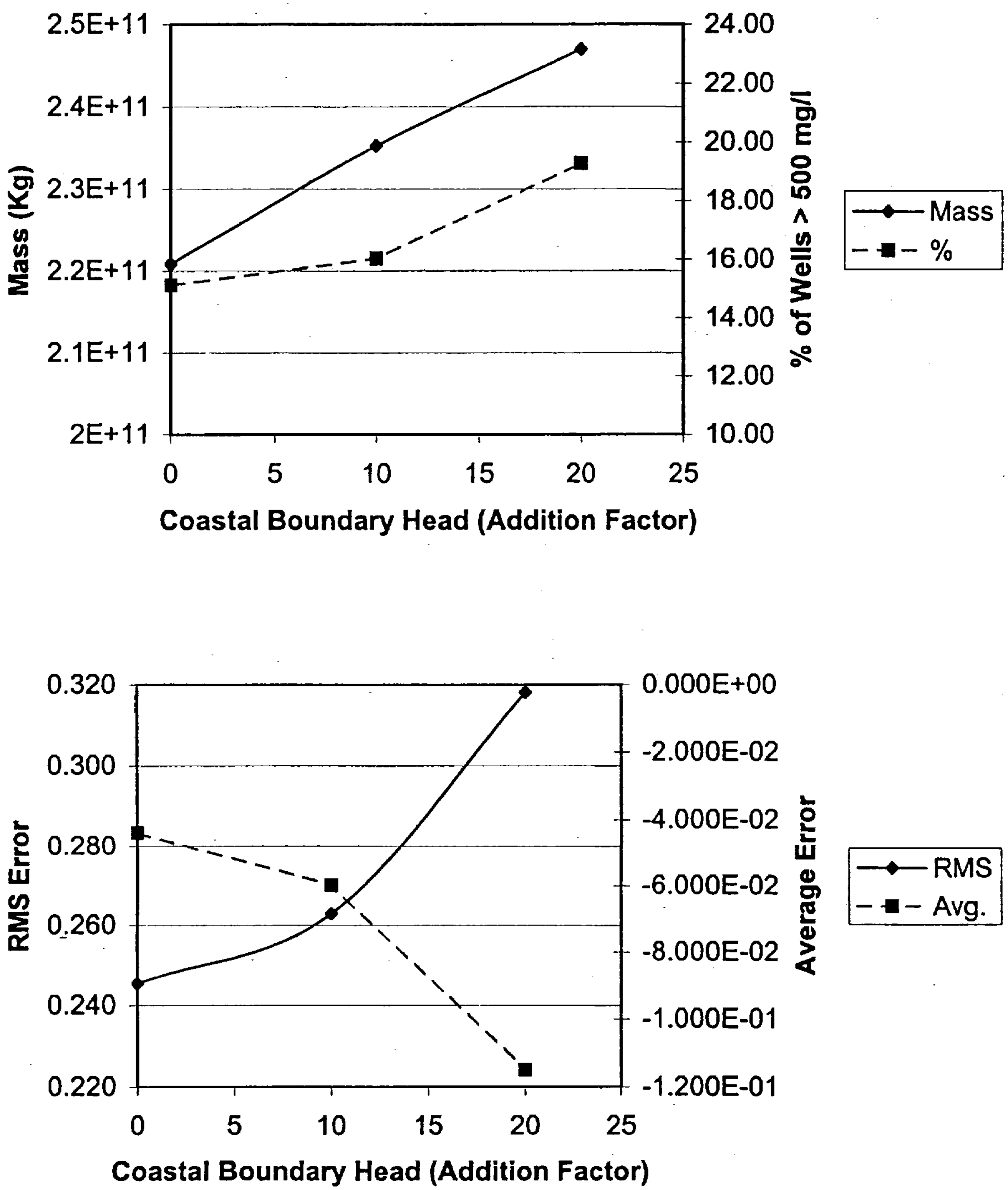


Figure 6.1 k. Sensitivity to Coastal Lateral Boundary Head

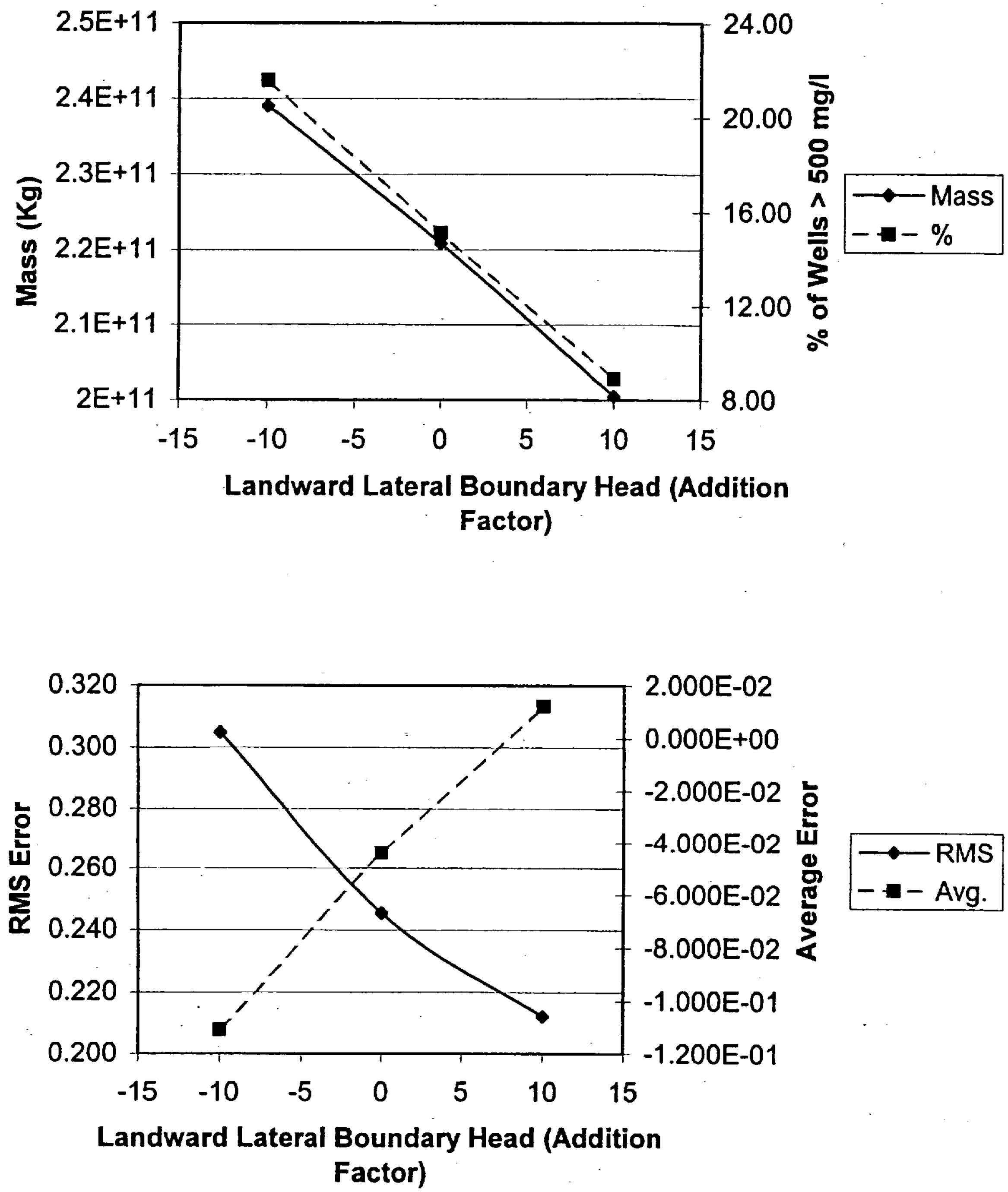
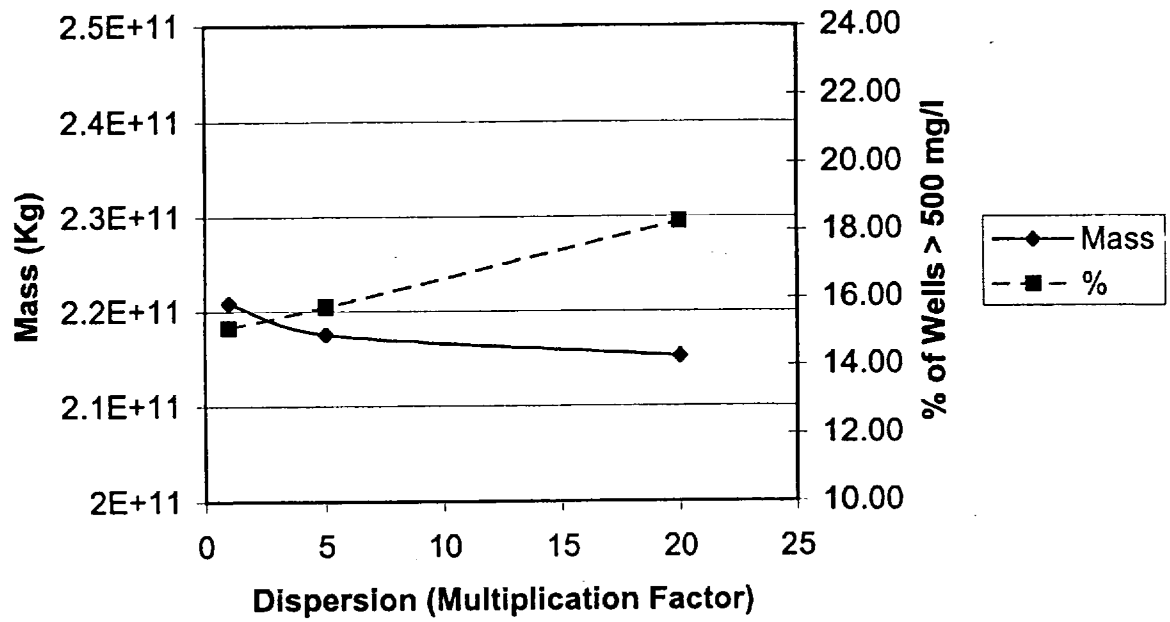


Figure 6.1 l. Sensitivity to Landward Lateral Boundary Head



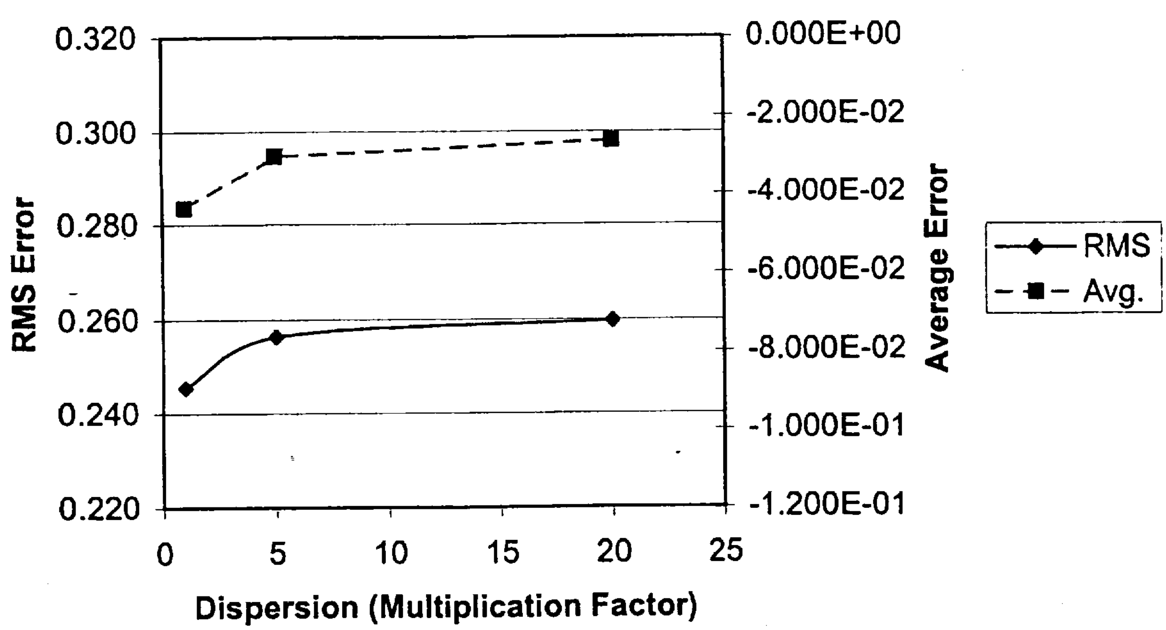
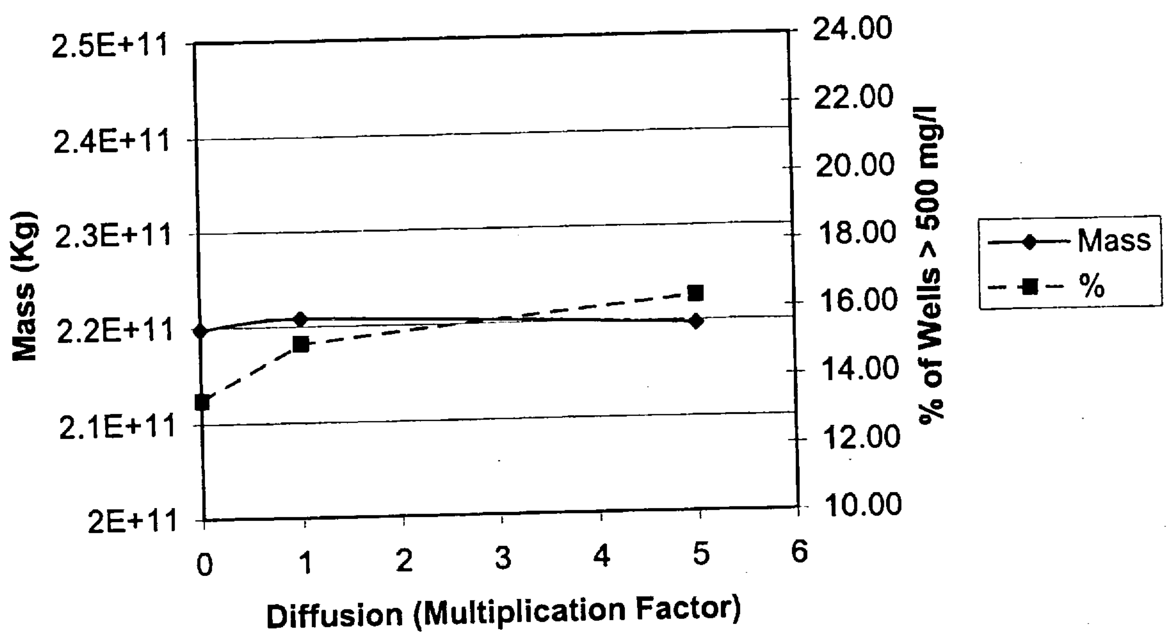


Figure 6.1 m. Sensitivity to Dispersion Coefficient



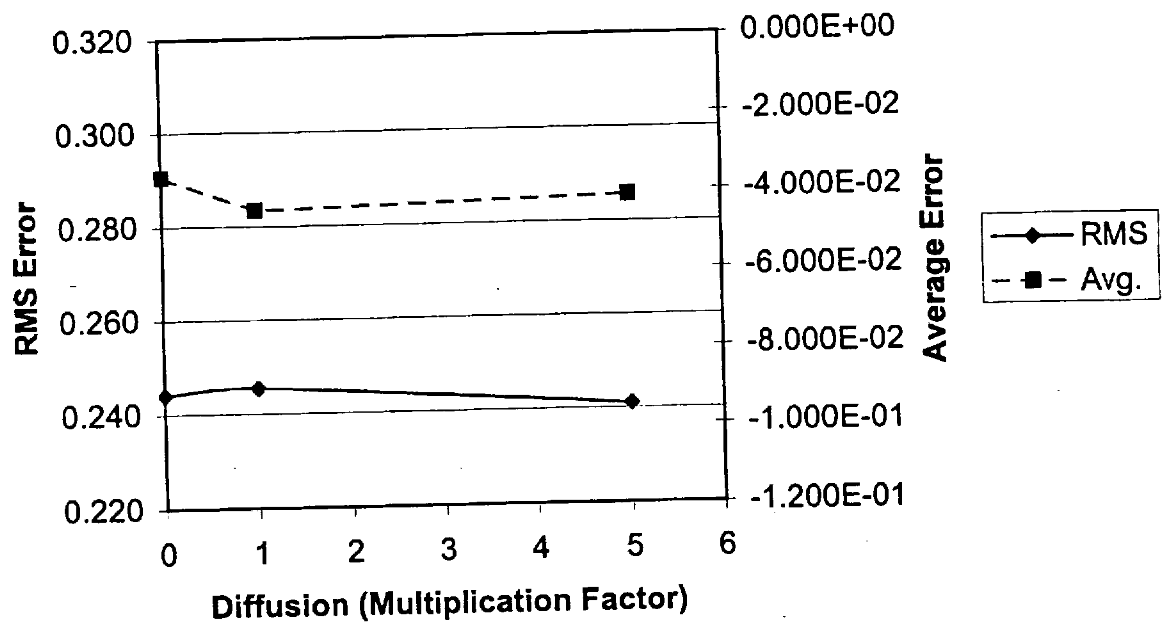
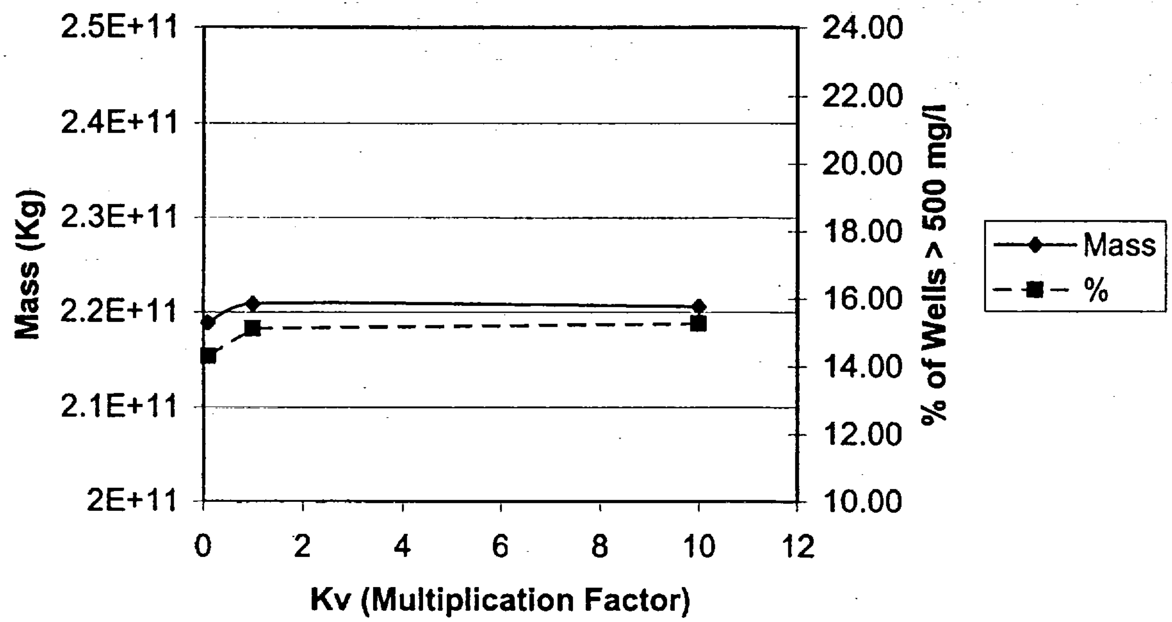


Figure 6.1 n. Sensitivity to Diffusion Coefficient



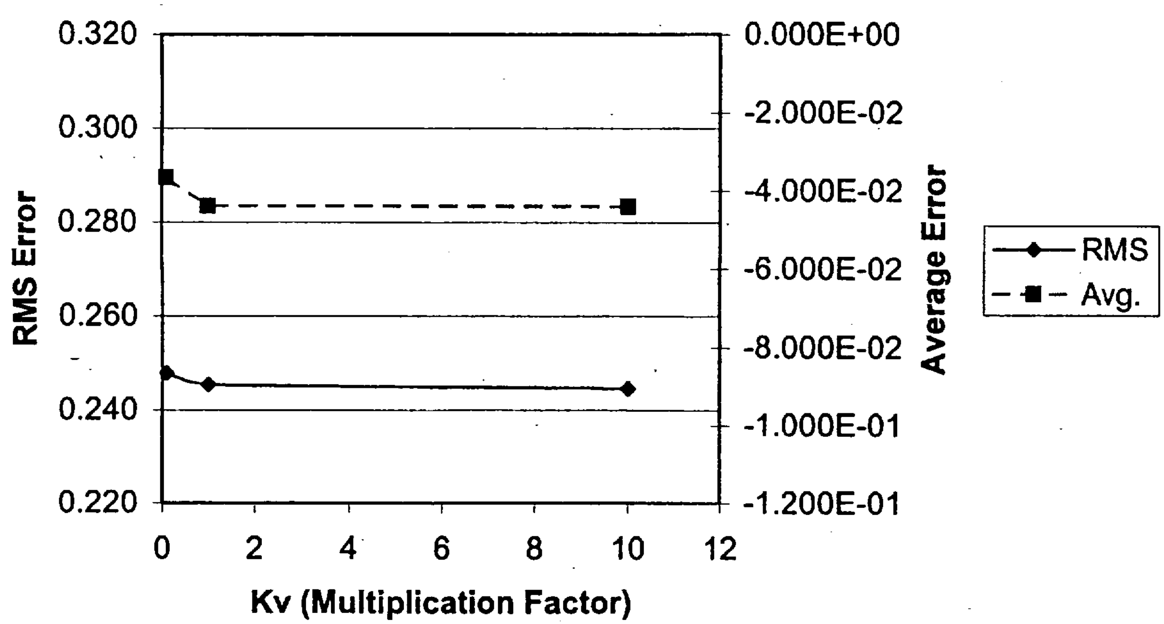
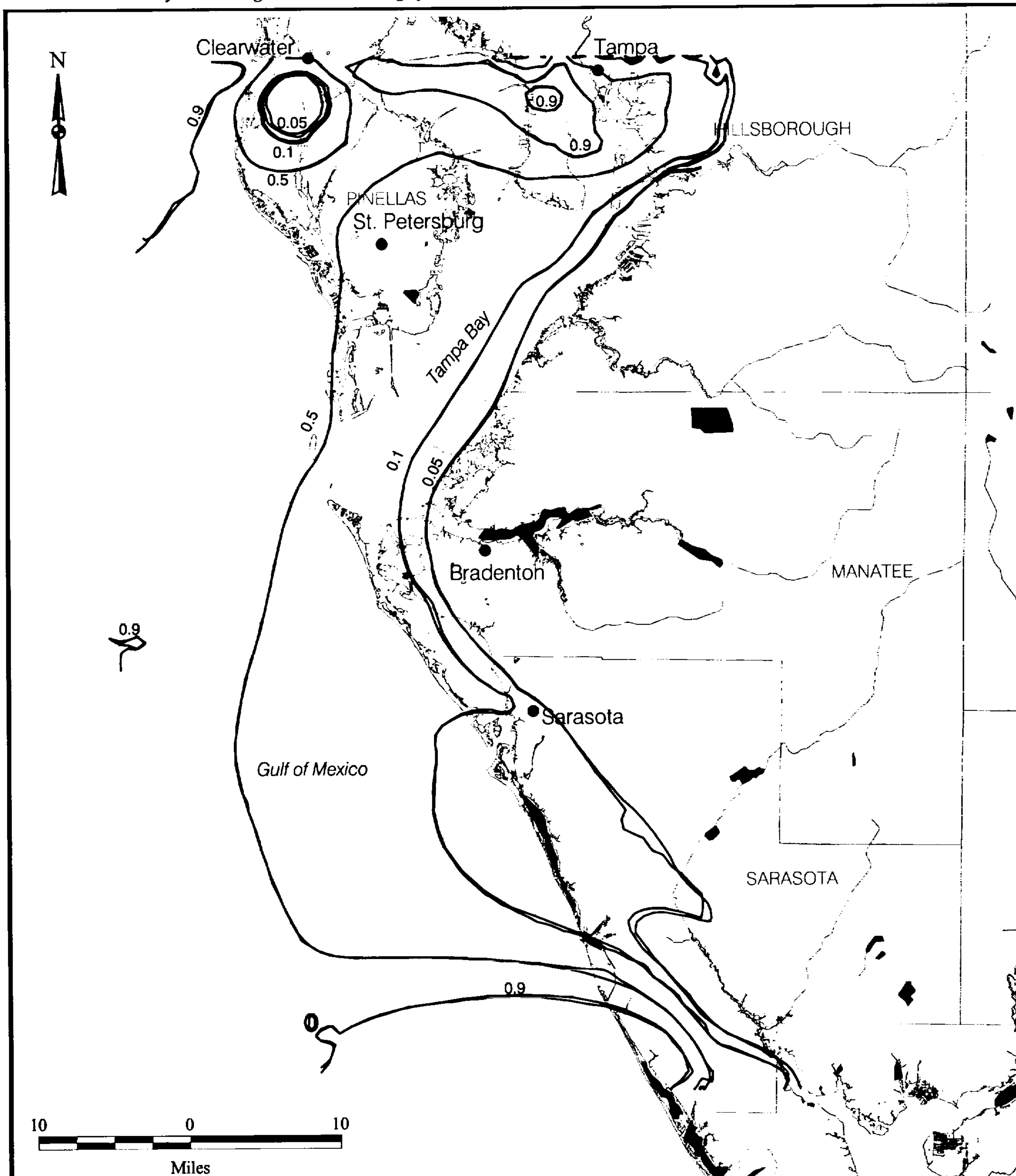


Figure 6.1 o. Sensitivity to Vertical Anisotropy in the Avon Park Formation



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/13/02 TB

HYDRO GeoLogic INC.

