Special Publication SJ94-SP6

GROUND-WATER FLOW AND SOLUTE TRANSPORT MODELING STUDY FOR SEMINOLE COUNTY, FLORIDA, AND ADJOINING REGIONS

Prepared for

St. Johns River Water Management District
Palatka, Florida

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March 1994

R11-93.468

EXECUTIVE SUMMARY

The Floridan aquifer is the primary source of water supply for the east-central Florida region. Rapid growth in the four-county region comprised of Brevard, Orange, Osceola, and Seminole counties is creating an ever increasing demand for freshwater. In most of Brevard County and easternmost Seminole and Orange counties, however, the Floridan aquifer contains water with chloride concentrations that exceed the Environmental Protection Agency (EPA) recommended limit of 250 milligrams/liter (mg/ℓ) for public supplies. Increased demands on the Floridan aquifer in Orange and Seminole counties, along with anticipated increases in water demand in the rapidly growing urban areas of western Orange and southwestern Seminole counties, have demonstrated the need for regional water resource management efforts.

The study described in this report is a portion of an ongoing program, led by the St. Johns River Water Management District (SJRWMD), to address the need for a long-term, environmentally sound water resources management policy. The primary purpose of this study is to provide a quantitative tool to assist with ground-water resources planning and management efforts in Seminole County.

This study is based largely upon the results of a series of previous modeling studies conducted by HydroGeoLogic, Inc. for the SJRWMD, the City of Cocoa and the Orange County Public Utilities Division. These previous studies focused primarily on determining the potential effects of alternative withdrawal scenarios on the ground-water resources in eastern Orange County.

The first phase of the study (Phase I) involved the development of a regional, three-dimensional ground-water flow model encompassing all of Orange and Seminole counties and significant portions of Lake, Volusia, Brevard, Osceola and Polk counties as technical considerations warranted (Blandford et al., 1991). The primary purpose of the first-phase effort was to provide boundary conditions and estimates of regional aquifer parameters for the modeling efforts in the following phases. The Phase I modeling study was subsequently enhanced to assist the

SJRWMD in assessing the impacts of utilizing sources of fresh ground water in Orange and Seminole counties over a 20-year planning period (Blandford and Birdie, 1992b). The revised Phase I modeling study is referred to as the Phase IV study; the results of the Phase IV study supersede those of Phase I and are the basis of the modeling study documented herein. The second and third study phases involved detailed modeling for eastern Orange County (Blandford and Birdie, 1992a), and are not discussed further.

The fifth and final phase of the study (Phase V) is the topic of this report. The primary purpose of the Phase V modeling effort was to develop a three-dimensional, density-dependent ground-water flow and solute transport model capable of simulating the complex, variable density ground-water flow system of the Floridan aquifer in central and western Seminole County and immediately adjoining regions. Of primary concern is the potential for the degradation of fresh ground-water resources in the vicinity of the major municipal wellfields in Seminole County, including those of the towns of Sanford, Longwood and Oviedo. To accomplish this task, a model calibration was performed for average predevelopment and 1988 (postdevelopment) hydrologic conditions using the DSTRAM computer code. The Phase V model calibration was performed for a subregion of the Phase IV regional model domain (Blandford and Birdie, 1992b). The Phase IV modeling results formed the basis for many of the aquifer parameters and boundary conditions used in this study. A reasonable calibration was obtained for predevelopment and average 1988 conditions.

Although the Phase V model was successfully calibrated to known predevelopment and average 1988 conditions, it should be emphasized that the basic data available for use in constructing the model were quite limited in several significant areas:

1) Observed chloride concentrations (both areally and width depth) in the Lower Floridan aquifer

2) Observed potentiometric head in the Lower Floridan aquifer

3) Hydraulic properties of the Lower Floridan aquifer and the middle semiconfining unit

4) Solute transport parameters for both the Upper and Lower Floridan aquifers

Due to the above data constraints, the model could not be rigorously calibrated with respect to the Lower Floridan aquifer. This has potential implications for the simulation results within the Upper Floridan aquifer since the Lower Floridan aquifer is the major source of salt for this unit. At present, the simulated chloride concentrations in the Lower Floridan aquifer are in reasonable agreement with observed chloride concentrations at the Sand Lake Road test well, the Lake Ivanhoe test well, the Western Regional wellfield deep test wells, the results of a geophysical study and other nondirect observations or interpretations. However, taken as a whole with respect to the size of the modeled area, the available observation points are relatively sparse. To improve this, or another, model in the future and to add reliability to the simulation results, it is critical that additional hydrologic observations/data be collected for the Lower Floridan aquifer and the middle semiconfining unit.

Several important insights were obtained during the modeling process. First of all, the location and movement of the 250 mg/ℓ isochlor in Seminole County is highly sensitive to the location of the transition zone from Upper Floridan aquifer recharge to Upper Floridan aquifer discharge. Related to this point, the 250 mg/ℓ isochlor is influenced significantly by nearby zones of high recharge to the Upper Floridan aquifer. Of particular significance are the good recharge areas south of Sanford, in the vicinity of Oviedo, and in the vicinity of Chuluotta. In order to maintain fresh ground-water resources in Seminole County, it is very important that regions of high-moderate recharge are maintained as much as possible.

Secondly, the model simulations indicate that ground water with chloride concentrations equal to or exceeding 250 mg/ℓ underlies much of Seminole County in the middle semiconfining unit. This result is supported by the deep monitor well completed in Seminole County west of Sanford. It would seem that the most immediate threat to water quality at individual wellfields is not regional scale movement of the 250 mg/ℓ isochlor in the Upper Floridan, but rather local upconing of poor quality water from the middle semiconfining unit. Such upconing is a local scale phenomena highly dependant on local hydrogeologic conditions that are often unknown.

Along the western and northern borders of Seminole County, ground water with chloride concentrations exceeding 250 mg/ℓ exists in relatively narrow bands (several miles) centered along the Wekiva and St. Johns river channels. It is a particularly difficult task to simulate the movement of ground water and solutes in these regions, as there is a great deal of uncertainty with respect to the hydrogeologic conditions in the Lower Floridan aquifer, the existence and nature of preferential flow paths through the middle semiconfining unit due to geologic structure or other factors, and the ground-water budget (e.g. diffuse discharge rates). Fortunately, regional ground-water flow in the Upper Floridan aquifer (even for the 2010 predictive simulation) is to the north and northeast in this region, and hence these zones of high chloride concentration are not likely to pose a significant threat to the major municipal wellfields in Seminole County.

Using the calibrated Phase V model, a predictive simulation for the years 2010, 2060 and 2110 was conducted. The purpose of the predictive simulation was to estimate future impacts to the Floridan aquifer system, in terms of ground-water levels and chloride concentrations, that may be caused by projected increases in pumpage as of the year 2010. Of particular interest is the potential for increased chloride concentrations at the major wellfields in Seminole County due to the intrusion of poor quality ground water.

Estimates of pumping rates as of the year 2010 were compiled for the Phase IV modeling effort (Blandford and Birdie, 1992b). Projected pumping increases were only derived for municipal and industrial supplies obtained from the Upper and Lower Floridan aquifers; agricultural pumpage and recharge due to drainage wells was assumed to remain unchanged from the average 1988 values. Throughout the entire Phase IV study area, municipal pumping was projected to approximately double by the year 2010 in both the Upper and Lower Floridan aquifers.

In the southern portion of the Phase V model domain, in the vicinity of Oviedo and south of Casselberry, over 10 ft of drawdown is simulated in the Upper Floridan aquifer from average 1988 to 2010 conditions. In other regions of the Upper Floridan aquifer, simulated drawdowns from average 1988 conditions are about 5 ft or less. In the vicinity of Wekiva Falls Resort (near the point where Orange, Lake and Seminole Counties meet), simulated heads increase about 2-3 ft from 1988 to 2010 due to the imposed reduction in discharge from 12.75 MGD to 0.223 MGD. In the Lower Floridan aquifer, simulated drawdowns are 10-15 ft throughout most of the Phase V model domain. The simulated drawdowns cause about a 20 percent decrease in overall simulated spring flow from 1988 to 2010 conditions.

In the predictive simulation, the 250 mg/ℓ isochlor in the Upper Floridan aquifer regresses somewhat (less than a mile) in the general region between Lake Jessup and Sanford. This result, as explained in the text, is due to simulated increases in recharge to the Upper Floridan aquifer as drawdowns in the Upper Floridan aquifer increase. South of Lake Jessup, in the vicinity of Oviedo and Chuluotta, the predictive simulation indicates a western migration (intrusion) of the 250 mg/ℓ isochlor. The movement, however, is relatively limited (approximately 1-1.5 miles over a 100 year simulation period). The region of saltwater in the Upper Floridan aquifer along the Wekiva River where the river forms the boundary between Seminole and Lake counties is substantially reduced in areal extent and moves to the east in the predictive simulation. This result is not considered to be realistic, and is attributed to a limited understanding and ability to simulate the highly complex subsurface flow system in this region. This region is very complex hydrogeologically, and there is little direct information available with regard to aquifer parameters and geological controls. This result does not affect the isochlors in other regions of the model domain.

In the Lower Floridan aquifer, the 1988 and predictive simulation results indicate some upconing of saltwater due to pumping at the Casselberry Lower Floridan wells. This result is believed to be an artifact of the model, since the simulated saltwater wedge in the Lower Floridan aquifer is probably too far to the southwest. However, this region would be a good one in which to have at least one, and preferably a series, of deep monitor wells to record changes in chloride concentrations in the Lower Floridan aquifer, since it is centrally located within the simulated future cone of depression in the Lower Floridan aquifer.

The ground-water flow and solute transport model documented herein is appropriate and sufficiently accurate for the assessment of ground-water resources on a regional (county) scale. The model is not suitable for the short-term or seasonal prediction of chloride concentrations on the local scale at individual wells. As with all models used for predictive purposes, the modeling conceptualization and framework should be periodically updated and reevaluated to consider or incorporate new data and insites. For the purposes of future model calibration and validation efforts, it would be very useful, and indeed necessary if more accurate models are required, to obtain additional data on hydraulic parameters of the Lower Floridan aquifer and the middle semiconfining unit; chloride concentration observations in the Lower Floridan aquifer and the middle semiconfining unit; and potentiometric surface elevations in the Lower Floridan aquifer, particularly in northern and eastern Seminole County. The major sources of error in the Phase V model stem directly from a lack of data for the middle semiconfining unit and the Lower Floridan aquifer.

Lower Floridan aquifer and middle semiconfining unit data collection should be concentrated in central Seminole County in the vicinity of, or slightly east of, the major centers of pumping. Critical parameters that should be obtained are chloride concentrations with depth, vertical hydraulic conductivity or leakance of the middle semiconfining unit, and hydraulic gradients across the middle semiconfining unit. Obviously, the hydraulic gradients would be determined by collecting hydraulic head observations for the Upper Floridan and Lower Floridan aquifers, and if possible the middle semiconfining unit, at the same location.

In addition, it would be very useful to have at least one regional series of observation wells that intersect the saltwater front at approximately a right angle. Such an observation well network would run approximately parallel to the southern cross sections presented in this report. For each of the observation locations in this series, chloride concentrations with depth, preferably for the entire thickness of the Floridan aquifer system, should be collected. Such a network would permit a detailed picture of the saltwater wedge to be developed. If constructed, this network should be placed in the vicinity of the southern model boundary for two reasons. First of all, an observation network thus placed could act as a regional monitoring network for

Seminole County and eastern Orange County for the Floridan aquifer system. The network could be used to monitor long-term variations in chloride concentrations in both the Upper and Lower Floridan aquifers. Secondly, the northern portion of Seminole County is very complex hydrogeologically, and it is possible that numerous monitor wells would have to be constructed to obtain a detailed knowledge of the flow system in this area. Furthermore, the predictive simulation results indicate that substantial reductions in the Upper Floridan aquifer potentiometric surface will not occur in northern Seminole County in response to estimated 2010 withdrawal rates. Finally, due to the existence of various deep test wells completed in the vicinity of southwestern Seminole County (i.e., Altamonte Springs and regions west), this region is fairly well characterized hydrogeologically and additional test holes are not required.

For the immediate purpose of sustaining a good quality water supply for the major municipalities in Seminole County, one of the key unknowns that should, if possible, be addressed is the quality of ground water in the middle semiconfining unit which underlies the major wellfields. There is some uncertainty regarding this issue, since chloride sampling results and geophysical testing of the CDM deep test well west of Sanford seem to indicate conflicting results. Determining with reasonable accuracy the depth to 250 mg/ℓ water beneath the good recharge areas in central Seminole County is critical to predicting the potential for future degradation of ground-water resources within the county. Also, in order to accurately assess the potential for saltwater upconing on a local scale, it is necessary to obtain more accurate estimates of the vertical hydraulic conductivity in the middle semiconfining unit in the vicinity of individual well fields. The simulation results presented herein may be considered to be more on the conservative, or worse case, end of possibilities since significant chloride concentrations are simulated to exist within the middle semiconfining unit throughout much of Seminole County. If the depth to high chloride water is actually greater than the model simulations indicate, the potential for future water quality degradation is reduced, unless the calibrated values of middle semiconfining unit leakance are determined to be substantially underestimated.

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1 INTRODUCTION

1.1 Background

The Floridan aquifer is the primary source of water supply for the east-central Florida region. Rapid growth in the four-county region comprised of Brevard, Orange, Osceola, and Seminole counties is creating an ever increasing demand for freshwater. In most of Brevard County and easternmost Seminole and Orange counties, however, the Floridan aquifer contains water with chloride concentrations that exceed the Environmental Protection Agency (EPA) recommended limit of 250 milligrams/liter (mg/ℓ) for public supplies. Increased demands on the Floridan aquifer in Orange and Seminole counties, along with anticipated increases in water demand in the rapidly growing urban areas of western Orange and southwestern Seminole counties, have demonstrated the need for regional water resource management efforts.

The study described in this report is a portion of an ongoing program, led by the St. Johns River Water Management District (SJRWMD), to address the need for a long-term, environmentally sound water resources management policy. The primary purpose of this study is to provide a quantitative tool to assist with ground-water resources planning and management efforts in Seminole County.

This study is based largely upon the results of a series of previous modeling studies conducted by HydroGeoLogic, Inc. for the SJRWMD, the City of Cocoa and the Orange County Public Utilities Division. These previous studies focused primarily on determining the potential effects of alternative withdrawal scenarios on the ground-water resources in eastern Orange County.

The first phase of the study (Phase I) involved the development of a regional, three-dimensional ground-water flow model encompassing all of Orange and Seminole counties and significant portions of Lake, Volusia, Brevard, Osceola and Polk counties as technical considerations warranted (Blandford et al., 1991). The primary purpose of the first-phase effort was to provide boundary conditions and estimates of regional aquifer parameters for the modeling efforts in the following phases. The Phase I modeling study was subsequently enhanced to assist the SJRWMD in assessing the impacts of utilizing sources of fresh ground water in Orange and Seminole counties over a 20-year planning period (Blandford and Birdie, 1992b). The revised Phase I modeling study is referred to as the Phase IV study; the results of the Phase IV study supersede those of Phase I and are the basis of the modeling study documented herein.

The second phase of the study (Phase II) involved the development of a vertical cross-section model extending in an east-west direction through the Cocoa wellfield in eastern Orange County (Blandford, 1991). The purpose of this phase of the study was to assist with the conceptualization of the flow system using density-dependent ground-water flow and solute transport simulations. The third phase of the study (Phase III) is similar in scope to the study reported herein (Blandford and Birdie, 1992a). The Phase III study involved the construction of a three-dimensional, density-dependent ground-water flow and solute transport model for the sub-regional area centered about eastern Orange County.

The fifth and final phase of the study (Phase V) is the topic of this report. The Phase V study involved the construction of a three-dimensional, density-dependent ground-water flow and solute transport model for the sub-regional area centered about western and central Seminole County.

1.2 Purpose and Scope of Work

The primary purpose of the Phase V modeling effort is the development of a three-dimensional, density-dependent ground-water flow and solute transport simulation capability suitable for the prediction of ground-water levels and chloride concentrations in western and central Seminole County and immediately adjoining regions. Of particular importance is the potential for the degradation of fresh ground-water resources in the vicinity of several municipal wellfields, including those of the towns of Sanford, Longwood, and Oviedo. The scope of work for the Phase V modeling effort includes the following activities:

- Construction and calibration of a three-dimensional, density-dependent ground-water flow and solute transport model for predevelopment and current (1988) conditions for western and central Seminole County and adjoining regions.

- Assessment of drawdown impacts and water quality degradation due to the lateral or vertical encroachment of saltwater (water with chloride concentrations greater than 250 mg/ℓ) as of the years 2010, 2060 and 2110 at existing and proposed wellfields.

1.3 Organization of Report

This report is divided into six chapters designed to lead the reader through the technical effort in a sequential and logical manner. Chapter 1 provides background introductory materials, and Chapter 2 outlines the general technical approach. Chapter 3 provides a synopsis of the hydrogeological setting, with particular emphasis placed upon hydrostratigraphy and water quality. Chapter 4 provides the specifics of the ground-water modeling effort, including the details of model construction, calibration and sensitivity analysis. Chapter 5 is devoted to predictive simulations, and Chapter 6 consists of technical conclusions.

2 TECHNICAL APPROACH

2.1 Overall Approach

The overall technical approach for this study consisted of five major steps. First, the relevant hydrogeological literature and data pertaining to the study area were reviewed, with particular emphasis placed upon water quality observations and hydrostratigraphy. Secondly, the location of the three-dimensional modeling domain was determined based upon the conceptual model of the region, the locations of existing and proposed wells and wellfields, and the results of earlier modeling studies. The model domain was subsequently discretized, and the initial input parameters and boundary conditions were determined. The boundary conditions and initial input parameters were dependent largely upon the Phase IV regional modeling results (Blandford and Birdie, 1992b). The fourth and most labor intensive task was the calibration of the numerical model to estimated predevelopment and average 1988 hydrogeologic conditions. A sensitivity analysis was performed on the calibrated model results. Finally, predictive simulations were performed for the year 2010 and beyond based upon projected ground-water withdrawals and proposed wellfield locations.

2.2 Code Selection

The computer code DSTRAM was selected for use during this study. The name DSTRAM is an acronym for **D**ensity-dependent **S**olute **TR**ansport **A**nalysis finite-element **M**odel (Huyakorn and Panday, 1991). DSTRAM is a three-dimensional finite-element code that simulates density-dependent, single-phase fluid flow and solute transport in saturated porous media. The code is designed specifically for complex situations where the flow of fluid (ground water) is influenced significantly by variations in solute concentration. DSTRAM can perform steady-state and transient simulations in a cross section, an axisymmetric configuration, or a fully three-dimensional mode. A wide range of boundary conditions can be accommodated including those involving water table conditions, infiltration, aquitard leakages, and pumping and injection wells.

For contaminant transport simulation, DSTRAM can account for advection, hydrodynamic dispersion, linear equilibrium sorption, and first-order degradation.

DSTRAM was developed by HydroGeoLogic, Inc. and is based on an earlier code, SWICHA (Huyakorn et al., 1986). The DSTRAM 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, such as the Geneva groundwater lens modeling project (Panday et al., 1990), and a water resource evaluation study of eastern Orange County (Blandford and Birdie, 1992a). DSTRAM has also been verified against problems with known solutions (Huyakorn and Panday, 1991).

- DSTRAM employs the most advanced finite element and matrix computation techniques available. The code has robust (Preconditioned Conjugate Gradient and ORTHOMIN) matrix solvers unavailable in other standard codes which make it more efficient and versatile.

- The DSTRAM code can easily be applied in a variety of configurations (i.e., areal two-dimensional, cross-sectional, axisymmetric, and fully three-dimensional regions). The code was specifically designed to analyze problems of lateral seawater intrusion and/or upconing in complex hydrogeologic settings.

3 HYDROGEOLOGICAL SETTING

3.1 Introduction

The geological and hydrogeological setting of the study region has been described by numerous authors. One of the most recent and comprehensive discussions is provided by Tibbals (1990). A summary of the relevant literature as it pertains to the study at hand is provided in Chapter 3 of the Phase IV report (Blandford and Birdie, 1992b). Rather than reproduce that discussion, after a brief overview of the regional hydrogeology, the emphasis in this chapter is placed upon the vertical hydrostratigraphy and water quality in the vicinity of the Phase V study area (Figure 3.1).

3.2 Overview of Hydrogeology

A simplified geological section and corresponding hydrogeologic units are illustrated in Figure 3.2. Only about the upper 2,800 ft of sediments and geologic formations are of concern in this study. In general, the subsurface within the study area is dominated by the Lower Tertiary Ocala Limestone and the Avon Park, Oldsmar and Cedar Keys formations. This thick sequence of carbonate rocks is overlain by the Hawthorn Group, which consists of marine interbedded sands and clays that are often phosphatic. The Hawthorn Group is in turn overlain by surficial Quaternary deposits consisting of undifferentiated sands, silts and clays. A series of isopach and depth-to-surface maps for the major units within the study area were produced by Miller (1986) and are reproduced in Tibbals (1990). The correlation between principal geologic and hydrologic units is based primarily on the permeability of the geologic media.

The ground-water flow system is composed of three distinct aquifers separated by two semiconfining units. The surficial aquifer is unconfined and is composed of interbedded, Quaternary-age sands, silts, clays and some peat. Thickness of the surficial aquifer sediments ranges from about 20 ft to perhaps as high as 100 ft. The primary hydrologic function of the

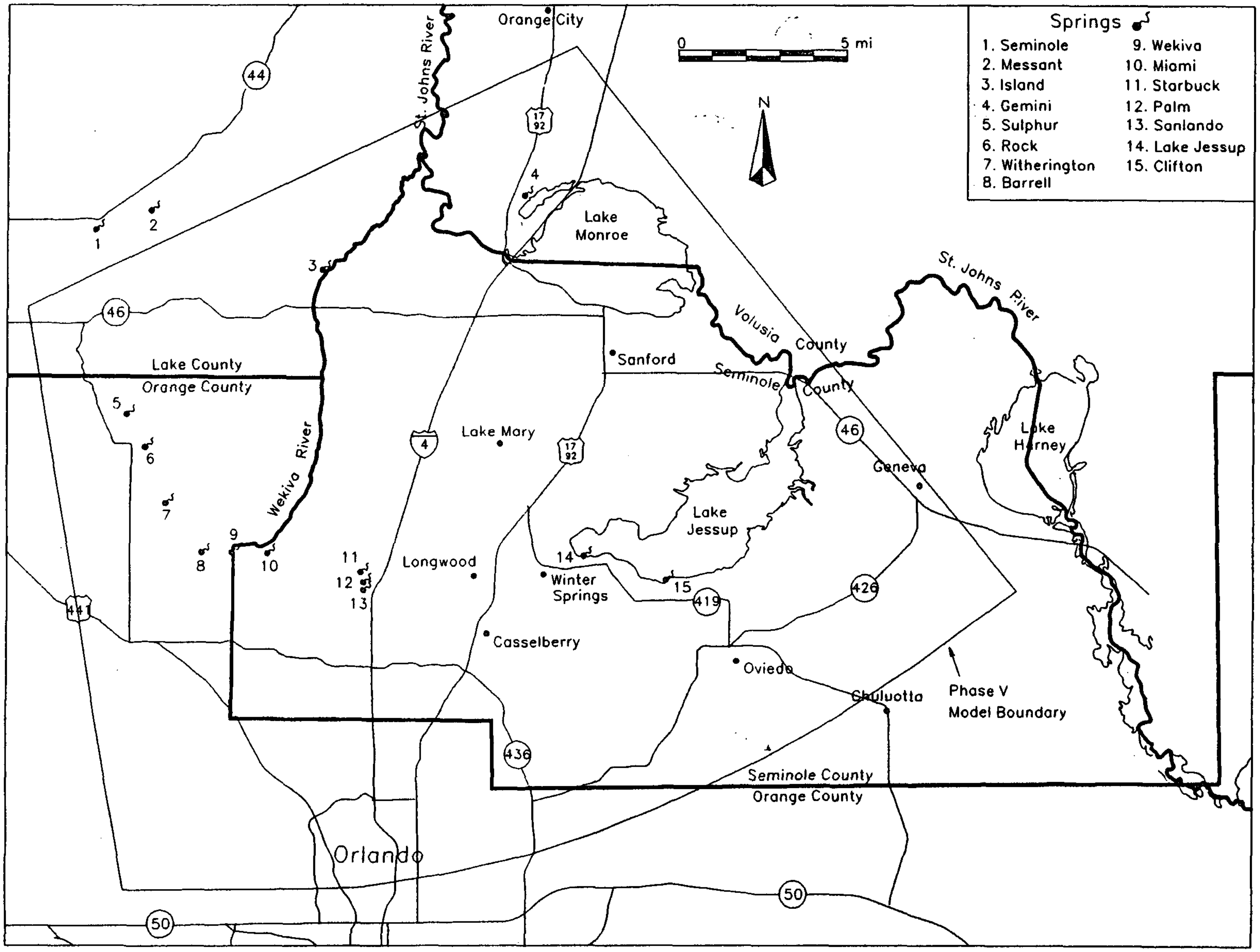


Figure 3.1 General base map for the Phase V study area and location of model domain.

GEOLOGIC UNITS

Geologic Age	Thickness (feet)	Lithology/ Hydrogeology
Quaternary	20-100	Primarily quartz sand with varying amounts of clay and shell. Forms major portion of the surficial aquifer.
Miocene-Hawthorn Group	0-200+	Marine interbedded quartz sand, silt and clay, often phosphatic. Generally relatively impermeable, but may form secondary artesian aquifer locally due to presence of limestone, shell and sand beds.
Upper Eocene-Ocala Limestone	0-125	Cream to tan, fine, soft to firm marine limestone. Moderately high transmissivity; forms the top of the Upper Floridan.
Middle Eocene-Avon Park Formation	600-1600	Upper section mostly cream to tan crystalline porous limestone. Lower section is brown, crystalline layers of dolomite alternating with chalky, fossiliferous layers of limestone. Upper portion forms about lower 2/3 of Upper Floridan. Lower portion forms upper part of Lower Floridan. Central portion has decreased porosity and forms middle semiconfining unit.
Lower Eocene-Oldsmar Formation	300-1350	Light brown to chalky, white, porous limestone with interbedded brown, porous crystalline dolomite. Forms significant portion of Lower Floridan.
Paleocene-Cedar Keys Formation	500-2200	Marine dolomite with considerable anhydrite and gypsum. Forms impermeable base of Floridan aquifer.

PRINCIPAL HYDROGEOLOGIC UNITS

Surfical Aquifer
Upper Semiconfining Unit
Upper Floridan Aquifer
Middle Semiconfining Unit
Lower Floridan Aquifer
Lower Confining Unit
Basement Rocks

Figure 3.2 Principal geologic and corresponding hydrogeologic units in east-central Florida. Based on Faulkner (in Tibbals, 1990), Lichtler et al. (1968), McKenzie-Arenberg and Szell (1990) and Miller (1986).

surficial aquifer on a regional scale is either to recharge the underlying Upper Floridan aquifer, or to discharge ground water to surface water bodies such as lakes, streams, ditches and swamps. The upper confining unit, which is composed of sands, sandy-clay and clay (often phosphatic) of the Hawthorn Formation and other Miocene and post-Miocene sediments, separates the surficial aquifer from the highly permeable Tertiary limestones that form the Floridan aquifer system. The primary hydrologic functions of the upper confining unit are to confine the Floridan aquifer system under artesian pressure, and to transmit water between the surficial and Upper Floridan aquifers. In eastern Orange County, however, portions of the Hawthorn Formation form what is called the secondary artesian aquifer (or the "intermediate aquifer system"), which is considered as a potential source of water supply. McKenzie-Arenberg and Szell (1990) report that the intermediate aquifer occurs randomly throughout large portions of the study area at depths of 60 - 150 ft below land surface. Occurrence of the secondary artesian aquifer is related to the presence of highly permeable lenses of sand and shell within the Hawthorn Formation. These lenses are relatively local geologic features (Tibbals and Frazee, 1976) and therefore have limited regional significance.

The Floridan aquifer system lies below the upper confining unit and is the major source of ground water within the study area. Tibbals (1990) states "The top of the Floridan is defined as the first occurrence of vertically persistent, permeable, consolidated, carbonate rocks." The thickness of the Floridan aquifer system increases from about 2,100 ft in northwest Seminole County to about 2,350 ft in southeastern Seminole County. On a regional scale, the Floridan aquifer system has two distinct permeable zones separated by a middle semiconfining unit. The upper permeable zone is referred to as the Upper Floridan aquifer, or simply the Upper Floridan. The Upper Floridan consists entirely of the Tertiary age Ocala Limestone and the top portion of the Avon Park Formation. These marine limestones form an extremely prolific aquifer due to their high secondary porosity.

The middle semiconfining unit separates the Upper Floridan and Lower Floridan production zones. This unit is composed of the Middle Eocene members of the Avon Park Formation, which are less permeable dolomitic limestones. The flow of ground water between the Upper and Lower Floridan is controlled by the relative head differences between each zone as well as the permeability and thickness of the middle semiconfining unit.

The Lower Floridan is composed primarily of the Middle Eocene Avon Park Formation and the Lower Eocene Oldsmar Formation. Although capable of providing vast quantities of water, utility of the Lower Floridan for municipal water supply is limited in eastern Seminole, Orange and Brevard Counties due to its high saline content. In western Orange County, however, the Lower Floridan supplies high quality water to several major pumping centers in the vicinity of Orlando and Apopka. The Paleocene Cedar Keys Formation forms the base of the Lower Floridan throughout the study area. This geologic unit has very low permeability due to high amounts of gypsum and anhydrite.