Legend

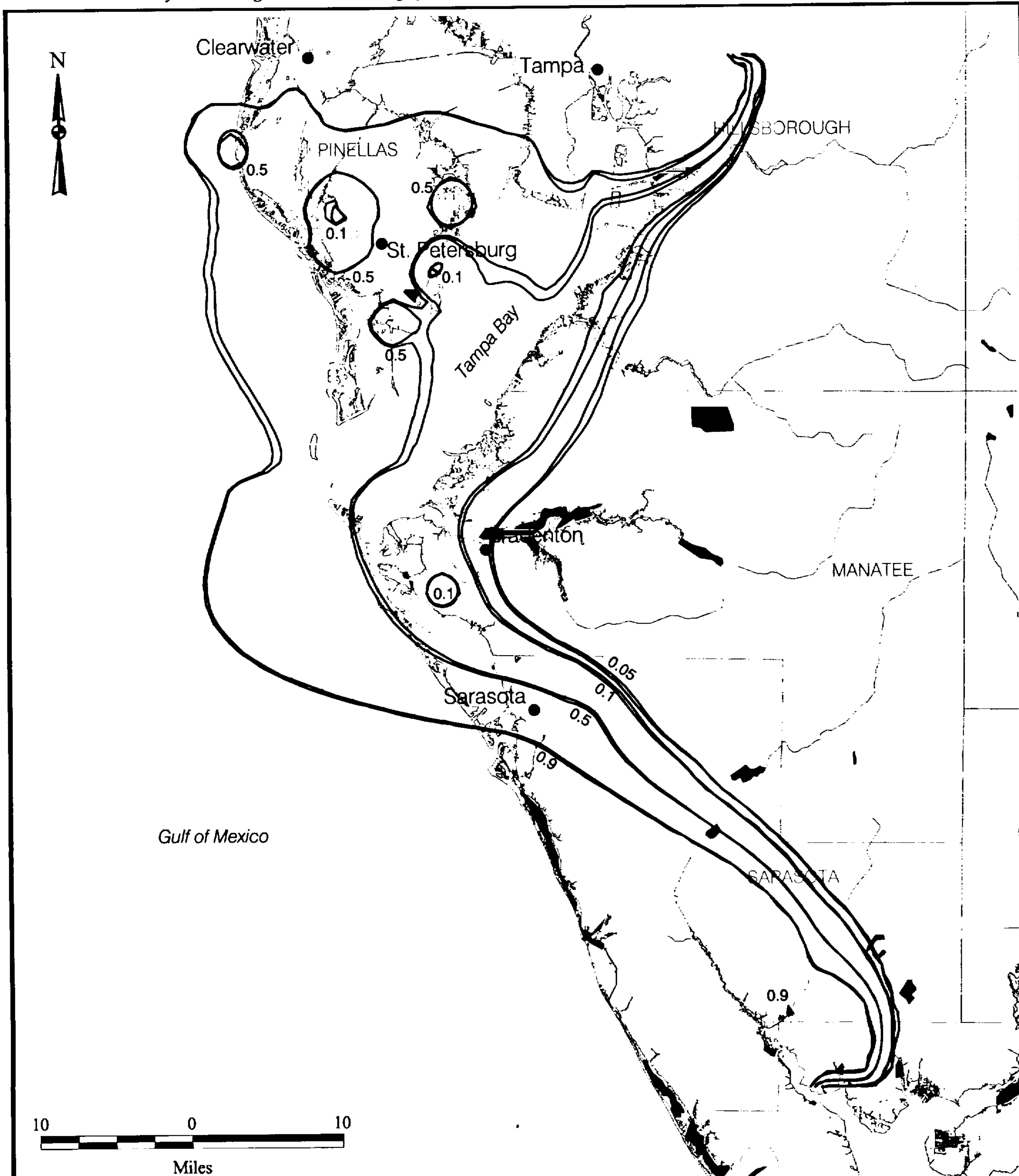
County Boundary — Surface Drainage

0.05 Relative Chloride Concentration Contour 0.05 = 1000 mg/l

0.05 Relative Chloride Concentration Contour 0.05 = 1000 mg/l for Corrected Model

0.1 = 1,900 mg/l — 0.7 = 13,300 mg/l
0.3 = 5,700 mg/l — 0.9 = 17,100 mg/l
0.5 = 9,500 mg/l

Figure 6.2
Comparison of Calibrated Model Results to Corrected Well Depths for the Suwannee Limestone (Model Layer 2)



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Revised: 06/13/02 TB

Legend

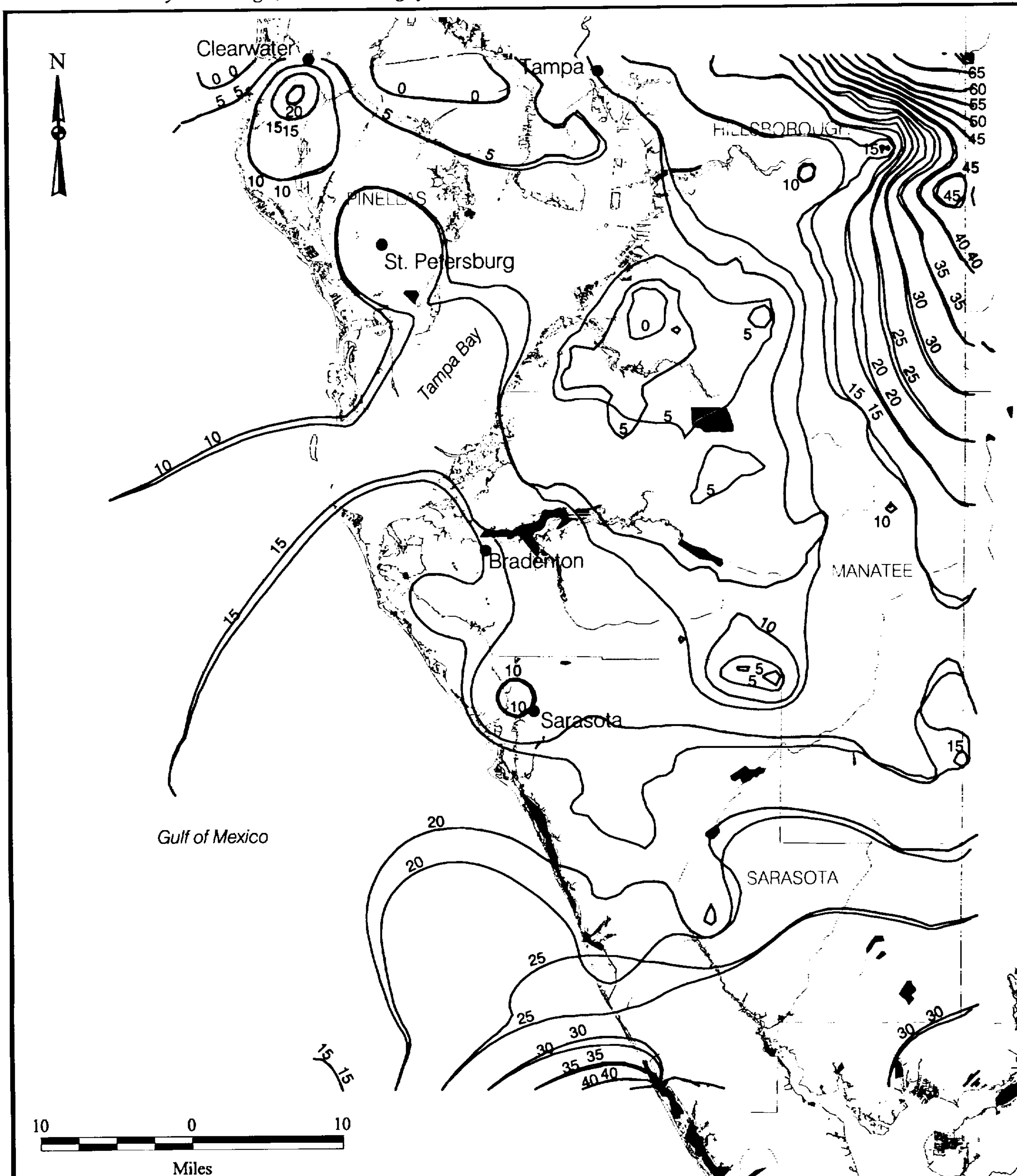
County Boundary — Surface Drainage

0.05 Relative Chloride Concentration Contour 0.05 = 1000 mg/l

0.05 Relative Chloride Concentration Contour 0.05 = 1000 mg/l for Corrected Model

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 6.3
Comparison of Calibrated Model Results to Corrected Well Depths for the Avon Park Formation (Model Layer 6)



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Created: 11/28/01 TH
Revised: 06/13/02 TB

HYDRO GeoLogic Inc.

Legend

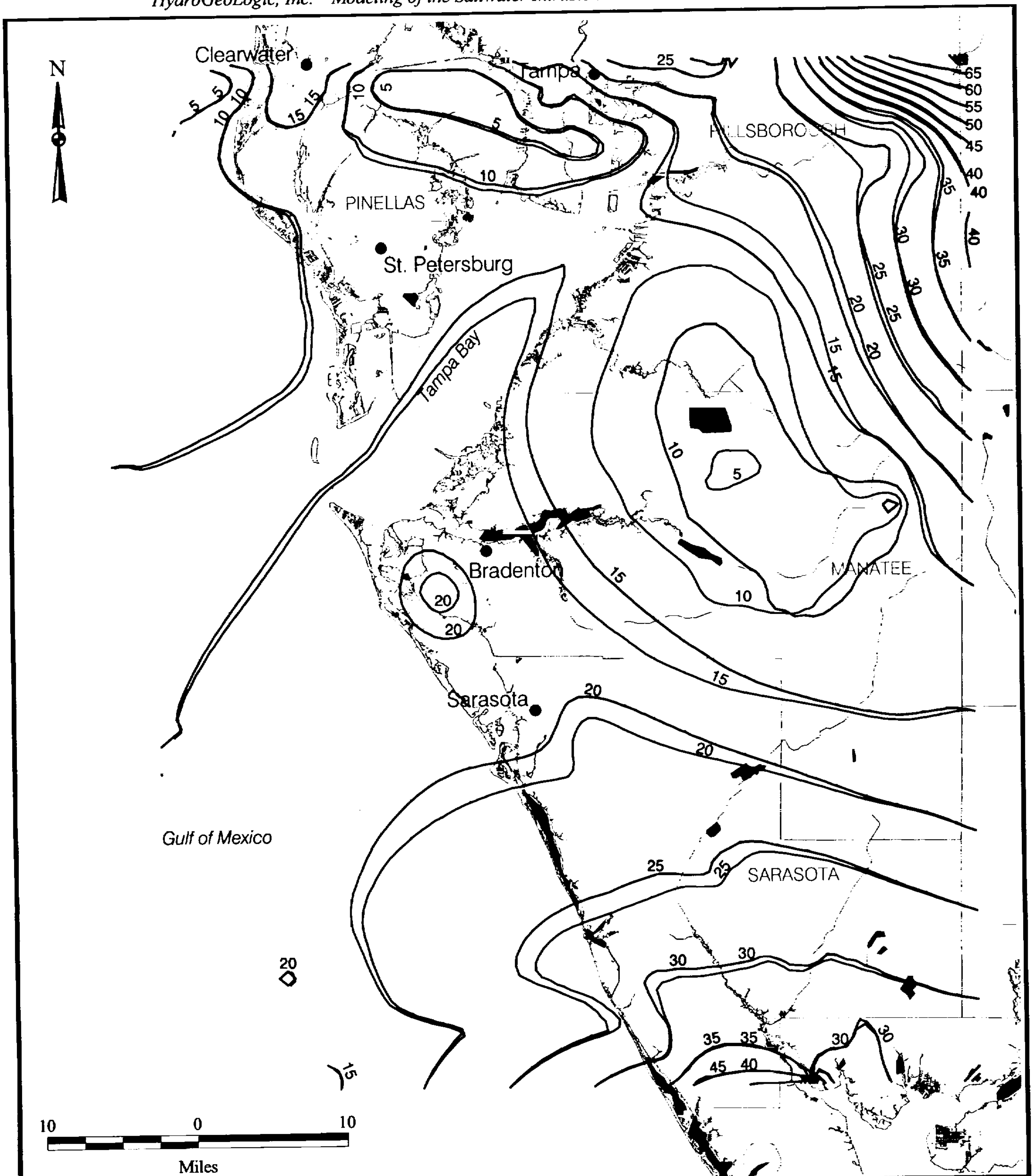
County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 2)

60 Corrected Potentiometric Surface Elevation (ft, msl)

Figure 6.4 Comparison of Calibrated and Corrected Potentiometric Surface - September 2000 (Suwannee Limestone, Model Layer 2)



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Revised: 06/13/02 TB

HYDRO GeoLogic INC.

Legend

County Boundary

Surface Drainage

60 Calibrated Model Potentiometric Surface Elevation Contour (ft, msl) (Model Layer 7)

60 Corrected Potentiometric Surface Elevation (ft, mls)

Figure 6.5
Comparison of Calibrated and Corrected Potentiometric Surface - September 2000 (Avon Park Formation, Model Layer 7)

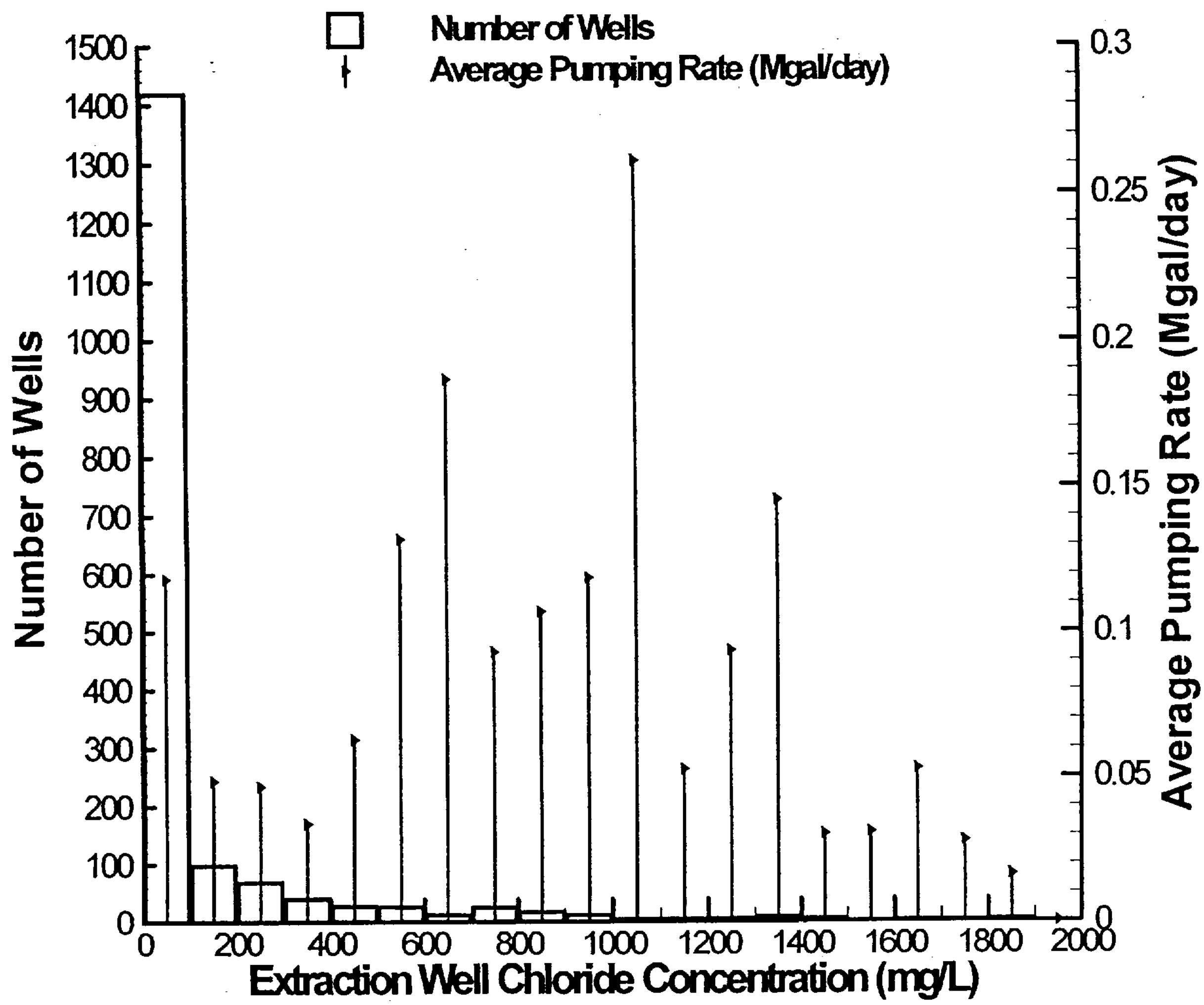
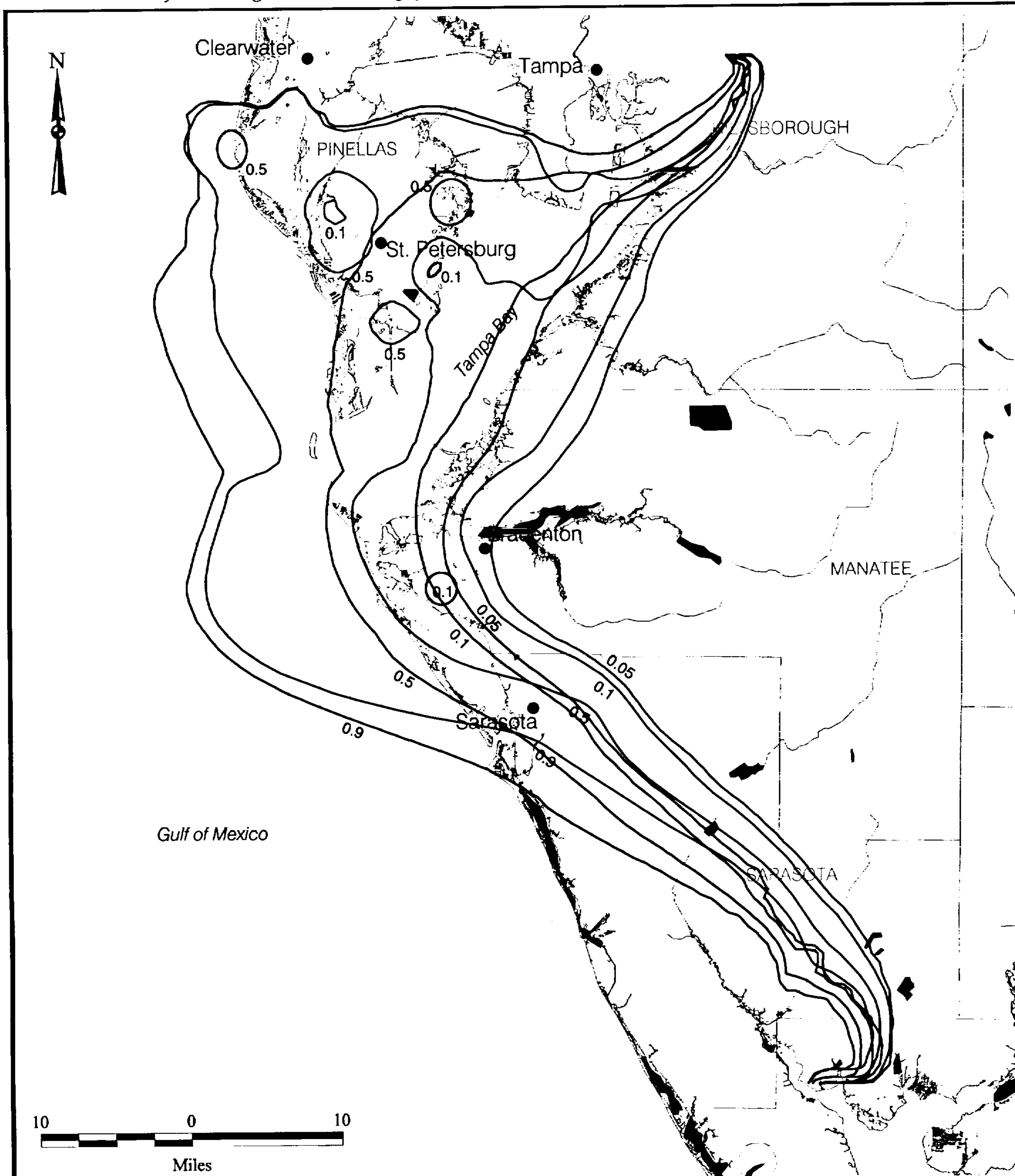


Figure 7.1 Extraction well chloride concentration histogram for December 2000



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Created: 11/28/01 TH
Revised: 06/14/02 TB

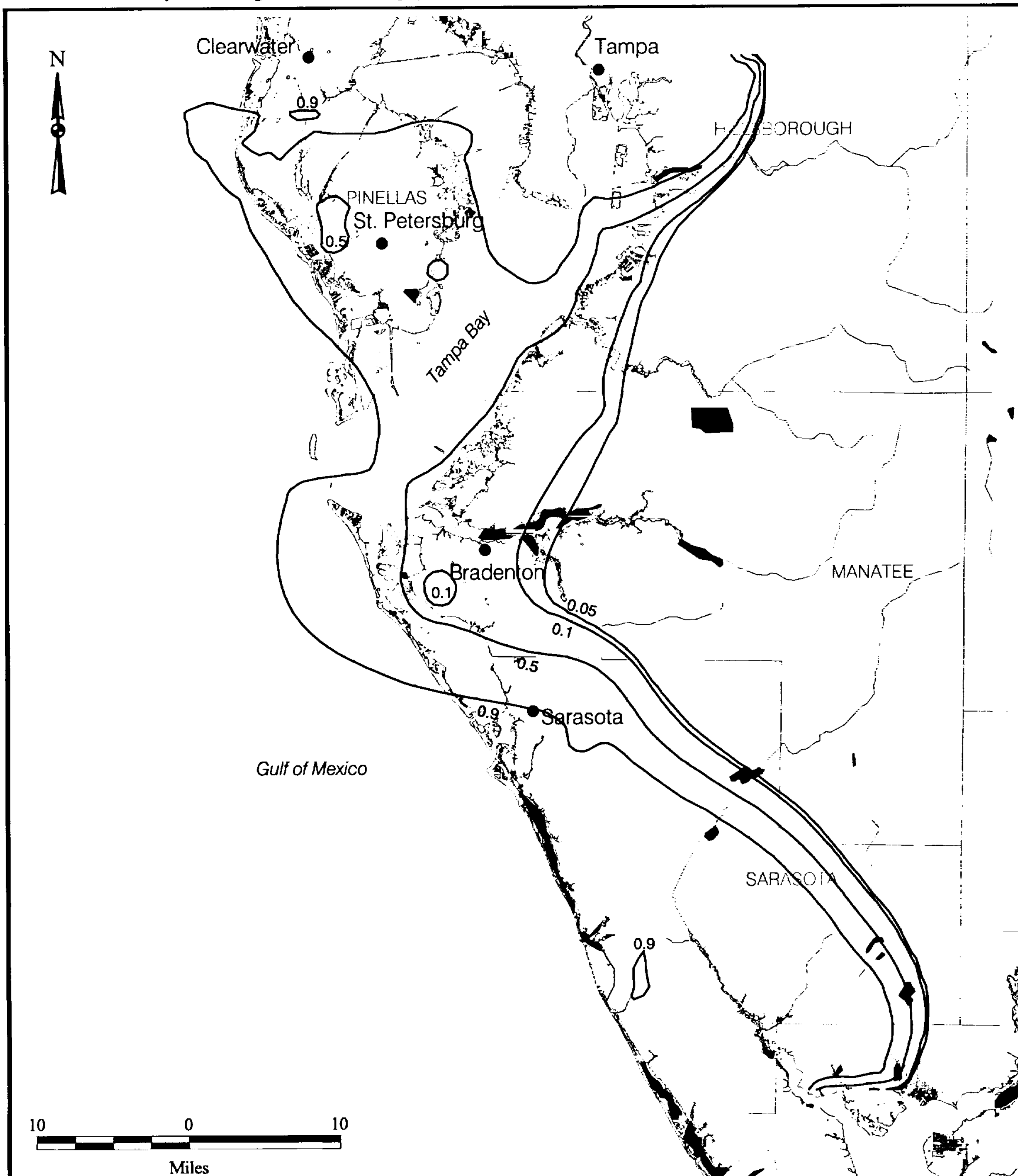
HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
0.05 Predevelopment Conditions
0.05 Relative Chloride Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 7.2
Relative Chloride Concentrations Predicted Using the Calibrated Model for Pre and Post Development Conditions for the Avon Park Formation (Model Layer 6)



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Project: SWF024-001-01
Created: 11/28/01 TH
Revised: 06/14/02 TB

HYDRO GeoLogic INC.

Legend

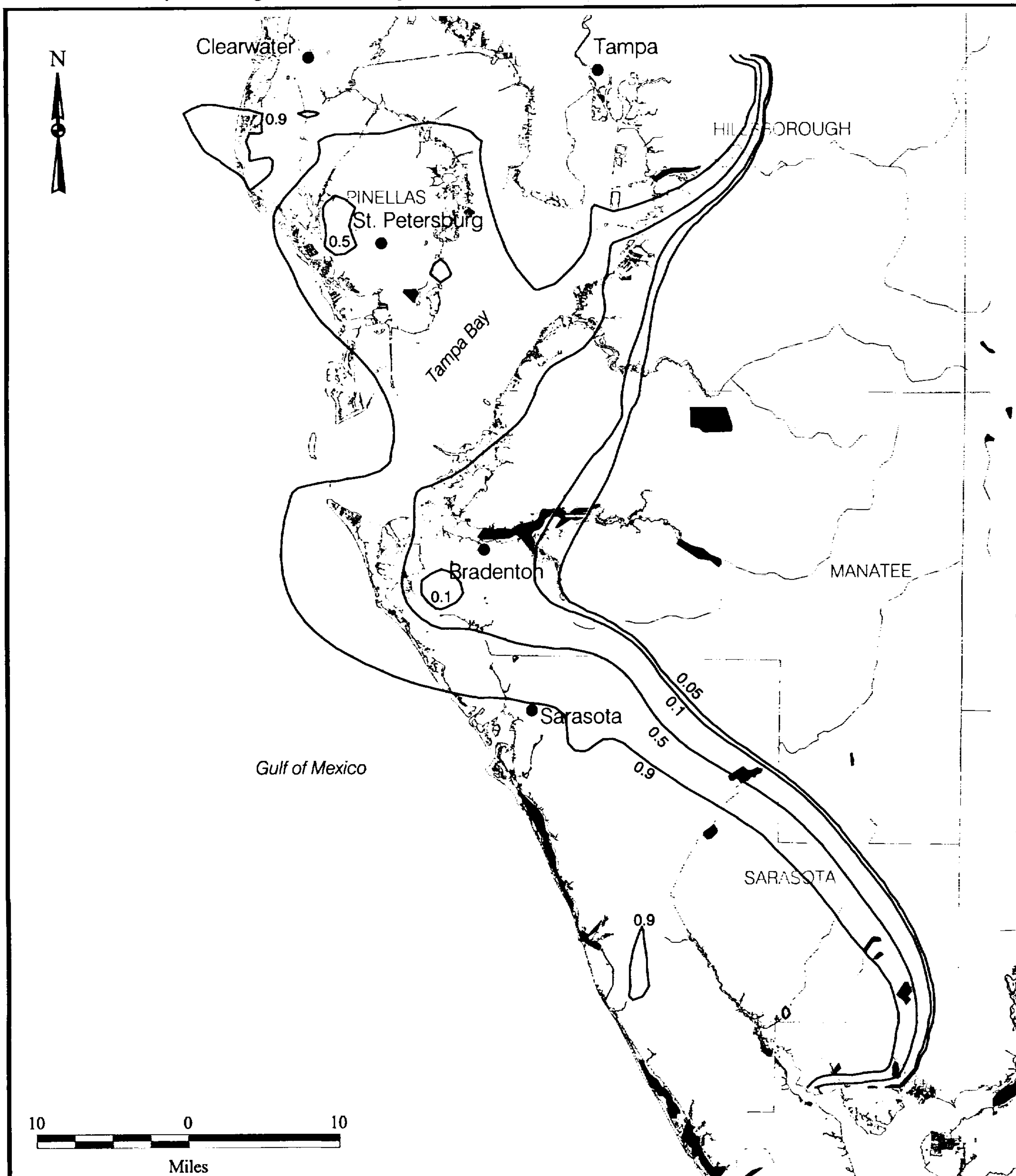
County Boundary

Surface Drainage

0.05 Areal Distribution Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 7.3
Areal Distribution of Chlorides within the Highly Permeable Zone of the Avon Park Formation (Model Layer 7) after 50 years of Pumping 400 MGD



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Revised: 06/14/02 TB

HYDRO GeoLogic INC.

Legend

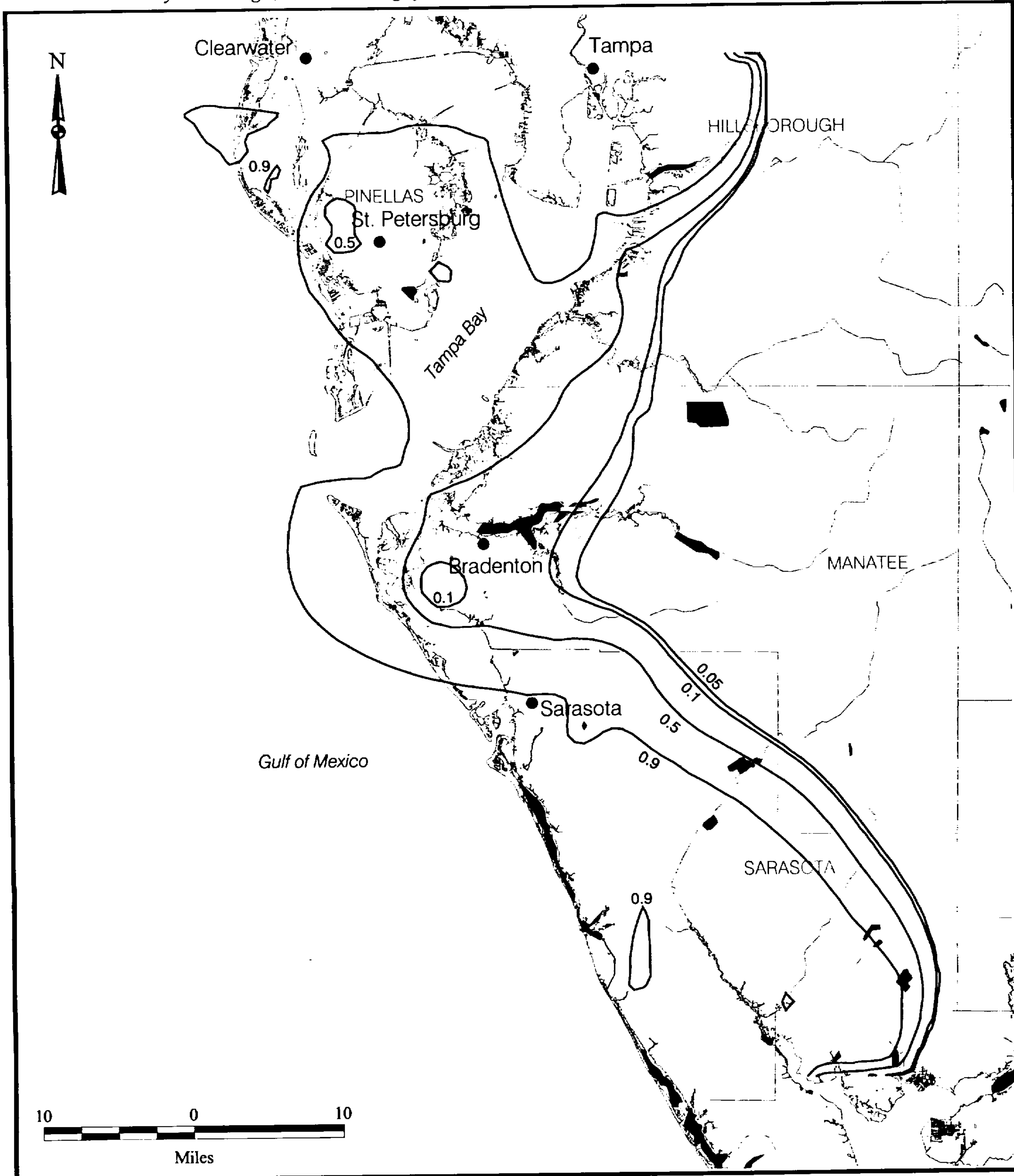
County Boundary

Surface Drainage

0.05 Areal Distribution Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 7.4
Areal Distribution of Chlorides within the Highly Permeable Zone of the Avon Park Formation (Model Layer 7) after 50 years of Pumping 600 MGD



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Created: 11/28/01 TH
Revised: 06/14/02 TB

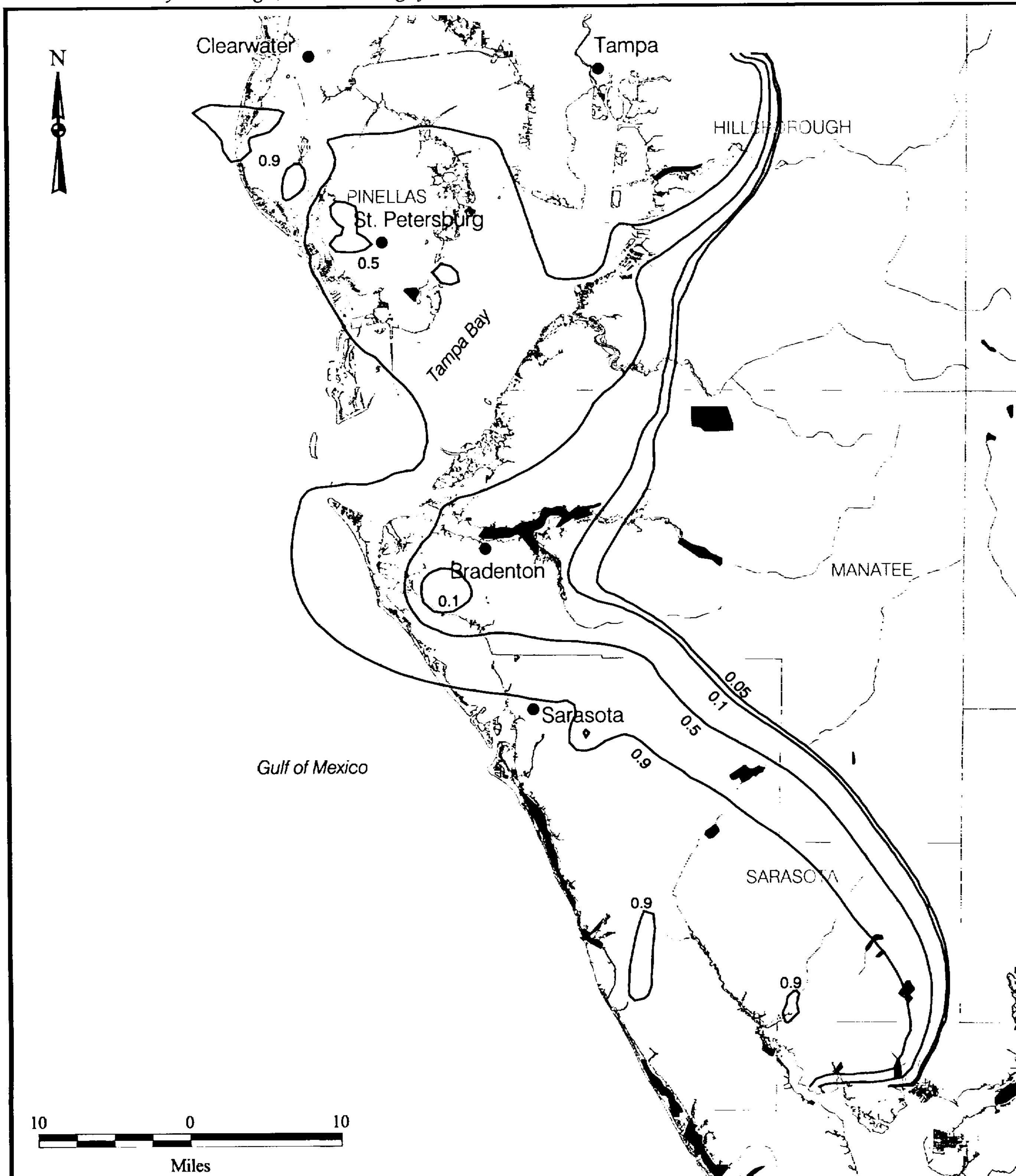
HYDRO GeoLogic INC.

Legend

County Boundary
Surface Drainage
0.05 Areal Distribution Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 7.5
Areal Distribution of Chlorides within the Highly Permeable Zone of the Avon Park Formation (Model Layer 7) after 50 years of Pumping 800 MGD



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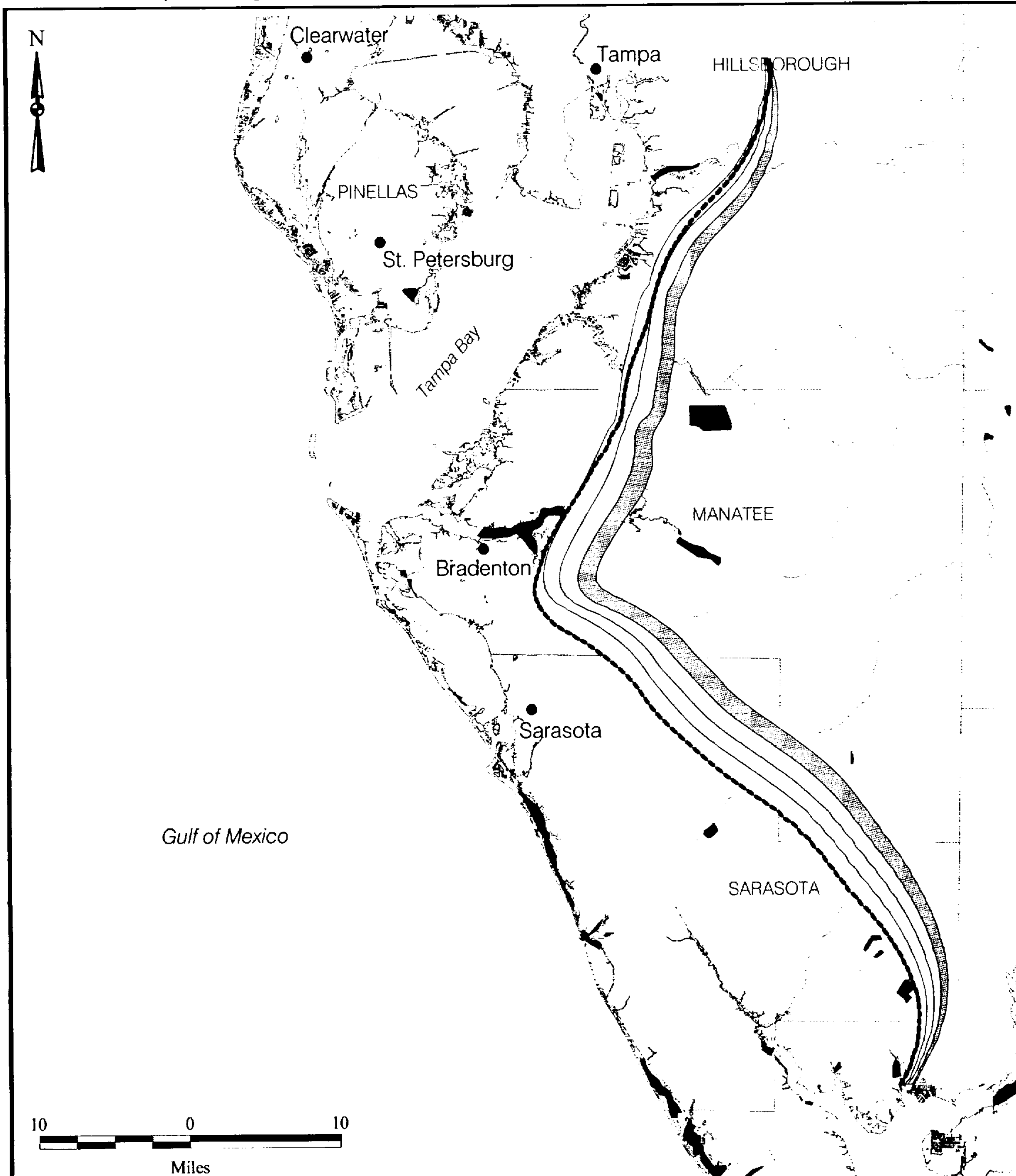
Revised: 06/14/02 TB

Legend

County Boundary
Surface Drainage
0.05 Areal Distribution Concentration Contour
0.05 = 1000 mg/l

0.1 = 1,900 mg/l
0.3 = 5,700 mg/l
0.5 = 9,500 mg/l
0.7 = 13,300 mg/l
0.9 = 17,100 mg/l

Figure 7.6
Areal Distribution of Chlorides within the Highly Permeable Zone of the Avon Park Formation (Model Layer 7) after 50 years of Pumping 1000 MGD



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Revised: 06/14/02 TB

HYDRO GeoLogic INC

Legend

County Boundary
Surface Drainage
------ Present Postion
400 MGD
600 MGD
800 MGD
1000 MGD

Figure 7.7
Extent of the Simulated 1000 mg/L Chlorides in the Highly Permeable Zone of the UFAS - Fifty Year Position for the Various Pumping Cases

TABLES

Table 2.1
Geology and Hydrogeology of the Eastern Tampa Bay WUCA
(modified from Barr, 1996, Miller, 1986, and Basso, 2001)

Series	Stratigraphic Unit		Hydrogeologic Unit		Lithology
Holocene to Pliocene	Undifferentiated Surficial Deposits		Surficial Aquifer		Sand, silty sand, clayey sand, peat, and shell
Miocene	Hawthorn Group	Peace River Formation	UICU	Intermediate Aquifer System	Predominantly phosphatic clay, gray to green to brown, plastic, ductile, minor sand, residual limestone, and dolostone
			PZ2		
			MICU		
		Arcadia Formation			
		Tampa Member	PZ 3		Limestone, gray to tan, sandy, soft, clayey, minor stone, phosphatic. Chert found locally
			LICU		
Oligocene	Suwannee Limestone		UPZ	Upper Floridan Aquifer	Limestone, cream to tan, sandy, vuggy, fossiliferous
Eocene	Ocala Limestone		SCU		Limestone, white to tan, friable to micritic, fine-grained, soft, abundant foraminifera
	Avon Park Formation		LPZ		Limestone and dolomite. Limestone is tan, recrystallized. Dolomite is brown, fractured, sucrosic, hard. Peat found locally at top. Interstitial gypsum in lower part.
			Middle Confining Unit		

Table 2.2
Conceptual Model Components and Related Uncertainties

Conceptual Model Component	Integration into the Numerical Model	Conceptual Model Uncertainties and Possible Resolution
Physical Framework		
The Middle Confining Unit, because of the presence of evaporites, has a very low hydraulic conductivity.	The top of this unit may be assumed to be the base of the Upper Floridan Aquifer System (bottom of the model domain) and will be assigned no flow boundaries.	Hickey (1989) performed an assessment to evaluate the potential for groundwater from below the Middle Confining Unit to flow vertically upward into the permeable zone of the Avon Park. Hickey concluded that flow is upward and velocities vary by approximately 1 order of magnitude between pre and post-development conditions. Waterstone (2001) present calculations that show that the amount of vertical flow derived from below the Middle Confining Unit would have negligible impact on the water quality in the permeable portion of the Avon Park. This aspect of the conceptual model will probably not be tested during the model calibration. However, a sensitivity analysis could be performed in which the sensitivity of the effects of upward flow into the Avon Park on the water quality would be evaluated. This would also involve varying the chloride concentration derived from the anhydrites (see conceptual model components pertaining to lower boundary transport conditions).
The lower permeable zone (i.e., Avon Park Formation) of the Upper Floridan Aquifer may have discrete zones of high permeability.	The Avon Park will be discretized into multiple layers.	Aquifer tests of the Avon Park generally test the entire interval and are not at a resolution sufficient to differentiate individual zones in the Avon Park that may be laterally extensive. The implications of these zones are that they could create "fast paths" for chloride intrusion. The best means to investigate the potential existence of these high permeability zones is to calibrate the model to the high resolution chloride profiles available from the ROMP wells (Figure 2.10). This alternative conceptualization will also be evaluated during the sensitivity analysis if it is found to produce a reasonable calibration.

Table 2.2 (continued)
Conceptual Model Components and Related Uncertainties

Conceptual Model Component	Integration into the Numerical Model	Conceptual Model Uncertainties and Possible Resolution
The Ocala Formation behaves as a semi-confining unit.	The Ocala will be discretized separately from the Avon Park Formation.	Similar hydraulic responses were observed in the Suwannee and Avon Park during aquifer stress tests. This observation suggests that the Ocala is not fully confining and will not prevent water from moving upward. Therefore, upward coning from the Avon Park through the Ocala and into the Suwannee is a possibility. HydroGeoLogic (1994) evaluated a scenario in which the confining properties of the Ocala were decreased and found that the 1,000 mg/l isochlor rose over 200 feet in 50 years. Until more information becomes available from field tests of the Ocala vertical hydraulic conductivity, reliance will have to be placed on the model calibration and on the Southern District Model parameterization for estimating the actual conductivity of the Ocala.
Productive zones in the Intermediate Aquifer System are hydraulically isolated from the Upper Floridan Aquifer by clay units in the Hawthorn Group.	Units above the Suwannee Limestone do not have to be explicitly simulated, but can be treated as a general head boundary that considers the vertical conductance and overlying hydraulic heads, since these units are not of consequence to saltwater intrusion.	This aspect of the conceptual model could be tested by turning the wells on in the Suwannee and Ocala/Avon Park of the Southern District Model and observing head changes within the intermediate aquifer system in the Southern District Model.
All of the aquifer units behave as an equivalent porous media for both flow and transport.	The localized effects of fractures and molecular diffusion into matrix blocks is negligible.	There is evidence that suggest that flow and transport through the Avon Park may be controlled by dual porosity and/or dual permeability conceptualizations. The dual porosity conceptualization collapses to the equivalent porous medium representation for two extreme cases. When the fracture-matrix interaction is large, the equivalent porous medium representation allocates all pore spaces in the domain (fracture plus matrix) to transport. When this interaction is small, the equivalent porous medium representation allocates only the pore spaces within the fractures to transport approximate. Porosity values used in simulations will be adjusted to note the more appropriate representation.
Hydraulic conductivity does not show anisotropy in the horizontal direction within each respective confining unit and aquifer.	Horizontal hydraulic conductivities will be assumed to be isotropic within each respective unit.	Previous aquifer testing has not suggested that there are strong anisotropic components to flow. The validity of this assumption can be evaluated during sensitivity analyses to the regional model.

Table 2.2 (continued)
Conceptual Model Components and Related Uncertainties

Conceptual Model Component	Integration into the Numerical Model	Conceptual Model Uncertainties and Possible Resolution
	Hydrologic Framework	
The majority of the water entering the study area from the north, east and south is of good quality.	The boundary conditions on these borders will all assume freshwater.	This component of the conceptual model is currently well supported by the existing field data, and will not be tested further.
Lateral encroachment of seawater and subsequent upconing in areas where wells are completed above the wedge is the primary source of high salinity water.	The boundary conditions on the western border (i.e., ocean) will be set at chloride concentrations measured in the bay.	This component of the conceptual model may be tested during model calibration by adjusting the chloride source concentrations.
Upconing of high salinity water derived from beneath the anhydrites in the Avon Park is not a significant source of chloride.	The lower boundary will be assumed to be impermeable to both water and chloride.	The effect of upconing of high salinity waters from the Middle Confining unit could be tested during the model calibration by placing a diffusion controlled chloride source at the base of the model (i.e., evaporites at the top of the Middle Confining Unit). As mentioned above, however, it is unlikely that the volume of chlorides derived from below the Middle Confining Unit would significantly affect the water quality.
The hydraulic heads along the ocean are probably not in hydrostatic equilibrium with the Gulf of Mexico, since the upper confining unit isolates the aquifer from the Gulf along this boundary, and the Upper Floridan aquifer outcrops into the Gulf probably more than a 100 miles offshore.	Prescribed equivalent freshwater heads will be used for the saltwater flow regime along the western lateral boundaries.	There is very little available data with respect to the equivalent freshwater heads along the western boundary. Consequently, these values will be adjusted during the model calibration.
The chloride concentrations in the Gulf of Mexico are approximately 14,500 mg/l.	The chloride concentrations along the western boundary will be assumed to be that of seawater (relative concentration equal to one). For inflow nodes, this chloride concentration is applied along the boundary. For outflow nodes, the concentration is not prescribed, and chloride levels will depend on the concentration of the outflowing water.	The information regarding chloride data for the post-development time period is relatively good. However, the chloride concentrations assumed for the pre-development time period, which are used to initialize the model, are relatively uncertain. This uncertainty will probably not be addressed during model calibration.

Table 2.2 (continued)
Conceptual Model Components and Related Uncertainties

Conceptual Model Component	Integration into the Numerical Model	Conceptual Model Uncertainties and Possible Resolution
	Chloride Transport Characteristics	
The effects of elevated sulfate and constituents other than chloride can be neglected.	Fluid densities will be dependent solely upon chloride concentration values.	Different geochemical facies within the model area may impact the fluid densities. The effects, however, are expected to be small and will not be explicitly addressed during the model calibration.
The interface is relatively sharp and dispersion values are small.	As presented in Section 4.6, a four component dispersivity approach may be appropriate	Field tests typically do not provide reasonable estimates of dispersivity. Therefore, the dispersivity values will be based on calibration results. Based on earlier modeling activities it is expected that small dispersivity values will result in a better calibration.

Table 4.1
Transport Properties

Parameter	Value
Effective porosity	0.15
Freshwater density	1.0
Saltwater density	1.025
Storativity	$1\text{x}10^{-4}$
Dispersivity	(please see discussion below)

Table 4.2
Dispersivity Values Used to Initiate Calibration of the Density-dependent Model

Formation/Unit	Longitudinal dispersivity (ft)	Transverse dispersivity (ft)	Vertical transverse dispersivity (ft)
Suwannee Limestone	100	20	10
Ocala Limestone	10	5	5
Avon Park Formation	80	15	10

Table 5.1
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
1) Chloride intrusion from the Tampa Bay area to the east (landward) is too limited, particularly in the Avon Park Formation.	Resistance caused to landward movement of chlorides by the zone of high hydraulic conductivity extending under Tampa Bay abutting lower conductivity regions to the east.	The zone of high hydraulic conductivity under Pinellas county and Tampa Bay is extended to the Hillsborough County shoreline.	Chloride intrusion will accordingly move landward until the shoreline.	Chlorides move shoreward but not proportionately. More shoreward movement in upper layers of Avon Park Formation causes interface slant to become more vertical.	Experiment successful to a certain degree. However, this conceptualization was undesirable since the hydraulic conductivities are no longer representative of the District's conceptualization. A more vertical interface is also less desirable.
	Freshwater is not flowing out of the top of the model (i.e., Suwannee) at a sufficient rate to allow saltwater to intrude.	The general head boundary (GHB) conductance term of Layer 1 is increased by a factor of four.	Chloride intrusion will be greater.	In Tampa Bay area, chlorides intrude about 3 miles in layer 6 and about half a mile in layer 10 making the interface more vertical.	Desirable intrusion effects but undesirable effect on the slope of the interface.
	Saltwater is moving vertically up through the Ocala, rather than intruding further laterally.	The vertical hydraulic conductivity of the Ocala is lowered by an order of magnitude.	Chlorides should intrude more inland with less saltwater moving upwards.	In northern part of the model domain, chlorides move seaward. In south, chlorides remain the same.	The lower vertical (Kv) hydraulic conductivity of the Ocala also reduces upward freshwater flow pushing chlorides seawards in the North. In the South, the Ocala is thick, so the confining effect is not altered by reducing Kv further.