3.3 Hydrostratigraphy

In the Phase IV regional ground-water flow model, the Upper and Lower Floridan aquifers were treated as single model layers separated by a less permeable semiconfining unit. Variations of thickness in the aquifer layers were assumed to be incorporated in the respective transmissivity value for each model cell. The middle semiconfining unit was incorporated into the model by providing a leakance value between the two model layers. Leakance is defined as the ratio of the vertical hydraulic conductivity of the middle semiconfining unit to the thickness of the middle semiconfining unit within a given model cell. The amount of water that could be exchanged between the model layers, therefore, was equal to the leakance value times the hydraulic head difference between the layers. Variations in the thickness or vertical hydraulic conductivity of the middle semiconfining unit were, therefore, considered to be incorporated directly into the leakance value. This approach is reasonable for the regional characterization of ground-water flow.

This Phase V modeling effort, however, examines the three-dimensional flow of ground-water and the associated movement of dissolved salts within the model domain. The flow of ground water and the transport of salt is density dependent, since the density of a given volume of water will increase with the dissolved solids content. The dissolved solids content may vary substantially vertically and laterally. It was important, therefore, to develop a more detailed conceptualization of the three-dimensional geometry of the pertinent hydrogeological units within the model domain. This task was accomplished through the compilation and interpretation of published and unpublished hydrogeological reports, maps and cross sections, and various lithologic and geophysical well logs. All unpublished data was supplied by the SJRWMD (Brian McGurk, personal communication, 1993).

The thickness of the Upper Floridan, as presented in Miller (1986), is approximately 300 ft throughout much of the Phase V study area. During the initial stages of this study, Brian McGurk of the SJRWMD conducted a detailed analysis of the depths of municipal supply wells in central and western Seminole County. It appears that in Seminole County, many wells withdraw water from about 100 ft of the Avon Park Formation which is mapped on a regional scale as part of the middle semiconfining unit by Miller (1986). This portion of the Avon Park Formation is composed of very hard, well-cemented dolomite that is fractured and contains abundant solution cavities (Brian McGurk, personnel communication, 1993). This 100-ft zone is considered in this study to be part of the Upper Floridan, which therefore has an average thickness of about 400 ft throughout the Phase V study area.

The thickness of the middle semiconfining unit ranges from about 300 ft in northwestern Seminole County to about 450 ft in southeastern Seminole County. These values are based upon the revised Upper Floridan thicknesses as described above and upon the bottom of the middle semiconfining unit as mapped by Miller (1986). Within the study area, the middle semiconfining unit consists of poorly cemented to well-cemented interbedded limestone, dolomitic limestone and dolomite.

As discussed in Chapter 4, a curvilinear finite element mesh was used to discretize the three-dimensional domain. The varying thicknesses and dips of the hydrogeologic units, therefore, were explicitly incorporated into the modeling grid. Figures 3.3-3.7 illustrate the altitude, relative to mean sea level (msl), of the top of the Upper Floridan aquifer, the top of the 100 ft

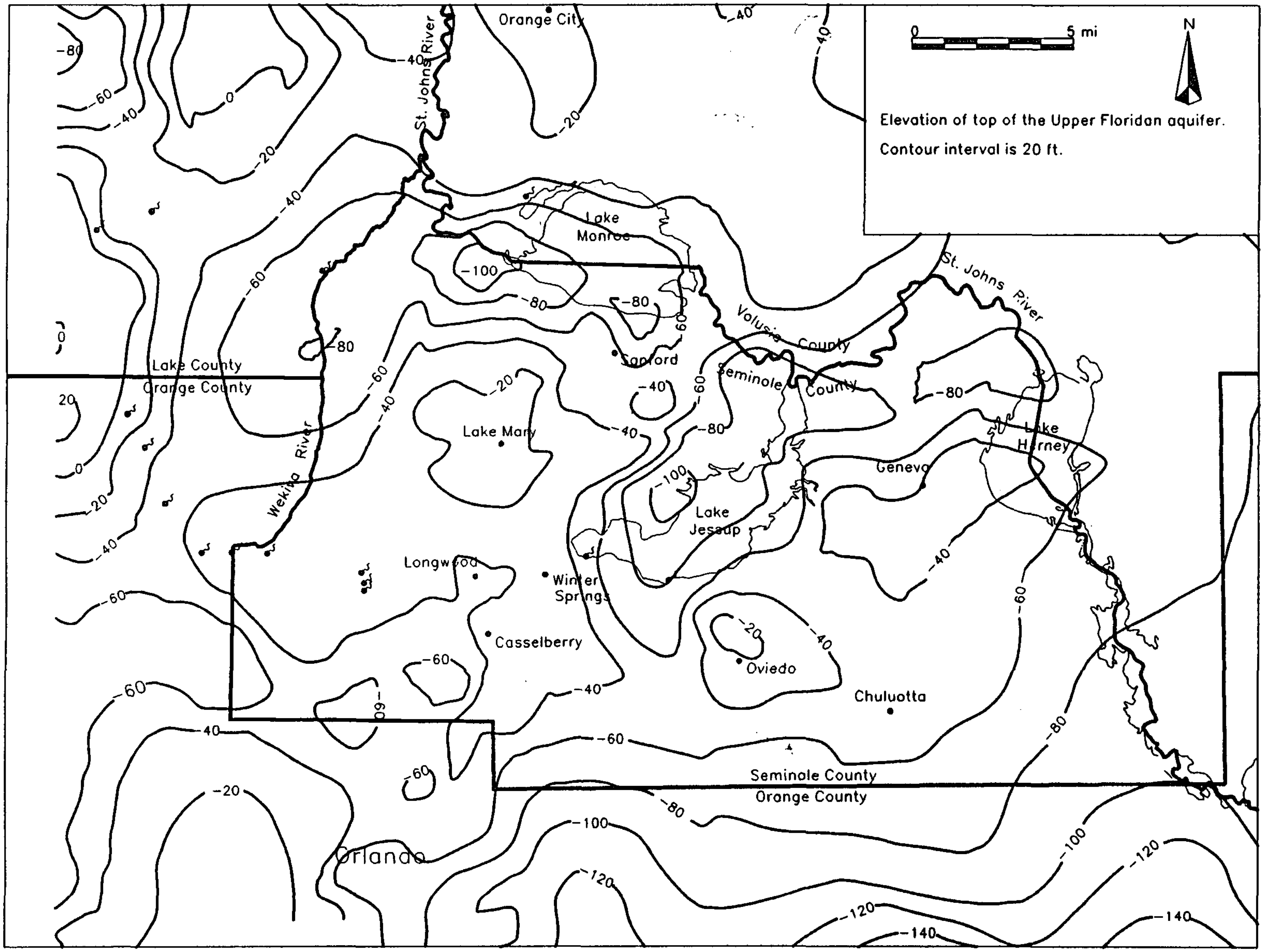


Figure 3.3 Altitude of the top of the Upper Floridan aquifer supplied by the SJRWMD. Datum is mean sea level.

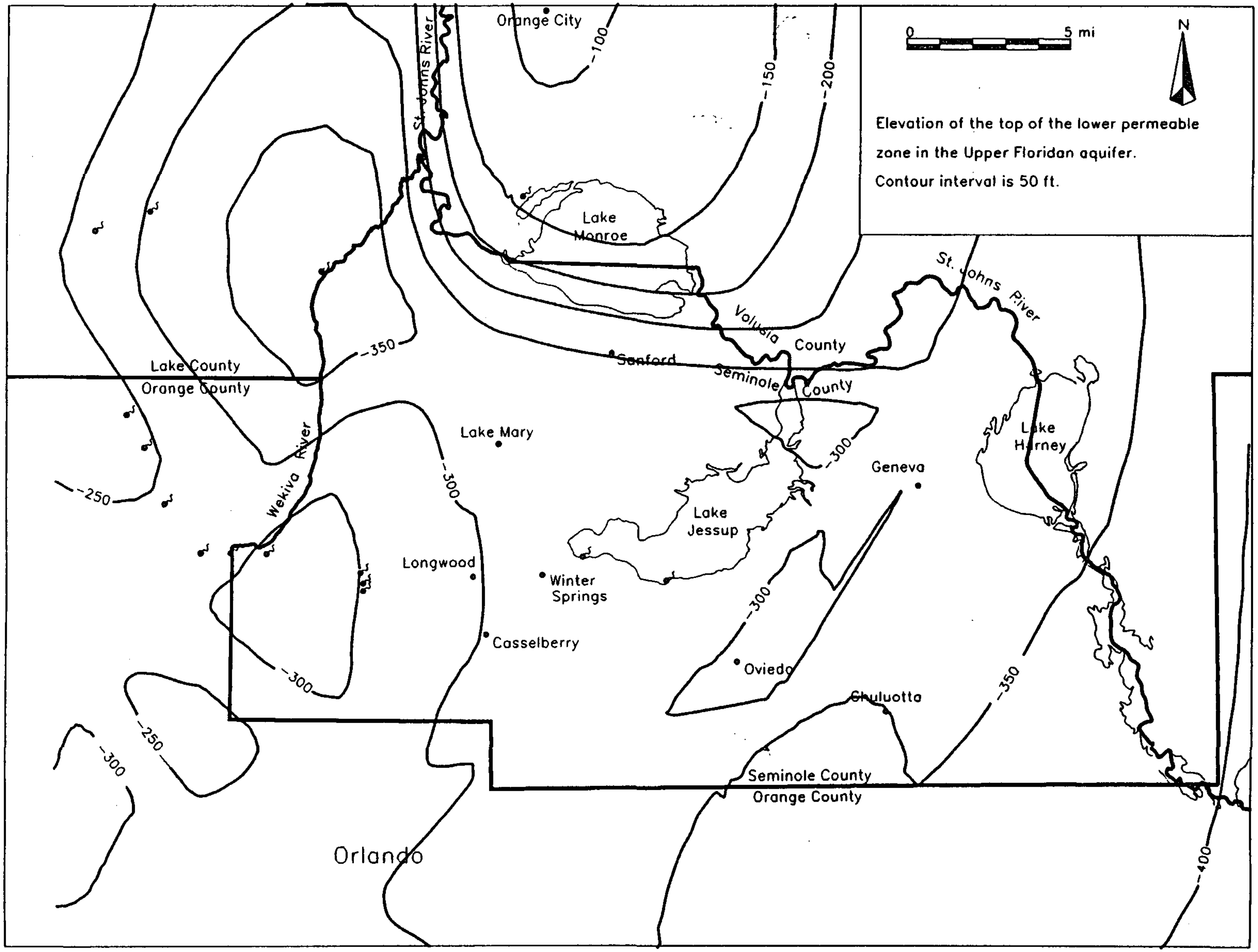


Figure 3.4 Altitude of the top of the lower permeable zone in the Upper Floridan aquifer supplied by the SJRWMD. Datum is mean sea level.

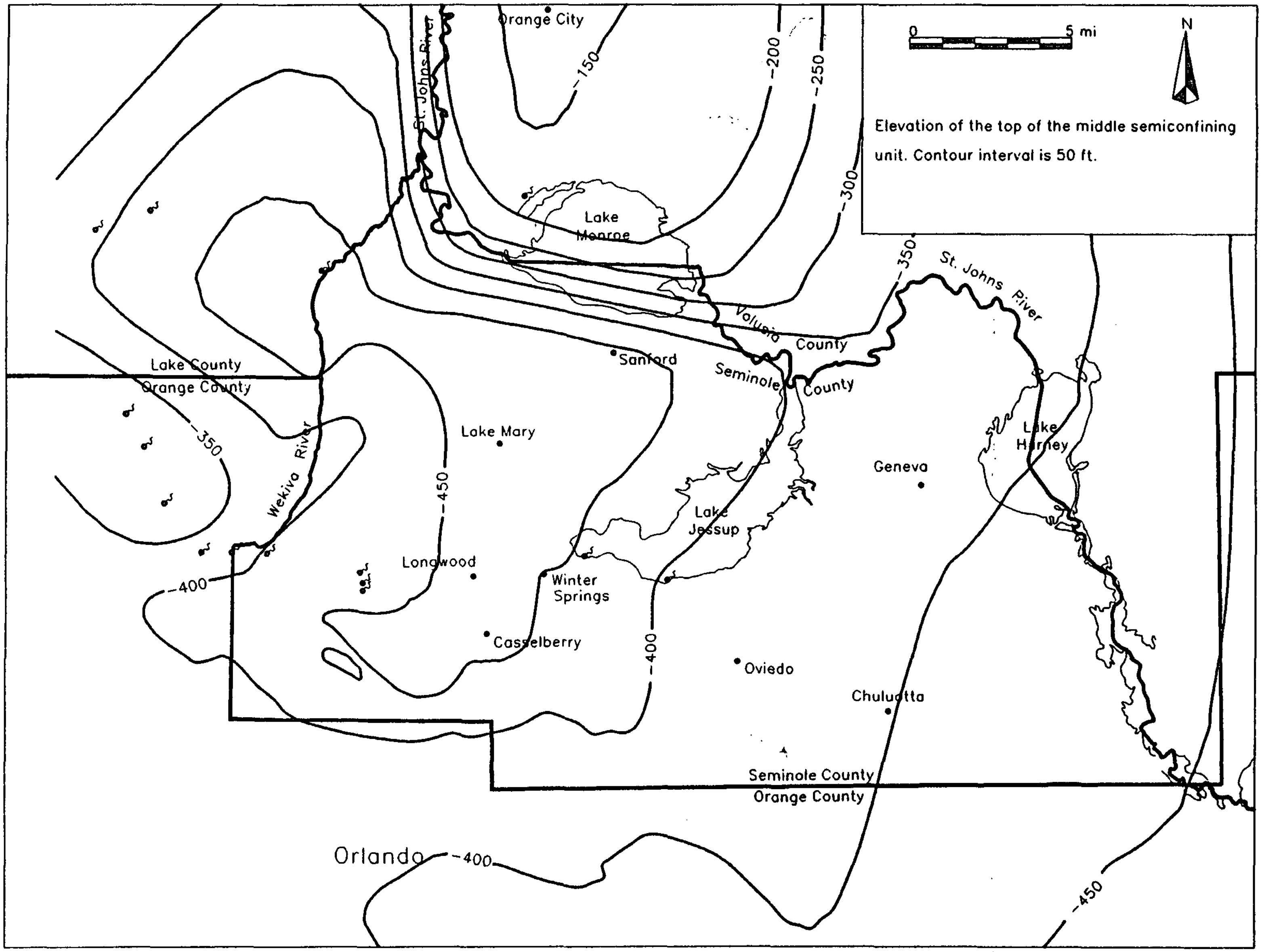


Figure 3.5 Altitude of the top of the middle semiconfining unit supplied by the SJRWMD. Datum is mean sea level.

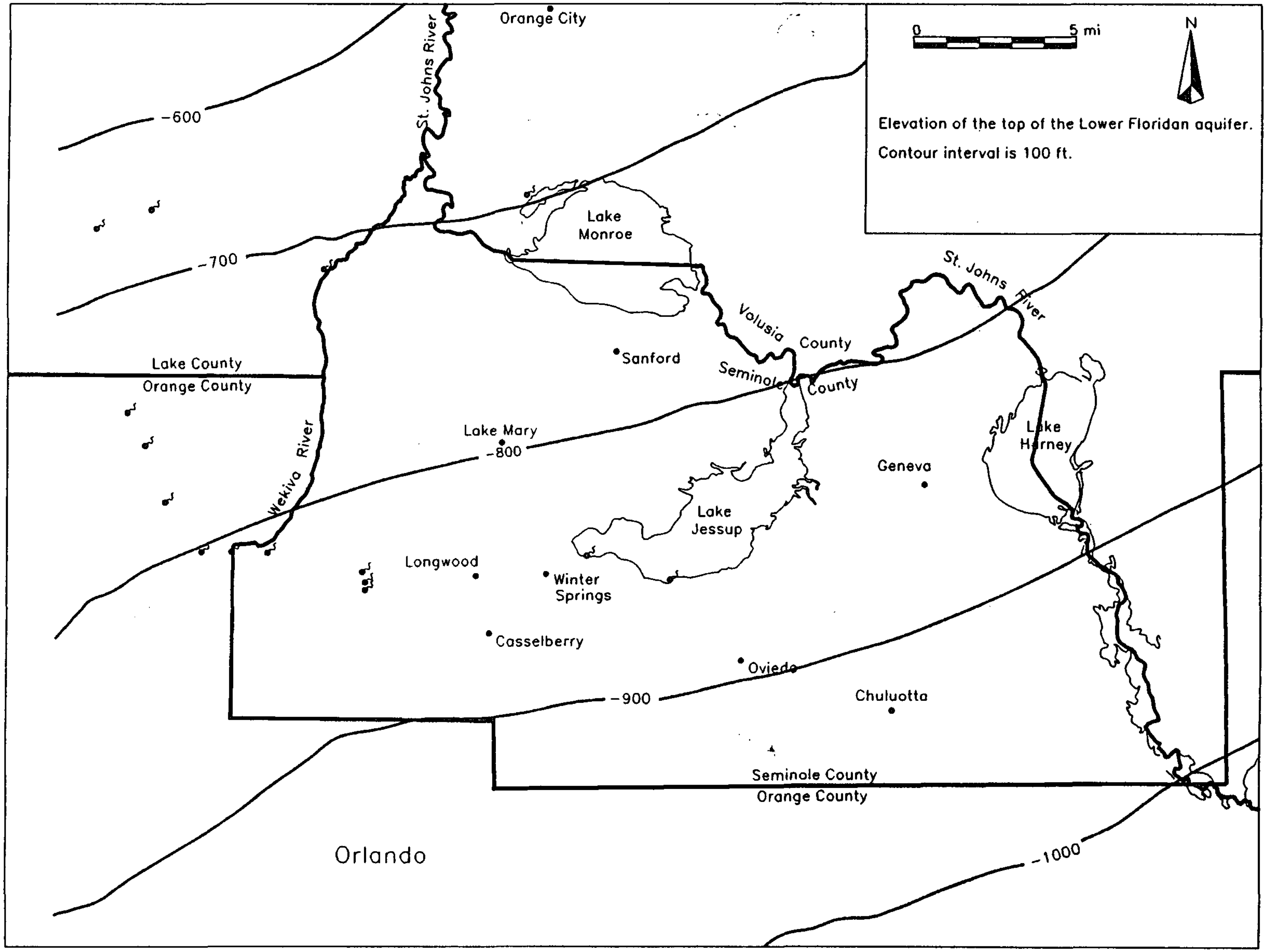


Figure 3.6 Altitude of the top of the Lower Floridan aquifer after Miller (1986). Datum is mean sea level.

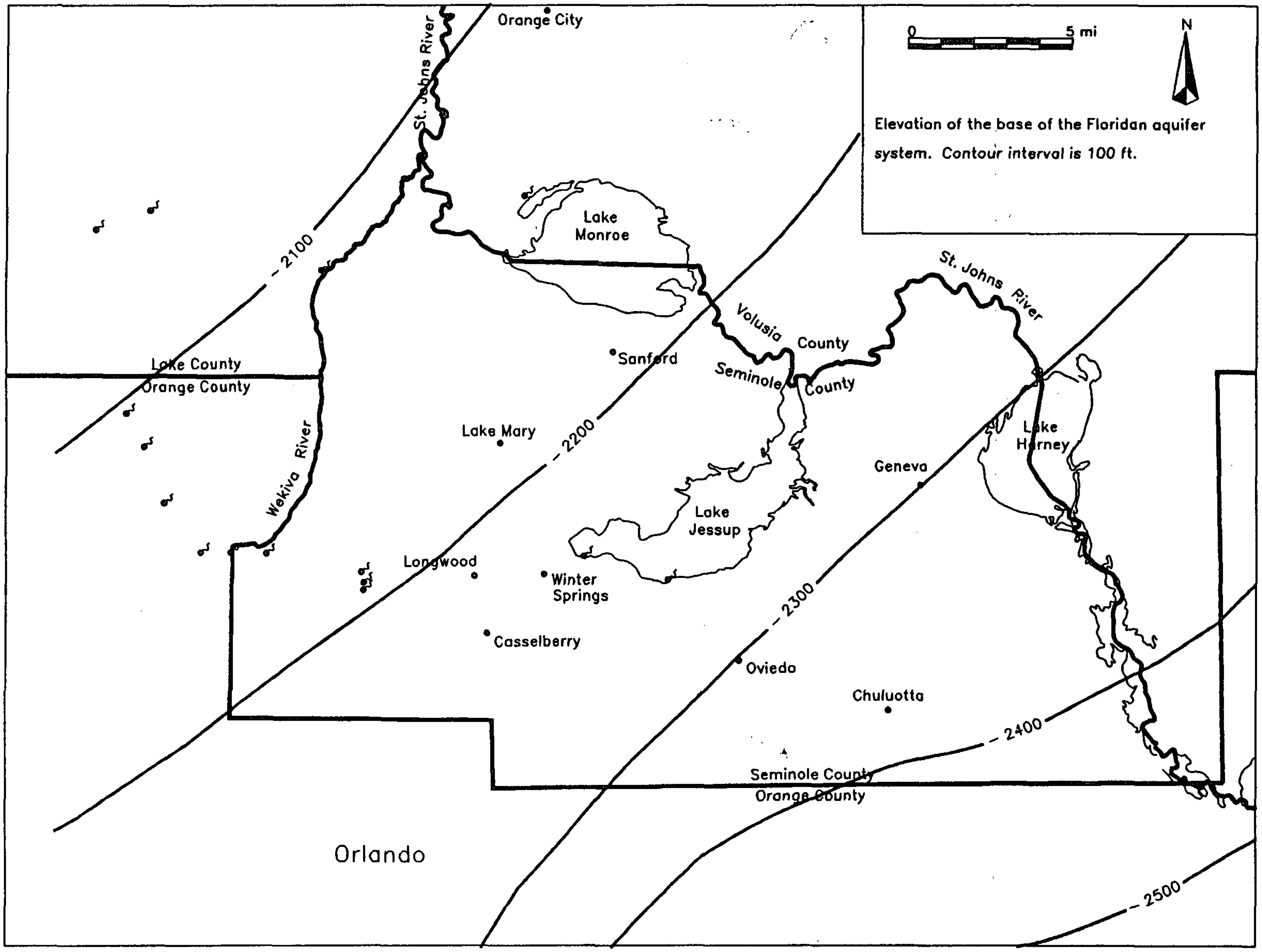


Figure 3.7 Altitude of the bottom of the Floridan aquifer system after Miller (1986). Datum is mean sea level.

thick production zone identified by the SJRWMD, the top of the middle semiconfining unit, and the bottom of the Lower Floridan aquifer. The top of the middle semiconfining unit is equivalent to the bottom of the Upper Floridan, and the bottom of the middle semiconfining unit is equivalent to the top of the Lower Floridan. Elevations for the bottom of the middle semiconfining unit and the bottom of the Lower Floridan aquifer were taken from Miller (1986), and the elevations of all other surfaces were taken from maps provided by the SJRWMD.

3.4 Water Quality

This section provides an overview of the water quality in the Upper and Lower Floridan aquifers within the Phase V study area. Since chloride is the predominant anion in seawater, most technical work focuses upon the chloride concentration as an indicator of overall water quality. The following discussions, therefore, will be limited to water quality in terms of dissolved chloride concentrations.

3.4.1 Upper Floridan

Several studies, including Tibbals (1977 and 1990), Toth et al. (1989), Blackhawk Geosciences (1992), Camp, Dresser and McKee (1991), and Phelps and Rohrer (1987) provide extensive discussions concerning water quality in the Upper Floridan, and to some degree the Lower Floridan, within the study area. In general, the dissolved solids (and chloride) content of the ground water is smaller in the western and southern portions of Seminole County, and increases to the northeast (Figure 3.8). The poor quality water in eastern Seminole and Orange counties and regions further east is attributed to the presence of relict seawater, which presumably entered the Floridan aquifer system when sea level was higher than it has been in the recent past (Tibbals, 1990). It is believed that this water is being "flushed" from the system at a rate so slow that regionally the saltwater body may be considered to exist at steady-state conditions. This conclusion is supported by Toth (1988), who found no apparent trend in chloride concentrations (increasing or decreasing) from the mid 1940's to the late 1970's and early 1980's in various Upper Floridan wells in north-central Brevard County, and by Toth et al. (1989), who

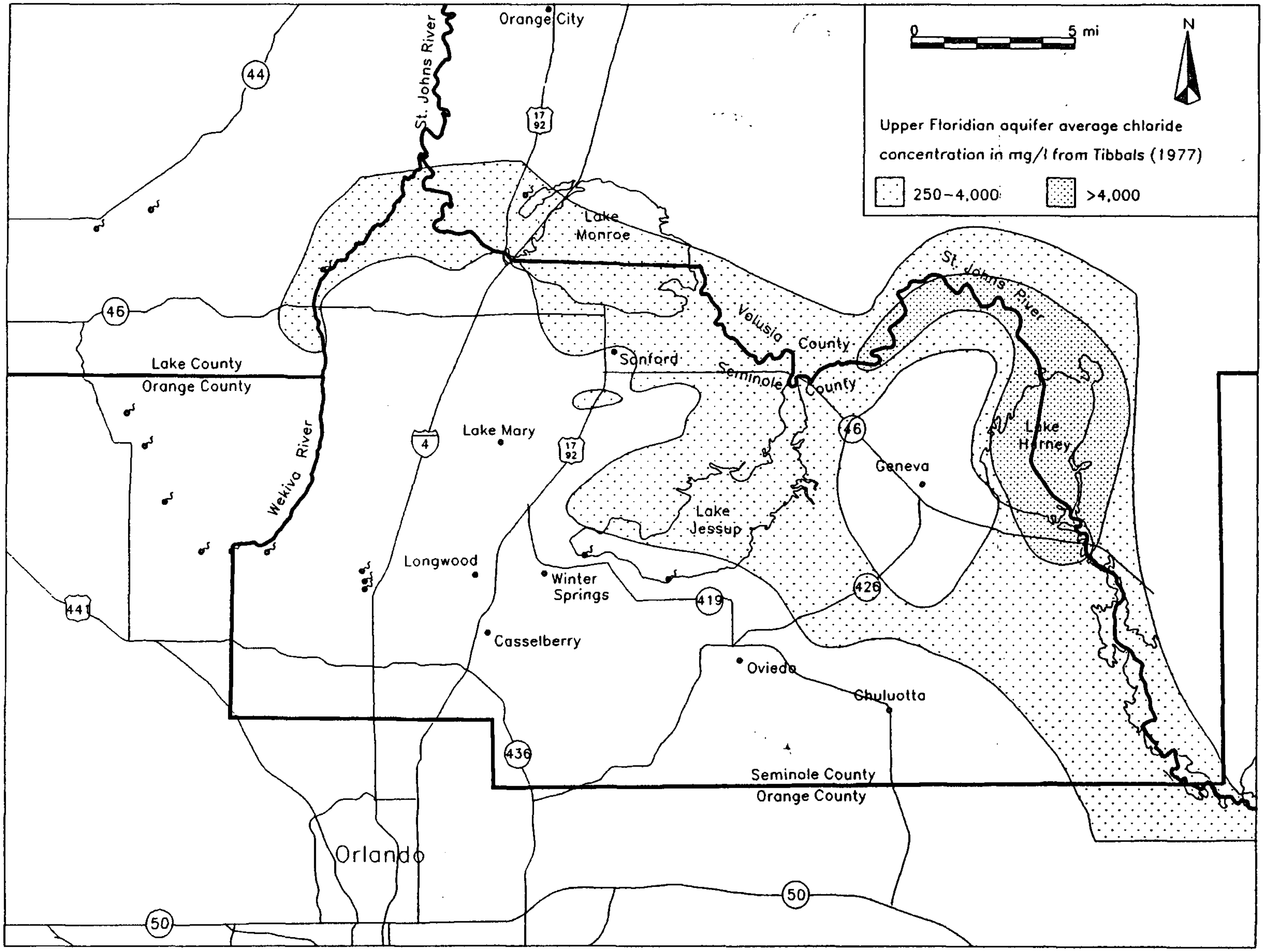


Figure 3.8 Estimated zones of chloride concentrations in mg/ℓ for the Upper Floridan (adapted from Tibbals, 1977).

found no increasing trend in chloride concentrations for wells sampled in the Wekiva River basin during 1973 and 1986.

The estimated zones of chloride concentration illustrated in Figure 3.8 were derived by Tibbals (1977). Tibbals derived these zones based upon chloride concentration samples obtained from various Upper Floridan aquifer wells throughout Seminole County. Presumably, each of these wells were completed to various depths and were open to different intervals within the aquifer. Consequently, the zones of chloride concentration presented in Figure 3.8 are interpreted as an average throughout the Upper Floridan aquifer, rather than the lateral position of an isochlor, for example, at the top or the middle of the aquifer.

Several significant features of the occurrence of saltwater in Seminole County are illustrated by Figure 3.8. First of all, the 250 mg/ℓ isochlor generally has a southeast-northwest orientation across the county, although locally the orientation of the isochlor is quite variable. For example, due east of Lake Mary the 250 mg/ℓ isochlor forms a local reentrant. Secondly, high chloride concentrations tend to occur in the vicinity of the St. Johns River, as well as along the Wekiva River. The highest chloride concentrations in the Upper Floridan in the study area occur in the vicinity of the St. Johns River and Lake Harney in eastern and northeastern Seminole County. Finally, the Geneva freshwater lens exists in eastern Seminole County under the Geneva Hill topographic high.