Table 5.1 (continued)
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
1) Chloride intrusion from the Tampa Bay area to the east (landward) is too limited, particularly in the Avon Park Formation. (continued)	From previous experiment described above, it was determined that freshwater needs to exit the Avon Park Formation faster than saltwater for further intrusion top layer of the model (i.e., Suwannee) to allow saltwater intrusion.	The vertical hydraulic conductivity of the Ocala is made four times higher throughout the model domain.	Chlorides should push more inland with more freshwater escaping upwards.	Chlorides move landward throughout domain. More movement is observed in layer 6 than in layer 8. Thus, the slope on the interface becomes more vertical.	Helps with front location but not with interface slope. Higher Kv reduces confining effect of thick Ocala in south. Experiments 12 and 13 suggest non-uniform (from east to west) changes in Ocala Kv may be needed.
	Intruding seawater follows path of least resistence upwards to Tampa Bay.	Use a 1,000:1 (Kh/Kv) anisotropy ratio for Avon Park Formation to reduce its vertical conductance.	Chloride front will move more landward.	Almost no change in front location, or in simulated heads.	Uniform anisotropy reduction slows down upward movement of both salt and freshwater. A non-uniform reduction in vertical hydraulic conductivity over Tampa Bay may be needed.
	Possible chloride intrusion from bottom of model (i.e., evaporites) is ignored.	Allow chloride intrusion from bottom using a GHB condition	More chlorides in domain due to intrusion from bottom.	Chloride landward intrusion is too far especially in southern portions of the model domain.	Chloride intrusion from the bottom could help solve the problem of chlorides being to far seaward.

Table 5.1 (continued)
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
1) Chloride intrusion from the Tampa Bay area to the east (landward) is too limited, particularly in the Avon Park Formation. (continued)	Too much freshwater is coming into the model domain from upstream (i.e., northen, southern and eastern) boundaries.	Reduce transmissivity of Avon Park Formation by 30% to allow less water to enter/flow through the domain	Less freshwater entering domain allows for the saltwater to intrude more.	Chlorides move landward in Avon Park Formation.	Reduced flows help saltwater intrusion, however smaller transmissivities are not justifiable based on the field data.
2) Chloride upconing from the base of model (i.e., evaporites) is too large, once this conceptualization is included.	Conductivity of GHB on the base of the model is too high allowing excessive brine to intrude from the bottom.	Reduce GHB conductance value at bottom.	Less saltwater entering the domain from bottom will push chlorides seaward.	Chlorides are more seawards in the south, but too far seawards in Tampa Bay area in the north.	Bottom boundary GHB of constant value either underpredicts chlorides in north or overpredicts them in south. It may be necessary to assign variable GHB boundaries and/or chloride concentrations on the GHB.
	Bottom GHB instantly supplies chlorides which results in chloride concentrations being too high.	Add one more layer representing the middle confining unit (i.e., evaporites) at bottom, through which chlorides move before reaching the Avon Park Formation.	Chlorides residing within middle confining unit should now move towards Avon Park Formation thereby reducing the intrusion rates.	Chlorides do not instantly upcone into Avon Park Formation.	An extra layer for MSU is needed at the bottom to appropriately represent the transients in the chloride migration.

Table 5.1 (continued)
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
3) Chlorides are too dispersed vertically, thereby limiting lateral intrusion.	Vertical dispersivity is too large.	Apply a 4-component dispersivity formulation and reduce longitudinal vertical dispersivity.	Chloride front will be less vertically diffuse causing more intrusion in lower layers of the model.	Areal chloride contours became more closely spaced in Suwannee Limestone but are still too dispersed vertically.	Reduction in vertical dispersivities results in greater saltwater intrusion inland.
	Diffusion is spreading the chlorides.	Diffusion coefficient is set to zero.	Chloride spread should be less due to no diffusion.	Very slight effect, although helpful.	Reducing diffusion helps but only marginally.
	Dispersion is spreading the chlorides.	All dispersion coefficients are reduced.	Chloride spread should be less due to lower dispersion coefficients.	Reduced the chloride spread considerably. The slope of the interface is also improved although more improvement is needed.	Low dispersivities are needed to reduce spread of chlorides and provide a slope to the interface.
4) Boundary conditions may not be appropriate	Western boundary heads are not representative of field conditions. These heads were taken from the Southern District Model which already account for average density effects.	Heads along western boundary set to zero (previously ranged from 10 - 20 ft), increasing with depth to account for chloride density.	Conceptualization is consistent. Chlorides will move seaward due to reduction of seaward heads.	Chlorides move seaward by about 1 mile. Environmental heads drop but still high as compared to Southern District Model.	Head field is satisfactory but chlorides need to move landward especially in Tampa Bay area. Effect of this on chlorides exists, but is not very prominent.

Table 5.1 (continued)
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
4) Boundary conditions may not be appropriate (continued)	Need to test the effect of northern lateral boundary heads on the area of interest.	Variation of heads along this boundary from west to east changed.	Unknown.	No change in chloride concentrations throughout the domain, or in heads in areas of interest.	Northern lateral boundary heads insensitive to intrusion and can be used from the Southern District Model.
5) Chloride front not sloped like observed under Tampa Bay.	A vertically consistent high K region under Tampa Bay makes the chlorides sit vertically abutting it.	Remove the high K region with K of a similar order as those landward.	Deeper seawater will flow further inland as compared to shallower regions without being controlled by a "wall effect".	Chlorides move seaward due to lower conductivities in the seawater region, but the interface slant is not affected.	For the current state being simulated, the high K region under Tampa Bay is not a controlling mechanism.
6) Avon Park Formation conceptualization does not account for vertical zones of higher conductivity.	All Avon Park Formation model layers have same conductivity value as calculated from Southern District Model.	Model layers 6 and 7 conductivities increased with associated decrease in conductivity of layers 8, 9 and 10 to produce the same transmissivity values as for the Southern District Model.	Conceptualization is consistent with observations. Chloride intrusion behavior will change due to the further vertical zonation.	Chlorides at about the same location in lower layers, but moves westward in upper layers. Therefore, the interface slope is less vertical in layers 6, 7 and 8 (as needed), but becomes more vertical in the lower layers.	Chlorides need to be further landward. Also, interface slope needs to be less vertical specifically in model layers 9 and 10.

Table 5.1 (continued)
Representative Calibration Simulations for the Saltwater Intrusion Model

Statement of the Problem	Hypotheses for the Cause	Experiments Designed to test the Hypotheses	Predicted Results	Observed Results	Conclusions from Results
7) Vertical zones of higher conductivity in AP do not have the hydraulic conductivity characterized. Interface needs to be less vertical.	Southern District Model does not include this conceptualization.	Model layers 6 and 7 conductivities increased by factor of 3 from the above experiment, with reduction of conductivity of layers 8, 9 and 10 for same effective transmissivity as that of Southern District Model.	Problem 6 above made the interface less vertical, so furthering the conductivity contrast of layers 6 and 7 with layers 8, 9 and 10 should make it even less vertical.	No change in chlorides.	Conductivity contrast of high K flow zones within AP is not significant beyond what is provided in experiment 6 above.
8) Post-development heads are higher than for Southern District Model or observed cases.	Water entering from bottom GHB in addition to Southern District Model conceptualization causes higher heads.	Reduce bottom GHB conductance to allow less water in.	Less water inflow will allow for larger drawdowns during pumping.	Drawdowns are greater, but salt intrusion is not sufficient in Tampa Bay area.	Need more water inflow from bottom to maintain salts. Note that pre-development heads are also higher, than the Southern District Model, so drawdowns are not that different.
	Excess freshwater entering domain from north and east supplies wells.	Lower northern and eastern boundary heads by 10 ft.	Less freshwater entering domain will cause for larger drawdowns with pumping as well as greater intrusion of saltwater.	Drawdowns are greater, and, as desired, saltwater intrusion is more extensive in the Avon Park Formation in the Tampa Bay area, but also greater in the south which is undesirable.	Allowing less freshwater into the system from lateral boundaries helps calibrate heads and chlorides in the north but worsens chloride behavior in the south.

Table 5.2
Calibrated Transport Properties

Parameter	Value
Effective porosity	0.15
Freshwater density	1.0
Saltwater density	1.025
Storativity	$1x10^{-4}$

Formation/Unit	Longitudinal dispersivity (ft)	Transverse dispersivity (ft)	Vertical transverse dispersivity (ft)
Suwannee Limestone	100	20	10
Ocala Limestone	10	5	5
Avon Park Formation	80	15	10

Table 5.3
Calibration Statistics for Observed ROMP Well Data

Well	Elevation (ft)	Average Fraction of Seawater at ROMP Well	Simulated Post-development Fraction of Seawater	Residual (data - model)	Residual Squared (data - model)^2
ROMP 22	-416.3	1.12E-03	9.88E-12	1.12E-03	1.25E-06
	-548.7	1.07E-03	4.19E-11	1.07E-03	1.15E-06
	-686.9	1.10E-03	2.43E-10	1.10E-03	1.21E-06
	-904.5	1.03E-03	2.65E-08	1.03E-03	1.05E-06
	-1073.9	9.47E-04	5.79E-06	9.42E-04	8.87E-07
	-1126.5	1.05E-03	4.40E-04	6.12E-04	3.75E-07
	-1197.6	1.16E-03	1.08E-03	7.65E-05	5.86E-09
	-1312.4	1.07E-03	2.32E-06	1.07E-03	1.13E-06
	-1455.9	1.42E-03	3.92E-06	1.42E-03	2.01E-06
	-1598.6	4.51E-03	9.36E-04	3.57E-03	1.28E-05
	-1837.0	5.37E-01	2.73E-02	5.10E-01	2.60E-01
ROMP AB-1	-314.4	1.65E-03	1.36E-03	2.85E-04	8.14E-08
	-413.2	1.64E-03	6.24E-03	-4.60E-03	2.11E-05
	-502.6	1.39E-03	9.69E-03	-8.29E-03	6.88E-05
	-623.0	8.84E-02	1.45E-02	7.39E-02	5.47E-03
	-716.7	4.67E-01	4.66E-02	4.20E-01	1.77E-01
	-750.2	6.70E-01	8.05E-02	5.89E-01	3.47E-01
	-800.5	9.65E-01	1.59E-01	8.06E-01	6.49E-01
ROMP 39	-439.5	8.42E-04	8.37E-28	8.42E-04	7.09E-07
	-541.5	9.82E-04	4.79E-25	9.82E-04	9.65E-07
	-624.4	1.05E-03	4.40E-22	1.05E-03	1.11E-06
	-720.6	9.87E-04	5.84E-19	9.87E-04	9.74E-07
	-839.6	9.37E-04	3.50E-14	9.37E-04	8.78E-07
	-922.4	9.58E-04	1.33E-12	9.58E-04	9.18E-07
	-1055.6	9.74E-04	5.55E-11	9.74E-04	9.48E-07
	-1222.0	1.18E-03	1.54E-07	1.18E-03	1.40E-06
	-1387.3	1.21E-03	2.04E-04	1.01E-03	1.01E-06
	-1617.0	1.25E-01	8.17E-03	1.16E-01	1.36E-02
ROMP TR SA-1	-552.5	2.75E-02	6.80E-02	-4.05E-02	1.64E-03
	-685.0	3.76E-02	1.09E-01	-7.18E-02	5.16E-03
	-803.8	2.66E-02	2.22E-01	-1.95E-01	3.80E-02
	-964.4	4.52E-02	2.66E-01	-2.20E-01	4.86E-02
	-1088.8	8.49E-02	4.88E-01	-4.03E-01	1.63E-01
	-1128.5	2.29E-01	6.78E-01	-4.49E-01	2.02E-01
	-1184.2	7.16E-01	7.86E-01	-6.95E-02	4.82E-03

Table 5.3 (continued)
Calibration Statistics for Observed ROMP Well Data

Well	Elevation (ft)	Average Fraction of Seawater at ROMP Well	Simulated Post-development Fraction of Seawater	Residual (data - model)	Residual Squared (data - model)^2
ROMP 20	-522.8	4.78E-03	2.27E-02	-1.79E-02	3.21E-04
	-630.0	8.25E-03	6.55E-02	-5.73E-02	3.28E-03
	-781.2	2.30E-02	2.34E-01	-2.12E-01	4.47E-02
	-1071.5	3.94E-02	5.20E-01	-4.81E-01	2.31E-01
	-1297.3	7.17E-02	9.84E-01	-9.13E-01	8.33E-01
	-1355.5	6.54E-02	9.92E-01	-9.27E-01	8.59E-01
	-1420.6	5.18E-01	9.96E-01	-4.78E-01	2.28E-01
	-1524.7	8.82E-01	9.94E-01	-1.12E-01	1.27E-02
ROMP TR 7-2	-491.6	2.99E-03	1.22E-03	1.77E-03	3.14E-06
	-611.0	8.59E-03	5.05E-03	3.54E-03	1.25E-05
	-709.8	1.13E-02	9.77E-03	1.50E-03	2.24E-06
	-825.9	1.09E-02	1.07E-02	1.50E-04	2.24E-08
	-915.9	1.11E-02	2.11E-02	-1.01E-02	1.02E-04
	-963.7	1.79E-02	5.12E-02	-3.33E-02	1.11E-03
	-1051.4	2.62E-01	1.14E-01	1.48E-01	2.20E-02
ROMP TR 8-1	-565.3	5.32E-03	2.12E-02	-1.59E-02	2.52E-04
	-667.7	4.32E-03	3.34E-02	-2.91E-02	8.44E-04
	-773.1	5.49E-03	3.93E-02	-3.39E-02	1.15E-03
	-854.0	4.95E-03	8.07E-02	-7.57E-02	5.73E-03
	-885.4	7.17E-02	1.16E-01	-4.39E-02	1.93E-03
	-937.0	2.01E-01	2.07E-01	-6.60E-03	4.35E-05
	-1018.7	8.11E-01	6.59E-01	1.52E-01	2.31E-02
ROMP 33	-517.5	7.76E-04	1.77E-25	7.76E-04	6.03E-07
	-610.0	8.16E-04	2.22E-22	8.16E-04	6.66E-07
	-695.0	7.89E-04	1.02E-19	7.89E-04	6.23E-07
	-813.6	7.47E-04	3.64E-17	7.47E-04	5.59E-07
	-905.3	7.37E-04	1.65E-14	7.37E-04	5.43E-07
	-944.1	7.37E-04	3.28E-13	7.37E-04	5.43E-07
	-1008.8	7.16E-04	4.17E-12	7.16E-04	5.12E-07
	-1111.0	6.84E-04	2.83E-10	6.84E-04	4.68E-07
	-1238.4	8.68E-04	6.58E-07	8.68E-04	7.53E-07
	-1367.2	8.60E-04	4.58E-04	4.01E-04	1.61E-07
	-1575.2	9.10E-04	1.35E-02	-1.26E-02	1.58E-04
ROMP TR 9-2	-311.8	2.37E-03	5.83E-04	1.79E-03	3.19E-06
	-410.1	3.86E-03	2.63E-03	1.24E-03	1.53E-06
	-500.2	5.33E-03	5.11E-03	2.19E-04	4.79E-08
	-622.2	6.18E-03	8.14E-03	-1.96E-03	3.83E-06

Table 5.3 (continued)
Calibration Statistics for Observed ROMP Well Data

Well	Elevation (ft)	Average Fraction of Seawater at ROMP Well	Simulated Post-development Fraction of Seawater	Residual (data - model)	Residual Squared (data - model)^2
ROMP TR 9-2 (cont.)	-717.0	4.95E-03	2.74E-02	-2.24E-02	5.03E-04
	-750.8	1.58E-01	5.13E-02	1.07E-01	1.14E-02
	-802.4	7.01E-01	1.15E-01	5.86E-01	3.44E-01
	-884.4	9.53E-01	5.97E-01	3.56E-01	1.27E-01
	-987.2	9.72E-01	9.76E-01	-4.13E-03	1.71E-05
	-1090.0	6.47E-01	9.98E-01	-3.51E-01	1.23E-01
	-1255.1	9.36E-01	1.00E+00	-6.40E-02	4.09E-03
ROMP TR AB-3	-594.5	1.78E-03	9.61E-04	8.15E-04	6.64E-07
	-680.8	1.65E-03	3.08E-03	-1.43E-03	2.05E-06
	-718.3	1.66E-03	6.09E-03	-4.43E-03	1.96E-05
	-781.2	1.09E-02	1.90E-02	-8.07E-03	6.52E-05
	-881.9	5.22E-02	2.86E-01	-2.34E-01	5.48E-02
ROMP 49	-1203.3	9.08E-04	3.94E-04	5.14E-04	2.65E-07
	-1406.0	2.51E-01	1.42E-02	2.36E-01	5.59E-02
ROMP TR 7-4	-500.4	2.56E-03	1.37E-04	2.42E-03	5.86E-06
	-621.2	2.28E-03	7.31E-04	1.55E-03	2.39E-06
	-724.0	2.65E-03	1.97E-03	6.82E-04	4.65E-07
	-853.1	2.27E-03	2.26E-03	3.21E-06	1.03E-11
	-953.7	2.00E-03	4.84E-03	-2.84E-03	8.08E-06
	-998.7	2.04E-03	1.20E-02	-9.94E-03	9.88E-05
	-1075.8	2.37E-03	2.99E-02	-2.75E-02	7.56E-04
ROMP TR SA-3	-689.4	3.16E-03	3.56E-02	-3.24E-02	1.05E-03
	-813.7	3.83E-03	1.00E-01	-9.61E-02	9.24E-03
	-984.6	5.32E-03	1.16E-01	-1.11E-01	1.23E-02
	-1117.8	5.30E-03	2.75E-01	-2.70E-01	7.27E-02
	-1159.4	5.05E-03	5.72E-01	-5.67E-01	3.22E-01
	-1216.1	2.77E-01	7.25E-01	-4.48E-01	2.01E-01
ROMP 61	-277.8	9.11E-04	1.41E-21	9.11E-04	8.29E-07
	-923.4	7.89E-04	1.20E-09	7.89E-04	6.23E-07
ROMP TR 9-1	-326.7	1.52E-03	7.63E-03	-6.11E-03	3.73E-05
	-452.4	1.47E-03	2.15E-02	-2.00E-02	4.02E-04
ROMP 50	-506.0	7.11E-04	1.41E-05	6.96E-04	4.85E-07
	-608.7	8.42E-04	5.17E-05	7.90E-04	6.25E-07
	-732.9	9.12E-04	2.30E-04	6.82E-04	4.65E-07
	-814.5	8.33E-04	1.24E-03	-4.07E-04	1.66E-07
	-945.8	8.90E-04	8.65E-02	-8.56E-02	7.33E-03
	-1110.2	9.34E-04	3.88E-01	-3.87E-01	1.50E-01

Table 5.3 (continued)
Calibration Statistics for Observed ROMP Well Data

Well	Elevation (ft)	Average Fraction of Seawater at ROMP Well	Simulated Post-development Fraction of Seawater	Residual (data - model)	Residual Squared (data - model)^2
ROMP 50 (cont.)	-1274.1	1.20E-03	9.05E-01	-9.04E-01	8.17E-01
	-1491.4	5.44E-01	9.82E-01	-4.39E-01	1.92E-01
				Average	RMS
				-4.39E-02	0.245498591

Table 5.4
Global Mass Budget for Pre-development Conditions

Budget Term	inflow (ft^3/d)	outflow (ft^3/d)	inflow (MGD)	outflow (MGD)
Eastern fresh boundary	10628115.2	16296.6	79.50	0.12
Southern fresh boundary	2778218	3212346	20.78	24.03
Northern fresh boundary	2239468	556303	16.75	4.16
lateral salt boundary	15783043.9	17658496	118.07	132.10
drain	0	5573737.8	0.00	41.69
bottom boundary	5318106.6	2226518	39.78	16.66
top boundary	6899861.6	14403115.9	51.61	107.74
Total	43646813.3	43646813.3	326.50	326.50

Table 5.5
Global Mass Budget for Post-development December 2000 Conditions

Budget Term	Inflow (ft^3/d)	Outflow (ft^3/d)	Inflow (mgal/day)	Outflow (mgal/day)
Eastern fresh boundary	8279517.2	739059	61.94	5.53
Southern fresh boundary	4420335.7	4336057.2	33.07	32.44
Northern fresh boundary	3927792.3	303590.3	29.38	2.27
lateral salt boundary	15234670	8991555	113.96	67.26
drain	0	3201738.9	0.00	23.95
bottom boundary	9743780.6	64614.9	72.89	0.48
top boundary	13128151.8	10080930.4	98.21	75.41
well	3571827.5	29861022	26.72	223.38
storage	70.6	727578	0.00	5.44
Total	58306145.7	58306145.7	436.16	436.16

Table 6.1
Scenarios and Results of Parameter Sensitivity Analysis

Sensitivity Parameter or Boundary Condition	Multiplication / Addition Factor	Chloride Data Fit			Hydraulic Head Data Fit			
		Percentage of Calibration Targets that are Overpredicted	Normalized Concentration		Change in final heads		Difference in head	
			Avg. Error (data-model)	RMS Error (data-model)	Avg. Error (base-final)	RMS Error (base-final)	Avg. Error (L6-L2)	RMS Error (L6-L2)
Sensitivity Parameter 0 : Base Case	n/a	45.9	-4.386E-02	0.245	0.0	0.0	2.3	3.7
Sensitivity Parameter 1 :	Multiply 0.5	56.8	-8.194E-02	0.269	0.2	0.4	2.2	3.6
Porosity	Multiply 0.2	70.3	-2.136E-01	0.375	0.8	1.3	2.1	3.4
	Multiply 2	42.3	-2.707E-02	0.238	-0.1	0.2	2.3	3.7
Sensitivity Parameter 2 :	Multiply 0.5	59.5	-8.342E-02	0.251	3.6	4.4	1.6	3.2
Avon Park Formation Conductivity (Layer 6-10)	Multiply 2	40.5	-2.065E-02	0.254	-3.0	3.5	2.9	4.3
Sensitivity Parameter 3 :	Multiply 0.5	60.4	-7.658E-02	0.242	3.5	4.2	1.7	3.2
Avon Park Formation Conductivity (Layer 6-7)	Multiply 2	39.6	-2.812E-02	0.259	-2.9	3.4	2.9	4.3
Sensitivity Parameter 4 :	Multiply 0.5	44.1	-3.582E-02	0.241	-0.1	1.0	3.8	5.3
Ocala Region Leakance (Layer 3-5)	Multiply 2	49.5	-4.808E-02	0.248	0.1	0.6	1.4	2.7
Sensitivity Parameter 5 :	Multiply 0.5	45.0	-3.947E-02	0.244	0.1	0.5	2.3	3.8
Suwannee Region Conductivity (Layer 1-2)	Multiply 2	50.5	-4.928E-02	0.248	-0.3	0.6	2.2	3.6
Sensitivity Parameter 6 :	Multiply 0.5	45.0	-3.513E-02	0.237	-0.2	1.3	2.5	3.6
Top GHB conductance	Multiply 2	50.5	-5.263E-02	0.256	-0.2	1.8	1.8	4.0
Sensitivity Parameter 7 :	Multiply 0.5	44.1	-3.815E-02	0.242	-0.5	0.8	2.2	3.6
Top GHB conductance under Tampa bay	Multiply 2	50.5	-4.965E-02	0.248	0.6	1.0	2.4	3.8
Sensitivity Parameter 8 :	Add -10	55.0	-5.826E-02	0.256	0.8	1.0	2.6	3.8
Top GHB head	Add +10	39.6	-2.070E-02	0.232	-2.0	2.7	1.7	3.3

Table 6.1 (continued)
Scenarios and Results of Parameter Sensitivity Analysis

Sensitivity Parameter or Boundary Condition	Multiplication / Addition Factor	Chloride Data Fit			Hydraulic Head Data Fit			
		Percentage of Calibration	Normalized Concentration		Change in final heads		Difference in head	
		Targets that are Overpredicted	Avg. Error (data-model)	RMS Error (data-model)	Avg. Error (base-final)	RMS Error (base-final)	Avg. Error (L6-L2)	RMS Error (L6-L2)
Sensitivity Parameter 9 :	Add -10	33.3	-1.176E-02	0.247	0.7	0.8	2.2	3.6
Bottom GHB head	Add +10	63.1	-8.453E-02	0.251	-0.6	0.8	2.4	3.7
Sensitivity Parameter 10 :	Multiply 0.5	42.3	-2.816E-02	0.254	0.7	1.0	2.2	3.6
Bottom GHB conductance	Multiply 2	55.0	-6.308E-02	0.238	-1.2	1.6	2.4	3.8
Sensitivity Parameter 11 :	Add +10	47.7	-5.979E-02	0.263	-2.5	3.5	2.5	4.0
Coastal Lateral Boundary head	Add +20	50.5	-1.149E-01	0.318	-5.1	6.7	2.8	4.3
Sensitivity Parameter 12 :	Add -10	64.9	-1.107E-01	0.305	3.9	4.8	2.1	3.8
Landward Lateral Boundary head	Add +10	41.4	-5.341E-02	0.578	-2.9	4.3	2.3	3.7
Sensitivity Parameter 13 :	Multiply 5	52.3	-3.021E-02	0.256	0.0	0.3	2.3	3.7
Dispersion coefficients	Multiply 20	54.1	-2.634E-02	0.260	0.0	0.4	2.3	3.7
Sensitivity Parameter 14 :	Multiply 0	43.2	-3.531E-02	0.244	0.0	0.2	2.3	3.7
Diffusion coefficient	Multiply 5	52.3	-4.128E-02	0.241	0.0	0.1	2.3	3.7
Sensitivity Parameter 15 :	Multiply 0.1	43.2	-3.660E-02	0.248	-0.5	2.0	2.2	3.6
Avon Park Formation vertical anisotropy	Multiply 10	47.7	-4.390E-02	0.245	0.1	0.4	2.3	3.7