The existence of saltwater in the Upper Floridan in Seminole County is highly dependent upon the distribution of recharge and discharge areas within the county, upon structural geological controls such as faults, and upon natural ground-water flow features such as springs. Figure 3.9 illustrates the areal distribution of Upper Floridan recharge and discharge areas throughout the study area. Regions of high to moderate recharge generally correspond to regions of high topography, poorly developed surface drainage and numerous sinkhole lakes. Such conditions are prevalent in west-central and portions of southern Seminole County. For the most part, the 250 mg/ℓ isochlor exists along the fringe of the moderate-high recharge regions of the county. The high recharge zone due west of Lake Harney exists due to the Geneva topographic high

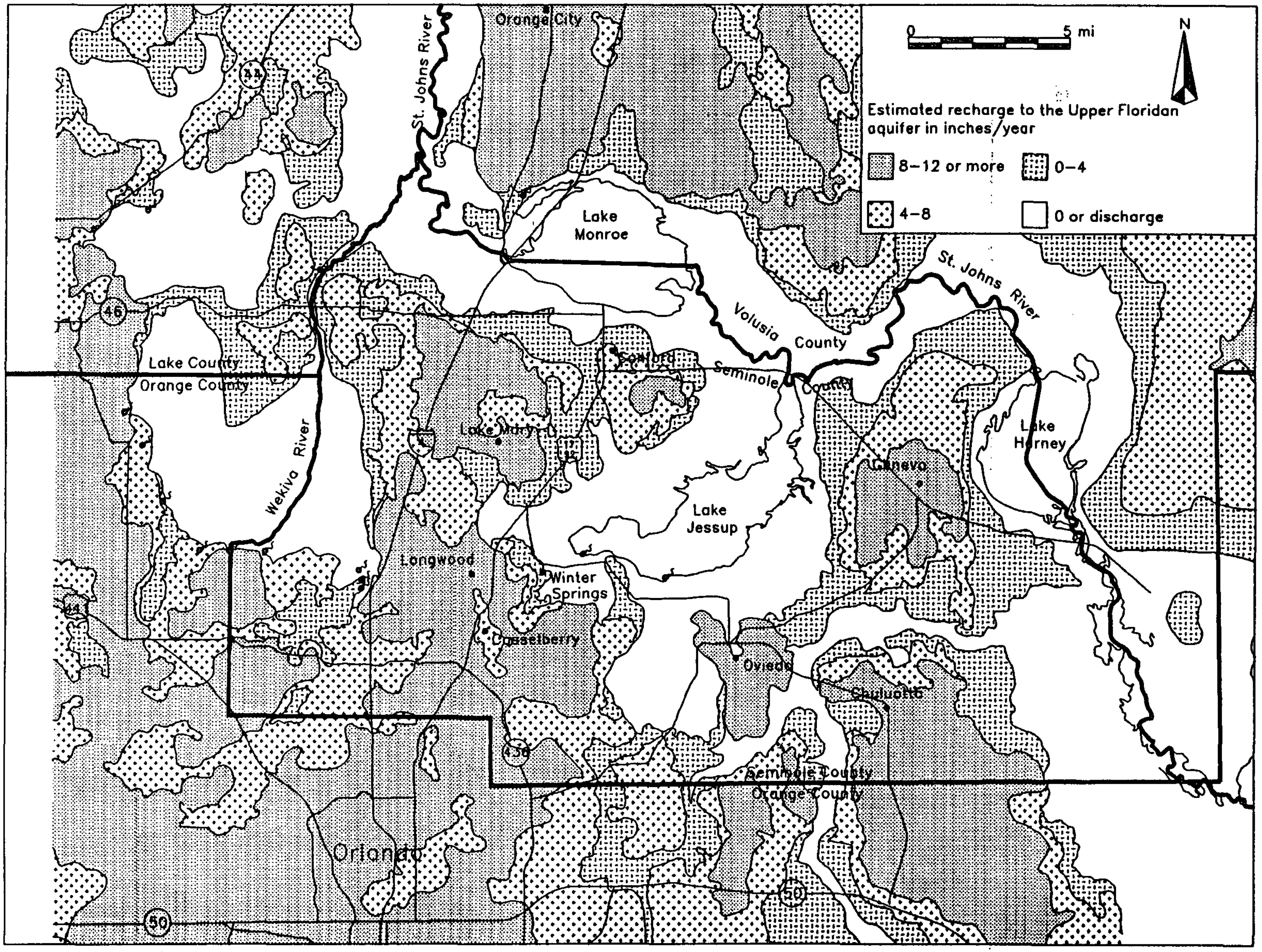


Figure 3.9 Zones of recharge and discharge to the Upper Floridan aquifer in Seminole County and adjoining regions (Boniol et al., 1993).

region, and it is this recharge zone that is responsible for the Geneva freshwater lens in the Upper Floridan aquifer.

The St. Johns River, which forms the eastern and northern boundaries of Seminole County, flows along postulated zones of subsurface faulting. The depth of displacement along the faults is generally believed to be relatively shallow, primarily affecting rocks that compose the Upper Floridan aquifer (Miller, 1986). However, in some areas, such as in the vicinity of Blue Spring just north of Seminole County, the effective depth of displacement due to faulting may be greater and rocks that form the middle semiconfining unit may be affected (Tibbals, 1990). It is clear that high chloride concentrations occur in the Upper Floridan centered along the St. Johns River and along the Wekiva River where it forms the boundary between Lake and Seminole Counties. It is generally believed that in these regions, upward movement of salty water from the Lower Floridan maintains the high chloride concentrations in the Upper Floridan. Tibbals (1990) states

> The faults that are believed to be present along the St. Johns River could provide an avenue for substantial upward movement of brackish water to replace that which is discharged either by springs or by diffuse upward leakage. However, even if faults are absent, brackish water can be discharged and still be continually replenished by brackish water from depth. The natural upward hydraulic gradient that is present near springs provides the hydraulic potential to move brackish water upward.

A third factor influencing the high chloride concentrations along the Wekiva and St. Johns Rivers in northern Seminole County is the nature of the regional ground-water flow system within the study area. In western Seminole County and in the northern portion of Orange County which adjoins Seminole County, there are a series of major springs (Rock, Wekiva, Miami, Starbuck, Sanlando, Palm) that occur along the edge of the Wekiva Swamp region, which is a low-lying swampy area that is a discharge zone for the Upper Floridan. These springs capture virtually all of the water in their flow fields, and consequently downgradient (generally to the east and northeast) of the springs hydraulic gradients are reduced and ground-water flow becomes sluggish (Tibbals, 1990). The sluggish ground-water flow in these regions reduces the capacity of the aquifer to "flush out" water with high chloride concentrations, whether the high chloride water is relict seawater or water that has moved vertically upward from the Lower Floridan.

Blackhawk Geosciences (1992) and CEES-Blackhawk Geosciences Division (1993) conducted a reevaluation of a series of time domain electromagnetic (TDEM) measurements made in Seminole County during the mid to late 1980s. The objective of the TDEM surveys was to determine information about water quality in the Upper Floridan aquifer; more specifically the depth to the 250 mg/ℓ and 5,000 mg/ℓ isochlors. The results of this analysis are reproduced in Figures 3.10 (location of the 250 mg/ℓ isochlor) and 3.11 (depth to 5,000 mg/ℓ isochlor). To facilitate the comparison of the Blackhawk Geosciences results with those of Tibbals (1977), the position of the 250 mg/ℓ isochlor as mapped by Tibbals (Figure 3.8) is also presented in Figure 3.10.

As noted previously, the 250 mg/ℓ isochlor, or front, presented by Tibbals (1977) is interpreted as the location where the average chloride concentration within the Upper Floridan aquifer is 250 mg/ℓ or greater. The 250 mg/ℓ isochlor determined by Blackhawk Geosciences (1992) using well data is interpreted to be analogous to the 250 mg/ℓ isochlor as determined by Tibbals (1977), since Blackhawk Geosciences used various wells throughout Seminole County to determine the isochlor position. The number of wells used by Blackhawk Geosciences (1992) during their study that correspond to wells used by Tibbals (1977) is unknown. The 250 mg/ℓ isochlor determined by Blackhawk Geosciences (1992) using TDEM measurements is called the "lateral boundary" in the Blackhawk Geosciences report. Based upon a depth to the 250 mg/ℓ isochlor plot in that report, the TDEM 250 mg/ℓ isochlor in Figure 3.10 appears to be the estimated isochlor location at or near the top of the Upper Floridan aquifer.

In general, the 250 mg/ℓ isochlor as mapped by Tibbals (1977) using well data, and that as mapped by Blackhawk Geosciences (1992) using well data are quite similar throughout Seminole County. The 250 mg/ℓ isochlor determined using TDEM measurements is similar to that obtained using well data in northern Seminole County and in central Seminole County in the vicinity of the western half of Lake Jessup. In other regions of the county, however, namely

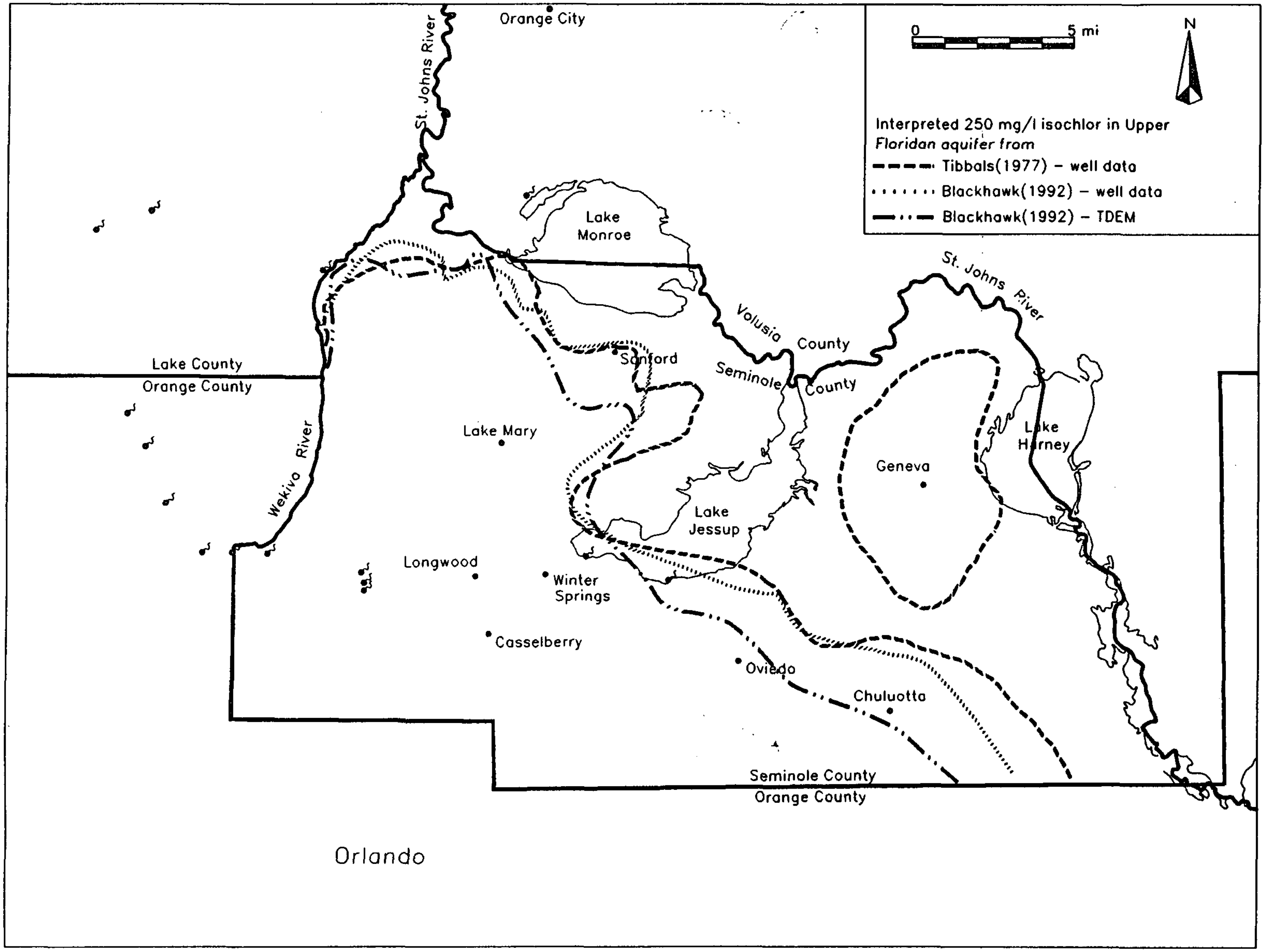


Figure 3.10 Position of the 250 mg/ℓ isochlor in the Upper Floridan aquifer as determined by CEES-Blackhawk Geosciences Division (1993) using TDEM measurements and well data, and as determined by Tibbals (1977) using well data.

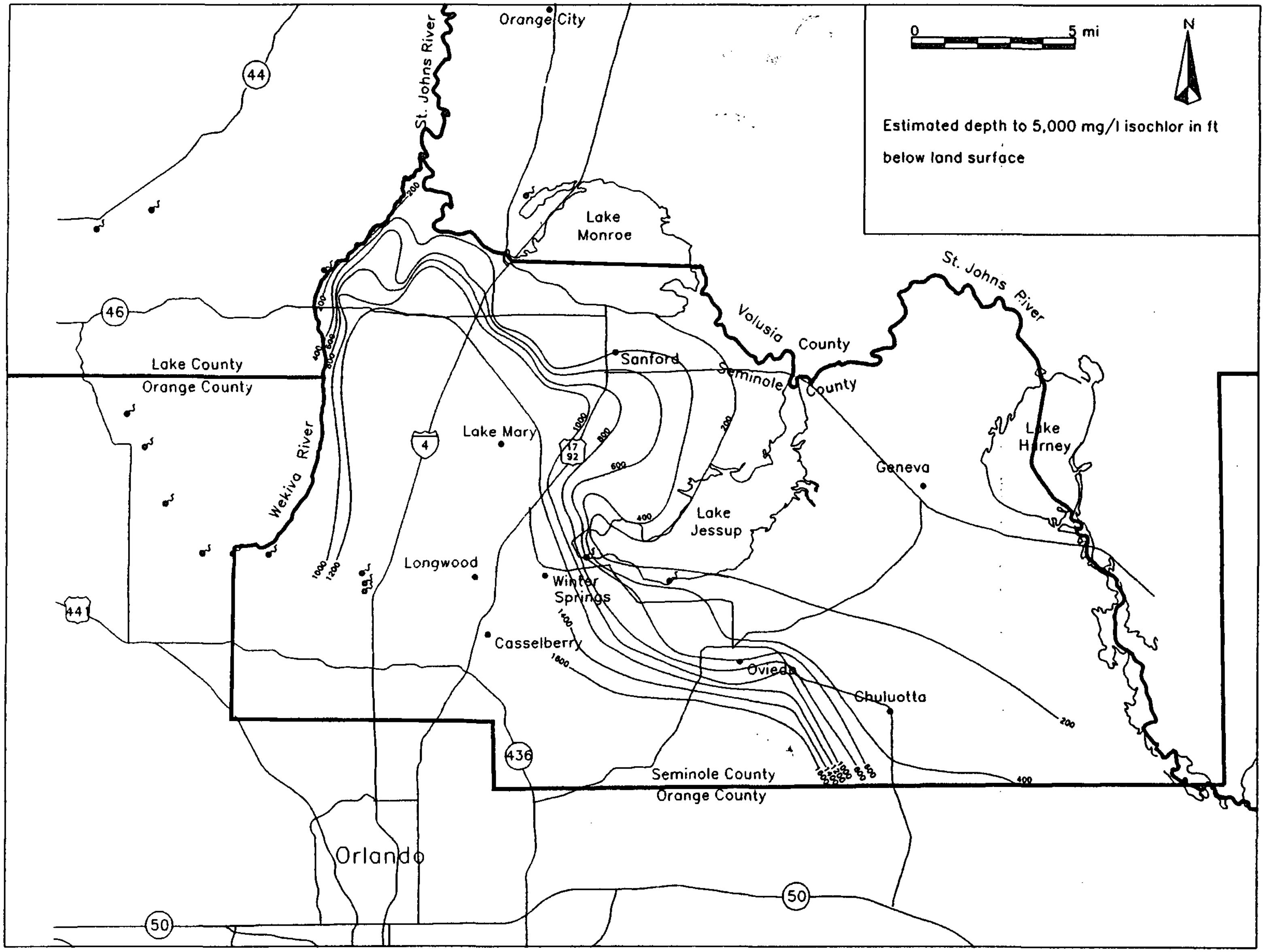


Figure 3.11 Location of the 5,000 mg/ℓ isochlor in the Floridan aquifer system as determined by CEES-Blackhawk Geosciences Division (1993) using TDEM measurements.

between Lake Monroe and Lake Jessup and southeast of Lake Jessup, the 250 mg/ℓ isochlor determined from TDEM measurements is further west by about 1.5-3 miles than that determined using well data. For the purposes of this study, it was assumed that the isochlors determined from well data are more indicative of field conditions than those determined using geophysical techniques.

Figure 3.11 illustrates the depth to the 5,000 mg/ℓ isochlor as mapped by CEES-Blackhawk Geosciences Division (1993). This map is a revised version of that presented in Blackhawk Geosciences (1992). In general, the shape of the 5,000 mg/ℓ isochlor is similar to that of the 250 mg/ℓ isochlor, only it occurs at greater depth. This figure indicates that in central and southeastern Seminole County, ground water with chloride concentrations of 5,000 mg/ℓ and greater exists in the Upper Floridan aquifer (see the 200 ft contour line in Figure 3.7). This assertion is not supported by observation well data, which generally indicate chloride concentrations of about 300-1,000 mg/ℓ in regions east of the 250 mg/ℓ isochlor in Seminole County.

In light of the preceding discussion, the position of various isochlors as indicated by TDEM measurements are believed to be indicative of general conditions on a large (regional) scale, but they are not sufficiently accurate for local scale analysis or for detailed model calibration purposes.

In order to check the accuracy of the 250 mg/ℓ isochlors determined by Tibbals (1977) and Blackhawk Geosciences (1992) using well data, and to determine the distribution of chloride concentrations higher than 250 mg/ℓ, the SJRWMD chloride concentration data base was utilized. The data base was screened to extract observation records for wells that have casing depth and total depth reported. Wells with a completion depth of 500 ft or less were considered to be open to the Upper Floridan aquifer. If a given well had multiple chloride samples, the reported chloride concentrations were averaged and the average concentration was plotted out to the base map scale.

This exercise confirmed that the 250 mg/ℓ isochlors as determined by Tibbals and Blackhawk Geosciences conform to the observation data as extracted from the SJRWMD data base. It should be noted, however, that there are very few observation points in the immediate vicinity of the 250 mg/ℓ isochlor, and consequently the exact position of the isochlor is somewhat uncertain. There was insufficient data to determine precisely the position of higher concentration isochlors, such as 1,000 mg/ℓ isochlor, but in general chloride concentrations in Seminole County east of the 250 mg/ℓ isochlor range from several hundred mg/ℓ to over 1,000 (about 1,200 or so) mg/ℓ.

Finally, there is chloride concentration vs. depth data within the Upper Floridan aquifer for two SJRWMD test wells in the SJRWMD database. Well S-0087 (actually a well cluster) is located about 3 miles northeast of Geneva slightly outside of the Phase V model domain. This well is within the Geneva freshwater lens (Figure 3.8). Water quality samples obtained from this well indicate that low chloride water (about 100 mg/ℓ) exists to a depth of about 200 ft below msl, which is about one-half of the thickness of the Upper Floridan aquifer at that location. From 200-375 ft below msl, which corresponds to the top of the middle semiconfining unit, chloride concentrations rapidly increase to about 8,000 mg/ℓ. Within the top portion of the middle semiconfining unit, from about 375-550 ft below msl, chloride concentrations fluctuate from about 8,300 mg/ℓ to 9,800 mg/ℓ, and average about 9,000 mg/ℓ.

Well V-0375 is at Gemini Springs on the northwest shore of Lake Monroe in Volusia County (Figure 3.1). Water quality samples obtained from this well indicate chloride concentrations of about 2,500 mg/ℓ throughout the Upper Floridan aquifer. At about the top of the middle semiconfining unit (185 ft below msl), chloride concentrations increase to more than 8,000 mg/ℓ, and chloride concentrations continue to increase to 11,600 mg/ℓ over the next 140 ft. The chloride concentrations observed for each of these wells, V-0375 and S-0087, indicate that at the bottom of the Upper Floridan aquifer and within the top of the middle semiconfining unit chloride concentrations increase substantially with depth, at least in the extreme northern and eastern reaches of the model domain.

3.4.2 Lower Floridan

Observed data concerning the variation of chloride concentrations in the Lower Floridan are very limited. Within the Phase V model domain, there are three test/monitor wells that penetrate the top of the Lower Floridan aquifer (Figure 3.12); these are the CDM test well 1, the Altamonte Springs test well, and two Lower Floridan aquifer test wells completed at Orange County's Western Regional wellfield site. In the southwest corner of the model domain, which corresponds to the northern half of the Orlando metropolitan area in Orange County, there are a number of Lower Floridan public supply wells with chloride concentration observations. Approximately 1 mi south of the model domain, near the center of Orlando, the Lake Ivanhoe test well nest penetrated almost the entire thickness of the Floridan aquifer system. The Sand Lake Road injection test well, located south of Orlando, which is about 8 miles south of the southwestern corner of the model domain, penetrates the entire thickness of the Floridan aquifer system. And finally, the Merritt Island injection test well, located near the center of Merritt Island, also penetrates the entire thickness of the Floridan aquifer system. The data obtained from each of these wells are summarized below.

The CDM test well 1 (Figure 3.12), marked well 8-6 in CDM (1991), was constructed and sampled in 1989 to confirm the relationship between chloride concentration and resistivity measured using the TDEM method (CDM, 1992). The well is located about 2 miles due west of Sanford and about 0.5 miles east of Twin Lakes. The well has a casing depth and completion depth of 130 ft and 1,280 ft, respectively, and is therefore open to the Upper Floridan aquifer, the middle semiconfining unit, and the upper 450 ft or so (approximately the upper one-third) of the Lower Floridan aquifer. A number of borehole geophysical logs were completed for this well, and 10 water quality samples were taken from depths of 1,170 ft to 1,300 ft below land surface (bls). The water quality samples indicated that chloride concentrations were low (18-35 mg/ℓ) in the interval 1,170 ft - 1,240 ft. Between 1,240 ft and 1,250 ft, chloride concentrations increased to 133 mg/ℓ, and they continued to increase to 241 mg/ℓ at 1,300 ft.

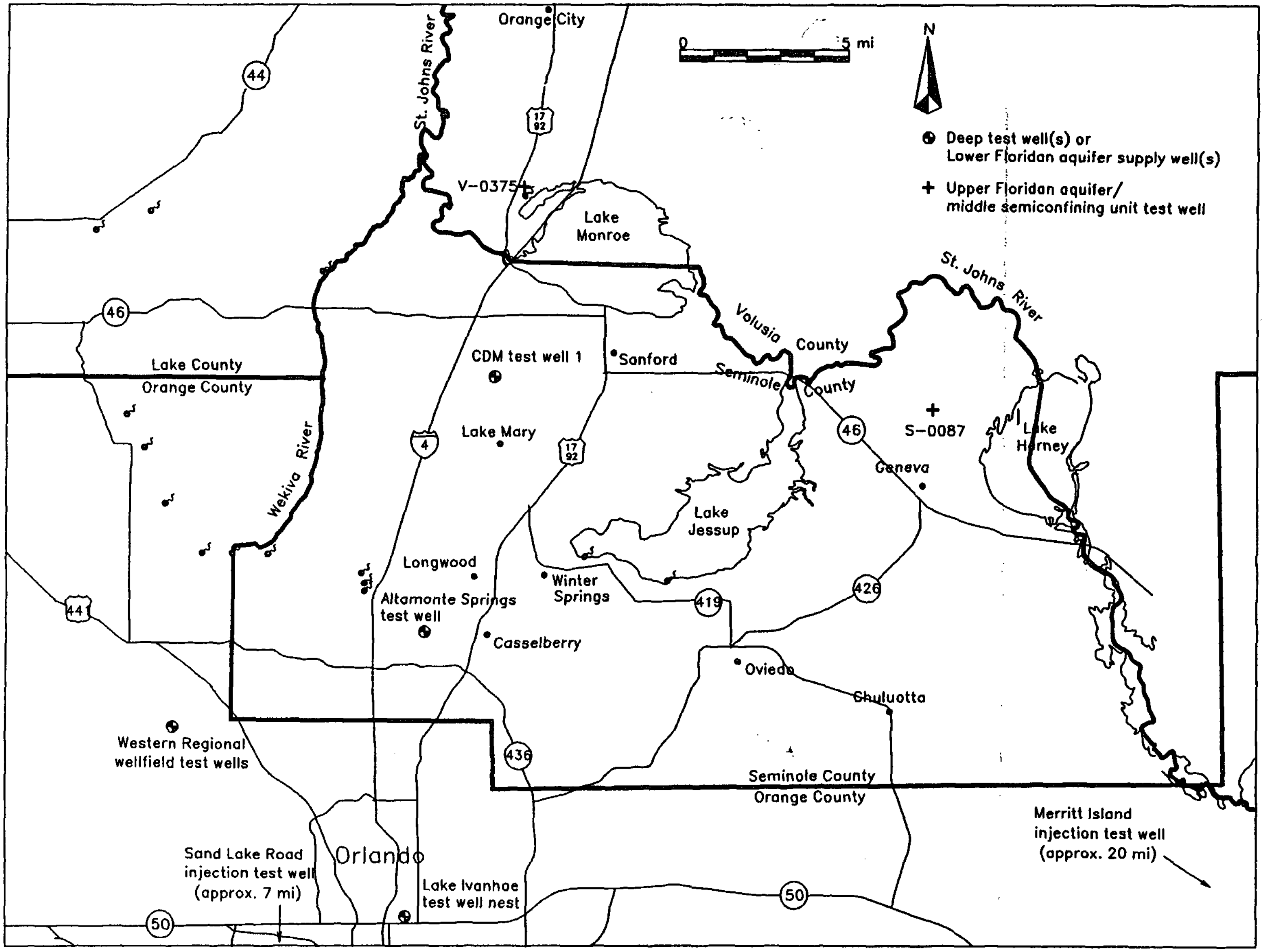


Figure 3.12. Locations of Lower Floridan test/monitor wells within and in the vicinity of the Phase V model domain.

However, in a supplemental report on the correlation of borehole data with TDEM survey results for Seminole County (Attachment A in CDM, 1992), prepared by Blackhawk Geosciences, it is stated that it is "very likely (that) the analyses of water samples is incorrect." This conclusion was reached after a comparison of water sample analyses for CDM test well 1 against borehole fluid conductivity and resistivity logs was conducted. The fluid conductivity and resistivity logs indicate a notable increase in TDS (and therefore chloride concentrations) at a depth of about 500 ft, rather than 1,240 ft as indicated by the water quality samples. In the vicinity of CDM test well 1, therefore, it would seem possible that water with chloride concentrations on the order of 250 mg/ℓ exists at about the top of the middle semiconfining unit, rather than in the Lower Floridan aquifer. Due to the apparently conflicting data obtained from this test well, the SJRWMD intends to resample the well for water quality.

The Altamonte Springs Lower Floridan aquifer test well in southwestern Seminole County (Figure 3.12) was completed in early 1993. Ardaman and Associates (1993) document the construction, testing and sampling of this well, which they call the City of Altamonte Springs Charlotte Street monitor well. This well was drilled to a depth of 1,506 ft below land surface (bls), which is approximately 550 ft into the Lower Floridan aquifer. The well was completed with 256 ft of open hole between 1,250 and 1,506 ft bls. Chloride concentrations for this well are very low; they range from 6.95 - 13.9 mg/ℓ. Major production zones at this location occur between 400 and 650 ft bls (Upper Floridan aquifer) and around 1,400 ft bls (Lower Floridan aquifer).

Orange County's Western Regional wellfield site is located within the model domain, approximately 1 mi east of the western model boundary (Figure 3.12). The hydrogeologic investigation of this site, which included the construction, testing and sampling of two Lower Floridan aquifer monitor-production wells, is documented in a report prepared by Post, Buckley, Schuh and Jernigan (1989). The first test-production well (TP-1) has a completion depth of 1,450 ft bls, with 418 ft of open hole along the bottom portion of the well. The second test-production well (TP-2) has a completion depth of 1,455 ft bls, and also has 418 ft of open hole along the bottom portion of the well. Each of these wells are open to about the upper 30 percent (approximately 400 ft) of the Lower Floridan aquifer.

Water quality samples obtained from wells TP-1 and TP-2 had very low chloride concentrations (less than 6 mg/ℓ). Step-drawdown tests conducted for both test wells indicated a range of Lower Floridan aquifer parameters, depending upon the method of analysis applied. Transmissivities ranged from about 260,000 ft^2/d - 936,000 ft^2/d, and storativity ranged from 1.7×10^{-3} - 4.1×10^{-3}. Water level observations collected at this site indicate that hydraulic heads in the Upper Floridan aquifer are about 2.5 ft higher than hydraulic heads in the Lower Floridan aquifer, indicating that in the vicinity of the Western Regional wellfield the Lower Floridan aquifer receives recharge (vertical leakage) from the Upper Floridan aquifer.

The Lake Ivanhoe test well nest is located about 1 mi south of the model domain near the center of Orlando (Figure 3.12). Three monitor wells compose the well nest; two wells are open to the Lower Floridan aquifer and one well is open to the Upper Floridan aquifer. The two Lower Floridan wells are discussed below. Physical information and sampling histories for the Lake Ivanhoe well nest were provided by the SJRWMD (unpublished data).

Well OR0465 is the deepest well; it has a total depth of 2,089 ft bls and a casing depth of 2,060 ft bls. Land surface elevation at this well is 83.11 ft msl. This well penetrates about 1,000 ft into the Lower Floridan aquifer, and samples a zone about 300 ft above the bottom of the Lower Floridan aquifer. Chloride concentrations for this well ranged from 11-23 mg/ℓ during 1987, and hydraulic head values ranged from 41.3-47.3 ft msl during 1989-1991, but averaged about 44 ft msl.

Well OR0467 is the second deepest well; it has a total depth of 1,350 ft bls and a casing depth of 1,300 ft bls. Land surface elevation at this well is 82.95 ft msl. This well penetrates about 250 ft into the Lower Floridan aquifer, and therefore samples a zone near the top of the aquifer. Chloride concentrations for this well are not available, but there is little doubt that they are quite low at this location. Hydraulic head values observed for this well ranged from 41.65-47.62 ft msl during 1989-1991, and averaged around 44.8 ft msl. The vertical hydraulic gradient between wells OR0467 and OR0465 fluctuates between upward and downward, and is on the order of 10^{-4}.

The Sand Lake Road injection test well, completed in 1977, is located just south of Orlando. The construction and testing of this well is documented in Geraghty and Miller (1977). This well has a total depth of 6,193 ft and fully penetrates the Floridan aquifer system. The highest chloride concentration sampled from the Floridan aquifer system at this site was 55 mg/ℓ at a depth of 2,350 ft bls. However, it is possible that this value could be artificially low due to the downward leakage of low-chloride water in the borehole (Geraghty and Miller, 1977). Using electric logs, the total dissolved solids (TDS) of the formation water is estimated at about 1,000 mg/ℓ at a depth of 2,113 ft bls, and at about 10,000 mg/ℓ at a depth of 2,293 ft bls. These numbers indicate that chloride concentrations in the bottom 100-200 ft of the Lower Floridan could be as high as 1,000 mg/ℓ or more. In a final attempt to obtain representative water samples from the lower portion of the Lower Floridan, the monitor tube in the annulus of the injection test well (screened interval 2,005 - 2,030 ft bls) was pumped for 600 hours, removing a total of approximately 288,000 gallons of water. Five water samples were collected during this period of pumping and analyzed for chloride content; each sample chloride concentration was extremely low (1 mg/ℓ or less). However, since the volume of water that moved down the borehole is unknown, the results of this analysis are inconclusive. One observation is clear: If high chloride water does exist in the Floridan aquifer system at this location, it is limited to the extreme bottom portion of the Lower Floridan. The first sample analyzed from the basal confining unit of the Floridan aquifer system (the Cedar Keys Formation) was obtained from a depth of 2,395 ft bls and had a chloride concentration of 65,000 mg/ℓ, which is far greater than the average chloride concentration of 19,000 mg/ℓ found in seawater.

Obviously, at the Sand Lake Road injection test well, water in the Floridan aquifer system is of very high quality and exhibits low concentrations of chloride. However, a rapid transition occurs below the Lower Floridan in the low permeability Cedar Keys Formation from freshwater to a very dense brine. The brine is probably the product of a stagnant or extremely sluggish ground-water flow system within the geologic units that underlie the Floridan aquifer system. The fact that brines of extremely high TDS content exist immediately below high-quality water in the Lower Floridan indicates that the hydraulic permeability of at least the upper portion of the Cedar Keys Formation must be extremely low in the vicinity of the well.

In the vicinity of Orlando, which corresponds to the southwestern corner of the model domain, there are a number of public supply wells completed to various depths in the Lower Floridan aquifer. All of these wells extract water of very low chloride concentration (on the order of 10 mg/ℓ). Since several of these wells are in close proximity to the Orange County - Seminole County border, it seems likely that throughout much of southwestern Seminole County, in the general vicinity of Altamonte Springs, water in the Lower Floridan aquifer is fresh throughout most or all of the aquifer thickness.

The Merritt Island injection test well is located on Merritt Island about 20 miles southeast of Seminole County. The construction and testing of this well was conducted in 1984 and is documented in Geraghty and Miller (1984). The well was drilled to a total depth of 2,701 ft below land surface (bls), and it penetrates the entire thickness of the Floridan aquifer system (the last 30 ft of the well were completed in the low permeability Cedar Keys Formation). The zones of high hydraulic conductivity identified from the test well data correlate well to the reported depths of the Upper and Lower Floridan aquifers in Miller (1986) and Tibbals (1990).

Table 3.1 lists observed values of chloride concentration and TDS versus depth at the Merritt Island test well. This table shows that the average chloride concentration within the top of the Upper Floridan at this point is about 2,200 mg/ℓ, and the freshwater/saltwater interface (9,500 mg/ℓ) occurs between 340 and 950 ft bls, probably within the middle semiconfining unit. Chloride concentrations in the bottom of the middle semiconfining unit and throughout the Lower Floridan are approximately equal to that of seawater (19,000 mg/ℓ).

In addition to the above point measurements of chloride concentrations in the Lower Floridan, there is a map of estimated depth to water having chloride concentration greater than 10,000

Table 3.1 Chloride and total dissolved solids concentrations for various depth intervals at the Merritt Island deep injection test well (Geraghty and Miller, 1984).

Interval (ft)	Chloride (mg/l)	TDS (mg/l)
128 - 340 a*	2,200	Not Analyzed
950 - 1055 b	14,800	23,630
1150 - 1315 c	20,100	36,010
1418 - 1501 c*	19,200	34,630
1506 - 1611 c	19,900	33,840
1615 - 1660 c	20,600	34,490
1685 - 1730 d	20,300	34,300
1693 - 1798 d	18,000	30,970
1730 - 1775 d	17,800	32,900
1800 - 1905 d	19,500	35,300

* Completed monitor well samples
a Ocala Group and upper Avon Park Limestone
b Lower Avon Park Limestone and upper Lake City Limestone
c Lake City Limestone
d Oldsmar Limestone

Note: The Avon Park Limestone and the Lake City Limestone compose the Avon Park Formation as used in this report, and the Oldsmar Limestone composes the Oldsmar Formation as used in this report.

mg/ℓ developed by C.L. Sprinkle and reproduced in Tibbals (1990). This map is reproduced for the Phase V study area in Figure 3.13. This map appears to be fairly accurate based upon an analysis of available chloride sampling locations and the depth to 5,000 mg/ℓ contour map produced by CEES-Blackhawk Geosciences Division (1993). Perhaps the most important feature that Figure 3.12 portrays for the purposes of this study is that the saltwater wedge in the middle semiconfining unit and the Lower Floridan has a northeast-southwest orientation. This orientation mimics that of chlorides in the Upper Floridan. This map proved useful in determining the Lower Floridan aquifer model boundary conditions, as is described in Chapter 4.

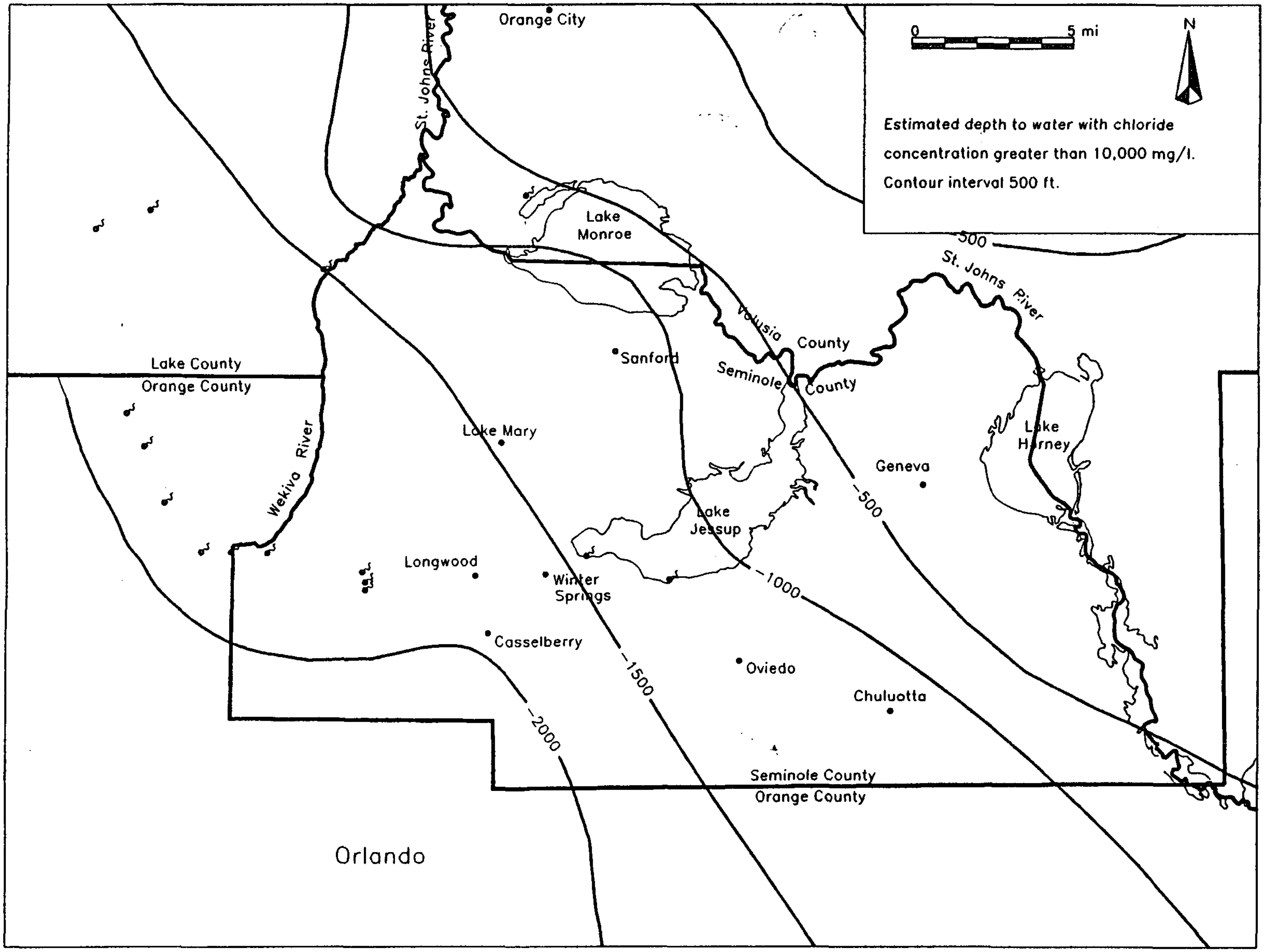


Figure 3.13 Estimated depth to water having chloride concentration greater than 10,000 mg/l. Datum is sea level. Adapted from Tibbals (1990).

4 THREE-DIMENSIONAL GROUND-WATER FLOW AND SOLUTE TRANSPORT MODEL CALIBRATION

4.1 Introduction

In this chapter, the development of a conceptual model of ground-water flow and solute transport within the study area, translation of the conceptual model into a numerical model, and calibration of the numerical model to predevelopment and average 1988 conditions are discussed. However, prior to presenting the details of the modeling effort, it is useful to outline the major capabilities, assumptions and limitations, and terminology associated with the DSTRAM computer code.

4.2 Overview of the DSTRAM Computer Code

The name DSTRAM is an acronym for Density-dependent Solute TRansport Analysis finite-element Model (Huyakorn and Panday, 1991). DSTRAM is a three-dimensional finite element code that simulates density-dependent, single-phase fluid flow and solute transport in saturated porous media. The code is designed specifically for complex situations where the flow of fluid (ground water) is influenced significantly by variations in solute concentration. DSTRAM can perform steady-state and transient simulations, and a wide range of boundary conditions can be accommodated. For contaminant transport simulation, DSTRAM can account for advection, hydrodynamic dispersion, linear equilibrium sorption, and first-order degradation. When DSTRAM is used to simulate the combined processes of density-dependent ground-water 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

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

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

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

$$h = \frac{p}{\rho_0 g} + z \tag{4.2}$$

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

$$H = \frac{h + z\eta c}{1 + \eta c} \tag{4.3}$$

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

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

For saltwater intrusion applications, this approximation leads to maximum errors of about 2.5 percent in zones where maximum concentrations are reached (i.e. c_s=19,000 mg/ℓ chloride). The percent error will decrease in direct proportion to the concentration. In DSTRAM, 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

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

where z_1 is the elevation above datum at which the environmental head (Φ) 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. Lusczynski (1961) provides a detailed derivation and explanation of the three types of head values (i.e., true, environmental and equivalent freshwater).

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

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

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 major assumptions and limitations incorporated into DSTRAM 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.

- 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 is assumed to correspond to that of an isotropic porous medium and is therefore related to two constants, α_L and α_T, which are the longitudinal and transverse dispersivities, respectively.

One final comment is appropriate concerning the DSTRAM 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 iteratives never become smaller than the tolerance, the solution is said to be non-convergent.

4.3 Conceptual Modeling Framework

The conceptual model adopted for the quantitative analysis of ground-water flow and solute (salt) transport in east-central Florida is that of a dual aquifer system separated by a semiconfining unit. The system is bounded at its base by an impermeable boundary, and at its top by a head-dependent flux boundary that provides areally distributed recharge or discharge directly to the Upper Floridan. For postdevelopment conditions pumpage occurs in both aquifers.

In many previous modeling studies of regional ground-water flow in east-central Florida, the Floridan aquifer system has been divided into two distinct producing zones separated by a semiconfining unit (see, for example, Tibbals (1990) or Blandford and Birdie (1992b)). In this approach, only the vertical leakage of water (up or down) through the middle semiconfining unit is simulated; horizontal ground-water flow through the semiconfining unit is assumed to be insignificant and is not accounted for. On a regional scale, the error associated with this assumption is insignificant because of the large contrast in hydraulic conductivities between the Upper and Lower Floridan aquifers and the middle semiconfining unit. Conversely, flow within the Upper and Lower Floridan aquifer units is assumed to be horizontal in this type of modeling framework.

For the current work, each of the major hydrogeologic units (Upper Floridan, middle semiconfining unit, Lower Floridan) had to be discretized into multiple layers to reasonably account for density-dependent ground-water flow and solute transport processes that occur in the vertical direction, since both the flow of ground-water and the distribution of chlorides is of primary importance. As is discussed in Section 4.5, the three-dimensional model domain was divided into 19 nodal layers for the purposes of this study. Furthermore, through the use of a curvilinear mesh, the variations in thickness of the hydrogeologic layers were directly incorporated into the simulation methodology. This approach is superior to that of using simple horizontal layers since the slope of the hydrogeologic units may significantly influence the density-dependent flow of ground water.

In order to correctly calibrate the DSTRAM model so that it could be applied with confidence to predict future conditions, it was necessary to calibrate the model to predevelopment, as well as postdevelopment, hydrogeologic conditions. Although the ground-water flow field in regions of the study area that contain primarily low-chloride water will equilibrate to imposed stresses rather quickly (stresses may be anthropogenic, such as pumping, or natural, such as rainfall higher or lower than average), the same cannot be said of chloride concentrations. Fresh ground-water flow fields may equilibrate to imposed stresses within a matter of days or weeks because changes in pressure are propagated rapidly throughout the aquifer system. Chloride concentrations, however, can take many tens or hundreds of years to equilibrate to changes in the physical system since the chloride ions in solution must migrate in response to the imposed stresses until a new equilibrium between chloride concentrations and the density-dependent ground-water flow field is achieved. Throughout most of the study area, and in particular the eastern regions where chloride concentrations are highest, chloride concentrations do not seem to have been significantly affected by the changes in hydrogeologic conditions from predevelopment to 1988 (Section 3.4).

4.4 Model Domain

The Phase V model domain, outlined in Figures 3.1 and 4.1, was selected after careful consideration of the ground-water flow system within the region of interest, the modeling objectives, and the computational requirements of the DSTRAM computer code. In general, an optimal mix of the following specific objectives and constraints was sought:

- The model boundaries should correspond to the degree possible to naturally occurring, known boundary conditions. This objective is more critical for the transport (chloride) boundary conditions than it is for the ground-water flow boundary conditions, since the ground-water flow boundary conditions were obtained directly from the Phase IV regional model (Blandford and Birdie, 1992b).

- The model domain had to include all of the major wellfields in western and central Seminole County.

- Computational time for the various simulation scenarios, and therefore the number of active model nodes, had to be commensurate with the available computational resources and data availability.

The model domain encompasses most of Seminole County and portions of Orange, Lake and Volusia counties. Moving from west to east, the model domain curves up in a northeasterly direction; this configuration is consistent with the conceptualized ground-water flow and solute transport boundary conditions. The estimated predevelopment and average 1988 potentiometric surfaces portray regional flow in Seminole County to be towards the northeast, rather than due east. The boundary condition conceptualizations that give rise to the active model domain configuration are presented in detail in Section 4.6.

4.5 Finite-Element Mesh Design

An areal view of the finite element mesh used for the Phase V model simulations is presented in Figure 4.1. The mesh consists of 58,803 nodal points and 53,504 finite elements. In plan view (x-y plane), there are 33 curvilinear rows and 89 curvilinear columns. The discretization (cell size) varies from about 0.25-0.5 miles in the x-direction, and is a uniform 0.6 miles in the y-direction. The finest discretization was used where the largest variations in chloride concentrations were expected. In the vertical dimension there are 19 nodal layers. The vertical curvilinear grid for two representative cross sections (one east-west and one north-south) is illustrated in Figure 4.2.

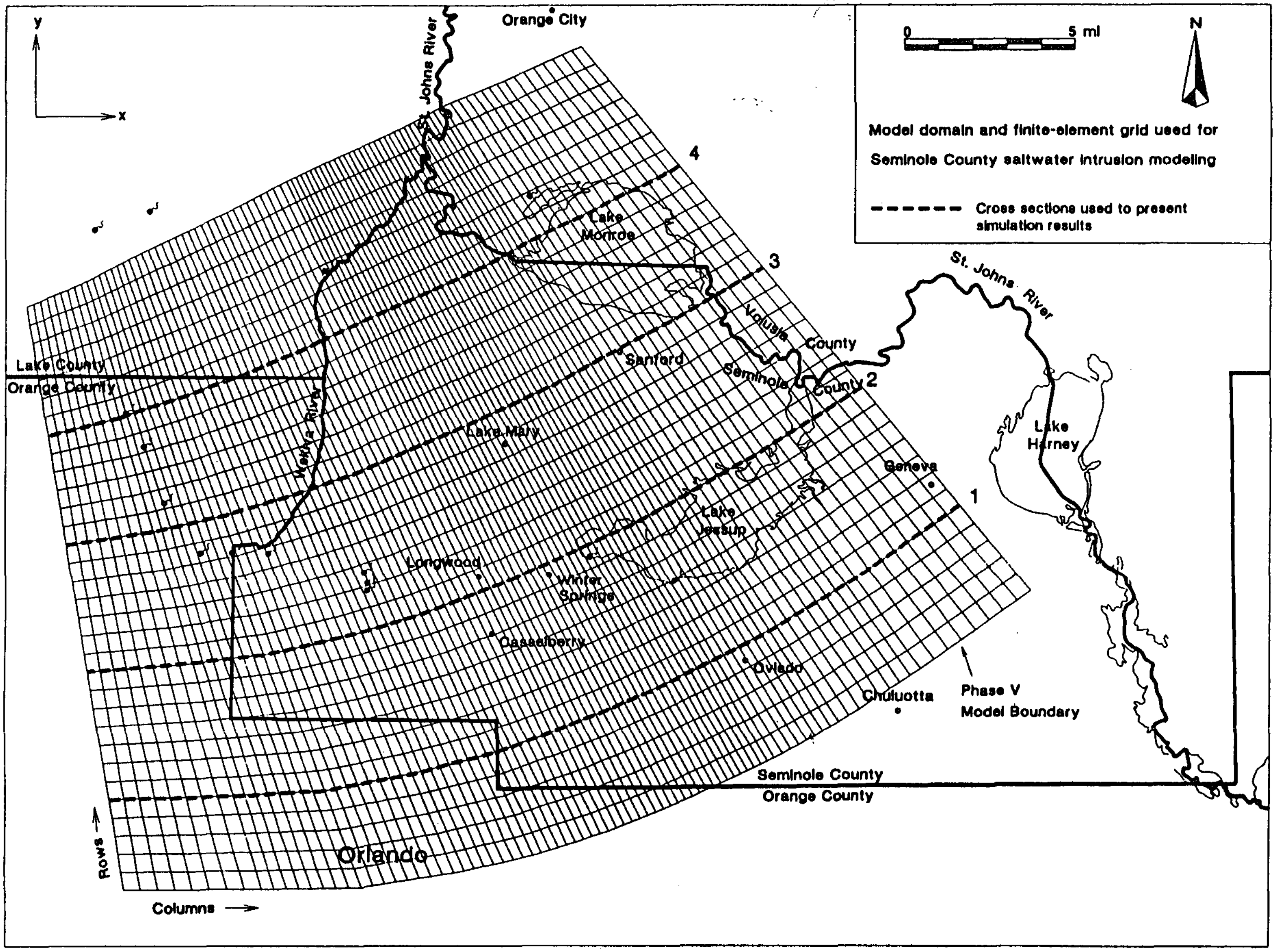
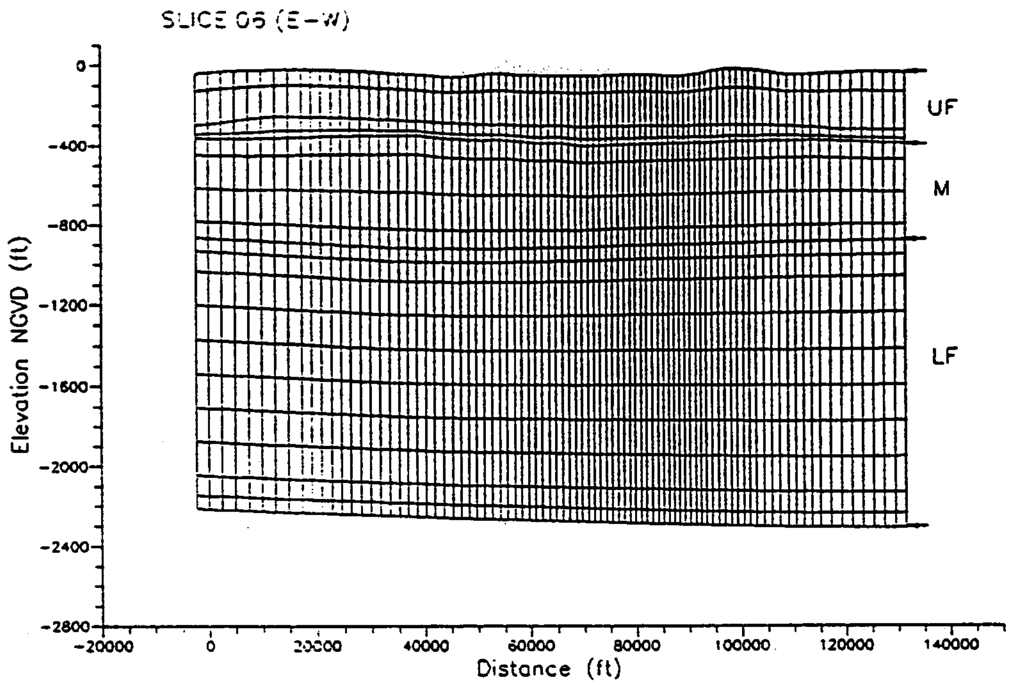
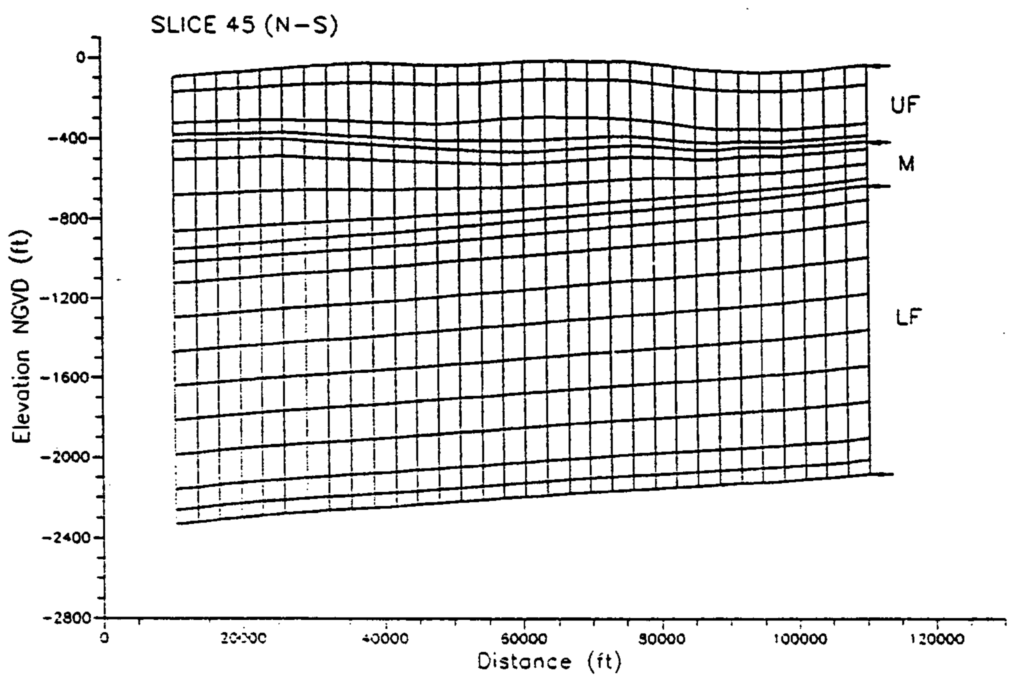


Figure 4.1 Finite-element mesh used for three-dimensional, density-dependent ground-water flow model calibration and location of four standard cross sections used to display simulation results.



(a)



(b)

Figure 4.2 Vertical discretization used for model calibration along row 6 (a) and middle column (b) of finite-element mesh.

The DSTRAM orthogonal curvilinear mesh option was used to discretize the model domain in the horizontal (x-y) and the vertical (z) dimensions. A curvilinear mesh is one where the gridlines are curved, rather than straight. This option permits a grid to be developed that conforms to the changing geometry of the various hydrogeological units, and to changing directions of ground-water flow. This option was invoked for this study because, in the vertical dimension, there are significant dips and variations in thickness of all of the major hydrogeologic units within the model domain; the slopes of the various hydrogeologic units could have a significant influence upon the density dependent ground-water flow field. In areal view, regional ground-water flow within the study area varies from due east in the vicinity of Orlando to northeast throughout most of Seminole County. Grid orientation along ground-water flow pathlines can enhance the stability, accuracy and convergence characteristics of the numerical solution scheme.

4.6 Model Boundary Conditions

This section describes the boundary conditions that were used for both ground-water flow and solute transport at the bottom, top and sides of the three-dimensional model domain. A conceptual diagram of the boundary conditions applied along the center row of the grid is presented in Figure 4.3 for reference purposes. Many of the boundary conditions are dependent upon the Phase IV modeling results documented in Blandford and Birdie (1992b), herein referred to simply as the Phase IV model.