Table 6.1 (continued)
Scenarios and Results of Parameter Sensitivity Analysis

Sensitivity Parameter or Boundary Condition	Top Flux (MGD)		Bottom Flux (MGD)		Chloride Mass (kg)	Percent of Wells		Sensitivity Type
	Flow in	Flow out	Flow in	Flow out		>1,000 mg/l	>500 mg/l	
Sensitivity Parameter 0 : Base Case	9.82E+01	7.54E+01	7.29E+01	4.83E-01	2.20863E+11	10.74	15.11	
Sensitivity Parameter 1 :	9.84E+01	7.37E+01	7.22E+01	4.95E-01	1.12936E+11	14.05	17.86	III
Porosity	9.91E+01	6.94E+01	7.08E+01	5.33E-01	47826342636	21.42	27.12	
	9.81E+01	7.63E+01	7.32E+01	4.78E-01	4.36786E+11	9.11	13.54	
Sensitivity Parameter 2 :	1.05E+02	6.15E+01	8.12E+01	3.87E-01	2.34559E+11	14.66	20.81	III
Avon Park Formation Conductivity (Layer 6-10)	9.27E+01	9.31E+01	6.65E+01	7.90E-01	2.06053E+11	4.17	11.25	
Sensitivity Parameter 3 :	1.05E+02	6.17E+01	8.09E+01	3.89E-01	2.34095E+11	14.25	20.51	III
Avon Park Formation Conductivity (Layer 6-7)	9.28E+01	9.29E+01	6.66E+01	7.44E-01	2.06426E+11	4.83	11.65	
Sensitivity Parameter 4 :	9.90E+01	7.16E+01	7.21E+01	4.92E-01	2.16348E+11	9.52	14.45	I
Ocala Region Leakance (Layer 3-5)	9.79E+01	7.82E+01	7.34E+01	4.81E-01	2.23172E+11	11.60	15.83	
Sensitivity Parameter 5 :	9.36E+01	7.10E+01	7.34E+01	4.83E-01	2.2047E+11	11.40	15.83	I
Suwannee Region Conductivity (Layer 1-2)	1.02E+02	8.14E+01	7.21E+01	4.89E-01	2.20661E+11	10.99	14.45	
Sensitivity Parameter 6 :	5.23E+01	4.77E+01	7.40E+01	4.67E-01	2.12184E+11	10.08	14.25	II
Top GHB conductance	1.78E+02	1.15E+02	7.08E+01	5.22E-01	2.30721E+11	12.42	16.90	
Sensitivity Parameter 7 :	9.66E+01	6.63E+01	7.26E+01	4.85E-01	2.15242E+11	9.97	14.81	I
Top GHB conductance under Tampa bay	1.00E+02	8.63E+01	7.32E+01	4.84E-01	2.26944E+11	11.30	15.98	
Sensitivity Parameter 8 :	6.91E+01	9.73E+01	7.37E+01	4.79E-01	2.264E+11	12.52	17.30	III
Top GHB head	1.65E+02	2.77E+01	7.08E+01	4.93E-01	2.04739E+11	8.75	12.57	
Sensitivity Parameter 9 :	9.91E+01	7.40E+01	4.28E+01	2.90E+00	2.13647E+11	6.51	10.74	III
Bottom GHB head	9.74E+01	7.62E+01	1.05E+02	1.75E-01	2.28308E+11	15.17	22.70	
Sensitivity Parameter 10 :	9.92E+01	7.44E+01	3.87E+01	2.53E-01	2.17107E+11	7.94	13.28	II
Bottom GHB conductance	9.66E+01	7.71E+01	1.32E+02	9.26E-01	2.25564E+11	12.57	17.51	
Sensitivity Parameter 11 :	9.40E+01	9.84E+01	5.91E+01	5.13E-01	2.35311E+11	11.30	16.03	II
Coastal Lateral Boundary head	8.99E+01	1.29E+02	4.36E+01	8.41E-01	2.46999E+11	15.11	19.29	
Sensitivity Parameter 12 :	1.27E+02	5.76E+01	7.99E+01	1.88E-01	2.39063E+11	15.67	21.58	III
Landward Lateral Boundary head	7.72E+01	1.45E+02	2.16E+01	3.08E+00	2.13392E+11	2.44	5.60	

Table 6.1 (continued)
Scenarios and Results of Parameter Sensitivity Analysis

Sensitivity Parameter or Boundary Condition	Top Flux (MGD)		Bottom Flux (MGD)		Chloride Mass (kg)	Percent of Wells		Sensitivity Type
	Flow in	Flow out	Flow in	Flow out		>1,000 mg/l	>500 mg/l	
Sensitivity Parameter 13 :	9.81E+01	7.60E+01	7.39E+01	4.76E-01	2.17542E+11	9.26	15.73	I
Dispersion coefficients	9.81E+01	7.65E+01	7.48E+01	4.72E-01	2.15226E+11	9.97	18.27	
Sensitivity Parameter 14 :	9.82E+01	7.57E+01	7.30E+01	4.81E-01	2.19801E+11	9.26	13.49	I
Diffusion coefficient	9.82E+01	7.55E+01	7.32E+01	4.82E-01	2.19707E+11	11.35	16.34	
Sensitivity Parameter 15 :	9.88E+01	7.48E+01	5.95E+01	3.83E-01	2.18882E+11	9.77	14.30	I
Avon Park Formation vertical anisotropy	9.81E+01	7.56E+01	7.50E+01	5.23E-01	2.20614E+11	10.74	15.27	

Table 6.2
Scenarios and Results of Conceptual Sensitivity Analysis

Sensitivity Parameter or Boundary Condition	Percent of data points where model is high	Chloride Data fit — Normalized Concentration Error: Avg. (data-model)	Chloride Data fit — Normalized Concentration Error: RMS (data-model)
Sensitivity Parameter 0 : Base Case	45.946	-4.386E-02	0.245
Sensitivity Parameter 1 : Bottom GHB only in North-West	32.432	-7.534E-03	0.265
With higher GHB conductances	33.333	9.774E-03	0.246
Sensitivity Parameter 2 : Avon Park conductivity uniform vertically	44.144	1.641E-02	0.240

Sensitivity Parameter or Boundary Condition	Change in final heads (ft)		Difference in head (ft)		Top Flux (MGD)	
	Avg. (base-final)	RMS (base-final)	Avg. (L6-L2)	RMS (L6-L2)	Flow in	Flow out
Sensitivity Parameter 0 : Base Case	0.0	0.0	2.3	3.7	9.82E+01	7.54E+01
Sensitivity Parameter 1 : Bottom GHB only in North-West	1.4	1.9	2.1	3.5	1.00E+02	7.33E+01
With higher GHB conductances	1.3	3.0	2.6	4.0	1.03E+02	7.80E+01
Sensitivity Parameter 2 : Avon Park conductivity uniform vertically	-0.4	1.2	2.3	3.7	9.78E+01	7.20E+01

Sensitivity Parameter or Boundary Condition	Bottom Flux (MGD)		Chloride Mass (kg)	Percent of wells with Chloride	
	Flow in	Flow out		>1,000 mg/l	>500 mg/l
Sensitivity Parameter 0 : Base Case	7.29E+01	4.83E-01	2.20863E+11	10.74	15.11
Sensitivity Parameter 1 : Bottom GHB only in North-West	2.24E+01	0.00E+00	2.14566E+11	5.85	9.87
With higher GHB conductances	1.82E+02	0.00E+00	2.21148E+11	6.72	9.67
Sensitivity Parameter 2 : Avon Park conductivity uniform vertically	7.45E+01	5.31E-01	2.17959E+11	9.52	14.25

Table 7.1
Predicted Impacts of Changes in Regional Groundwater Pumpage of Chloride Concentrations in Wells Completed in the Suwannee Limestone, Ocala Limestone, and Avon Park Formation

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Number of Wells Impacted Above Threshold Concentration	1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)	Change from Current Conditions		
						# of Wells	1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)
Current	2000	500	154	15.84	22.20	0	0.00	0.00
400	2020	500	151	15.22	21.61	-3	-0.62	-0.59
600	2020	500	162	16.02	23.18	8	0.18	0.98
800	2020	500	169	16.47	23.85	15	0.63	1.65
1,000	2020	500	183	17.60	26.24	29	1.76	4.04
400	2050	500	159	15.27	21.49	5	-0.57	-0.71
600	2050	500	188	17.09	25.49	34	1.25	3.29
800	2050	500	204	18.34	27.52	50	2.5	5.32
1,000	2050	500	224	19.95	31.05	70	4.11	8.85
Current	2000	1,000	63	6.35	8.31	0	0.00	0.00
400	2020	1,000	71	7.72	10.13	8	1.37	1.82
600	2020	1,000	82	8.77	12.08	19	2.42	3.77
800	2020	1,000	91	10.14	13.98	28	3.79	5.67
1,000	2020	1,000	104	12.22	17.99	41	5.87	9.68
400	2050	1,000	79	9.18	11.83	16	2.83	3.52
600	2050	1,000	104	12.02	17.40	41	5.67	9.09
800	2050	1,000	126	14.00	20.90	63	7.65	12.59
1,000	2050	1,000	147	15.33	23.24	84	8.98	14.93

Table 7.2
Predicted Impacts of Changes in Regional Groundwater Pumpage of Chloride Concentrations in Wells Completed in the Suwannee Limestone

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Number of Wells Impacted Above Threshold Concentration	1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)	Change from Current Conditions: # of Wells	Change from Current Conditions: 1995-1999 Avg. Annual Use (mgal/day)	Change from Current Conditions: 1999 Permitted Pumping (mgal/day)
Current	2000	500	82	8.68	12.33	0	0.00	0.00
400	2020	500	82	8.75	12.40	0	0.07	0.07
600	2020	500	86	8.84	12.52	4	0.16	0.19
800	2020	500	88	8.94	12.58	6	0.26	0.25
1,000	2020	500	93	9.04	12.82	11	0.36	0.49
400	2050	500	90	8.99	12.62	8	0.31	0.29
600	2050	500	103	9.20	13.04	21	0.52	0.71
800	2050	500	107	9.41	13.38	25	0.73	1.05
1,000	2050	500	113	9.44	13.41	31	0.76	1.08
Current	2000	1,000	29	2.45	3.30	0	0.00	0.00
400	2020	1,000	32	3.32	4.48	3	0.87	1.18
600	2020	1,000	34	3.34	4.50	5	0.89	1.2
800	2020	1,000	35	3.36	4.77	6	0.91	1.47
1,000	2020	1,000	38	4.94	6.68	9	2.49	3.38
400	2050	1,000	36	4.76	6.14	7	2.31	2.84
600	2050	1,000	40	4.93	6.79	11	2.48	3.49
800	2050	1,000	50	6.32	8.84	21	3.87	5.54
1,000	2050	1,000	56	6.62	9.35	27	4.17	6.05

Table 7.3
Predicted Impacts of Changes in Regional Groundwater Pumpage of Chloride Concentrations in Wells Completed in the Ocala Limestone

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Number of Wells Impacted Above Threshold Concentration	1995-1999 Avg. Annual Use (mgal/day)	Change from Current Conditions			
					1999 Permitted Pumping (mgal/day)	# of Wells	1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)
Current	2000	500	35	1.35	2.60	0	0.00	0.00
400	2020	500	35	1.35	2.60	0	0	0
600	2020	500	35	1.35	2.60	0	0	0
800	2020	500	35	1.35	2.60	0	0	0
1,000	2020	500	35	1.35	2.60	0	0	0
400	2050	500	35	1.35	2.60	0	0	0
600	2050	500	35	1.35	2.60	0	0	0
800	2050	500	35	1.35	2.60	0	0	0
1,000	2050	500	37	1.46	3.38	2	0.11	0.78
Current	2000	1,000	15	0.57	1.54	0	0.00	0.00
400	2020	1,000	18	0.99	1.96	3	0.42	0.42
600	2020	1,000	18	0.99	1.96	3	0.42	0.42
800	2020	1,000	19	1.00	1.98	4	0.43	0.44
1,000	2020	1,000	21	1.00	1.98	6	0.43	0.44
400	2050	1,000	21	1.00	1.98	6	0.43	0.44
600	2050	1,000	24	1.06	2.13	9	0.49	0.59
800	2050	1,000	25	1.06	2.13	10	0.49	0.59
1,000	2050	1,000	29	1.12	2.22	14	0.55	0.68

Table 7.4
Predicted Impacts of Changes in Regional Groundwater Pumpage of Chloride Concentrations in Wells Completed Wells in the Avon Park Formation

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Number of Wells Impacted Above Threshold Concentration	Change from Current Conditions				
				1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)	# of Wells	1995-1999 Avg. Annual Use (mgal/day)	1999 Permitted Pumping (mgal/day)
Current	2000	500	37	5.81	7.26	0	0.00	0.00
400	2020	500	34	5.12	6.61	-3	-0.69	-0.65
600	2020	500	41	5.84	8.06	4	0.03	0.8
800	2020	500	46	6.18	8.67	9	0.37	1.41
1,000	2020	500	55	7.22	10.82	18	1.41	3.56
400	2050	500	34	4.94	6.26	-3	-0.87	-1
600	2050	500	50	6.55	9.85	13	0.74	2.59
800	2050	500	62	7.58	11.54	25	1.77	4.28
1,000	2050	500	74	9.05	14.26	37	3.24	7
Current	2000	1,000	19	3.33	3.47	0	0.00	0.00
400	2020	1,000	21	3.42	3.69	2	0.09	0.22
600	2020	1,000	30	4.45	5.62	11	1.12	2.15
800	2020	1,000	37	5.79	7.23	18	2.46	3.76
1,000	2020	1,000	45	6.29	9.33	26	2.96	5.86
400	2050	1,000	22	3.43	3.71	3	0.1	0.24
600	2050	1,000	40	6.03	8.49	21	2.7	5.02
800	2050	1,000	51	6.61	9.94	32	3.28	6.47
1,000	2050	1,000	62	7.59	11.67	43	4.26	8.2

Table 7.5
Impacts Predicted by Sensitivity Analysis of Wells Completed in the Suwannee Limestone, Ocala Limestone, and Avon Park Formation[1]

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Base Case Number of Wells Impacted	Sensitivity Change from Base Case (# of Wells)					
				#1 (Porosity)		#9 (Bottom GHB Head)		#12 (Landward Lateral Heads)	
				X 0.2	X 2.0	Add -10	Add 10	Add -10	Add 10
Current	2000	500	154	206	-20	-44	160	130	-108
400	2020	500	151	262	-19	-43	175	144	-104
600	2020	500	162	298	-24	-47	176	149	-113
800	2020	500	169	359	-26	-47	180	155	-113
1,000	2020	500	183	434	-39	-56	176	155	-115
400	2050	500	159	409	-27	-51	173	149	-111
600	2050	500	188	483	-43	-59	170	160	-126
800	2050	500	204	579	-51	-53	181	182	-123
1,000	2050	500	224	666	-58	-58	187	193	-128
Current	2000	1,000	63	194	-8	-17	93	98	-44
400	2020	1,000	71	228	-14	-25	89	101	-53
600	2020	1,000	82	273	-22	-31	94	97	-59
800	2020	1,000	91	333	-30	-31	92	101	-65
1,000	2020	1,000	104	406	-40	-43	90	101	-75
400	2050	1,000	79	404	-18	-31	91	106	-59
600	2050	1,000	104	487	-39	-39	92	103	-77
800	2050	1,000	126	555	-46	-46	89	114	-87
1,000	2050	1,000	147	674	-56	-49	89	110	-93

[1] Note: For each sensitivity simulation, the total number of wells that are predicted to be impacted by chlorides above the 500 or 1,000 mg/l thresholds is the sum of the wells that are affected during the basecase simulation and the increase/decrease in the number of affected wells caused by perturbing the model parameter during the sensitivity run.

Table 7.6
Impacts Predicted by Sensitivity Analysis of Wells Completed in the Suwannee Limestone[1]

Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Base Case Number of Wells Impacted	Sensitivity Change from Base Case (# of Wells)					
				#1 (Porosity)		#9 (Bottom GHB Head)		#12 (Landward Lateral Heads)	
				X 0.2	X 2.0	Add -10	Add 10	Add -10	Add 10
Current	2000	500	82	102	-11	-20	111	90	-64
400	2020	500	82	141	-10	-20	123	96	-64
600	2020	500	86	150	-14	-24	120	101	-67
800	2020	500	88	177	-16	-24	124	103	-69
1,000	2020	500	93	203	-21	-28	126	105	-72
400	2050	500	90	256	-17	-27	119	99	-71
600	2050	500	103	283	-29	-36	117	102	-79
800	2050	500	107	316	-31	-31	120	115	-77
1,000	2050	500	113	347	-31	-37	120	120	-80
Current	2000	1,000	29	78	-4	-5	52	45	-26
400	2020	1,000	32	117	-6	-8	55	50	-29
600	2020	1,000	34	131	-7	-10	58	52	-31
800	2020	1,000	35	155	-9	-11	57	51	-32
1,000	2020	1,000	38	186	-11	-13	55	51	-34
400	2050	1,000	36	253	-8	-12	56	50	-32
600	2050	1,000	40	290	-11	-15	57	51	-36
800	2050	1,000	50	308	-18	-21	54	53	-46
1,000	2050	1,000	56	353	-22	-25	56	52	-51

[1] Note: For each sensitivity simulation, the total number of wells that are predicted to be impacted by chlorides above the 500 or 1,000 mg/l thresholds is the sum of the wells that are affected during the basecase simulation and the increase/decrease in the number of affected wells caused by perturbing the model parameter during the sensitivity run.

Table 7.7
Impacts Predicted by Sensitivity Analysis of Wells Completed in the Ocala Limestone[1]

Regional Pumping (Mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Base Case Number of Wells Impacted	Sensitivity Change from Base Case (# of Wells) #1 (Porosity) X 0.2	#1 (Porosity) X 2.0	#9 (Bottom GHB Head) Add -10	#9 (Bottom GHB Head) Add 10	#12 (Landward Lateral Heads) Add -10	#12 (Landward Lateral Heads) Add 10
Current	2000	500	35	40	0	-1	25	19	-24
400	2020	500	35	67	0	-1	26	22	-24
600	2020	500	35	68	0	-1	28	23	-24
800	2020	500	35	75	0	-1	29	23	-24
1,000	2020	500	35	85	0	-1	29	24	-23
400	2050	500	35	94	0	-1	28	22	-24
600	2050	500	35	110	0	-1	31	24	-23
800	2050	500	35	124	0	-1	36	27	-23
1,000	2050	500	37	133	-2	-3	38	30	-24
Current	2000	1,000	15	41	0	-1	12	22	-11
400	2020	1,000	18	54	-3	-4	10	21	-14
600	2020	1,000	18	58	-3	-4	12	21	-13
800	2020	1,000	19	66	-3	-3	13	24	-14
1,000	2020	1,000	21	77	-5	-5	13	24	-16
400	2050	1,000	21	95	-5	-5	12	24	-16
600	2050	1,000	24	102	-8	-7	13	21	-19
800	2050	1,000	25	108	-7	-6	13	21	-19
1,000	2050	1,000	29	131	-11	-9	12	17	-21

[1] Note: For each sensitivity simulation, the total number of wells that are predicted to be impacted by chlorides above the 500 or 1,000 mg/l thresholds is the sum of the wells that are affected during the basecase simulation and the increase/decrease in the number of affected wells caused by perturbing the model parameter during the sensitivity run.

Table 7.8
Impacts Predicted by Sensitivity Analysis of Wells Completed in the Avon Park Formation[1]

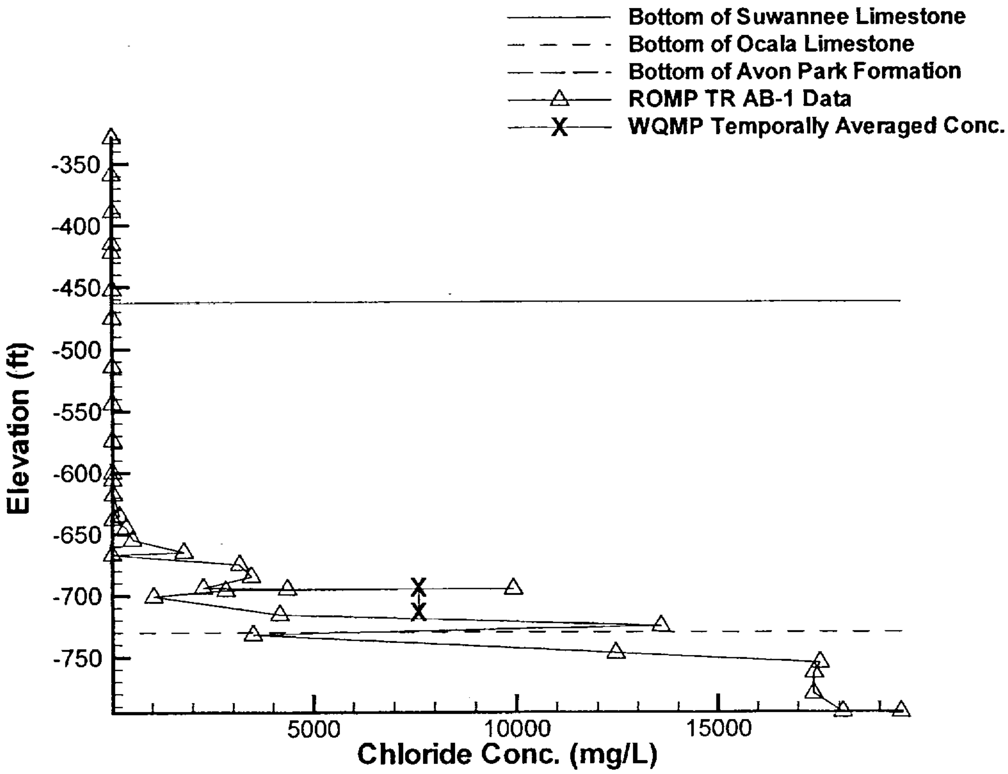
Regional Pumping (mgal/day)	Year	Chloride Concentration Threshold (mg/L)	Base Case Number of Wells Impacted	Sensitivity Change from Base Case (# of Wells)					
				#1 (Porosity)		#9 (Bottom GHB Head)		#12 (Landward Lateral Heads)	
				X 0.2	X 2.0	Add -10	Add 10	Add -10	Add 10
Current	2000	500	37	64	-9	-23	24	21	-20
400	2020	500	34	54	-9	-22	26	26	-16
600	2020	500	41	80	-10	-22	28	25	-22
800	2020	500	46	107	-10	-22	27	29	-20
1,000	2020	500	55	146	-18	-27	21	26	-20
400	2050	500	34	59	-10	-23	26	28	-16
600	2050	500	50	90	-14	-22	22	34	-24
800	2050	500	62	139	-20	-21	25	40	-23
1,000	2050	500	74	186	-25	-18	29	43	-24
Current	2000	1,000	19	75	-4	-11	29	31	-7
400	2020	1,000	21	57	-5	-13	24	30	-10
600	2020	1,000	30	84	-12	-17	24	24	-15
800	2020	1,000	37	112	-18	-17	22	26	-19
1,000	2020	1,000	45	143	-24	-25	22	26	-25
400	2050	1,000	22	56	-5	-14	23	32	-11
600	2050	1,000	40	95	-20	-17	22	31	-22
800	2050	1,000	51	139	-21	-19	22	40	-22
1,000	2050	1,000	62	190	-23	-15	21	41	-21

[1] Note: For each sensitivity simulation, the total number of wells that are predicted to be impacted by chlorides above the 500 or 1,000 mg/l thresholds is the sum of the wells that are affected during the basecase simulation and the increase/decrease in the number of affected wells caused by perturbing the model parameter during the sensitivity run.