In this section and throughout the remainder of the report, reference is frequently made to normalized concentration. Normalized concentration is a dimensionless number that varies from 0 to 1. It is obtained by dividing a given concentration by the maximum concentration in the system. For example, if the maximum concentration in the model domain is 19,000 mg/ℓ, and at some point a concentration of 5,000 mg/ℓ occurs, then the normalized concentration at that point would be 5,000 mg/ℓ $\div$ 19,000 mg/ℓ = 0.263. In this study, the maximum concentration of chloride was assumed to be 19,000 mg/ℓ (equal to that of seawater), the reference density (ρ_o) of the water was taken as 0.997 g/cm^3 (Drever, 1982) and the maximum density of the saltwater

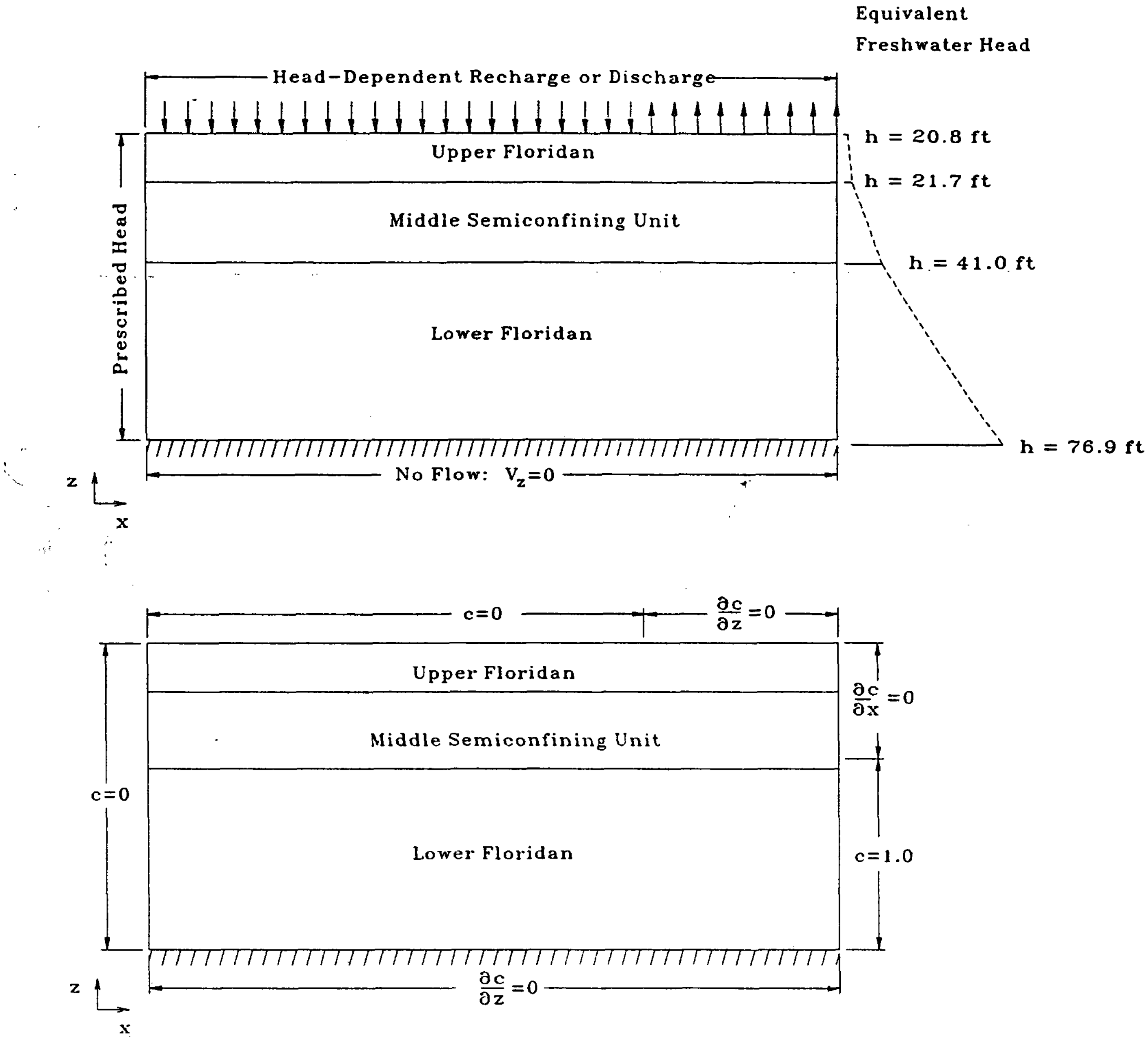


Figure 4.3 Schematic diagram of top, bottom, western and eastern boundary conditions applied along center gridline row (variable thicknesses of hydrogeologic units not reproduced).

(ρ_s) was taken as 1.02261 g/cm^3 (de Marsily, 1986). These density values are based upon an average ground-water temperature of 25°C.

An implicit relationship is assumed concerning chloride concentrations in the ground water relative to other dissolved constituents. The density values specified in the model are based upon the average concentration of the various solutes that are found in seawater. However, to determine boundary conditions, only the chloride concentrations are examined since this is the dominant anion in seawater and water quality data is generally reported in terms of chloride concentrations. The fundamental assumption in dealing with chloride concentrations rather than the concentrations of all dissolved constituents is that the proportion of chloride to the other dissolved constituents remains the same, or nearly the same, throughout the model domain.

4.6.1 Bottom Boundary

The bottom boundary of the cross section corresponds to the base of the Floridan aquifer system (bottom of the Lower Floridan). Throughout most of the model domain this boundary is considered to be impermeable to both the flow of water and the mass flux of solutes. This conceptualization is supported by the data obtained from deep test wells in the region, and in particular, the Sand Lake Road test well and the Lake Ivanhoe test well nest. At the Sand Lake Road test well, the basal unit of the Floridan aquifer system (the Cedar Keys Formation) was found to have an extremely low permeability. Furthermore, the chloride concentration in the Lower Floridan was low even at the bottom of the unit, but only a short depth into the Cedar Keys Formation chloride concentrations increased dramatically. At the Lake Ivanhoe test well nest, very low chloride concentrations were found at about 300 ft above the bottom of the Floridan aquifer system (see Section 3.4.2).

In a localized region along the Wekiva River where the river forms the boundary between Seminole and Lake counties, an influx of 19,000 mg/ℓ water was prescribed along the bottom boundary. The flux rate is equivalent to about 0.1 inches/year. This influx was required to replicate the zone of high chloride ground water that is observed in the Floridan aquifer system aligned along the Wekiva River (see Figure 3.11 and the conceptual cross section on p. E34 in Tibbals, 1990). Hydrogeologically, this zone of influx is conceptualized to correspond to a zone of increased permeability in the Cedar Keys Formation. Although several authors have indicated faults in shallower units in the region (Miller, 1986 and Tibbals, 1990), there is insufficient evidence to determine whether or not a zone of higher permeability may be caused by geological structural features.

4.6.2 Top Boundary

The top boundary of the model domain corresponds to the top of the Upper Floridan. Recharge to, and discharge from, the Upper Floridan is accounted for in the model using a head-dependent flux (third-type) boundary condition at the top of model layer one. Ground water that flows vertically to or from the Upper Floridan must pass through the upper confining unit and into, or out of, the surficial aquifer. The magnitude of the vertical ground-water flux may be calculated using Darcy's law:

$$q_v = \frac{-K'(h_u - h_s)}{b'} \tag{4.8}$$

where q_v is the vertical Darcy flux entering or exiting the Upper Floridan aquifer, h_s is the water-table elevation in the surficial aquifer, h_u is the hydraulic head at the top of the Upper Floridan aquifer, and K′ and b′ are the hydraulic conductivity and thickness of the upper confining unit, respectively. Note that if h_s is less than h_u, the q_v term is negative and water discharges, rather than recharges, the Upper Floridan aquifer. The term h_u is calculated by the ground-water flow model, while the remaining terms on the right-hand-side of equation 4.8 (h_s, K′, b′) are input parameters taken directly from the Phase IV regional model through spatial interpolation of h_s and leakance (K′/b′) from Phase IV model nodal locations to Phase V model nodal locations. Areal recharge that enters the Upper Floridan aquifer is limited to a maximum rate of 20 inches/year. The chloride concentration of recharging water was assumed to be zero. The chloride concentration of discharging water is calculated by the model.

4.6.3 Western Lateral Boundary Condition

The western model boundary has a slight northwest-southeast orientation. Nodal heads along this boundary were prescribed based upon the regional Phase IV modeling results. Chloride concentrations at the western boundary nodes were set to zero. This approach is consistent with sampling results obtained from the Lake Ivanhoe test well nest, the two test wells completed at Orange County's Western Regional wellfield site, and the Sand Lake Road injection test well. Also, there are several Lower Floridan municipal supply wells in the southwestern corner of the model domain that indicate consistently low chloride concentrations.

4.6.4 Northeastern Lateral Boundary Condition

The northeastern (or coastal) lateral boundary refers to the model boundary that is oriented in a northwest-southeast direction and extends from the vicinity of Orange City in Volusia County to about 6 miles southeast of Geneva in Seminole County. Conditions along this boundary were difficult to quantify because the chloride concentrations vary significantly with depth, but observed chloride concentration data is very limited.

In general, equivalent freshwater heads were prescribed along this boundary based upon assumed chloride concentrations and hydraulic heads obtained from the Phase IV model. Equivalent freshwater head was calculated using equation 4.6 rearranged to solve for h. Based on Figure 3.13, the 10,000 mg/ℓ isochlor was assumed to lie at 500 ft below msl along the entire extent of the northeastern boundary. This depth roughly corresponds to about 50 ft into the middle semiconfining unit (southeast end), or about the middle of the middle semiconfining unit (northwest end). The 19,000 mg/ℓ isochlor was assumed to lie 200 ft below the 10,000 mg/ℓ isochlor (i.e. at 700 ft below msl). The selected increase of 9,000 mg/ℓ over 200 vertical feet is in good agreement with that observed at the Merritt Island test well, at which a vertical gradient of about 44 mg/ℓ/ft between sampling zones 2 and 3 was estimated using the data in Table 3.3. A relatively sharp transition zone is also supported by the results of sampling conducted for a test well about 0.3 miles southwest of Blue Spring, where chloride concentrations increased from 1,300 mg/ℓ to 9,000 mg/ℓ over a vertical distance of about 140 ft (Tibbals, 1990).

For simplicity, chloride concentrations were assumed to vary from 10,000 mg/ℓ to 0 mg/ℓ over a 200 ft interval (-300 ft to -500 ft above msl). Although general estimates of chloride concentrations in the Upper Floridan along the northeastern boundary could be made, the detailed spatial distribution of chloride concentrations is not well-known. Along this boundary in the Upper Floridan, chloride concentrations are low along the southern part of the boundary in the Geneva lens area, they increase to perhaps 1,000 mg/ℓ or more in the vicinity of the St. Johns River, and concentrations decrease again along the northern portion of this boundary north of Lake Monroe. Even where substantial chloride concentrations are present in the Upper Floridan (1,000 mg/ℓ - 2,000 mg/ℓ or so), they do not significantly influence the computation of equivalent freshwater heads. For example, if the Upper Floridan aquifer is assumed to have a thickness of 350 ft and an average chloride concentration of 1,000 mg/ℓ, the resulting increase in equivalent freshwater head in addition to standard hydraulic head would be less than 0.5 ft.

It should be noted that there is some inherent error incorporated into the model in using the Phase IV model heads, in conjunction with estimated chloride concentrations, to derive the northeastern boundary condition (the Phase IV model heads were used as a rough approximation to H, or true head, in equation 4.6). The Lower Floridan heads were not calibrated during the Phase IV study, and the effect of chloride concentrations on the head field was implicitly neglected. However, the simulated Phase IV Lower Floridan heads do conform to the conceptual model of the flow system in that they generally lie within several feet of the observed Upper Floridan heads, and they form a flow field that on a regional scale mimics that of the Upper Floridan. Since there are no observed Lower Floridan head values in the vicinity of the northeastern model boundary, it was decided that utilizing the Phase IV model heads as a starting point was as good of an approach as any.

4.6.5 Northern and Southern Lateral Boundary Conditions

The northern and southern lateral model boundaries are oriented along approximate regional ground-water flow pathlines for both the Upper and Lower Floridan aquifers. The locations of the pathlines selected are similar for predevelopment and average 1988 conditions, and consequently the locations of the lateral boundaries were not altered between calibration periods. Furthermore, the northern and southern lateral boundaries intersect, at approximately right angles, the depth to greater than 10,000 mg/ℓ chloride concentration contours presented in Figure 3.13.

The location of the northern and southern lateral boundaries were selected carefully, with emphasis placed on the Lower Floridan aquifer, so that they could be conceptualized in the three-dimensional model as zero flux (with respect to ground water and solutes) boundary conditions. This boundary conceptualization is justified for the ground-water flow simulation because steady-state pathlines are effectively hydraulic barriers to ground-water flow. The conceptualization of zero mass flux of solutes across these boundaries is also justified based upon the limited amount of information available. In general, the existing wedge of high-chloride water in eastern Seminole County is oriented in a northeast to southwest fashion. Or, stated another way, chloride concentrations generally increase more or less uniformly along the regional direction of ground-water flow (except in the vicinity of the Wekiva River). This relationship is clearly demonstrated for the Upper Floridan aquifer by figures presented in Tibbals (1990). Although sufficient data are not available to delineate isochlors in a highly accurate manner within the middle semiconfining unit or the Lower Floridan, the same northwest-southeast orientation of the isochlors is suggested in Figure 3.13 which illustrates the estimated depth to water with chloride concentration 10,000 mg/ℓ or greater, and by the depth to 5,000 mg/ℓ isochlor estimate (Figure 3.11) presented in CEES-Blackhawk Geosciences Division (1993).

For the Lower Floridan aquifer and the middle semiconfining unit, no-flow (zero flux) boundary conditions were applied for both the predevelopment and average 1988 simulations along the entire boundary for ground-water flow and solute transport. Along the southern boundary in the Upper Floridan aquifer, a no-flow boundary was used along gridline columns 50-89, or from about the Seminole County - Orange County border to the tip of the model domain southeast of Geneva. For model columns 1-50 along the southern boundary, equivalent freshwater heads were prescribed based upon the MODFLOW Phase IV model simulation results, and chloride concentrations were set to zero. Along the entire extent of the northern boundary in the Upper Floridan aquifer equivalent freshwater heads based upon the Phase IV MODFLOW simulation results were prescribed. Where chloride concentrations are appreciable along the northern boundary, simulated ground-water flow is generally out of the model domain to the north or northeast, and therefore chloride concentrations were not prescribed. The boundary condition types were not changed between the predevelopment and 1988 simulation periods.

Based upon a detailed review of the available data within the study area, as well as the need to develop a workable and realistic modeling approach, the northern and southern lateral boundary conceptualizations are reasonable. Furthermore, although there is certainly some error involved in the precise placement and specification of these boundary conditions, the only alternative, which is to prescribe chloride concentrations throughout each boundary face (or at some distance from the boundary for a third-type boundary condition), would be extremely difficult to implement with a reasonable degree of confidence.

4.7 Model Calibration

4.7.1 Calibration Procedure

Model calibration is the general procedure of adjusting model input parameters within reasonable limits until the model output (in this case equivalent freshwater heads and chloride concentrations) resembles conditions observed in the field within some prescribed tolerance. Since the model domain is a subregion of the Phase IV regional model, all initial ground-water flow model parameters were obtained from Blandford and Birdie (1992b). These parameters include transmissivities for the Upper and Lower Floridan aquifers, leakances of the middle semiconfining unit, prescribed heads for the surficial aquifer and leakances of the upper confining unit. The derived thicknesses of the Upper and Lower Floridan and the middle semiconfining unit were used to back-calculate the hydraulic conductivities of each respective unit. As described in the previous section, certain boundary parameters (i.e., equivalent freshwater head) and conceptualizations were also based upon the Phase IV model results.

Since the Phase V model areal discretization is in general slightly coarser than that of the Phase IV model, no effort was made to refine the prescribed head values assigned to the surficial aquifer within the Phase V study area. The prescribed surficial aquifer head values were also not changed between the predevelopment and average 1988 calibration periods, which is consistent with the Phase IV modeling approach.

For the postdevelopment (average 1988) calibration, all stresses (pumpage and recharge due to drainage wells) to the Floridan aquifer system were averaged over the calendar year; pumping values were input in ft^3/d. Therefore, even though some pumping was seasonal, such as that for irrigation, the amount of pumpage was assumed to be spread evenly throughout 1988. This approach is reasonably accurate for determining Floridan aquifer parameters for the regional system over the long term. A detailed explanation of how the pumping estimates were derived or obtained is given in Blandford and Birdie (1992b).

In the Phase IV study, pumping was assigned to the grid cell that contained the respective well location. In this study, discharge was assigned to the nodal point closest to the well. For Upper Floridan wells, discharge was weighted by vertical nodal spacing for the bottom three nodal layers (a total of 4 nodal layers are used to discretize the Upper Floridan aquifer; see Figure 4.2). Similarly, recharge due to drainage wells in the vicinity of Orlando was applied to the bottom three nodal layers of the Upper Floridan. Discharge due to Lower Floridan wells was assumed to come from the upper one-half of this unit, since none of the wells fully penetrate the Lower Floridan. Based upon a sensitivity analysis, it was determined that the vertical distribution of withdrawals due to pumping has little influence upon the simulation results. No discharge was assumed to come from the middle semiconfining unit.

Some of the model input parameters could not be obtained from the Phase IV model because they were not required as inputs during that study. These parameters are the effective porosities of the Upper and Lower Floridan; the vertical hydraulic conductivities of the Upper and Lower Floridan; the horizontal hydraulic conductivity of the middle semiconfining unit; and the longitudinal and transverse dispersivities of each hydrogeologic unit. Since these parameters were not calibrated during the Phase IV modeling study, they were the focus of initial model calibration efforts.

The Phase V density-dependent ground-water flow and solute transport model was calibrated to predevelopment as well as postdevelopment (average 1988) conditions. Each calibration period is conceptualized as an average, long-term condition; the predevelopment condition without pumping, an the postdevelopment condition with pumping. A similar approach was used for the Phase IV regional model. Where required, the Phase V model boundary conditions are calibration-period specific. For example, the head values prescribed along the Phase V western model boundary for the predevelopment calibration were based on those obtained during the Phase IV model predevelopment calibration. All predevelopment model simulations were run to steady-state. The predevelopment and average 1988 Upper Floridan potentiometric surfaces are described in detail in Blandford and Birdie (1992b). There are insufficient data available to construct a Lower Floridan potentiometric surface for either predevelopment or 1988 conditions, but it is generally believed that regional ground-water flow directions in the Lower Floridan tend to mimic those in the Upper Floridan.

For the postdevelopment (1988) simulations, the assumption was made that present hydrogeologic conditions, to the extent that they differ from predevelopment conditions, are primarily a function of stresses placed upon the aquifer over about the last 30 years or so. All postdevelopment (average 1988) simulations, therefore, were transient simulations run for a time period of 30 years; predevelopment simulation results were used as a starting condition. The boundary conditions for each of the postdevelopment simulations were assumed to change instantaneously from the predevelopment to the average 1988 condition. This approach is consistent with the Phase III modeling study (Blandford and Birdie, 1992a). The calibration criteria for both the predevelopment and the average 1988 calibration are presented in the next section.

The calibration procedure described above assumes that for the 1988 calibration, ground-water withdrawals from the Floridan aquifer system within the study area have been occurring at a constant, 1988 average rate for the 30 years previous to 1988. This obviously is a very approximate assumption, but it is justified for several reasons. First of all, in freshwater portions of the aquifer system, the potentiometric surface responds to changes in pumping rather quickly (certainly within a time frame much smaller than 30 years). Therefore, for portions of the aquifer system within which chloride concentrations are not substantial, the configuration of the 1988 potentiometric surface is not dependent upon the time-history of pumping from predevelopment conditions. Secondly, the time-response of chlorides to imposed stresses may be quite large; it can take tens or hundreds of years for high-chloride water within the aquifer to reach a state of equilibrium with newly imposed stresses. The fact that stresses (pumping) may be variable over the short-term (period of years), therefore, is not critical to the long-term evaluation of chloride transport if only general trends are to be investigated. Finally, it is neither practical nor feasible to develop a chronological pumping data base for the past 30 years throughout the entire regional model (Phase IV) study area. The error involved in the construction of such a database would be substantial, and it is not at all clear that a better-calibrated model, or improved estimates of chloride transport, would be obtained.

Most of the DSTRAM model calibration runs involved iterative predevelopment and average 1988 simulations. However, some additional Phase IV model (MODFLOW) runs were also conducted, as it was necessary to recalibrate the hydraulic conductivity (transmissivity) of the Upper and Lower Floridan aquifers, and the vertical hydraulic conductivity of the middle semiconfining unit, within some regions of the Phase V model domain. These changes were consistently checked to insure that the Phase IV regional model results were not significantly altered.

The simulated spring flows obtained from MODFLOW for each calibration period and predictive scenario were input into DSTRAM as a withdrawal condition, since DSTRAM does not have a boundary condition type that directly corresponds to the MODFLOW drain package. This approach is appropriate and consistent, because 1) the environmental heads obtained using DSTRAM are very similar, and in many places identical, to those obtained using MODFLOW for the freshwater portion of the Upper Floridan aquifer and 2) the regional MODFLOW model simulations are used to prescribe boundary conditions for the DSTRAM predictive scenario. Therefore, all simulated spring flows documented or referred to were obtained from the regional MODFLOW model.

Finally, it must be emphasized that the calibrated model parameters are not unique, or, in other words, the same (or a very similar) potentiometric surface and chloride distribution might be obtained using other values and combinations of the model parameters. The goal of this modeling study was to obtain realistic calibration parameters that conform to the overall hydrogeologic framework, and that lie within a reasonable range that may be verified using field observations.

4.7.2 Calibration Criteria

The key three-dimensional model calibration criteria are outlined below:

1) A reasonable match between the simulated 250 mg/ℓ isochlor and the observed location of the 250 mg/ℓ isochlor as mapped using well data in Seminole County (Figures 3.8 and 3.10). From predevelopment to average 1988 conditions, the 250 mg/ℓ isochlor should be relatively stationary.

2) A reasonable match between simulated and observed and estimated chloride concentrations at depth, as indicated by various public supply wells and test wells completed in the Lower Floridan aquifer, and as generally depicted in Figures 3.11 and 3.13.

3) A reasonable match between simulated and observed predevelopment and average 1988 potentiometric surfaces for the Upper Floridan aquifer.

4) A reasonable match between simulated and observed or estimated predevelopment and average 1988 spring flows for springs within the Phase V model domain.

5) Overall reasonableness of the simulation results, relative to the developed conceptual model and various observed data, throughout all regions of the model domain.

The predevelopment and average 1988 model calibrations, and the extent to which each calibration criterion was met, is discussed in the following two sections.

4.7.3 Predevelopment Model Calibration Results

The calibrated model results for both the predevelopment and postdevelopment calibration periods are displayed in a series of areal and cross-sectional plots. The areal plots represent conditions at the middle of the respective hydrogeologic unit (i.e., nodal layer 6 for the Lower Floridan aquifer, and nodal layer 17 for the Upper Floridan aquifer). The four cross sections presented illustrate simulation results for vertical slices through the three-dimensional domain; the location of each vertical slice is indicated in Figure 4.1. Chloride concentrations are presented as normalized concentration, and hydraulic heads are plotted as environmental heads. Equivalent freshwater heads are corrected for chloride concentration and may vary significantly from true and environmental heads in regions of high chloride concentration, and therefore are not presented. The definitions of true head, environmental head and equivalent freshwater head are provided in Section 4.2. A detailed explanation of each type of head value is provided by Lusczynski (1961). The DSTRAM code solves the governing partial differential equations in terms of equivalent freshwater head for convenience. Upon completion of a simulation, the environmental head is computed based upon equation 4.7. The environmental head is presented because it is most indicative of potentiometric surface observations that would be obtained in the field from wells with significant lengths of open hole. Since DSTRAM accounts for density effects, and the regional Phase IV MODFLOW model does not, the simulated head fields obtained from the Phase V and the Phase IV modeling studies may not match precisely within the model domain, even in regions with low chloride concentrations.

Several velocity vector plots are also presented to aid with visualization of the results. In these plots, an arrow is plotted beginning at the center of each finite element in the model grid. The orientation of the arrow represents the direction of ground-water flow, and the length of the tail of each arrow represents the relative magnitude of the velocities (longer tails indicate higher velocities). It should be noted that along certain boundaries of the model domain where ground-water flow velocities are very small, the orientation of the velocity vectors may be erratic due to computational round-off errors within the computer plotting program. It should also be emphasized that the simulated ground-water flow velocities are three dimensional in terms of their direction. In the plots, however, only a two-dimensional projection (x-y in the areal plots and x-z in the cross-sectional plots) can be presented. For example, in an areal plot a certain velocity vector may indicate that ground-water flow is from west to east, but the vertical direction of flow (up or down) is not portrayed.

The predevelopment model calibration results are presented in Figures 4.4-4.13. Figures 4.4 and 4.5 illustrate the simulated environmental head and normalized chloride concentration for the Upper Floridan aquifer, respectively. Figure 4.6 is a contour plot of the difference between the observed potentiometric surface and the simulated environmental heads in the Upper Floridan aquifer. Figures 4.7 and 4.8 illustrate the simulated environmental head and normalized chloride concentration for the Lower Floridan aquifer, respectively. Figure 4.9 consists of areal velocity vector plots for both the Upper and Lower Floridan aquifers. And finally, Figures 4.10-4.13 portray the normalized chloride concentrations and velocity vectors for cross-sections 1-4.

A critical comparison of Figures 4.4-4.13 with the observed data indicates that the predevelopment model calibration is reasonable. In the Upper Floridan, the difference between the estimated (observed) predevelopment potentiometric surface and the simulated potentiometric surface is generally less than 4 ft throughout the model domain (Figure 4.6). There is a region in western Seminole County where the simulated heads are more than 8 ft lower than those observed. The difference in this region is primarily due to the configuration of the estimated predevelopment potentiometric surface, in which there is a large bulge to the north in the 50-ft contour in southwestern Seminole County; the accuracy of this hydrographic feature is unknown.

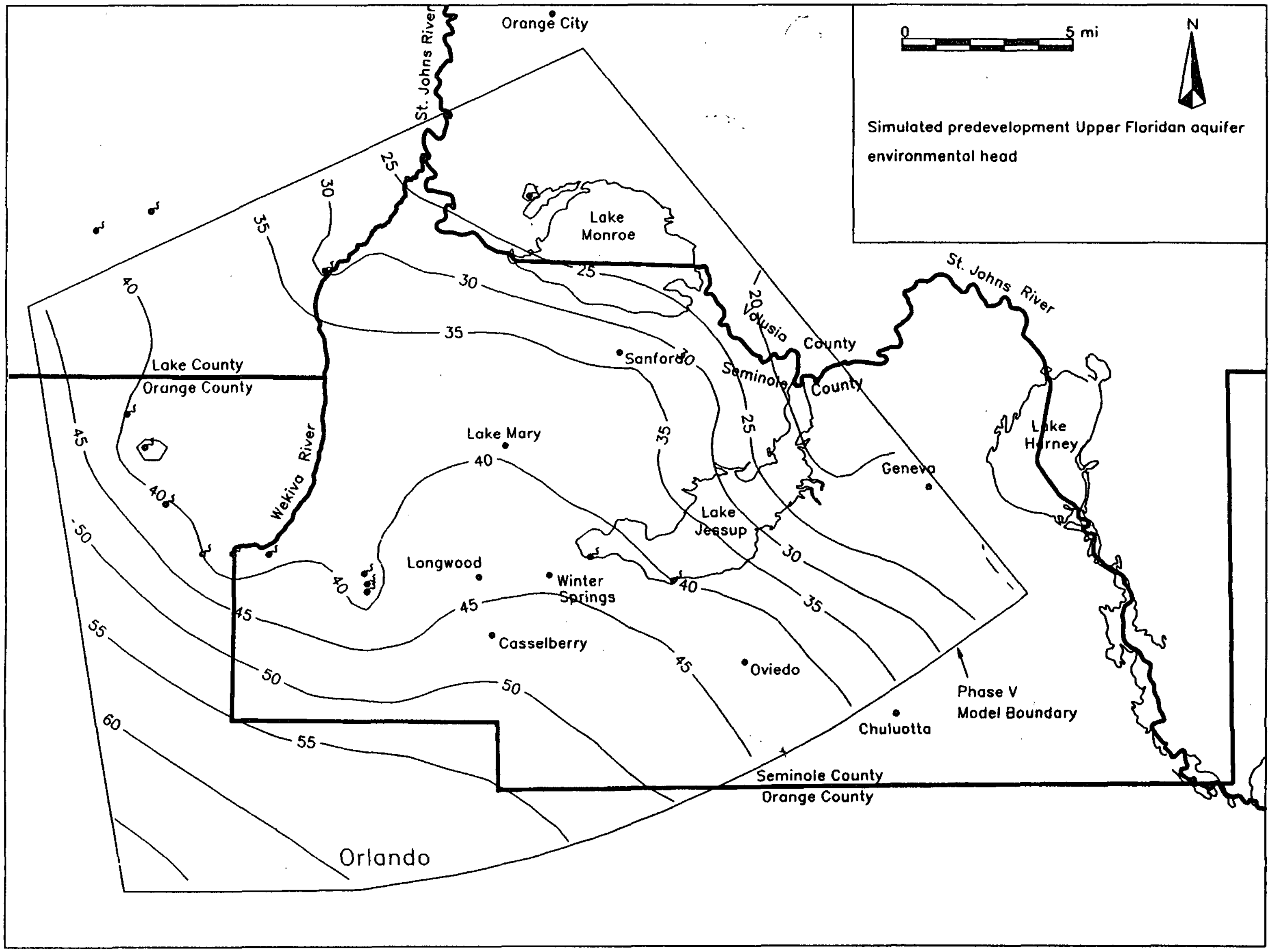


Figure 4.4 Simulated predevelopment environmental head in the Upper Floridan aquifer in ft. Datum is mean sea level.