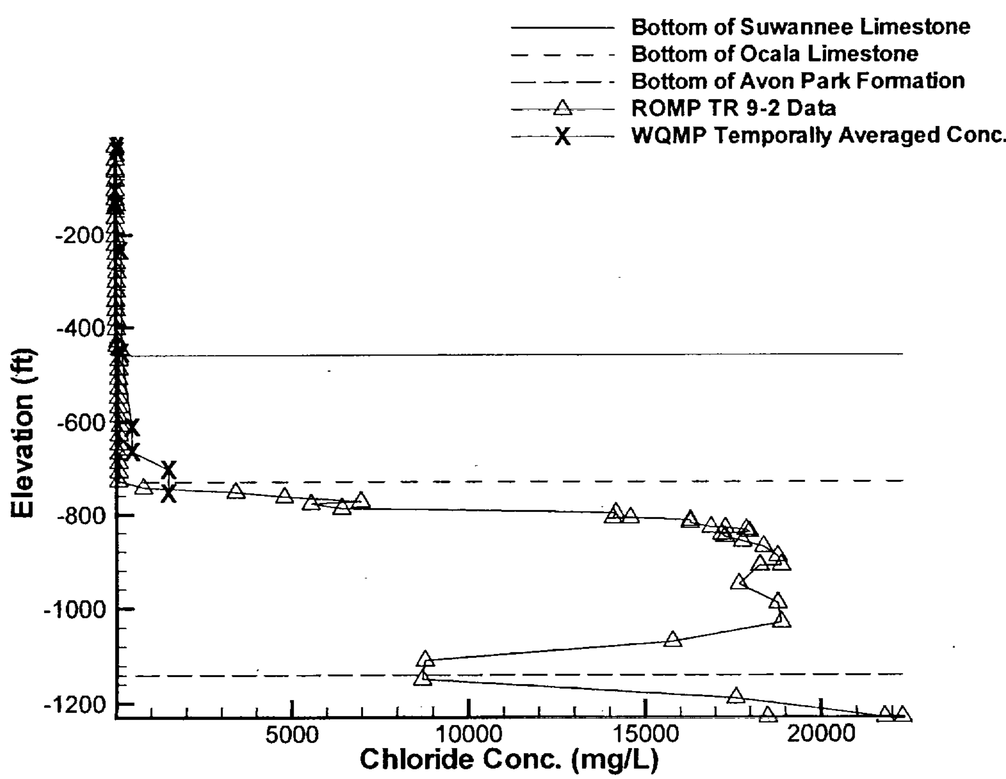
APPENDIX A

MEASURED VARIATION OF CHLORIDES WITH DEPTH FOR THE ROMP WELLS

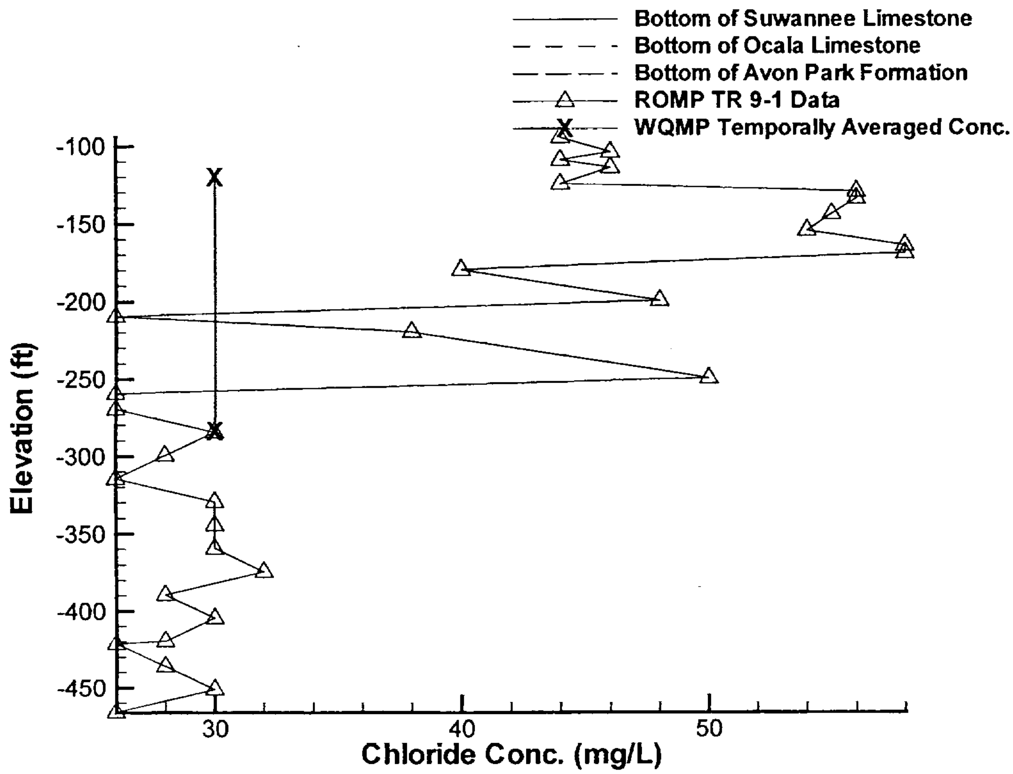
ROMP TR AB-1



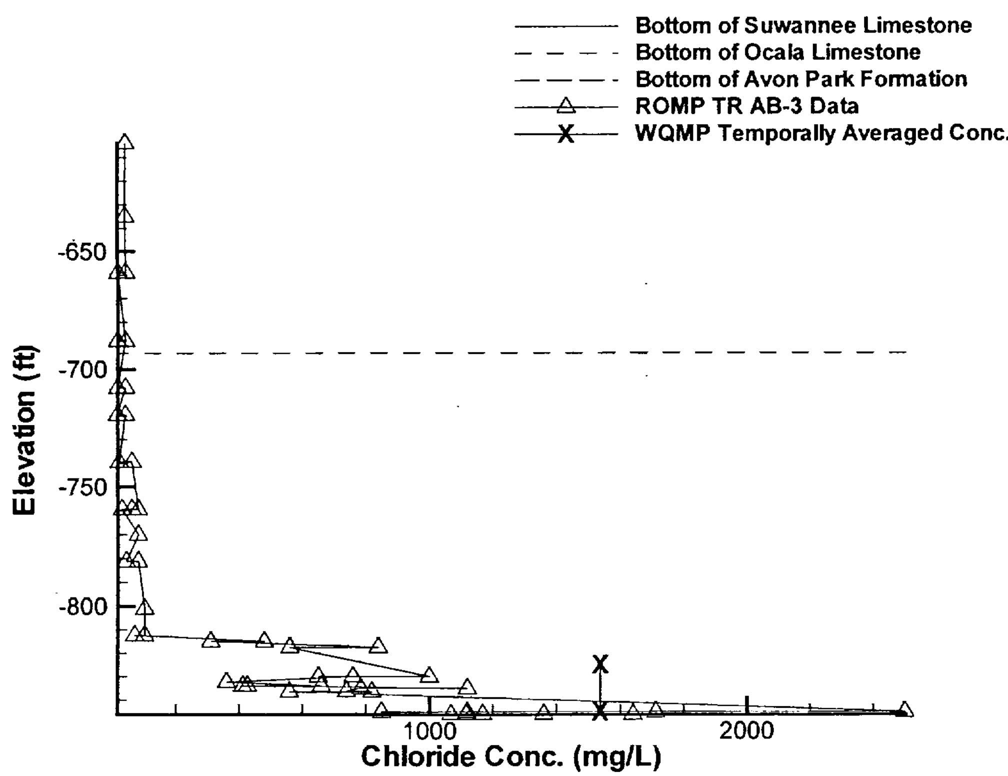
ROMP TR 9-2



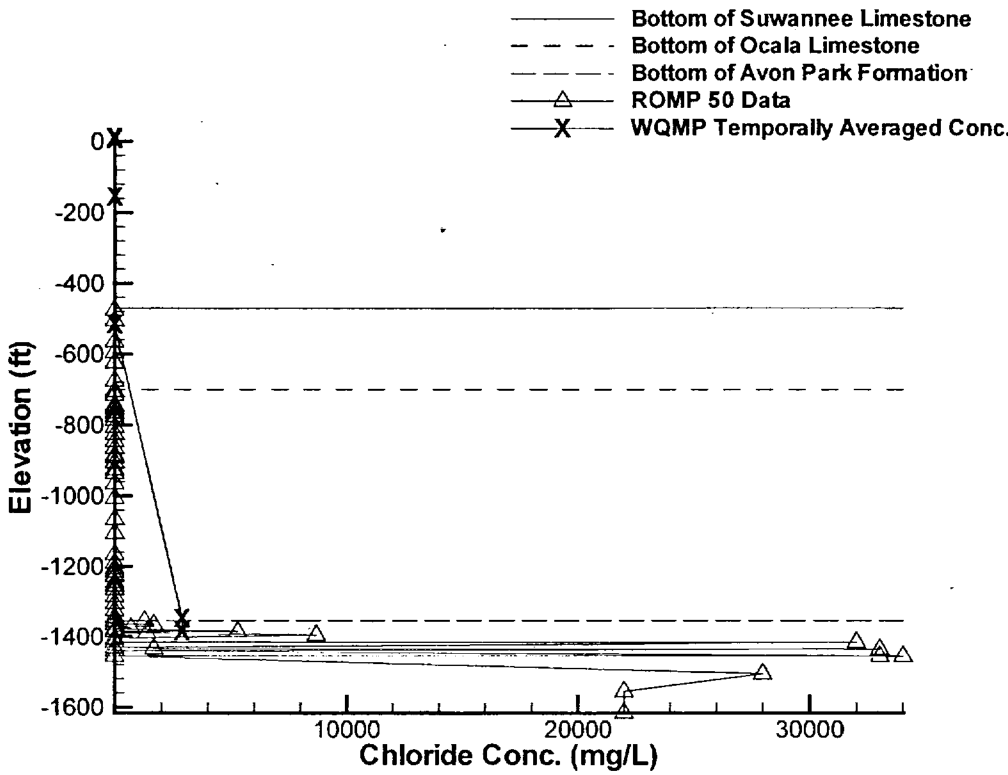
ROMP TR 9-1



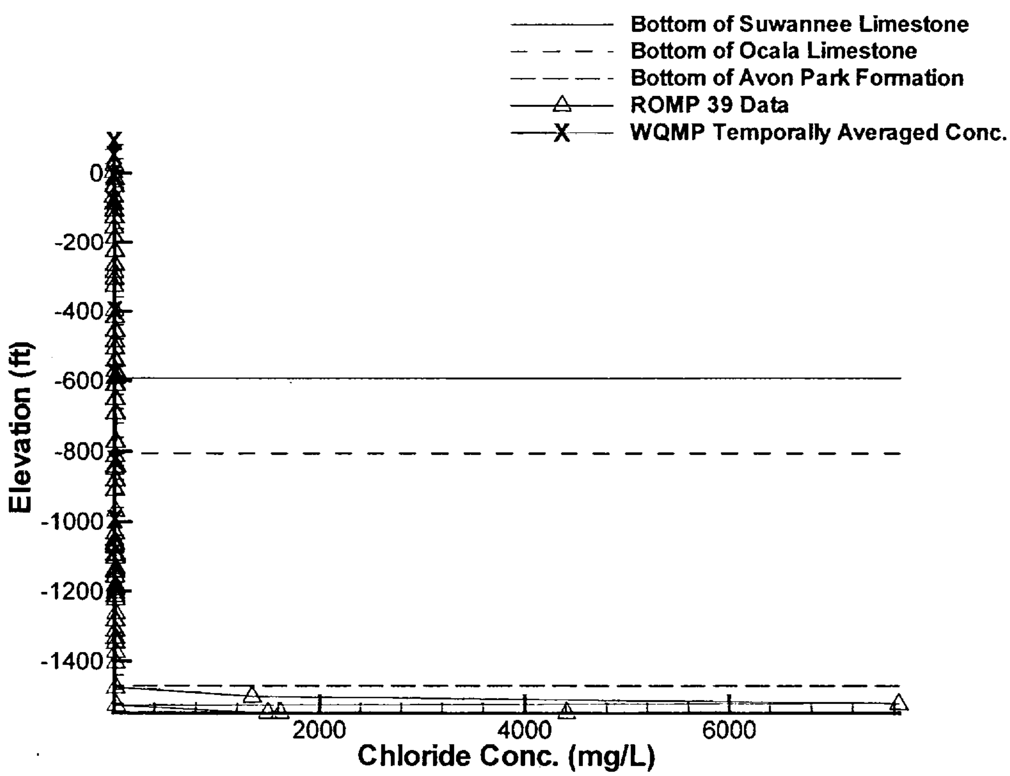
ROMP TR AB-3



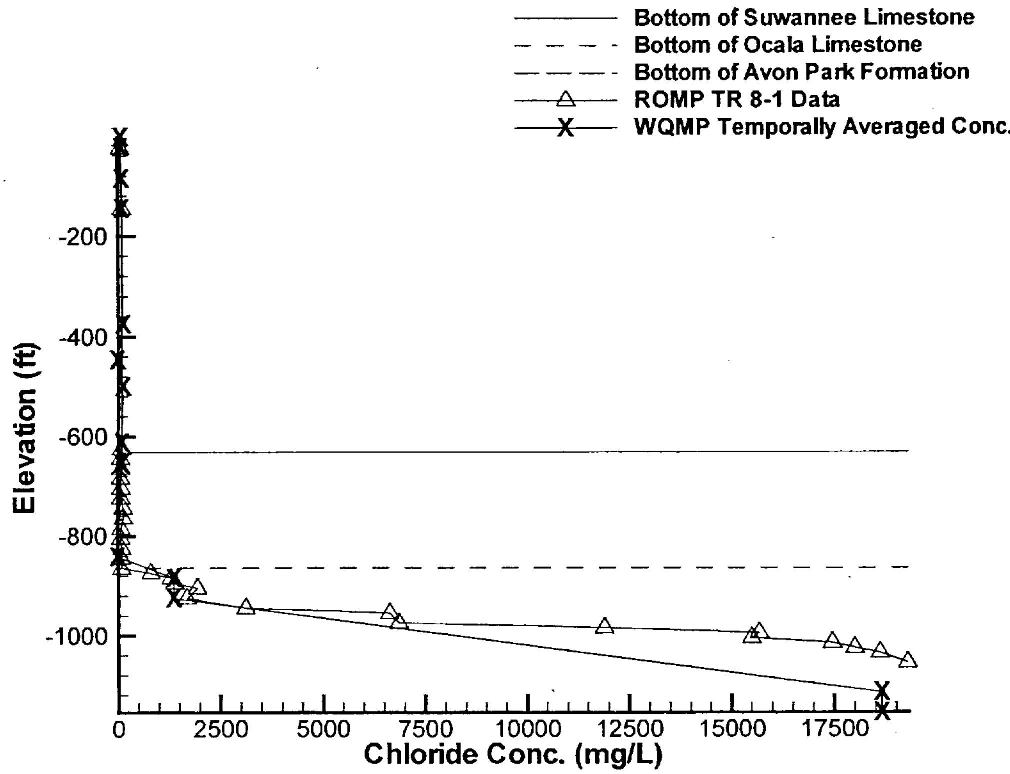
ROMP 50



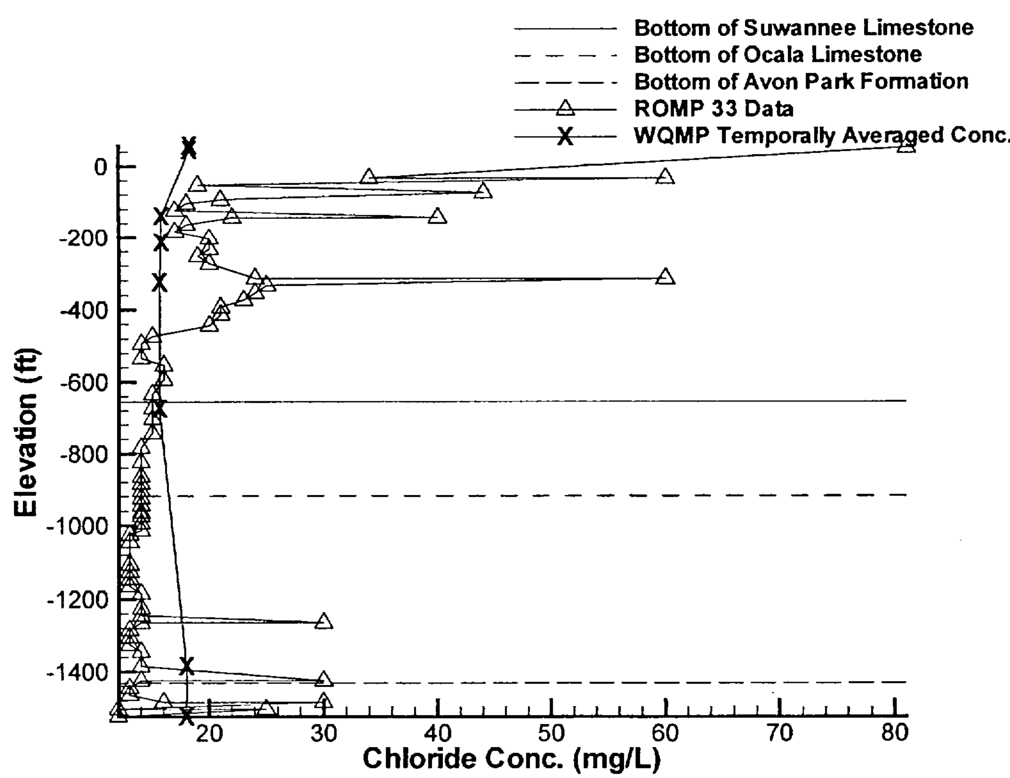
ROMP 39



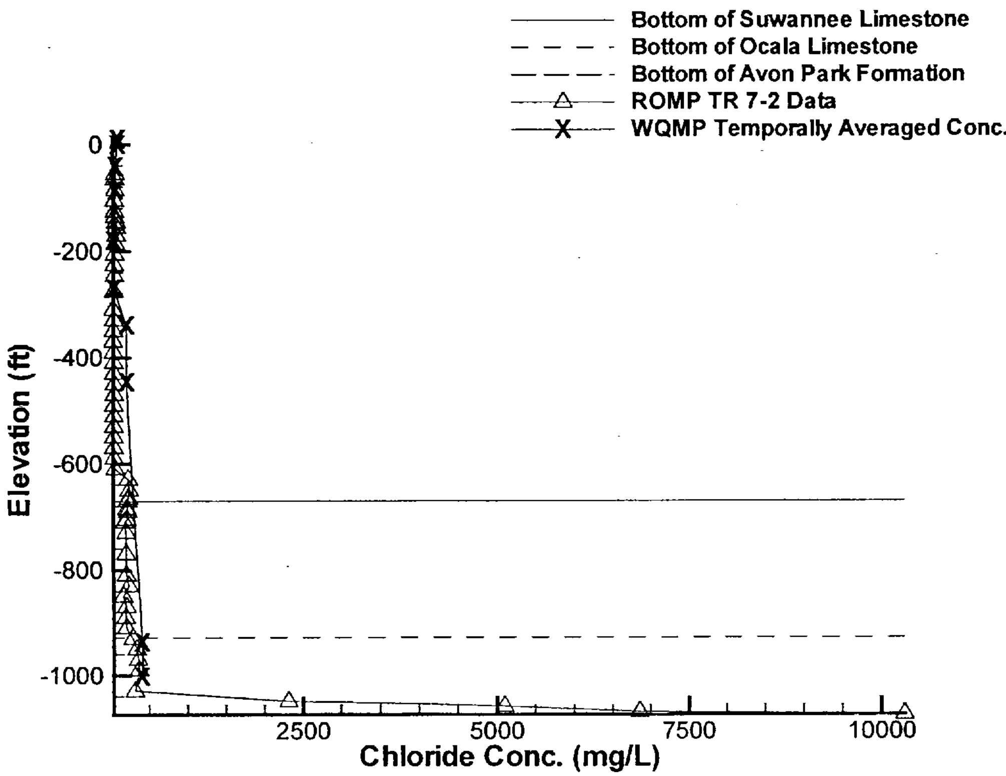
ROMP TR 8-1



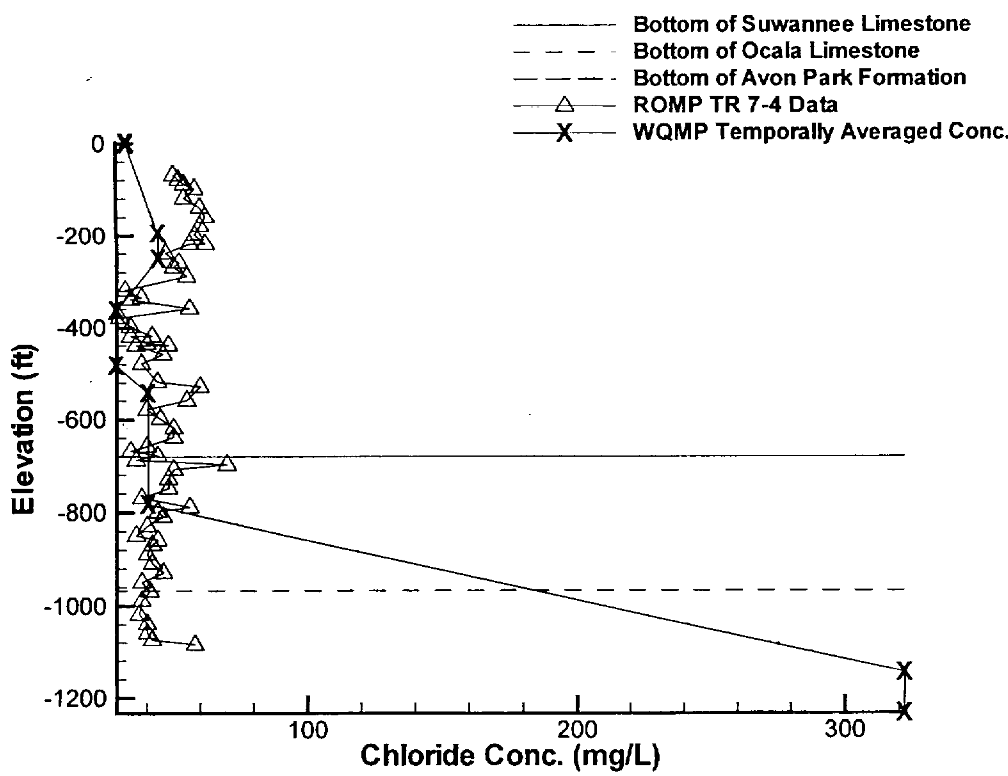
ROMP 33



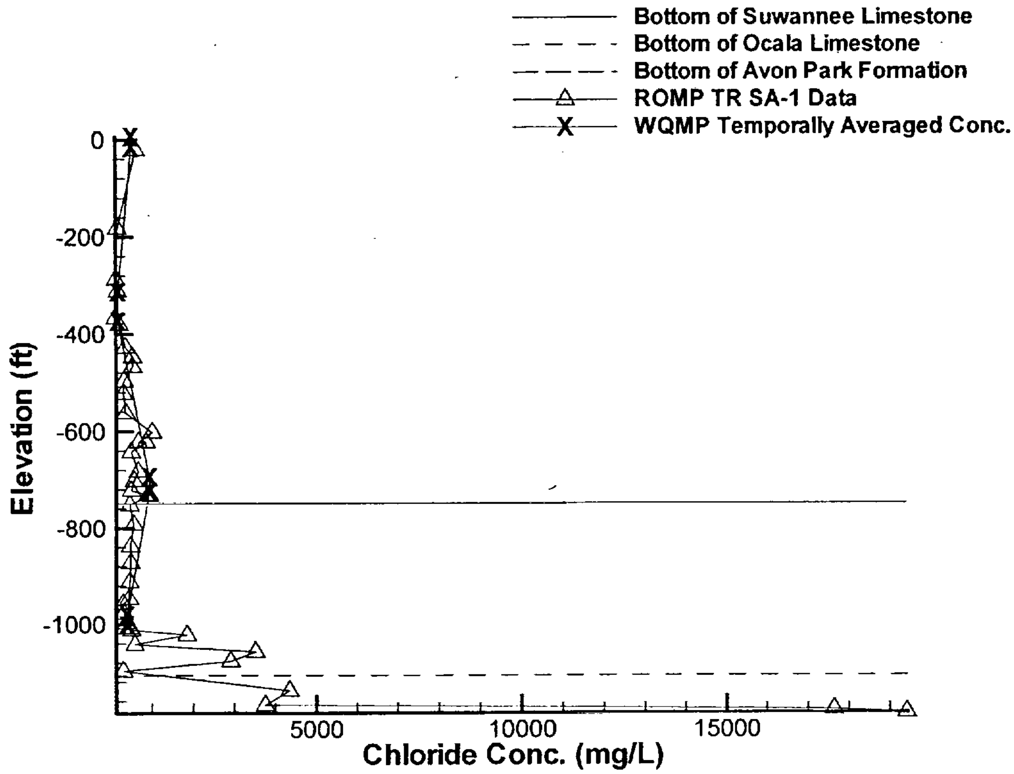