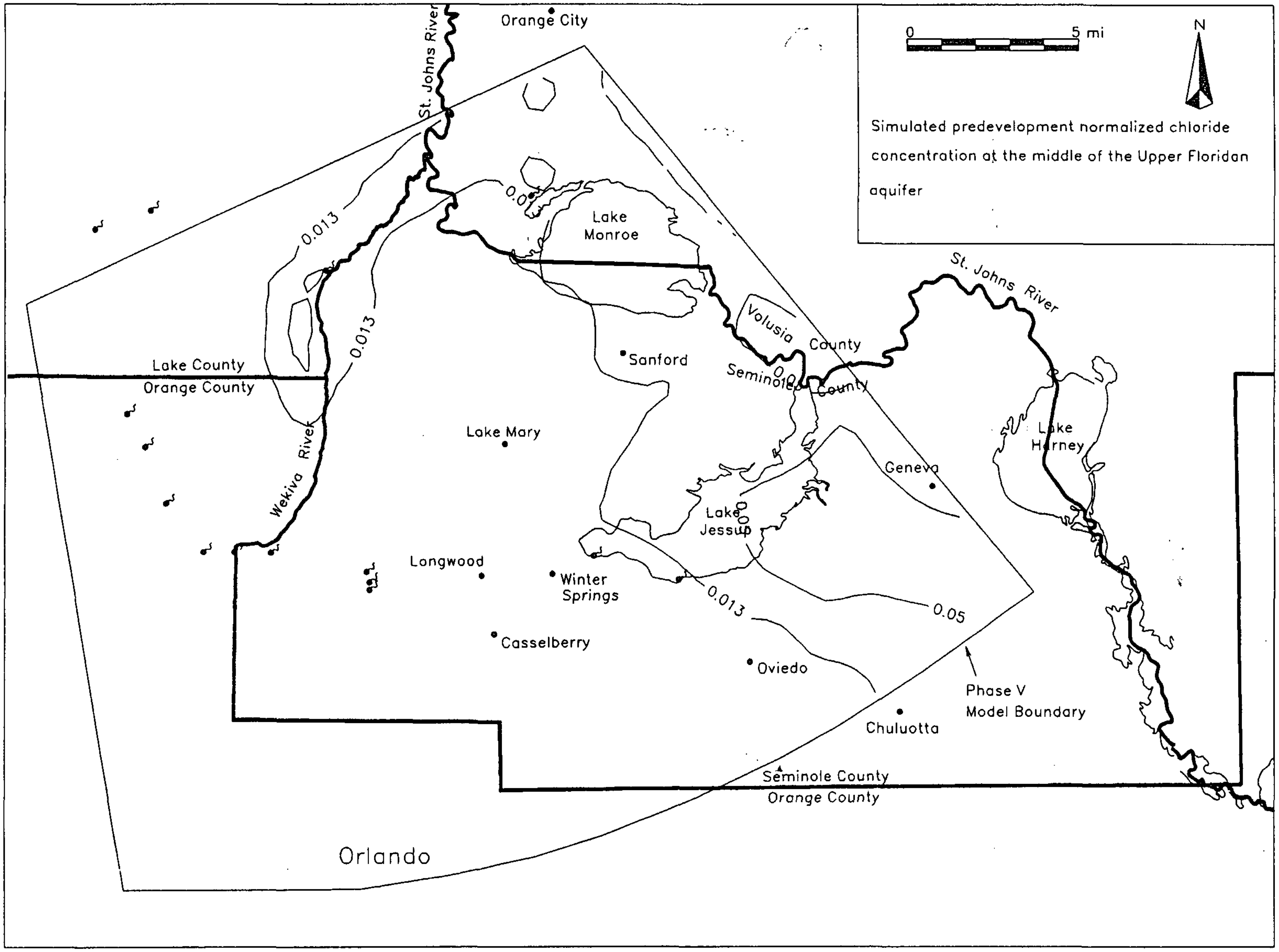


Figure 4.5 Simulated predevelopment normalized chloride concentration in the Upper Floridan aquifer.

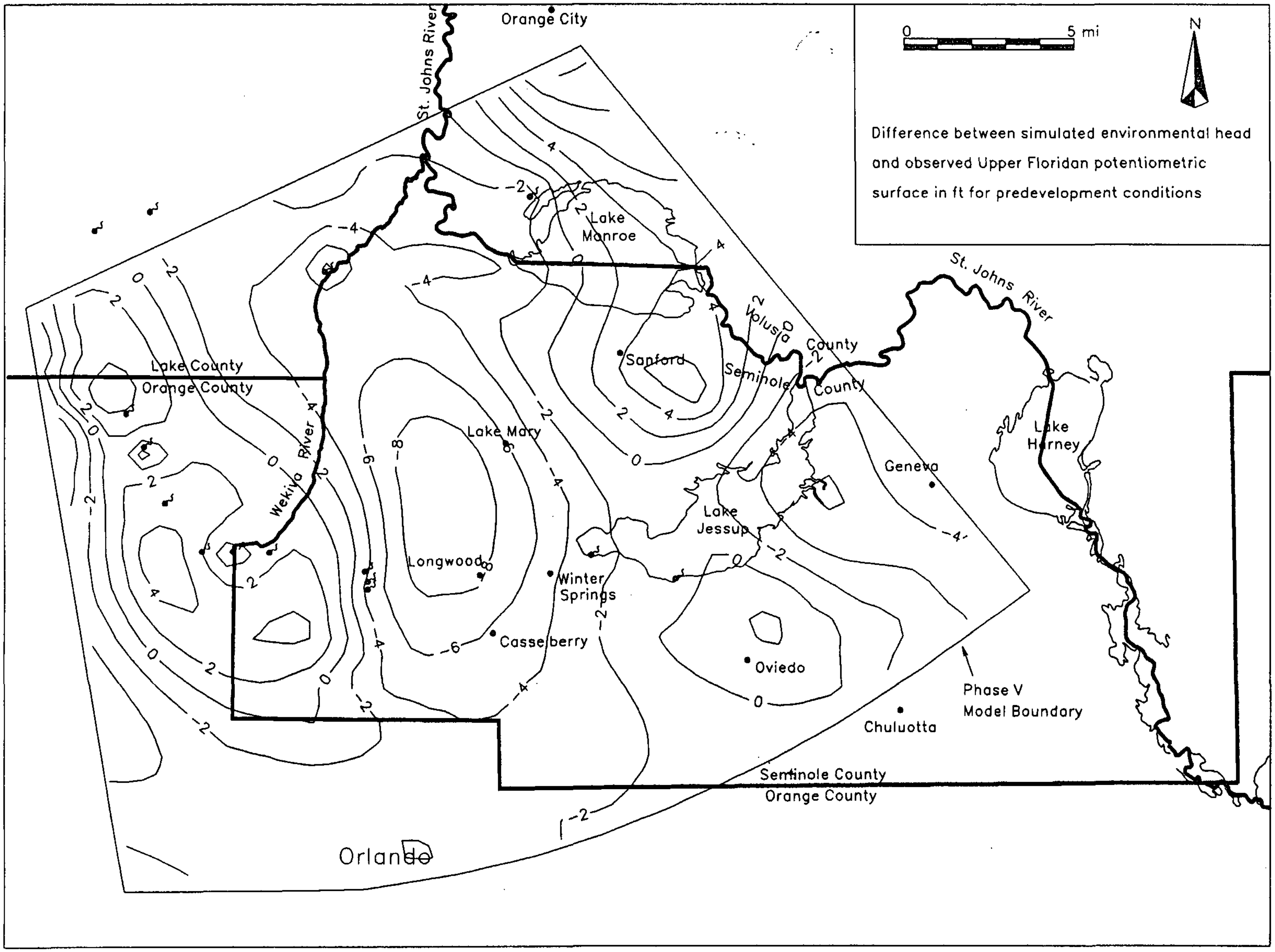


Figure 4.6 Difference between estimated potentiometric surface and simulated environmental head in the Upper Floridan aquifer in ft.

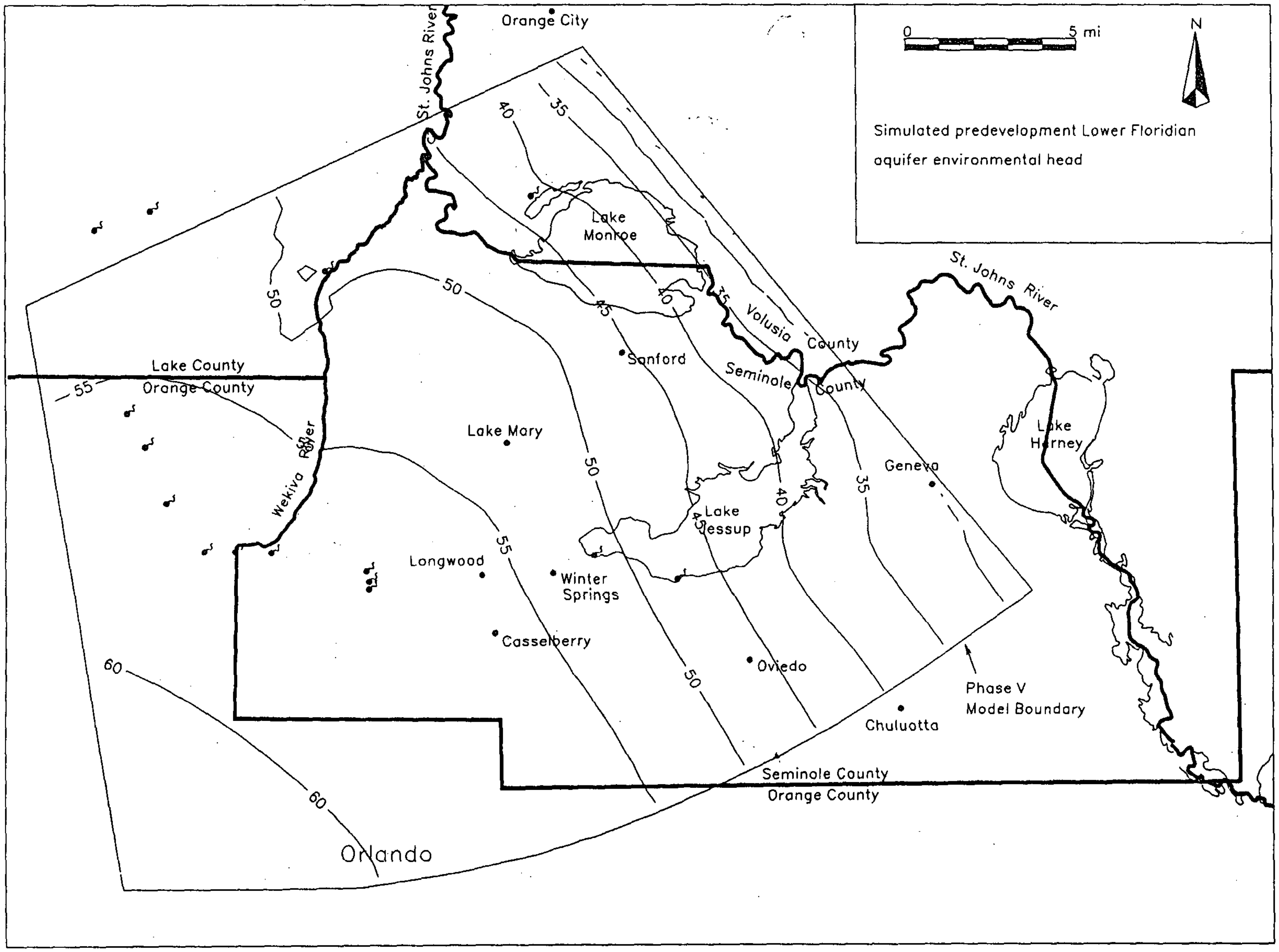


Figure 4.7 Simulated predevelopment environmental head in the Lower Floridan aquifer in ft. Datum is mean sea level.

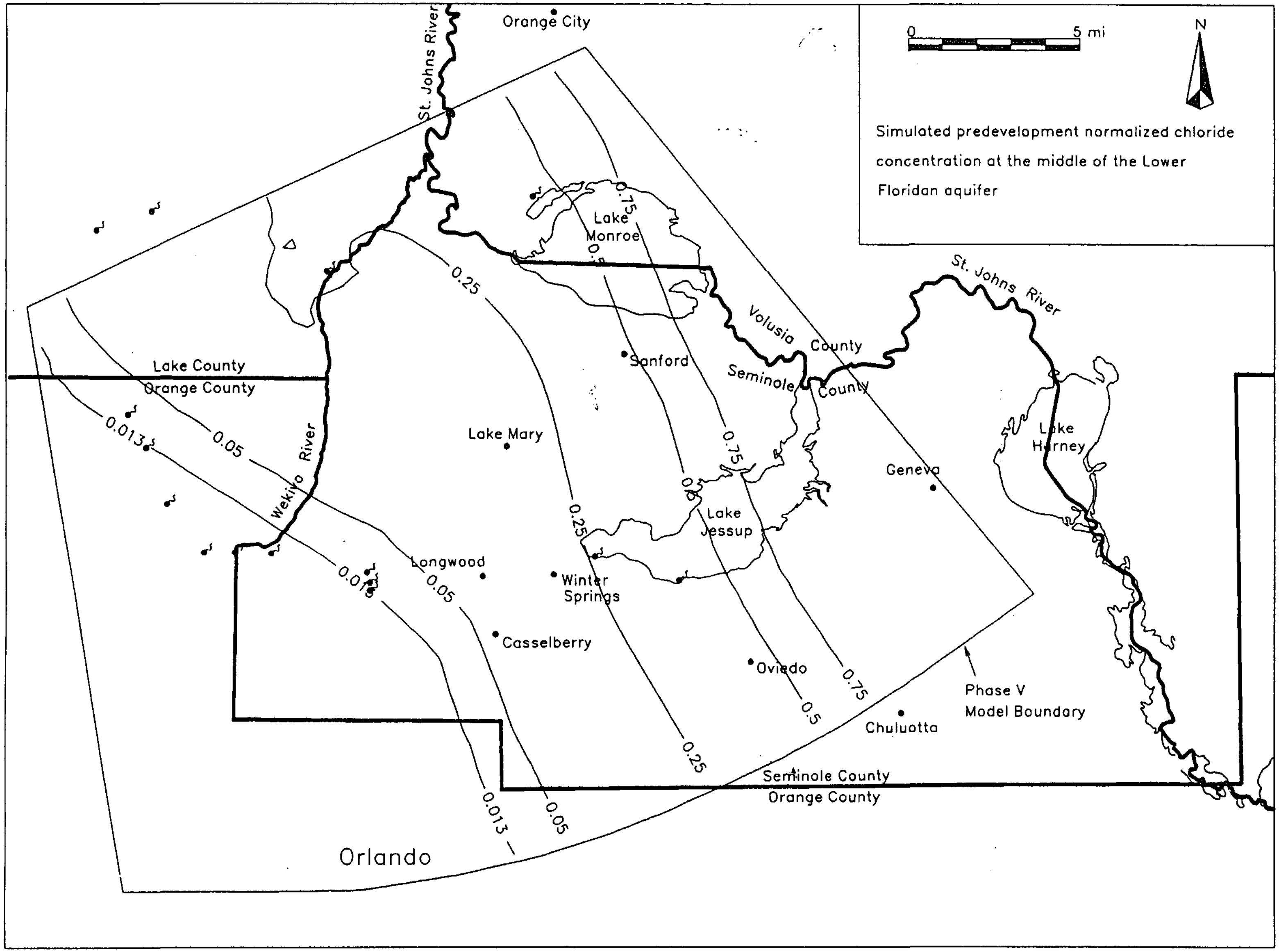
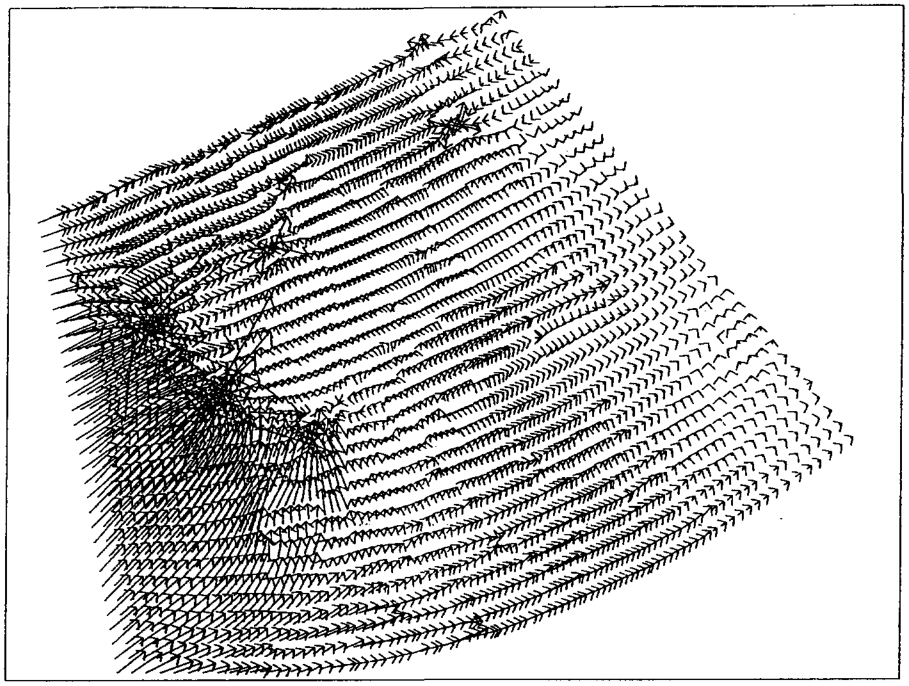
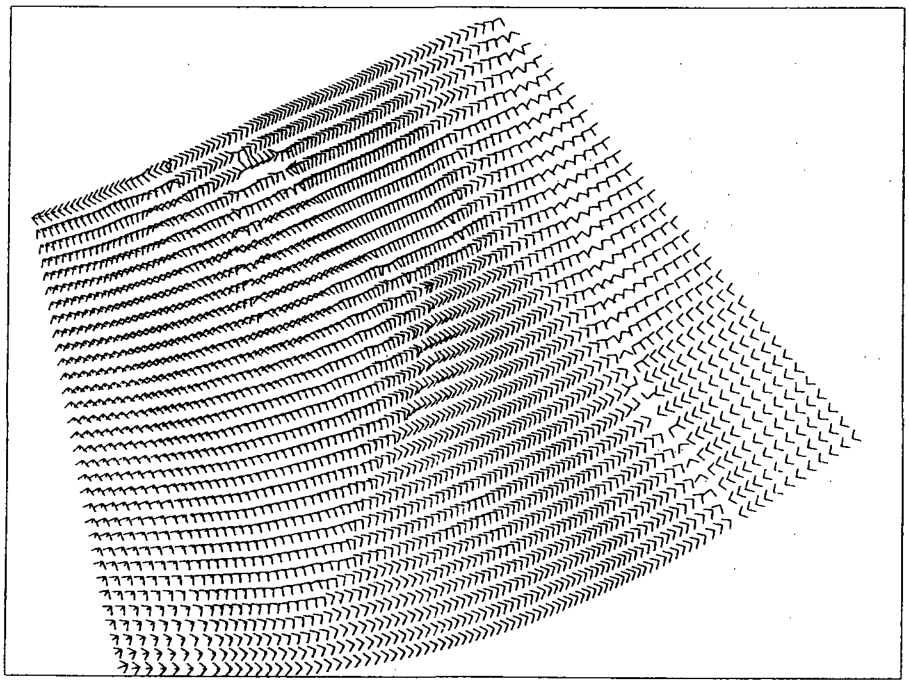


Figure 4.8 Simulated predevelopment normalized chloride concentration in the Lower Floridan aquifer.



(a)



(b)

Figure 4.9 Areal velocity vector plots for the Upper Floridan aquifer (a) and the Lower Floridan aquifer (b).

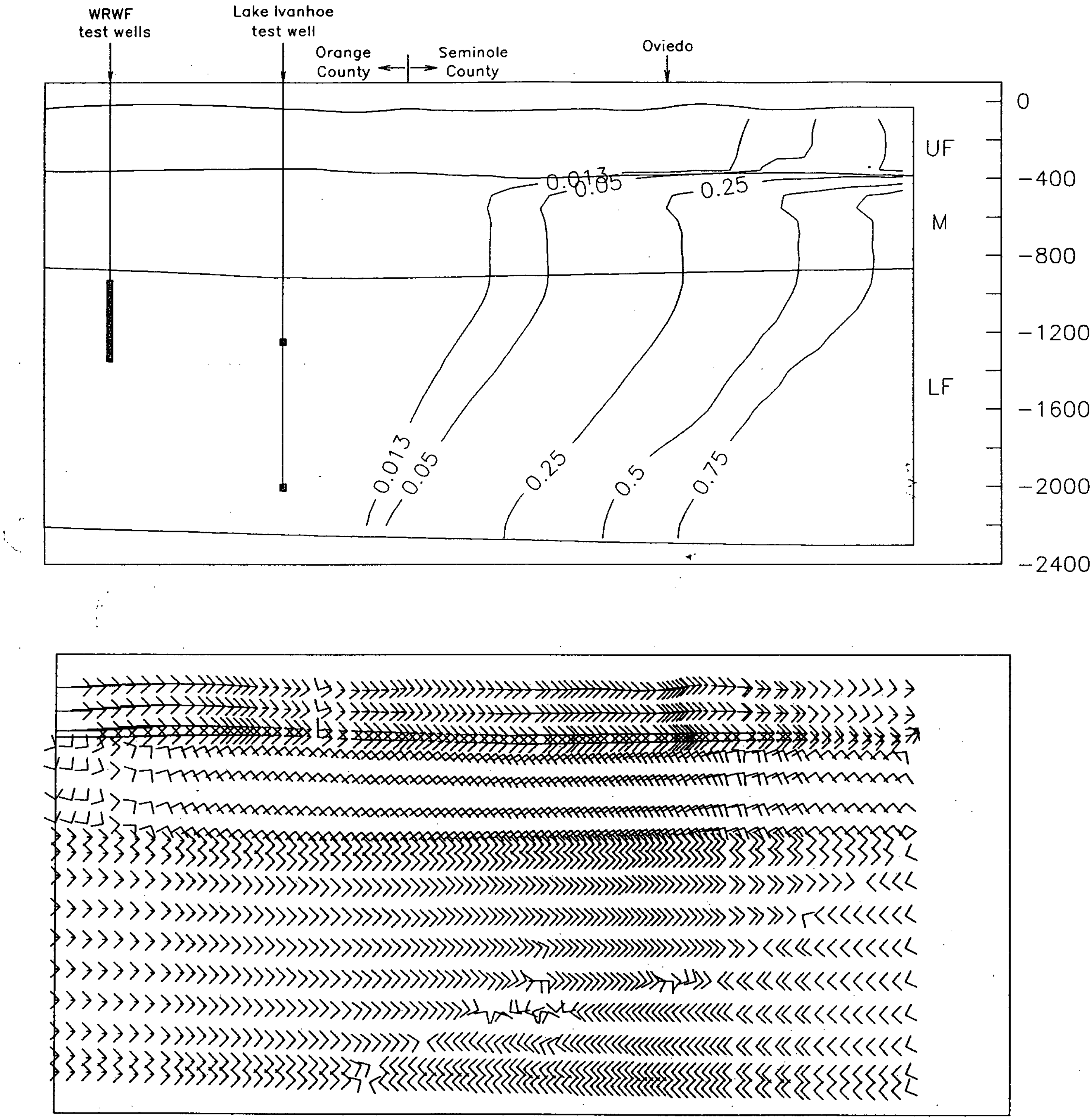


Figure 4.10 Simulated predevelopment normalized chloride concentration and velocity vector plot for cross-section 1.

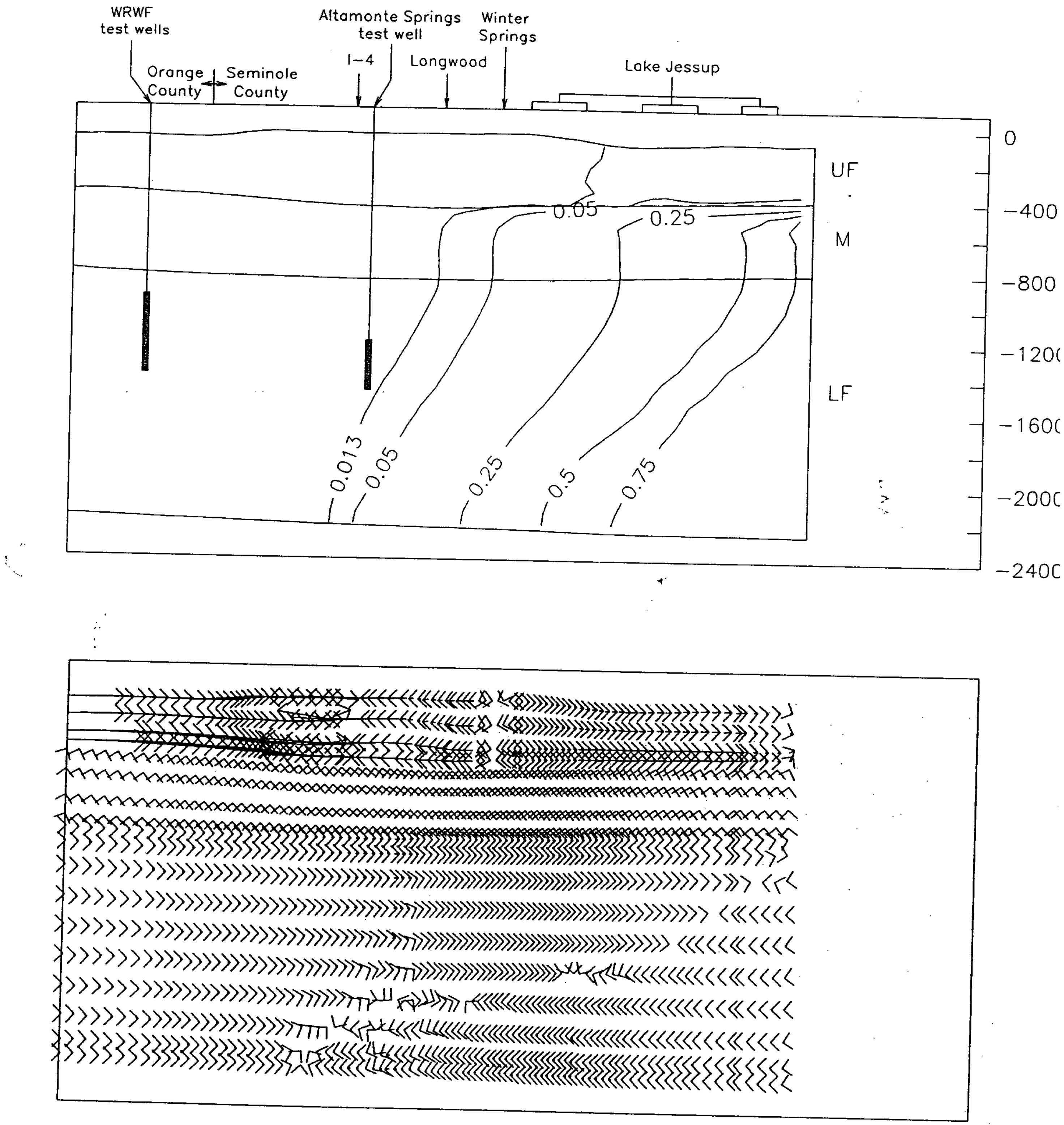


Figure 4.11 Simulated predevelopment normalized chloride concentration and velocity vector plot for cross-section 2.

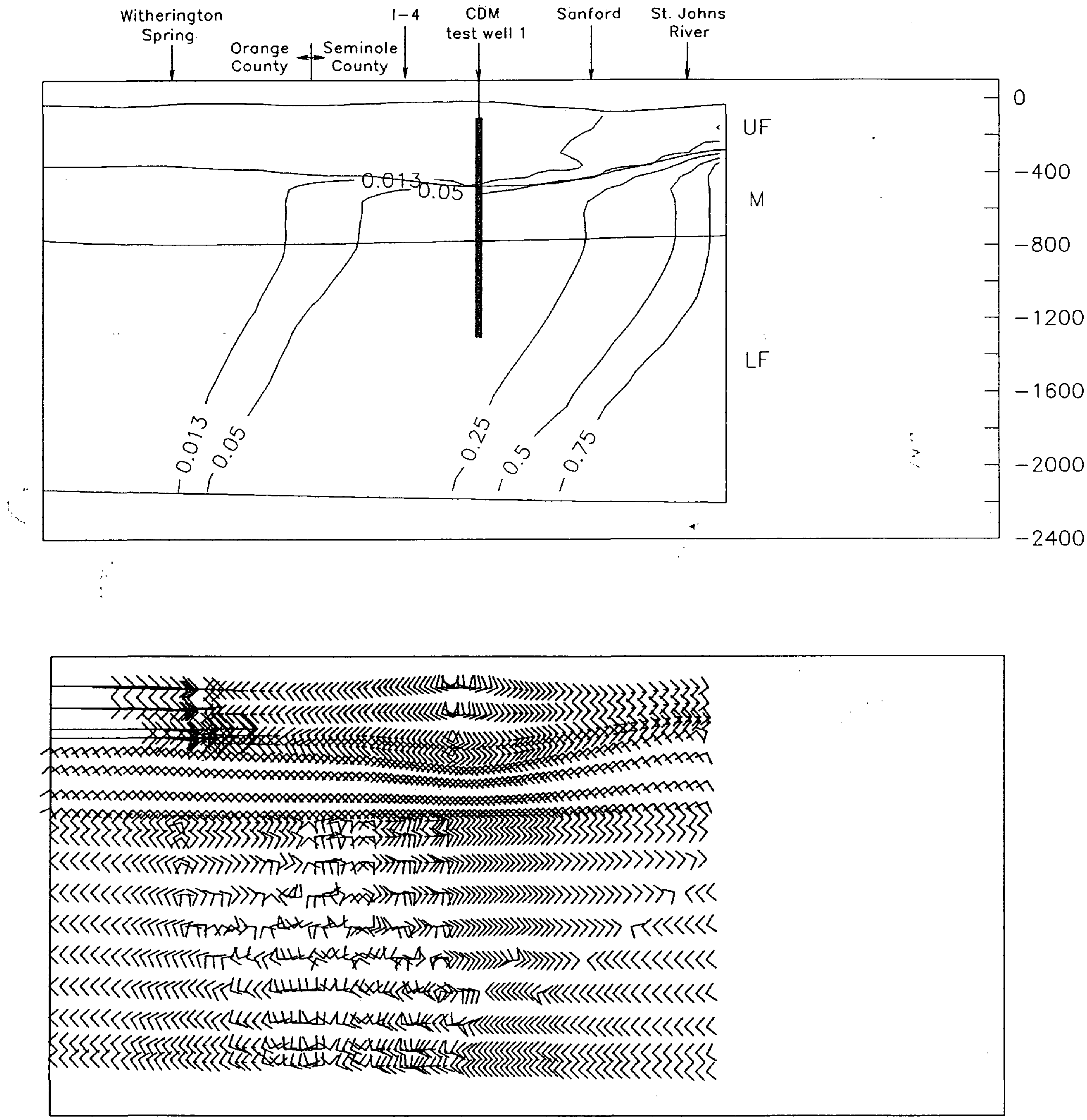
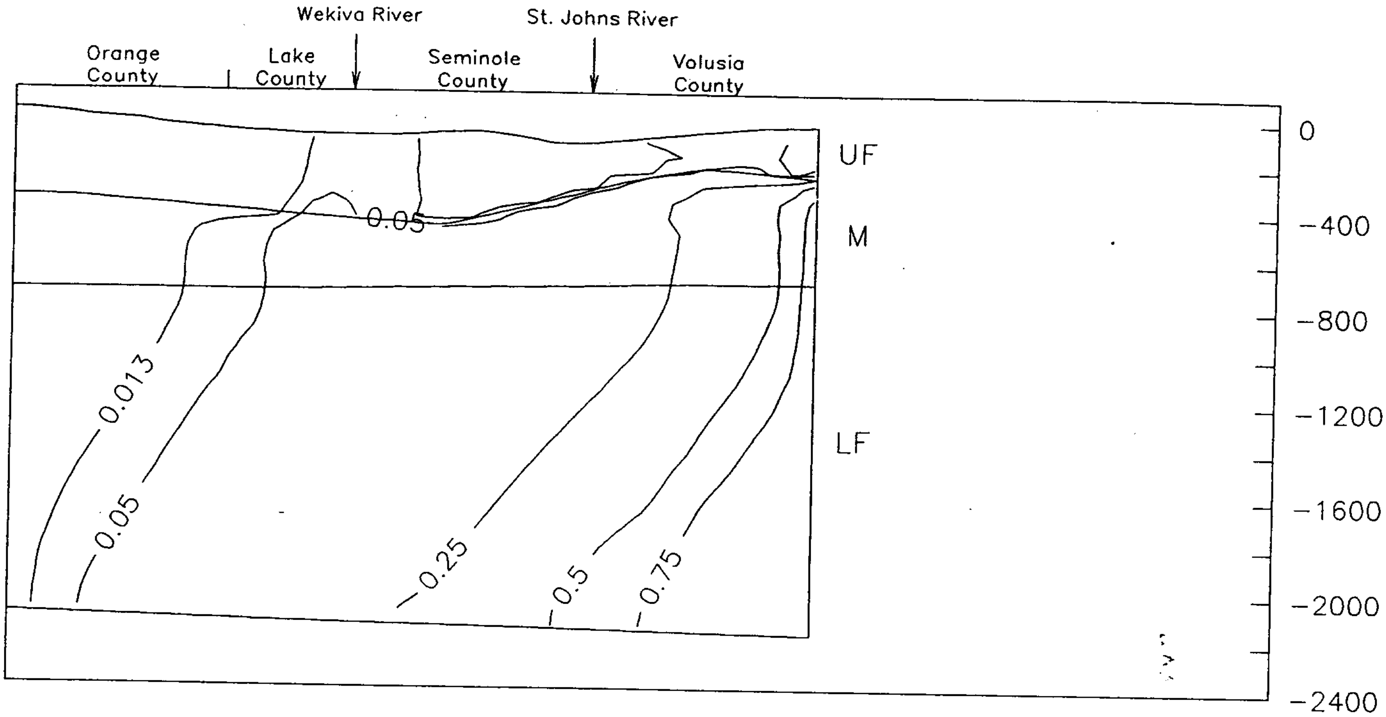


Figure 4.12 Simulated predevelopment normalized chloride concentration and velocity vector plot for cross-section 3.



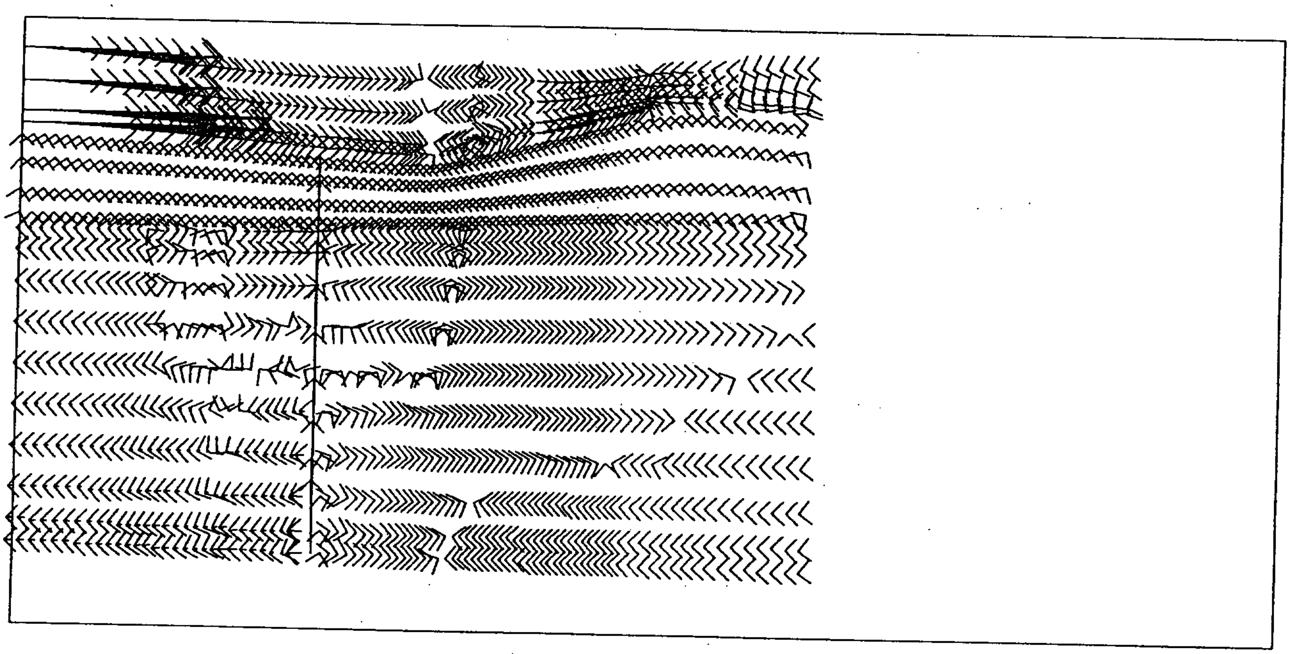


Figure 4.13 Simulated predevelopment normalized chloride concentration and velocity vector plot for cross-section 4.

Recent studies conducted by the USGS indicate that the estimated predevelopment potentiometric surface may indeed be too high in this region (personal communication, Brian McGurk, SJRWMD, 1993). Due to the inherent uncertainty in the estimated predevelopment potentiometric surface, the simulated predevelopment Upper Floridan potentiometric surface is deemed acceptable.

Table 4.1 presents the observed and simulated spring flows for springs within the Phase V model domain. For the major springs under predevelopment conditions, the simulated discharge is generally within 10-20 percent of the estimated predevelopment discharge. The simulated total spring discharge is about 11 percent greater than the observed total. These values are considered to be a good match for calibration purposes.

The areal concentration plots presented in Figures 4.5 and 4.8 conform well to chloride observations within most of the study area. Each of these plots indicate that the general northwest-southeast trend of the Upper and Lower Floridan isochlors in Seminole County is reproduced by the model. In the Upper Floridan, the 250 mg/ℓ isochlor (0.013 normalized concentration) is simulated quite well throughout most of Seminole County (compare Figure 4.5 with Figure 3.10). One region where the simulated 250 mg/ℓ isochlor does not match well with the observed isochlor is in an isolated region in northern Seminole County and southern Volusia County due west of Lake Monroe; in this region the simulated 250 mg/ℓ isochlor is about 2 miles farther to the north than it should be. In the vicinity of the Geneva freshwater lens along the eastern model boundary, simulated Upper Floridan aquifer chloride concentrations are higher than those observed. This result occurs because a detailed calibration of the Geneva lens region was not performed during this study, as the freshwater lens is a relatively local feature and does not significantly affect the distribution of chlorides to the west in central Seminole County. A detailed calibration of the Geneva freshwater lens area could be obtained by locally adjusting areal recharge to the Upper Floridan aquifer. Various regions of 1,000 mg/ℓ water (0.05 normalized concentration) exist to the east of the 250 mg/ℓ isochlor throughout much of Seminole County, which is consistent with field observations. The simulated Upper Floridan aquifer chloride concentration at Gemini Spring is about 1,600 mg/ℓ, which is less than, but in

Table 4.1 Observed and simulated spring flows for predevelopment and average 1988 conditions for springs within the Phase V model domain. Simulated spring flows are from the regional MODFLOW model.

Spring	Discharge (cfs)		Percent Discrepancy
	Observed	Simulated	
Predevelopment			
Gemini	8.00	8.57	7.1
Island	6.00	9.11	51.8
Rock	65.00	71.64	10.2
Witherington	4.00	4.69	17.2
Wekiva	74.00	81.46	10.1
Miami	5.00	5.47	9.4
Lake Jessup	1.00	0.86	-14.0
Clifton	2.00	1.73	-13.5
Starbuck	17.00	19.90	17.1
Palm	10.00	8.55	14.5
Sanlando	19.00	22.78	19.9
Sulphur	1.00	1.18	18.0
Total	212.00	235.94	11.3
Postdevelopment (1988)			
Gemini	8.00	7.88	1.5
Island	6.00	7.61	26.8
Rock	58.50	55.30	-5.5
Witherington	4.00	3.79	-5.3
Wekiva	69.50	69.78	0.4
Miami	5.15	4.54	-11.8
Lake Jessup	0.65	0.70	7.7
Clifton	1.30	1.38	6.2
Starbuck	14.50	14.06	-3.0
Palm	6.25	6.08	-2.7
Sanlando	19.50	15.89	-18.5
Sulphur	1.0	1.00	0.0
Total	194.35	188.01	-3.3

reasonable agreement with, the observed value of about 2,500 mg/ℓ.

In the Lower Floridan aquifer, the middle of which is at about -1,500 ft msl, the 5,000 mg/ℓ isochlor (0.26 normalized concentration) generally matches that as determined through TDEM measurements (see Figure 3.11). The simulated isochlor is shifted slightly to the east (about 1 mile or so) of the position determined using TDEM measurements, but the simulated position is acceptable given the inherent uncertainty in the TDEM analysis. Furthermore, in the Upper Floridan aquifer the position of the 250 mg/ℓ isochlor as determined using TDEM methods is generally farther west than that determined using well data (Blackhawk Geosciences, 1992), and this same "bias" may apply to the 5000 mg/ℓ isochlor at depth. Simulated chloride concentrations in southwestern Seminole County and the portions of Orange County within the model domain are low (less than 250 mg/ℓ), which is consistent with chloride concentration samples obtained from Lower Floridan wells in this region.

Figure 4.9 presents the simulated areal velocity vector plots for the middle layer of the Upper and Lower Floridan aquifers. In the Upper Floridan aquifer, ground-water flow velocities are generally oriented northeast or north. The highest velocities occur in the western region of the model domain upgradient of and at the major springs where the hydraulic conductivities and/or simulated hydraulic gradients are highest. The smallest velocities occur in the central portion of the model domain downgradient of the springs and the Wekiva Swamp discharge area, and where the predominant direction of groundwater flow is to the north.

In the Lower Floridan aquifer, the simulated areal ground-water flow velocities are generally smaller than those in the Upper Floridan aquifer due to lower hydraulic conductivities. Ground-water flow is generally to the northeast and the north. In the northwest corner of the model domain, there is a small component of flow that moves north toward the northern model boundary, and then exits the model domain to the west due to the no-flow condition prescribed along the northern boundary. The true nature of ground-water flow in this region is unknown; and it is probably quite complex due to geologic structural controls and heterogeneities beneath the Wekiva and St. Johns River channels.

Simulated chloride concentrations and velocity vector plots are presented for cross sections 1-4 in Figures 4.10-4.13, respectively. In the cross-sectional plots, the various hydrogeologic units are marked by UF (Upper Floridan aquifer), M (middle semiconfining unit), and LF (Lower Floridan aquifer). In general, the simulated results indicate that water with chloride concentration of 250 mg/ℓ or greater exists within the middle semiconfining unit throughout most of Seminole County, as would generally be expected. Indeed, at CDM test well 1, a significant increase in TDS was observed to occur at a depth of about 500 ft, which roughly corresponds to the top of the middle semiconfining unit. As noted in Chapter 3, however, the testing results for this well are somewhat contradictory and further testing at this site is recommended.

For each of the cross-sectional velocity vector plots, the location of the saltwater interface can be determined in the Lower Floridan aquifer by delineating the points at which the velocity vectors oppose one-another. In the Lower Floridan aquifer, a density-driven convection cell forms in which dense saltwater flows from east to west, until it eventually meets and mixes with freshwater, becomes less dense, and moves vertically upward and back toward the east. As was noted with respect to the areal velocity plots, the magnitude of ground-water flow in the Upper Floridan aquifer is greater than that in the Lower Floridan aquifer. For cross sections 2-4, a reversal of flow direction from east to west in the vicinity of the various springs is indicated by the velocity vectors. Throughout most of the Phase V study area, ground water flows from the Lower Floridan aquifer to the Upper Floridan aquifer vertically upward through the middle semiconfining unit.

For the two northernmost cross sections (3 and 4), ground-water flow out the western model boundary is indicated by the velocity vectors. These plots are somewhat misleading, as the primary direction of flow in these regions is north, not west (Figure 4.9). The western component of ground-water flow in these regions is very small.

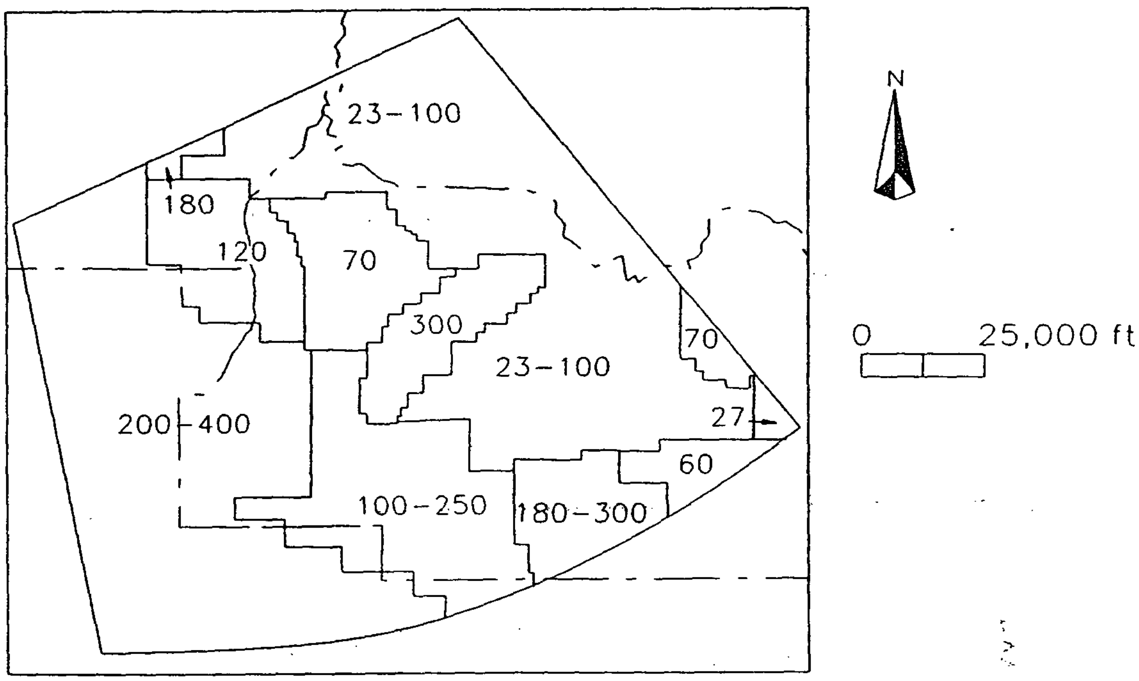
It should be emphasized that the cross sections presented in this report have a very high vertical exaggeration. If the cross-sectional figures were plotted to scale, they would be approximately

53 times as long as they are thick. Consequently, the simulated isochlors would form a true wedge shape, rather than appear vertical or nearly vertical as indicated by the figures in this report.

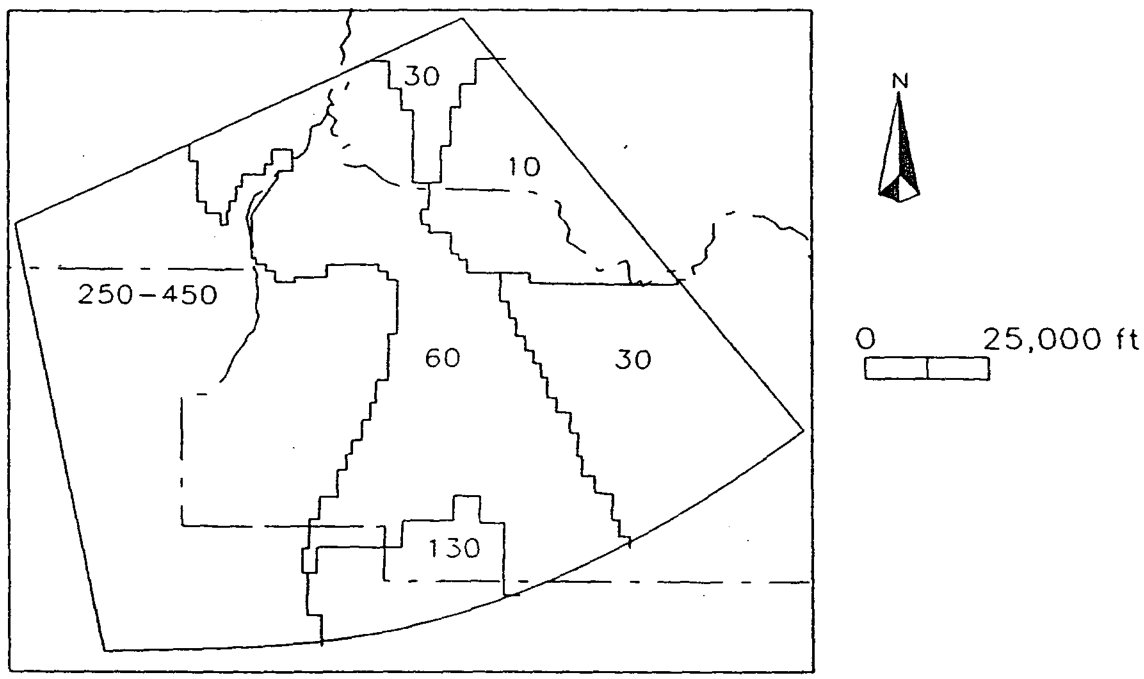
The calibrated model parameters are presented in Figures 4.14 and 4.15. Table 4.2 summarizes the various model input parameters. Transmissivity in the Upper Floridan ranges 400,000 to 23,000 ft^2/d, which corresponds to a range of horizontal hydraulic conductivities of about 4,000 to 60 ft/d. Over much of the domain, the Upper Floridan transmissivity values are similar to those used in the Phase IV model. Transmissivity of the Lower Floridan ranges from 450,000 to 30,000 ft^2/d within the model domain, which corresponds to a range of horizontal hydraulic conductivities of about 320 to 20 ft/d. Transmissivity of the Lower Floridan aquifer is highest in the western portion of the model domain, and decreases substantially to the east, which is consistent with Tibbals (1990) and GeoTrans (1991). To convert between the transmissivity used in the MODFLOW regional model and the horizontal hydraulic conductivity used in the DSTRAM model, the transmissivity was divided by the aquifer thickness. Furthermore, to approximately simulate a zone of higher permeability within the lower 100 ft or so of the Upper Floridan aquifer, the horizontal hydraulic conductivity in this unit was weighted to be 1.5 times that of the conductivity in the overlying portion of the Upper Floridan aquifer.

Calibrated leakances of the upper confining unit and the middle semiconfining unit are presented in Figure 4.15. In the middle semiconfining unit, the leakance varies from 1×10^{-6} d^{-1} to 8×10^{-5} d^{-1}. A zone of high leakance (3.0×10^{-4}) is prescribed along the Wekiva River where the river forms the boundary between Lake and Seminole counties. This zone of high leakance is consistent with the conceptual diagram in Tibbals (1990) and is required to simulate chloride concentrations of 250 mg/ℓ or more in this region. This zone is also closely linked to the prescribed 1988 withdrawal at the Wekiva Falls Resort, which is discussed later in this chapter.

In general, the leakance of the middle semiconfining unit throughout much of central and western Seminole County was reduced relative to the Phase IV calibrated values by about 5-50 times. Adjustment of the middle semiconfining unit leakance was necessary to obtain the desired

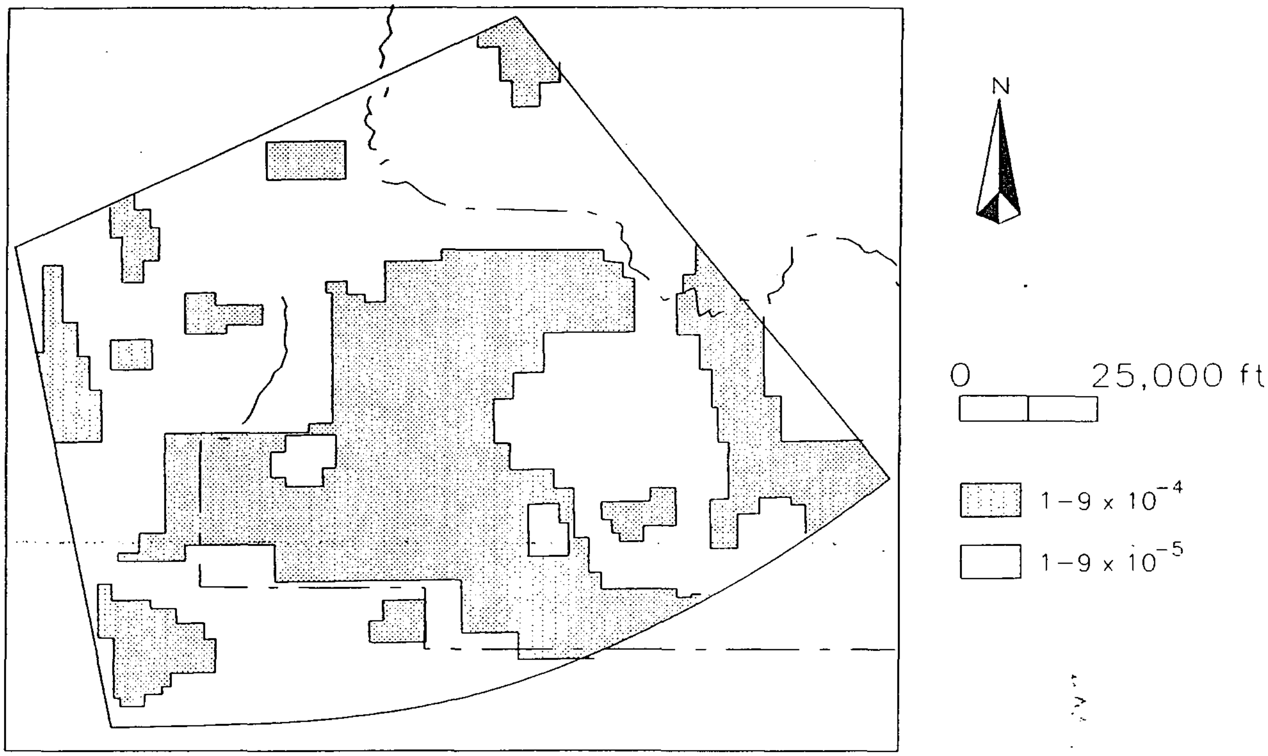


(a)

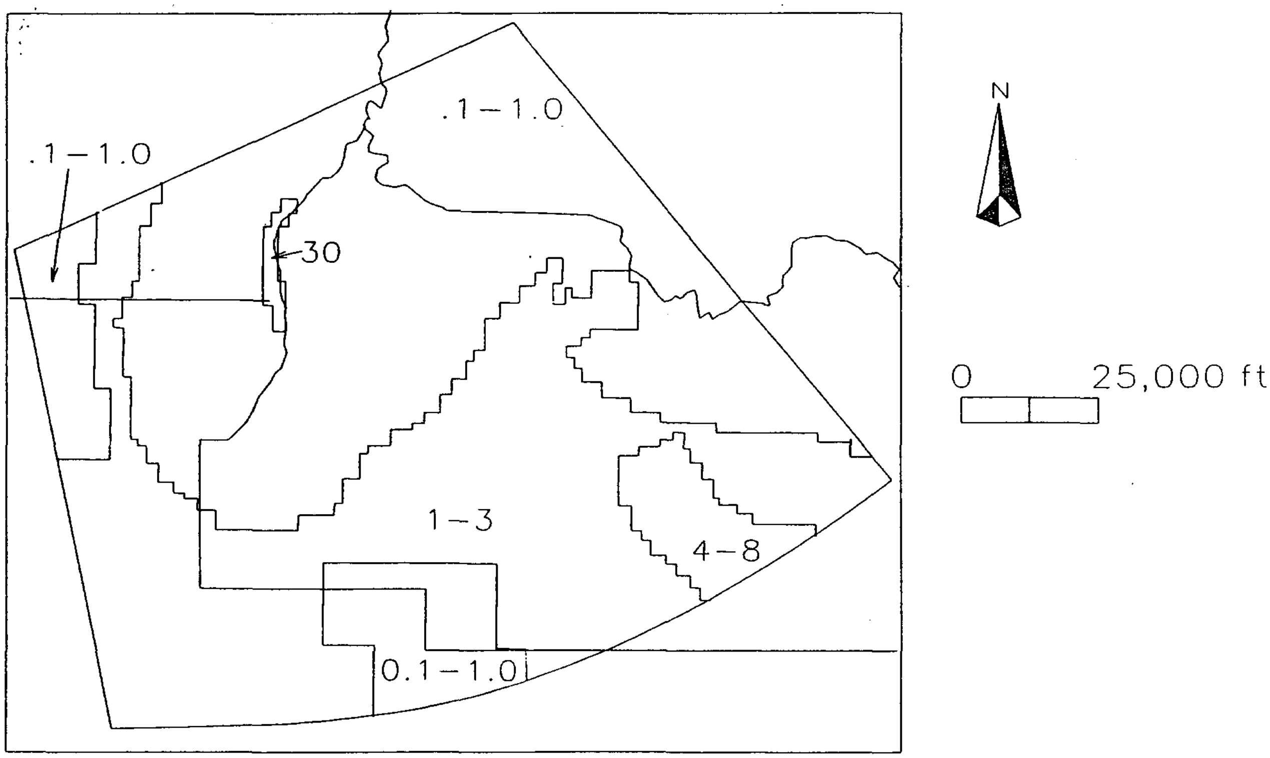


(b)

Figure 4.14 Transmissivity of the Upper Floridan (a) and Lower Floridan (b) aquifers in thousands of ft^2/d.



(a)



(b)

Figure 4.15 Leakance of the upper confining unit (a) and the middle semiconfining unit (b) times 10^{-5} d^{-1}.

Table 4.2 Summary of calibrated model input parameters.

Parameter		High	Low
Transmissivity (ft^2/d)	Upper Floridan	400,000	23,000
	Lower Floridan	450,000	10,000
Upper Confining Unit Leakance (d^{-1})		9×10^{-4}	1×10^{-5}
Middle Semiconfining Unit Leakance (d^{-1})		3×10^{-4}	1×10^{-6}
Porosity	Upper Floridan	0.25	0.25
	Lower Floridan	0.25	0.25
	Middle Semiconfining Unit	0.25	0.25
Dispersivity (ft) longitudinal/transverse	Upper Floridan	50/5	50/5
	Lower Floridan	50/5	50/5
	Middle Semiconfining Unit	50/5	50/5
Anisotropy Ratio*	Upper Floridan	1:10	1:10
	Lower Floridan	1:10	1:10
	Middle Semiconfining Unit	1:10	1:10
Specific Storage (ft^{-1})	Upper Floridan	3×10^{-6}	3×10^{-6}
	Lower Floridan	7×10^{-7}	7×10^{-7}
	Middle Semiconfining Unit	1.5×10^{-6}	1.5×10^{-6}

* Defined as the ratio of vertical hydraulic conductivity, K_z, to horizontal hydraulic conductivity, K_x.

distribution of chloride concentration in the Upper Floridan aquifer. Changes in this parameter had a relatively minor influence on the simulated hydraulic heads. It should also be stressed that, due to a general paucity of hydraulic head and chloride concentration data for the Lower Floridan aquifer, the calibrated values of middle semiconfining unit leakance are intrinsically more uncertain then those of the upper confining unit.