ROMP TR 7-2



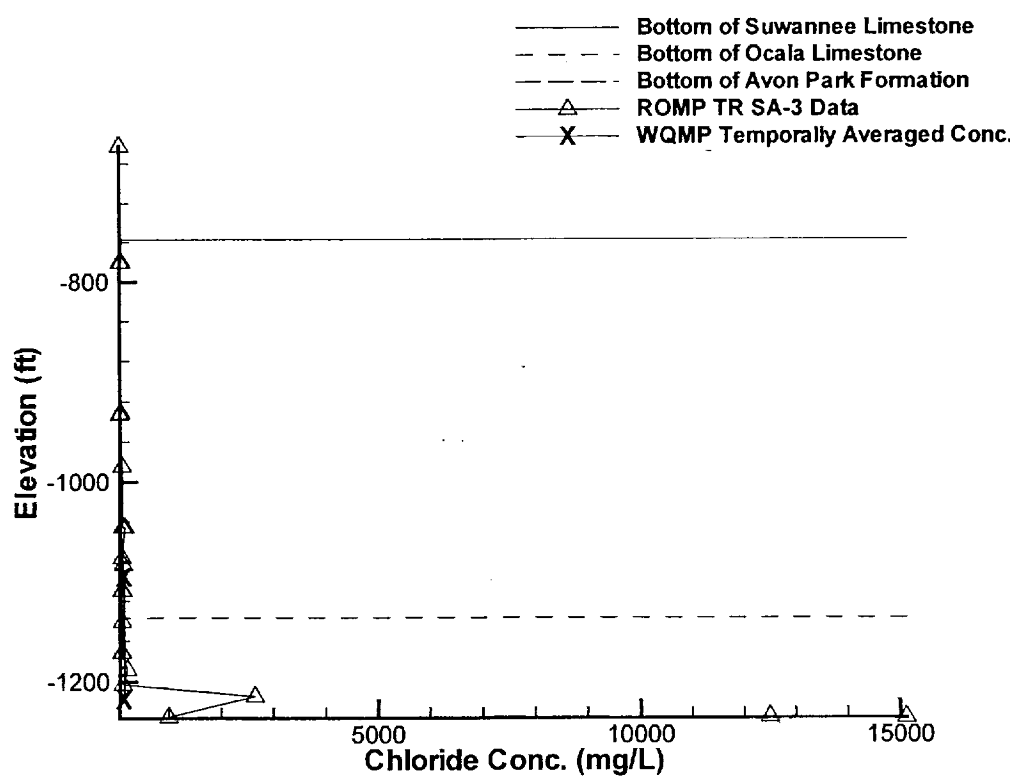
ROMP TR 7-4



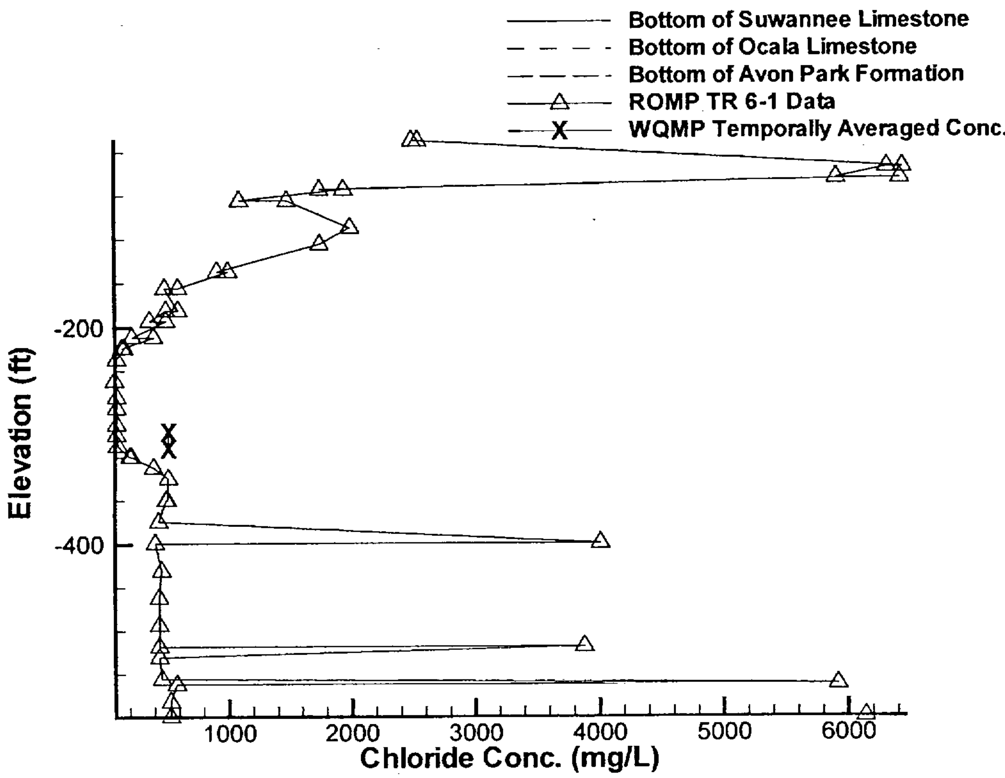
ROMP TR SA-1



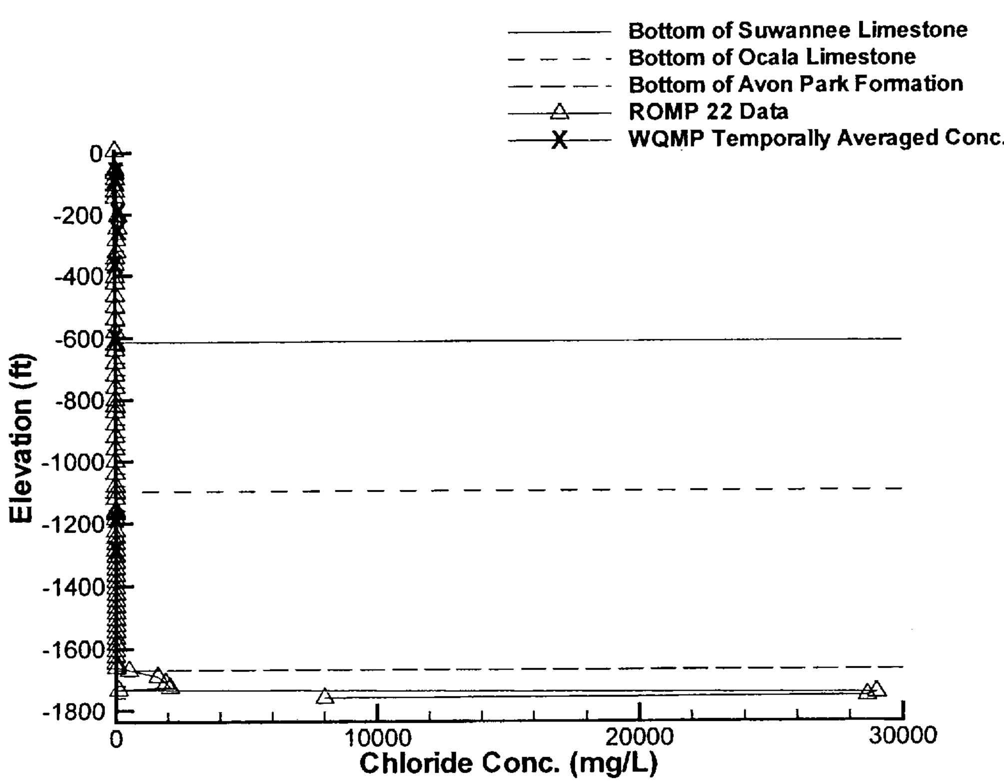
ROMP TR SA-3



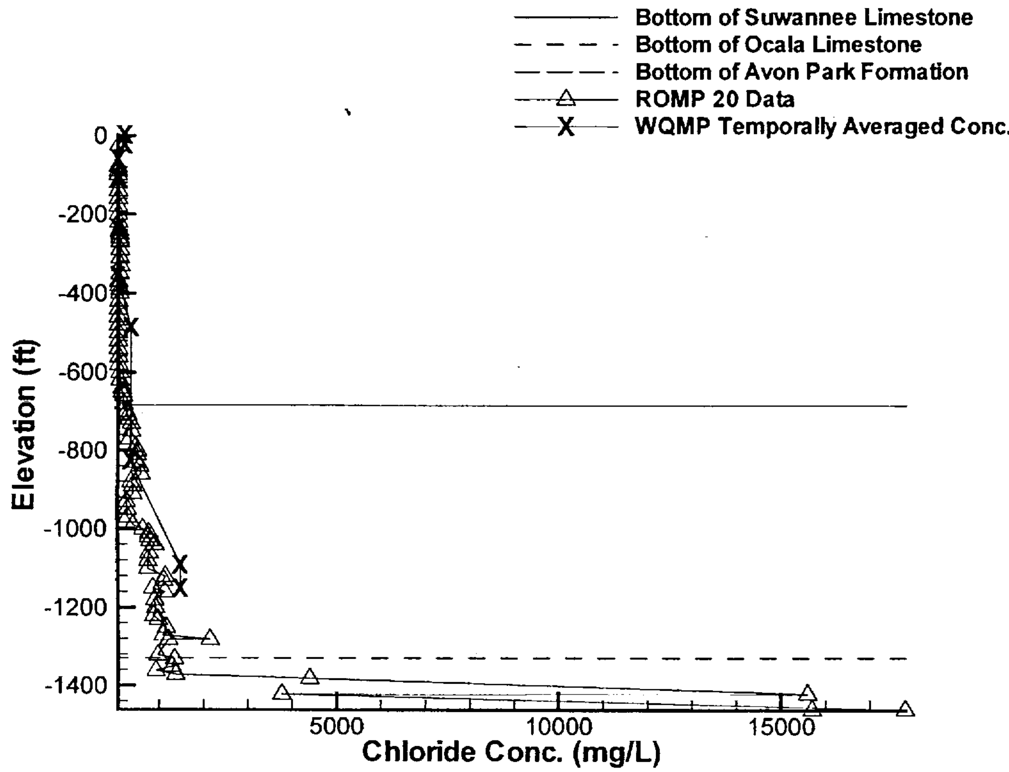
ROMP TR 6-1



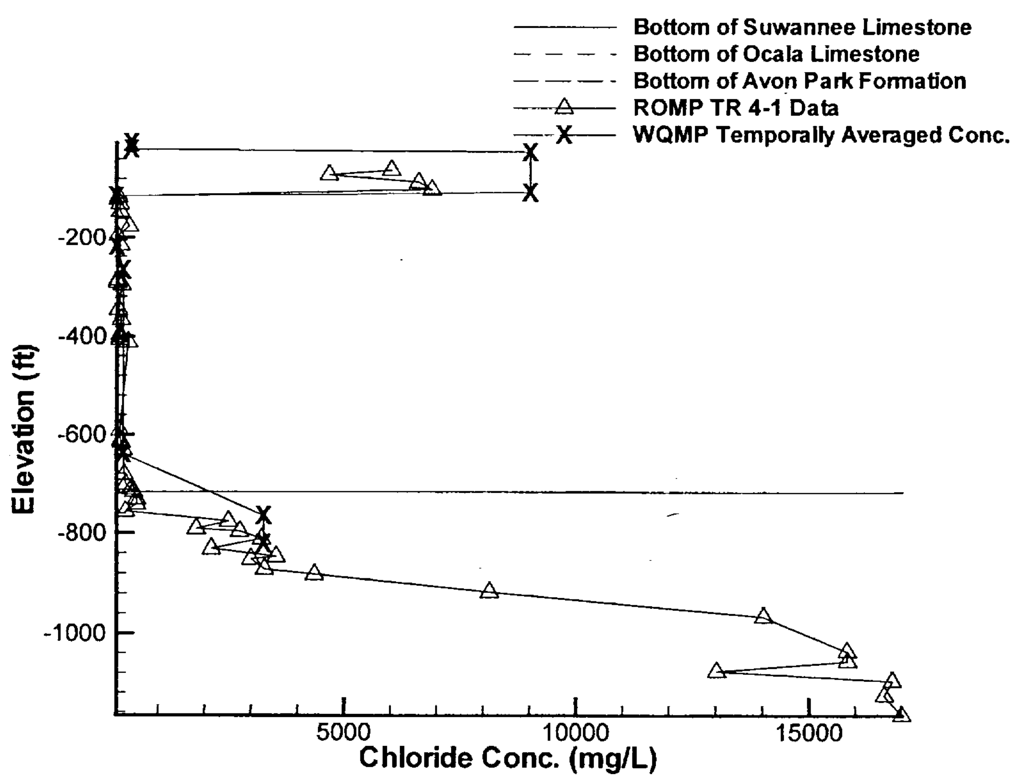
ROMP 22



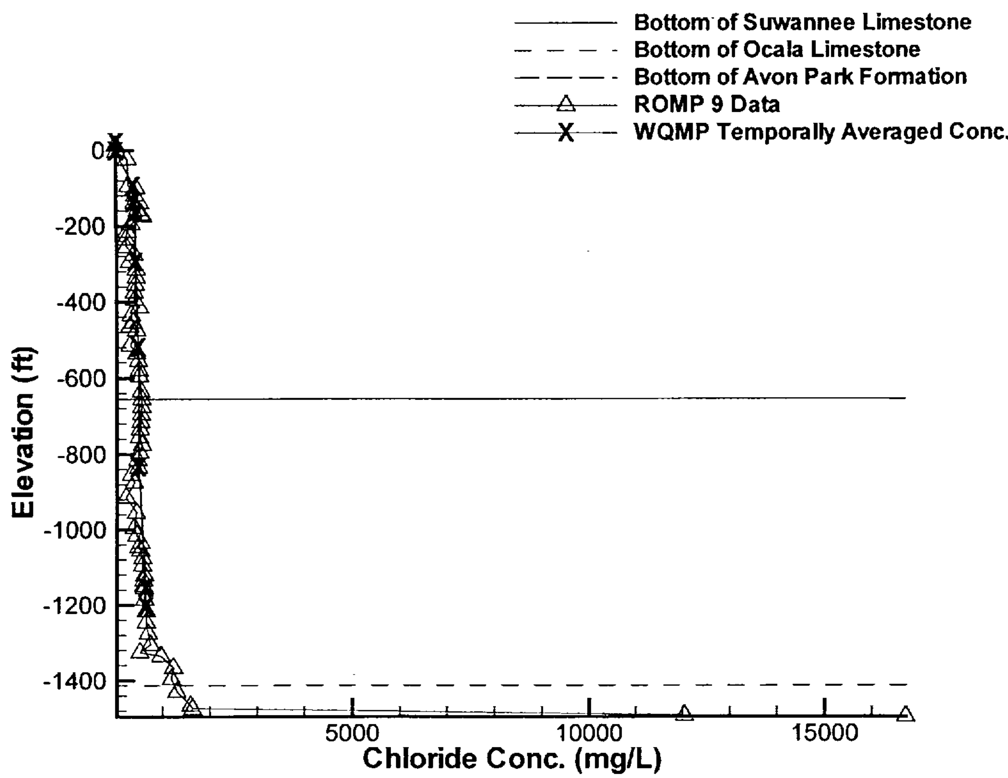
ROMP 20



ROMP TR 4-1



ROMP 9

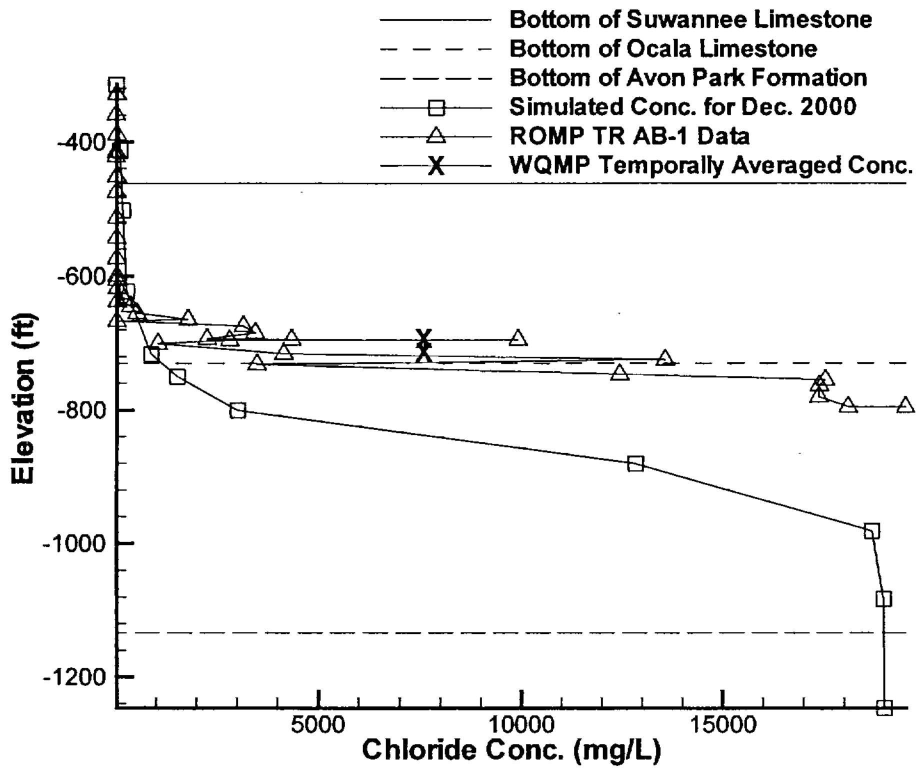


Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
ROMP 9 Data
WQMP Temporally Averaged Conc.
0
-200
-400
-600
-800
-1000
-1200
-1400
Elevation (ft)
5000
10000
15000
Chloride Conc. (mg/L)

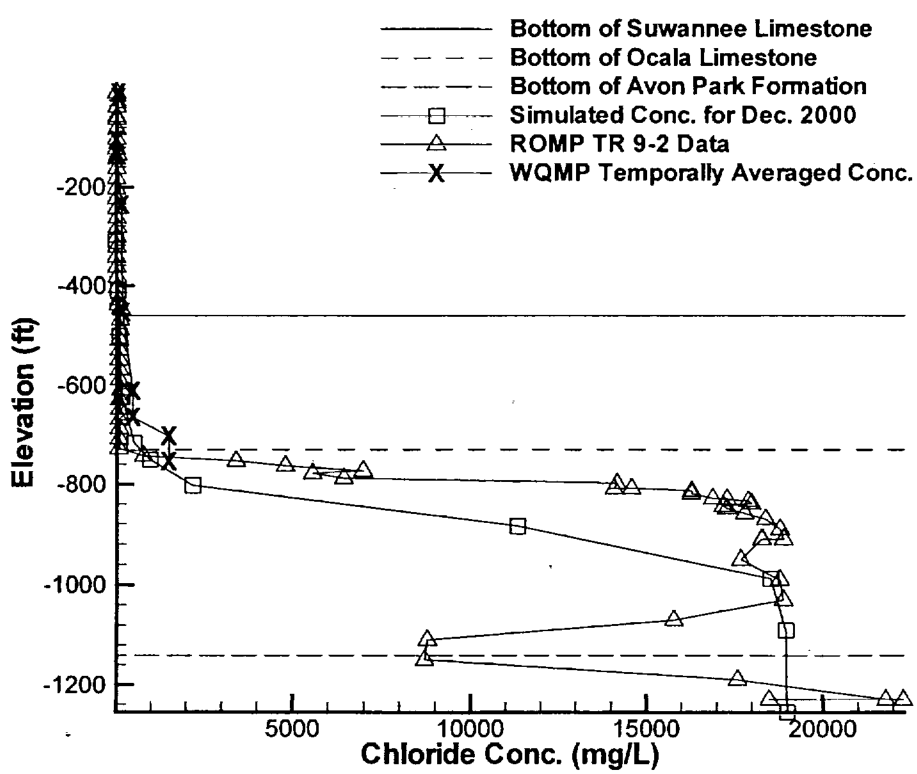
APPENDIX B

SIMULATED VARIATION OF CHLORIDES WITH DEPTH COMPARED WITH MEASURED VALUES FOR THE ROMP WELLS

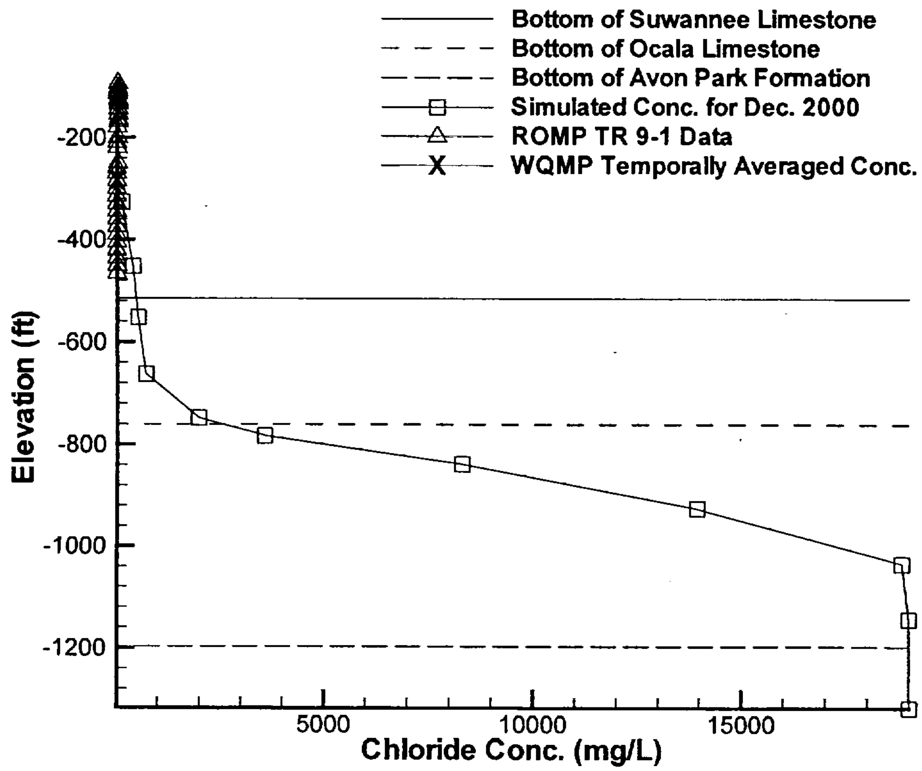
ROMP TR AB-1



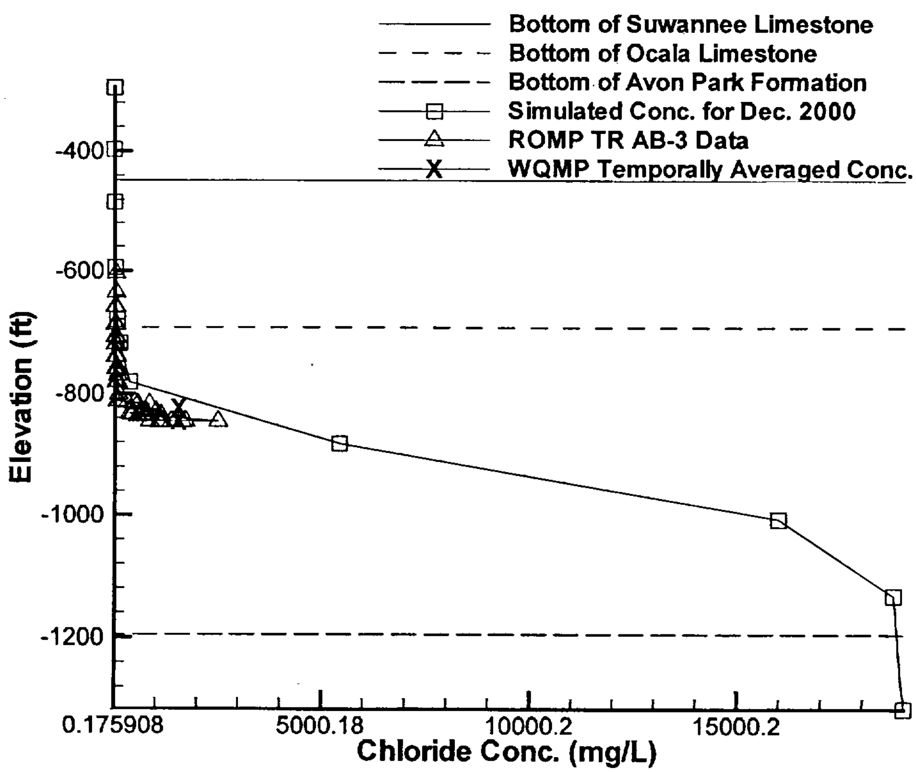
ROMP TR 9-2

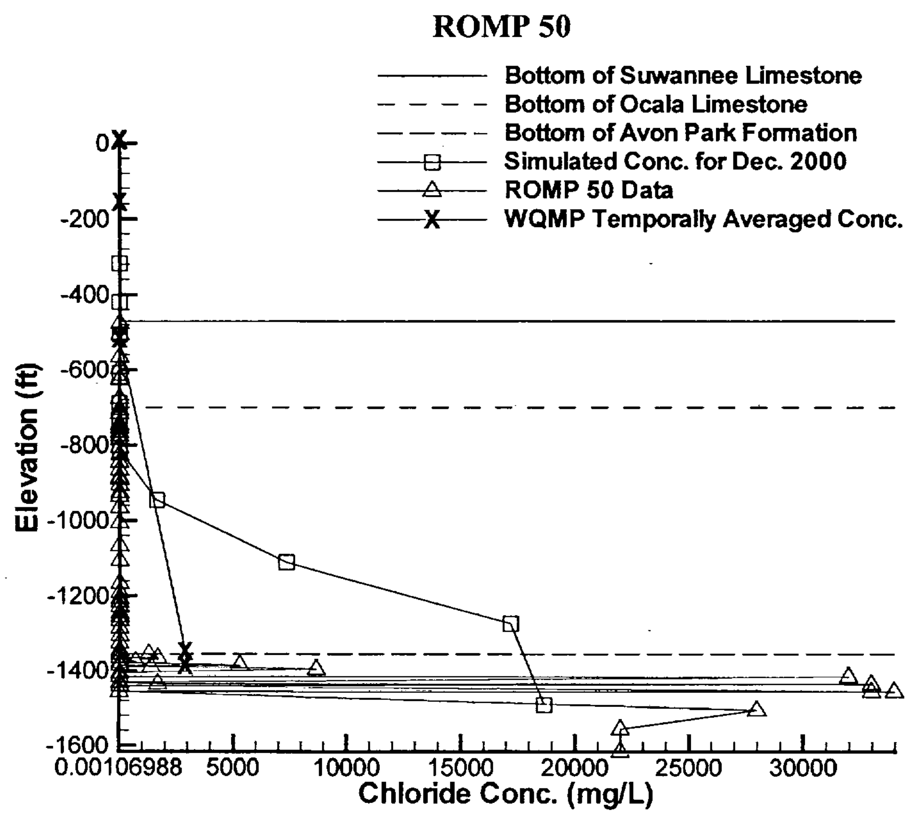


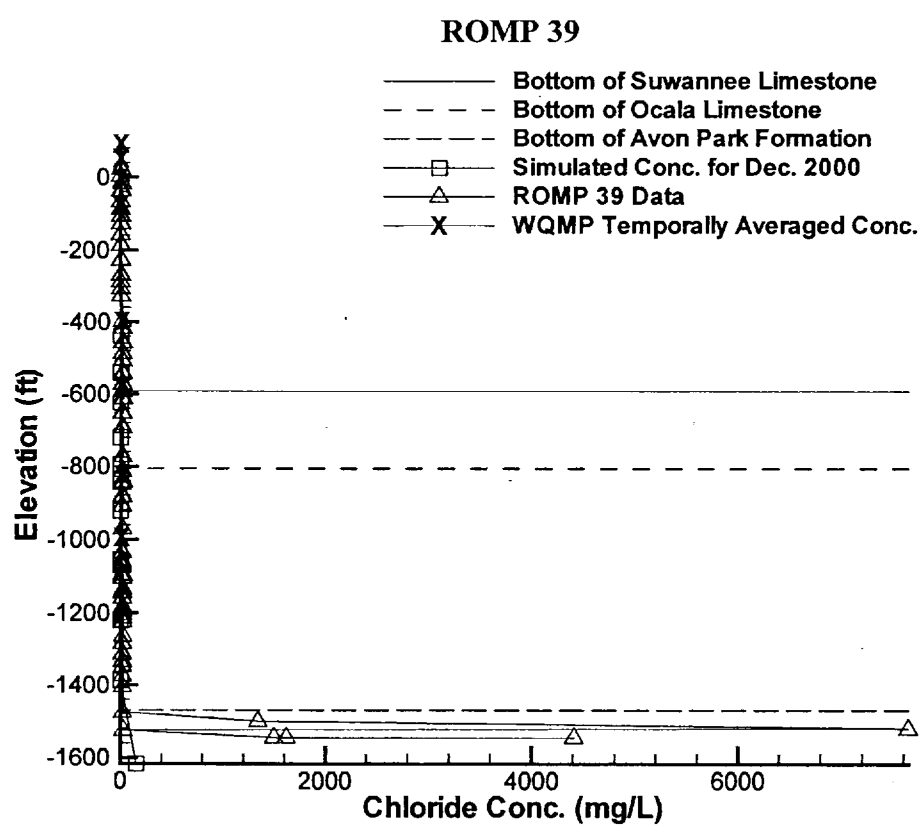
ROMP TR 9-1



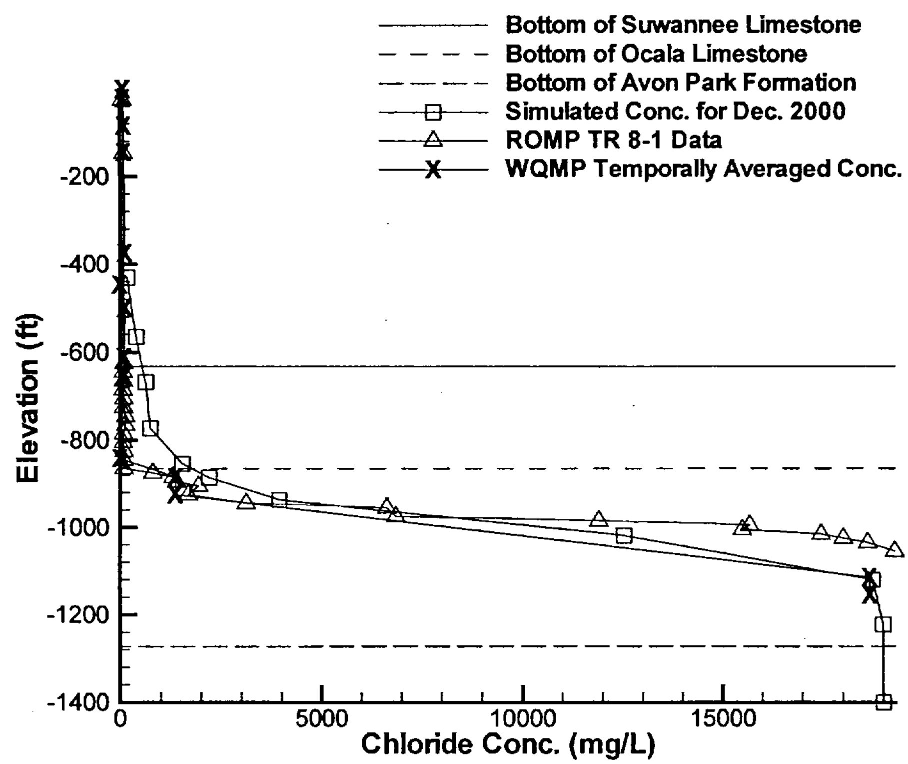
ROMP TR AB-3



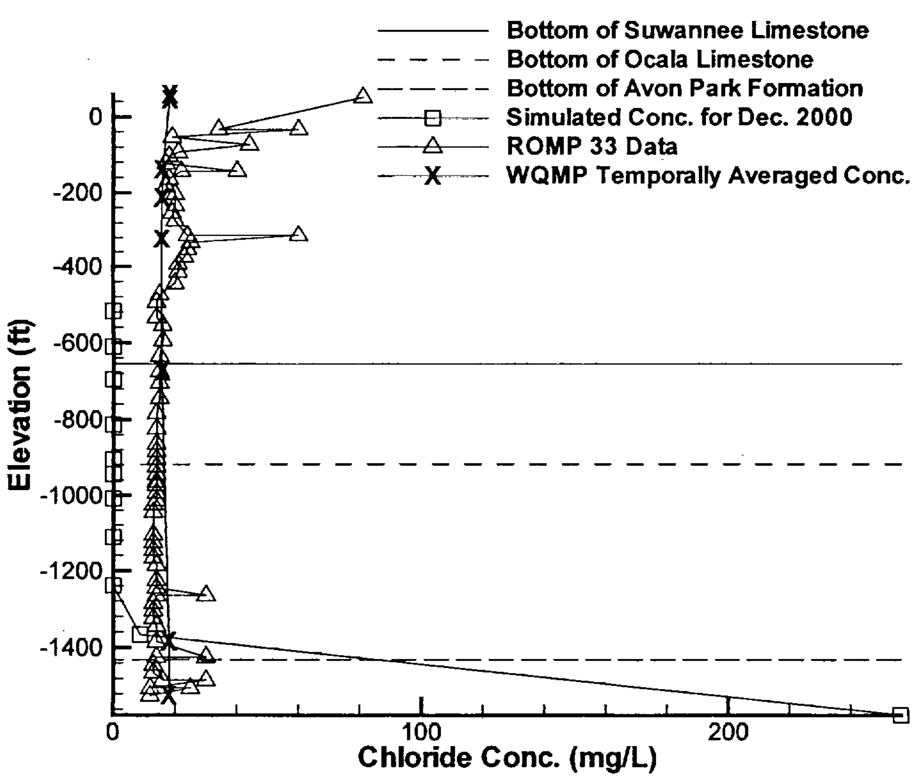

ROMP 50
Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
Simulated Conc. for Dec. 2000
ROMP 50 Data
WQMP Temporally Averaged Conc.
Elevation (ft)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0.00106988
5000
10000
15000
20000
25000
30000
Chloride Conc. (mg/L)


ROMP 39
Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
Simulated Conc. for Dec. 2000
ROMP 39 Data
WQMP Temporally Averaged Conc.
Elevation (ft)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0
2000
4000
6000
Chloride Conc. (mg/L)

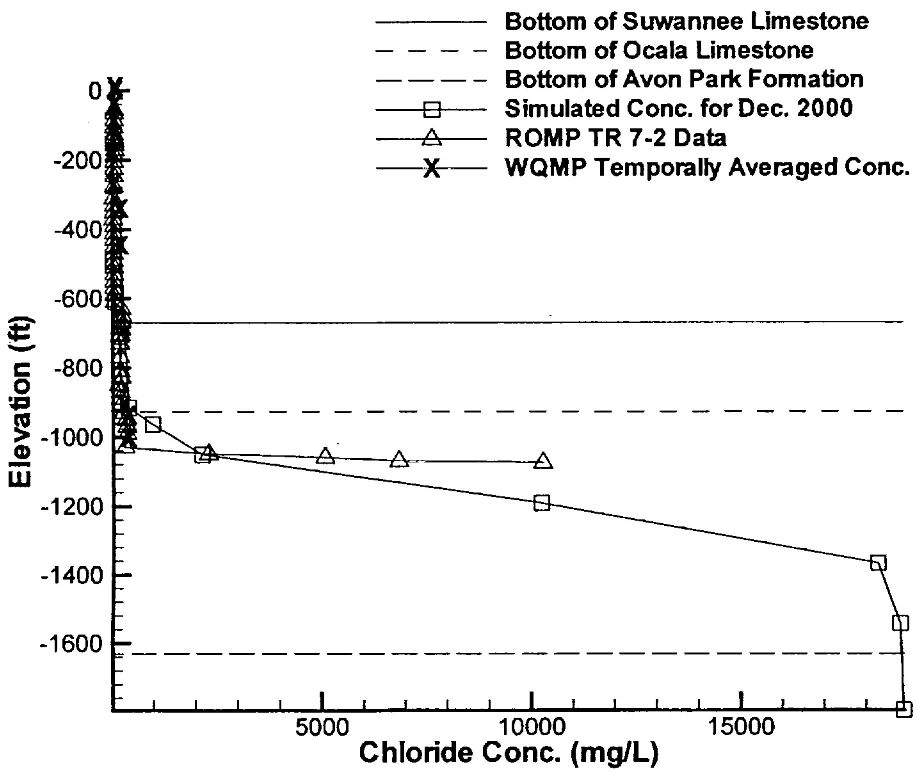
ROMP TR 8-1



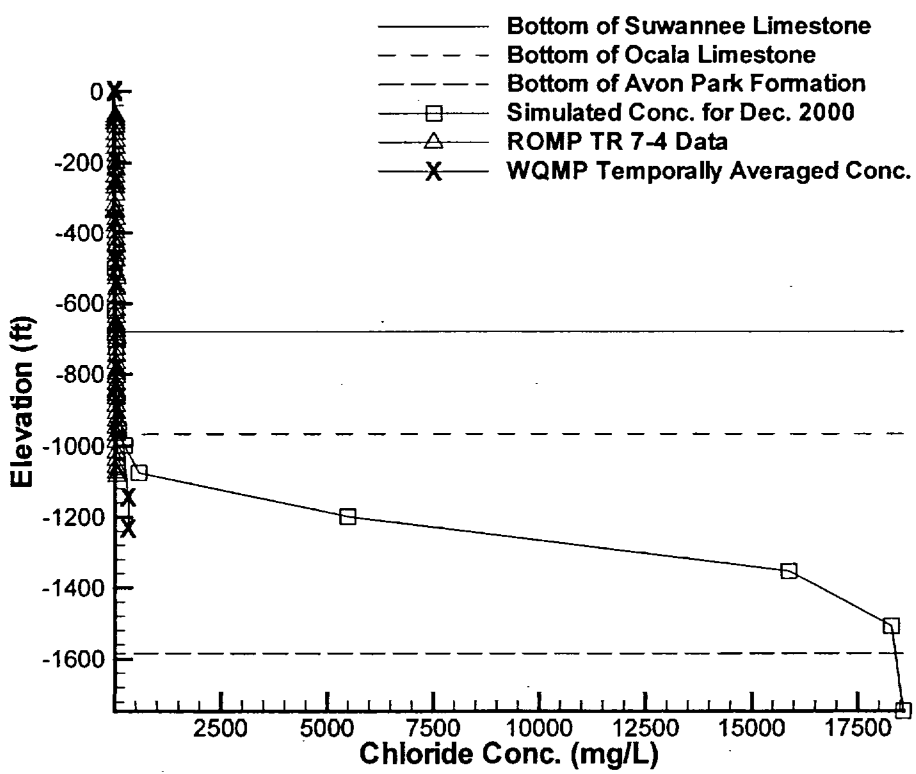
ROMP 33



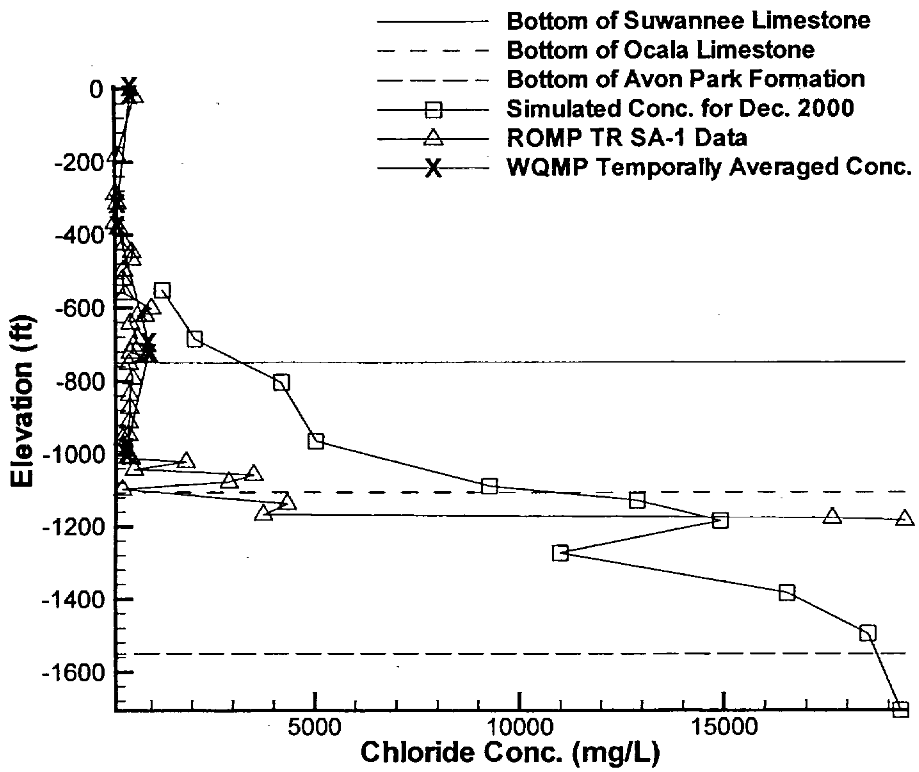
ROMP TR 7-2



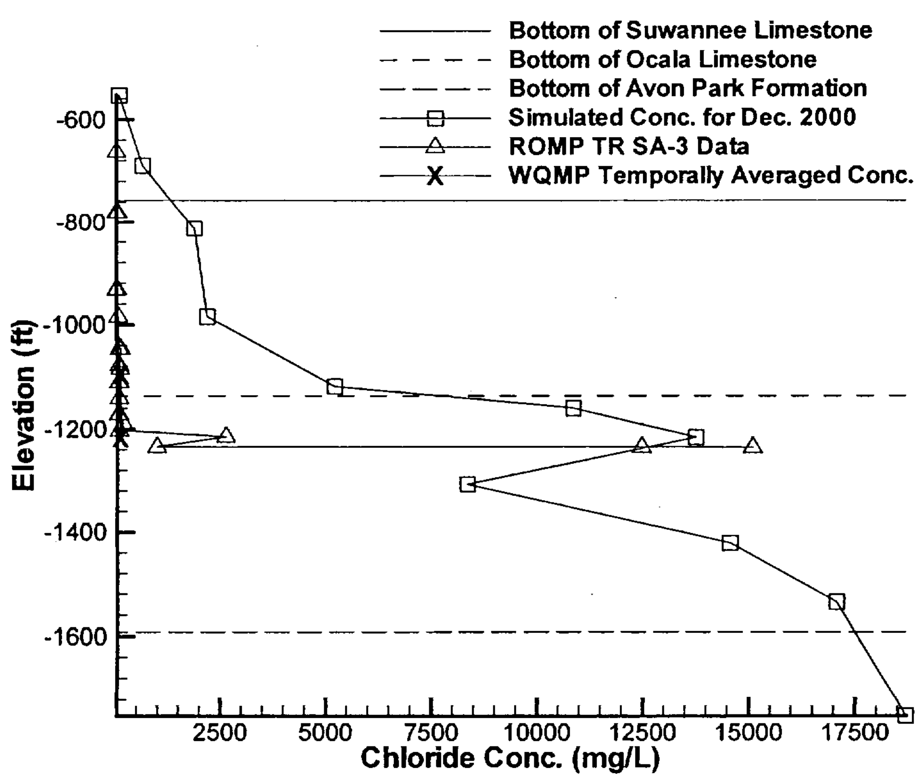
ROMP TR 7-4

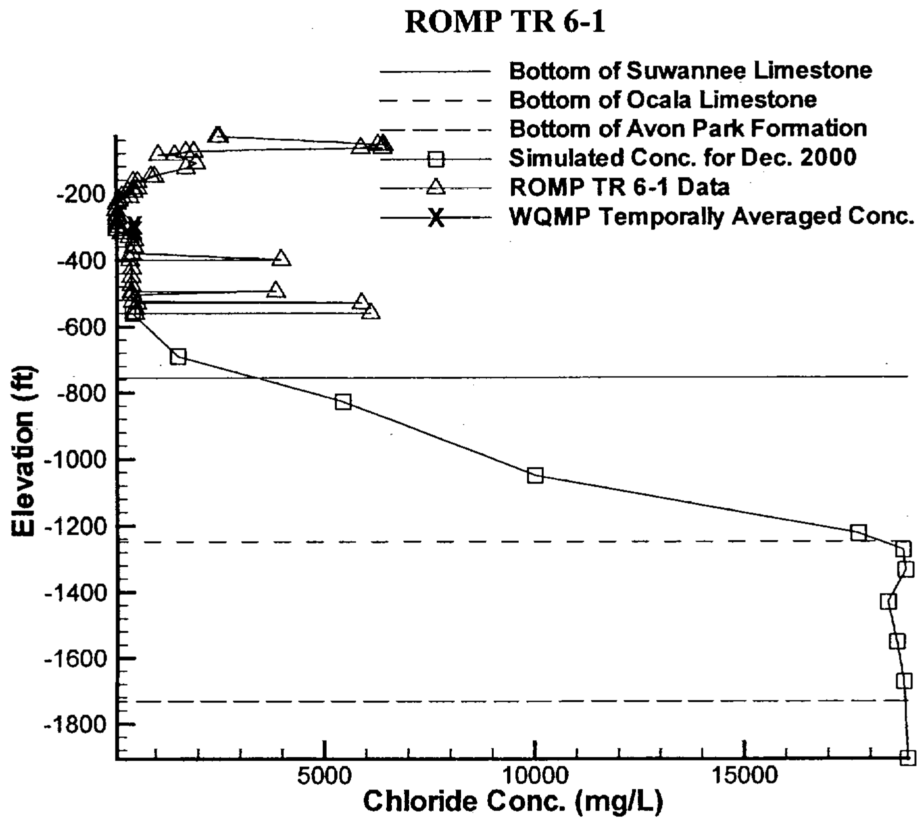


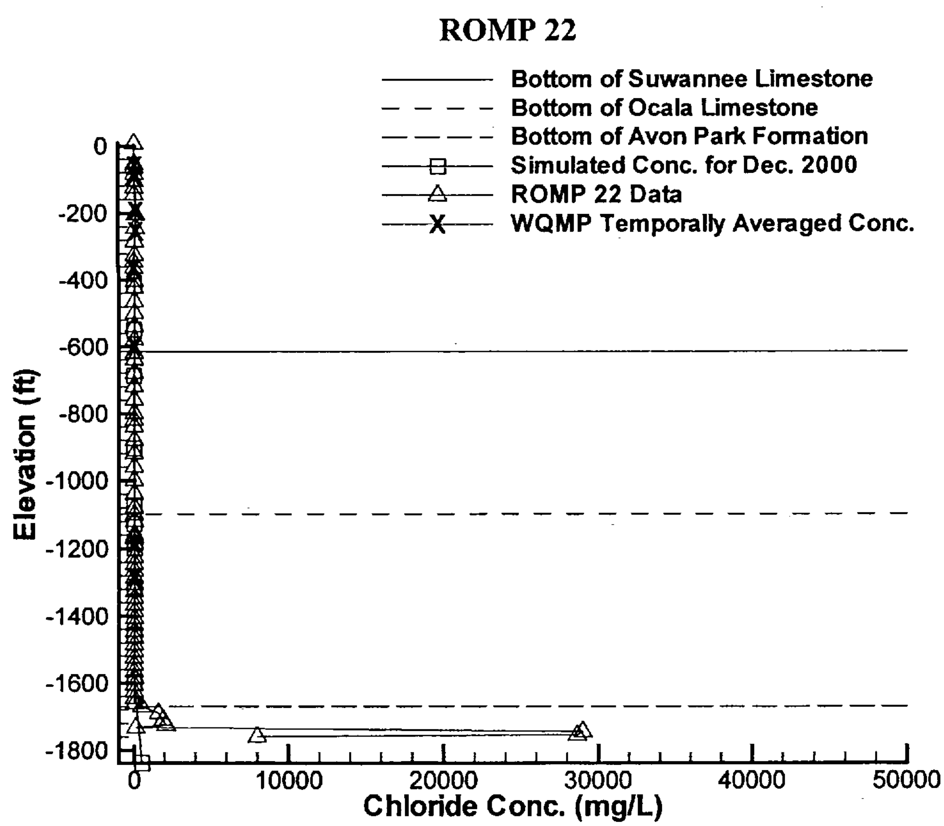
ROMP TR SA-1



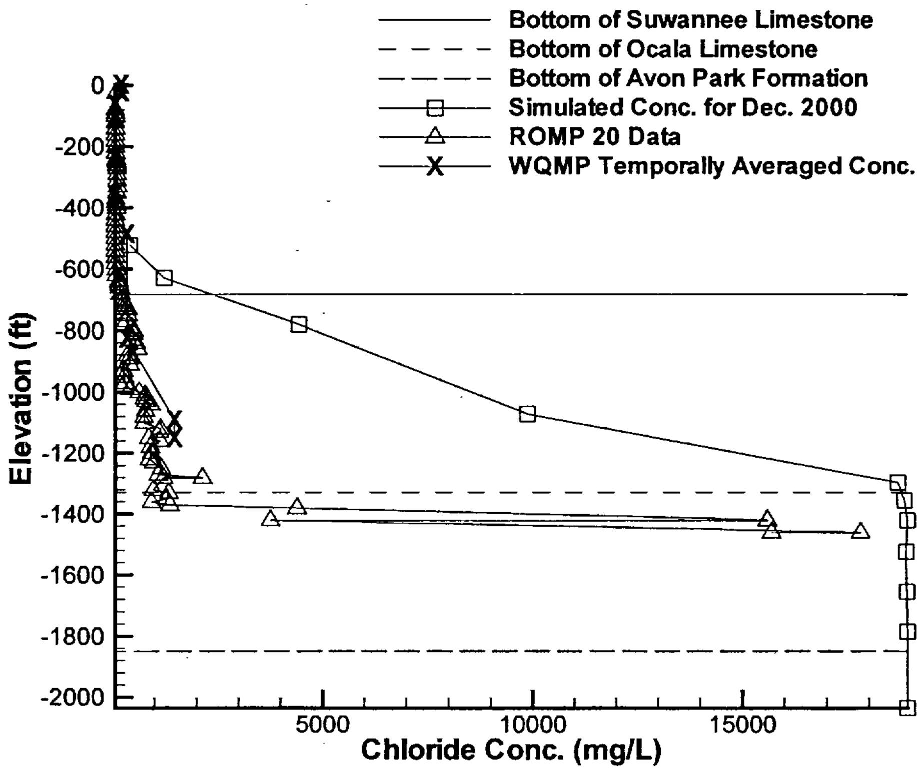
ROMP TR SA-3



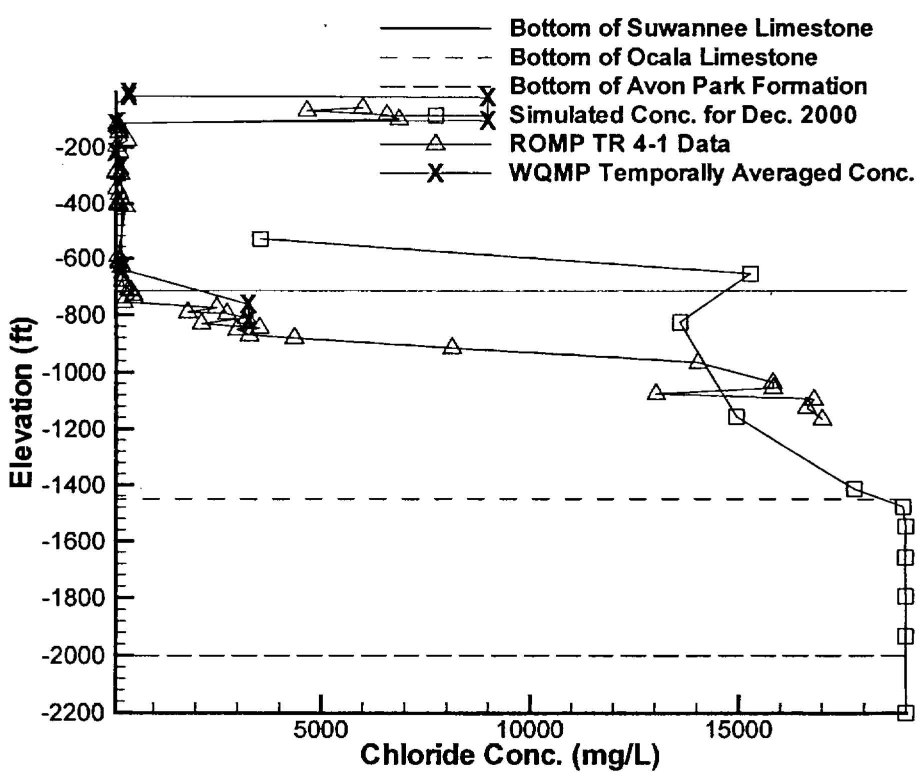

ROMP TR 6-1
Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
Simulated Conc. for Dec. 2000
ROMP TR 6-1 Data
WQMP Temporally Averaged Conc.
Elevation (ft)
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
5000
10000
15000
Chloride Conc. (mg/L)


ROMP 22
Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
Simulated Conc. for Dec. 2000
ROMP 22 Data
WQMP Temporally Averaged Conc.
Elevation (ft)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0
10000
20000
30000
40000
50000
Chloride Conc. (mg/L)

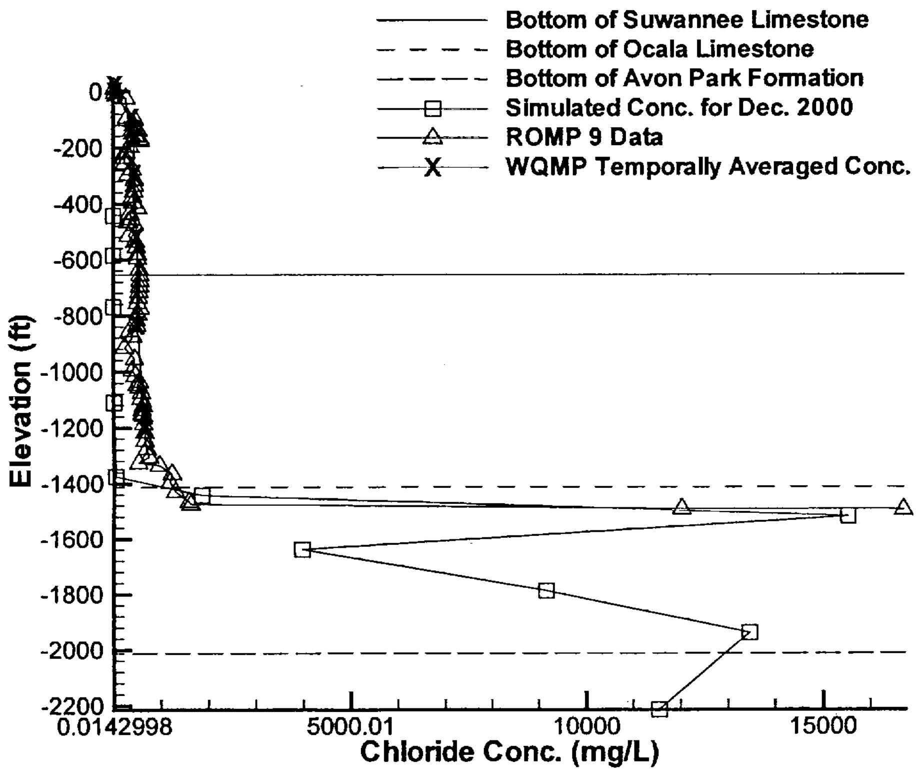
ROMP 20



ROMP TR 4-1



ROMP 9


Bottom of Suwannee Limestone
Bottom of Ocala Limestone
Bottom of Avon Park Formation
Simulated Conc. for Dec. 2000
ROMP 9 Data
WQMP Temporally Averaged Conc.
Elevation (ft)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
-2200
0.0142998
5000.01
10000
15000
Chloride Conc. (mg/L)

RP-04511

REPORT NAME:
THREE-DIMENSIONAL DENSITY-

AUTHOR & REPORT DATE:
HYDROGEOLOGIC, INC 06/01/2002

SUBJECT:
MODELING OF SALTWATER INTRUSIO

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