Calibrated leakances of the upper confining unit are on the order of 10^{-5} to 10^{-4} d^{-1}. The lowest values generally occur in discharge areas such as the Wekiva Swamp and along the Wekiva and St. Johns rivers. The largest values generally occur in the high recharge areas of Seminole County (see Figure 3.9).

An effective porosity of 0.25 was used for the Upper Floridan aquifer, the Lower Floridan aquifer and the middle semiconfining unit. This value is in reasonable agreement with numerous other studies.

The anisotropy ratio of vertical to horizontal hydraulic conductivity is 1:10 for both the Upper and Lower Floridan aquifers and the middle semiconfining unit. This ratio is in good agreement with other studies and is similar to that used in the Phase II vertical cross-sectional modeling (Blandford, 1991) and the Phase III modeling (Blandford and Birdie, 1992a).

The final calibrated longitudinal dispersivity (α_L) is 50 ft. This value is consistent with other transport modeling studies in the region (e.g., Panday et al. 1990). This value is also consistent with local-scale field studies conducted by Burklew (1989) south of the study area near Melbourne. Dispersivities at this field site of 18.48 ft and 31 ft were determined using single- and two-well tracer tests. Because these values were observed at a local scale, a larger α_L is not unreasonable for regional-scale modeling. A constant transverse dispersivity (α_T) of 5 ft was used throughout the modeling domain. In modeling studies it is common to set α_T to some fraction of α_L for two reasons: 1) α_T is rarely measured in the field and 2) α_T is known to be much smaller (by 1/5 to 1/100) than α_L (de Marsily, 1986 and Gelhar et al., 1992). In this study, α_T was assumed to be 1/10th of α_L. Since the size of the model elements is generally large relative to the selected dispersivities, it was necessary to utilize the DSTRAM variable upstream weighting option to obtain converged results. Utilization of this option introduces an additional dispersion component into the system, generally referred to as numerical or artificial dispersion. The effect of using a larger physical dispersivity was investigated during the sensitivity analysis (Section 4.8). In general, using a larger physical dispersivity had very little affect on the simulated isochlors in the Upper Floridan aquifer.

Numerical dispersion can occur in the vertical, as well as in the horizontal, dimension. Without constructing a finer simulation mesh and rerunning the same transport problem, it is not possible to identify the degree of numerical dispersion within the model domain. However, the simulation results may be too disperse in the vertical dimension, as evidenced by the few deep test wells for which chloride concentrations with depth are known. For example, at the Gemini Springs monitor well and the Merritt Island injection test well, chloride concentrations typically increase by thousands of mg/ℓ over a vertical distance of several hundred feet. The simulated increases in chloride concentrations with depth are typically not that high. Increasing chloride concentrations with depth could be better simulated using a finer grid discretization, or perhaps through the application of alternative velocity-dependent dispersion algorithms, such as heterogeneous dispersion or direction-dependent dispersion as documented by Reilly (1990).

For completeness, the values of specific storage (S_s) used during the transient simulations are included in Table 4.1. Specific storage values of 3.0×10^{-6}, 7×10^{-7} and 1.5×10^{-6} ft^{-1} were used for the Upper Floridan, the Lower Floridan, and the middle semiconfining unit, respectively. These values are in good agreement with the generally accepted physical limits of S_s (de Marsily, 1986), and other three-dimensional modeling studies in central Florida (see, for example, Panday and Birdie, 1992). The storativity, or storage coefficient, of an aquifer is defined as S_s multiplied by the aquifer thickness. Using the above S_s values, the storativity of the Upper and Lower Floridan aquifers would be about 9×10^{-4} and 1×10^{-3}, respectively. These values are in good agreement with those used by Tibbals (1990) and Jammal and Associates (1990).

4.7.4 Average 1988 Model Calibration Results

The average 1988 (postdevelopment) model calibration results are presented in Figures 4.16 - 4.25. Figures 4.16 and 4.17 illustrate the simulated environmental head and normalized chloride concentration for the Upper Floridan aquifer, respectively. Figure 4.18 is a contour plot of the difference between the observed potentiometric surface and the simulated environmental heads in the Upper Floridan aquifer. Figures 4.19 and 4.20 illustrate the simulated environmental head and normalized chloride concentration for the Lower Floridan aquifer, respectively. Figure 4.21 consists of areal velocity vector plots for both the Upper and Lower Floridan aquifers. And finally, Figures 4.22-4.25 portray the normalized chloride concentrations and velocity vectors for cross-sections 1-4.

The average 1988 simulation results were obtained by conducting a transient simulation from assumed predevelopment conditions to 1988 (simulation period of 30 years). A time step of 10 years was used for the transient simulation; this time step meets the local Courant number criterion for a stable solution presented in Huyakorn and Pinder (1983). The final calibrated 1988 simulation was double-checked by rerunning the simulation using a time step of 2 years, and no differences were observed in the simulation results. Note that since the postdevelopment results are obtained from a transient simulation, they are dependent upon effective porosity, whereas the predevelopment simulation results are not.

A comparison of Figures 4.16-4.25 with the observed data and the predevelopment simulation results (Figures 4.4-4.13) indicates that the postdevelopment model calibration is reasonable. In the Upper Floridan, the difference between the average 1988 observed potentiometric surface and the simulated potentiometric surface is generally less than 4 ft throughout the model domain (Figure 4.18). Local differences of up to 6 ft exist, generally in the vicinity of springs where observed hydraulic gradients are steep, and small errors in simulated heads lead to relatively large head differences.

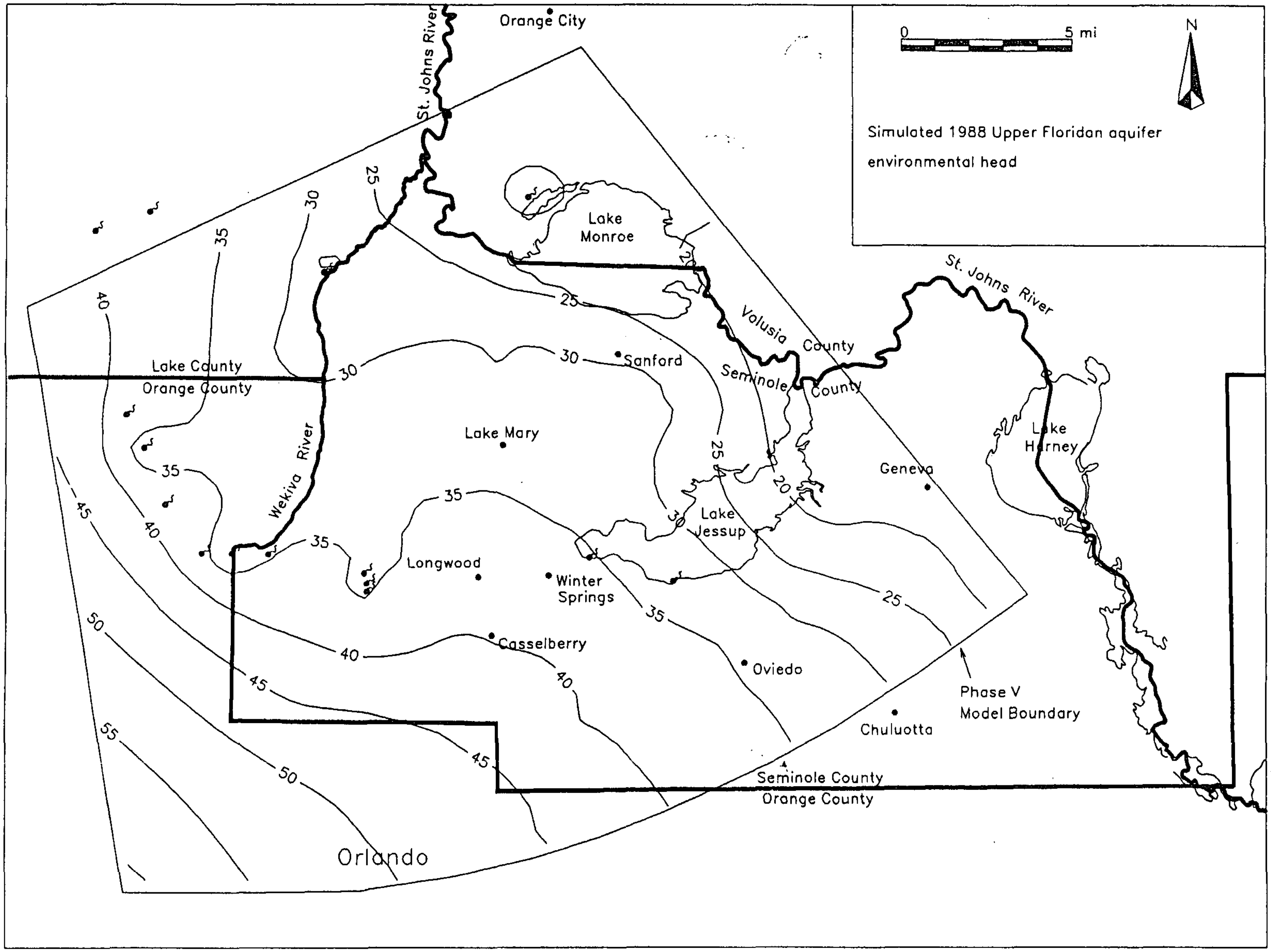


Figure 4.16 Simulated average 1988 environmental head in the Upper Floridan aquifer in ft. Datum is mean sea level.

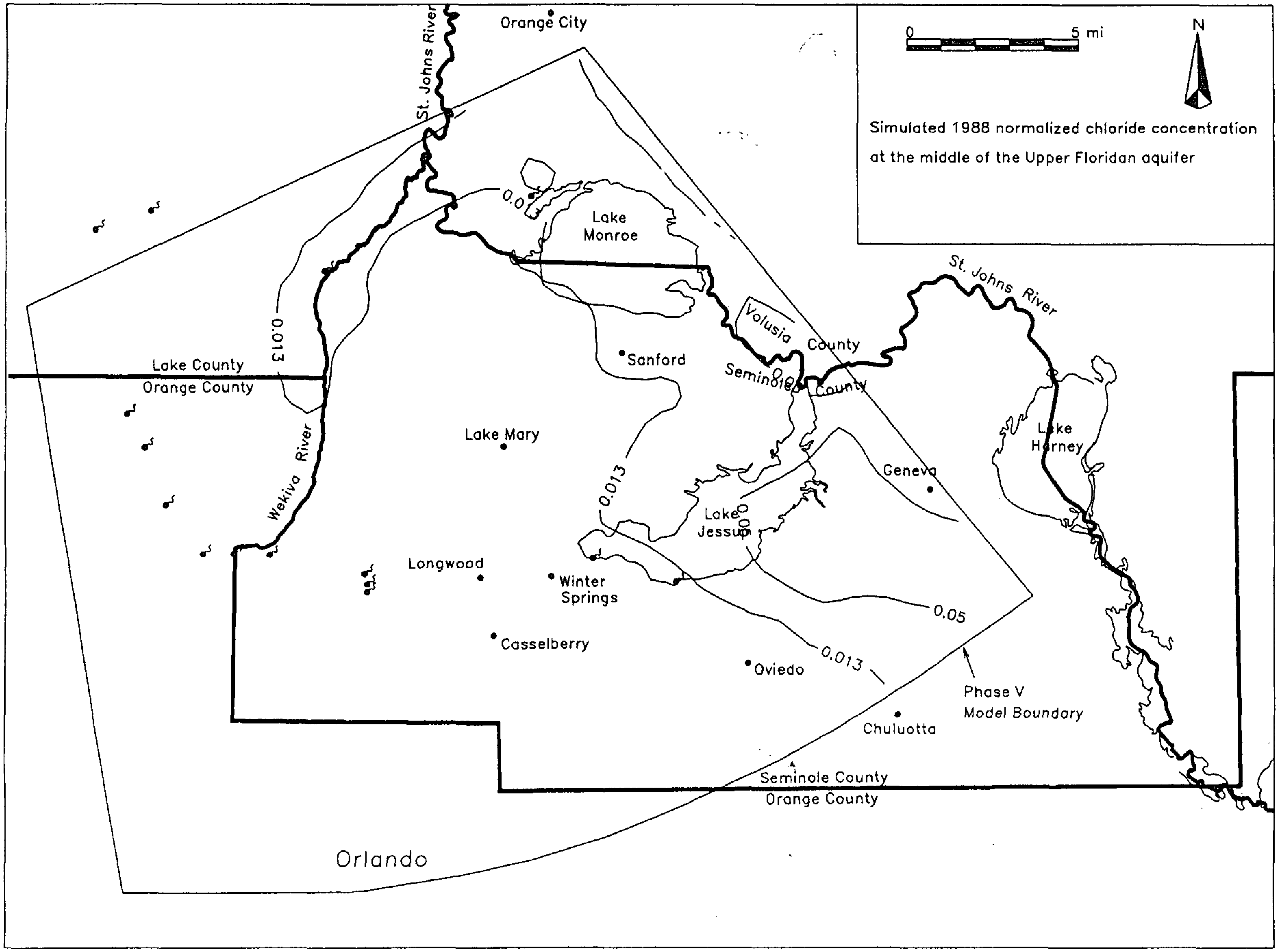


Figure 4.17 Simulated 1988 normalized chloride concentration in the Upper Floridan aquifer.

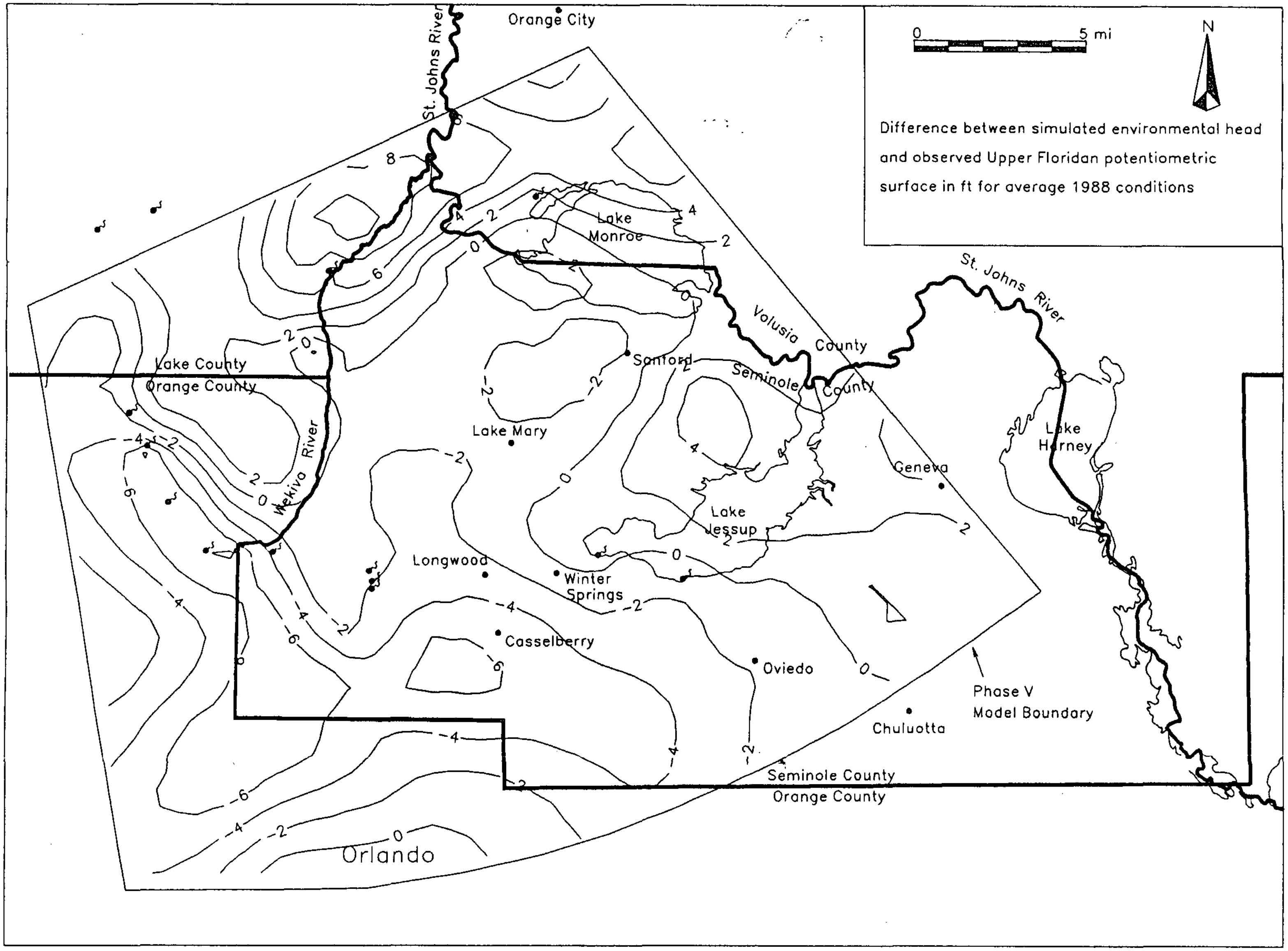


Figure 4.18 Difference between observed average 1988 potentiometric surface and simulated 1988 environmental head in the Upper Floridan aquifer in ft.

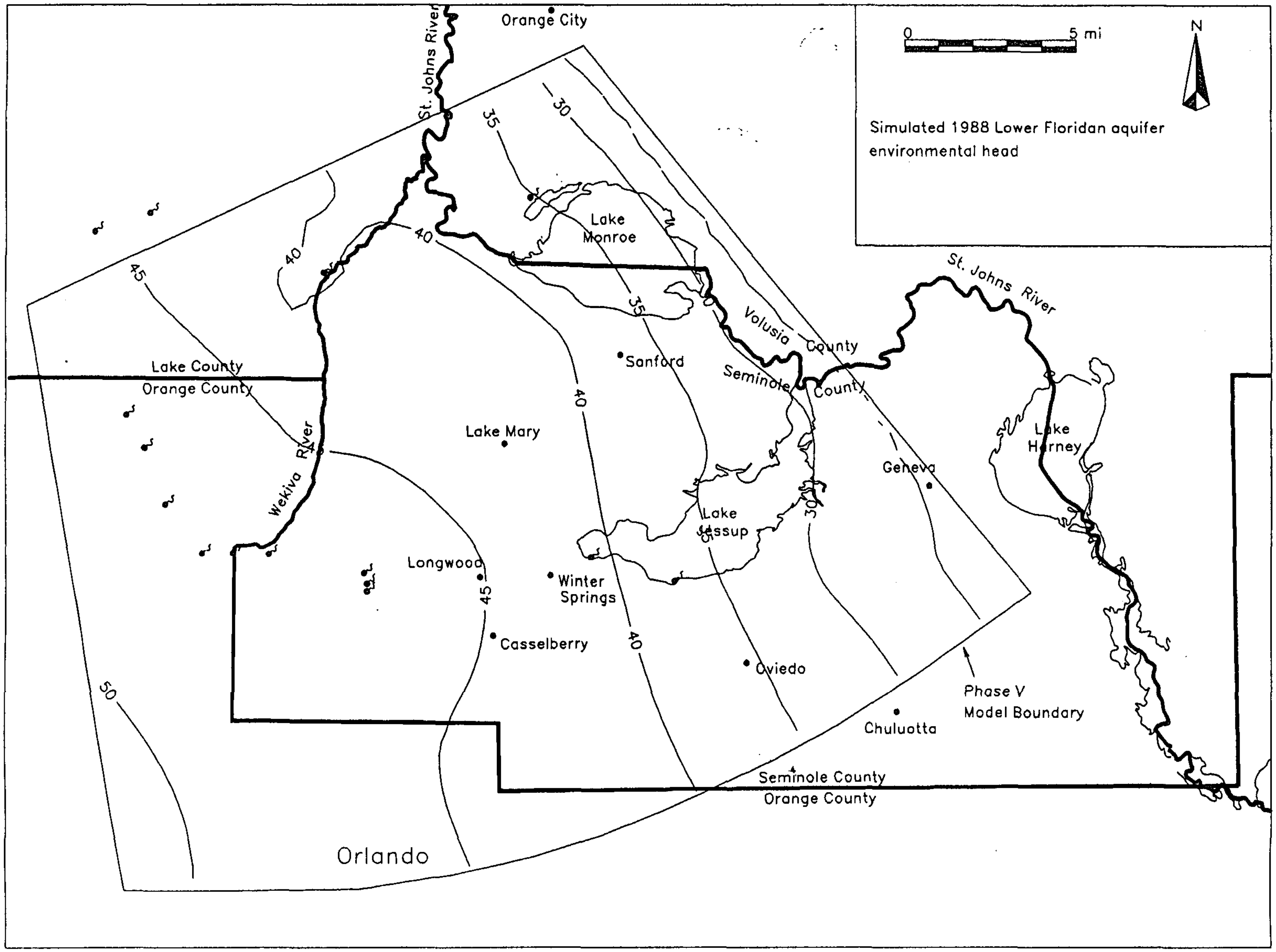


Figure 4.19 Simulated 1988 environmental head in the Lower Floridan aquifer in ft. Datum is mean sea level.

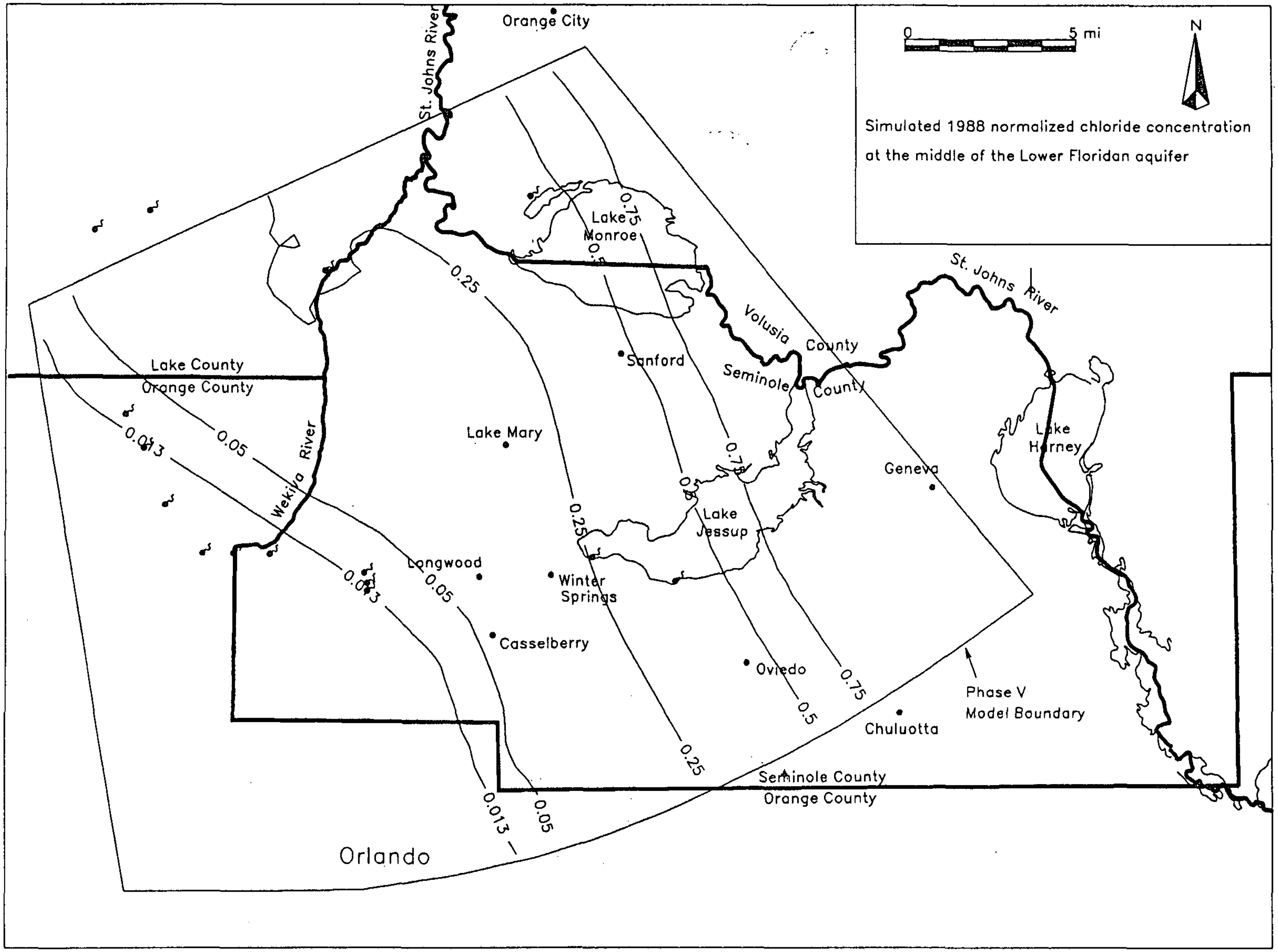
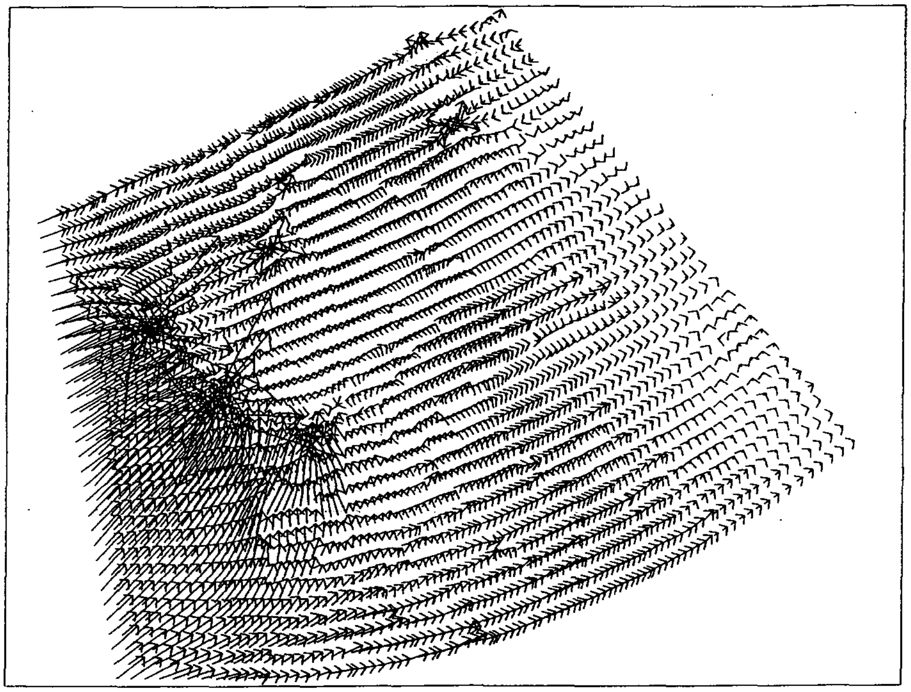
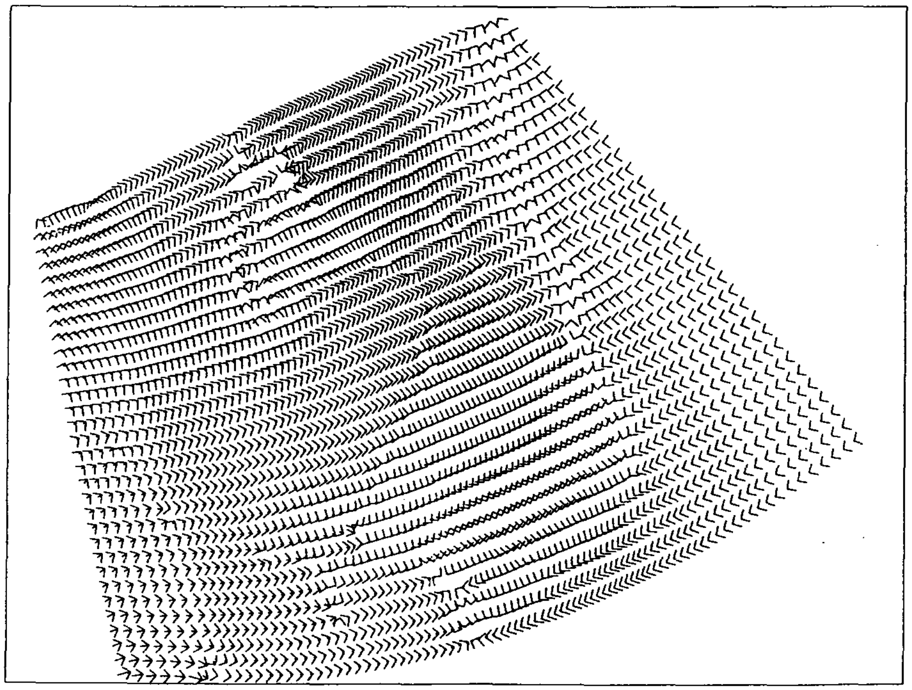


Figure 4.20 Simulated 1988 normalized chloride concentration in the Lower Floridan aquifer.



(a)



(b)

Figure 4.21 Areal ground-water flow velocity at the middle of the Upper Floridan aquifer (a) and the Lower Floridan aquifer (b) for simulated average 1988 conditions.

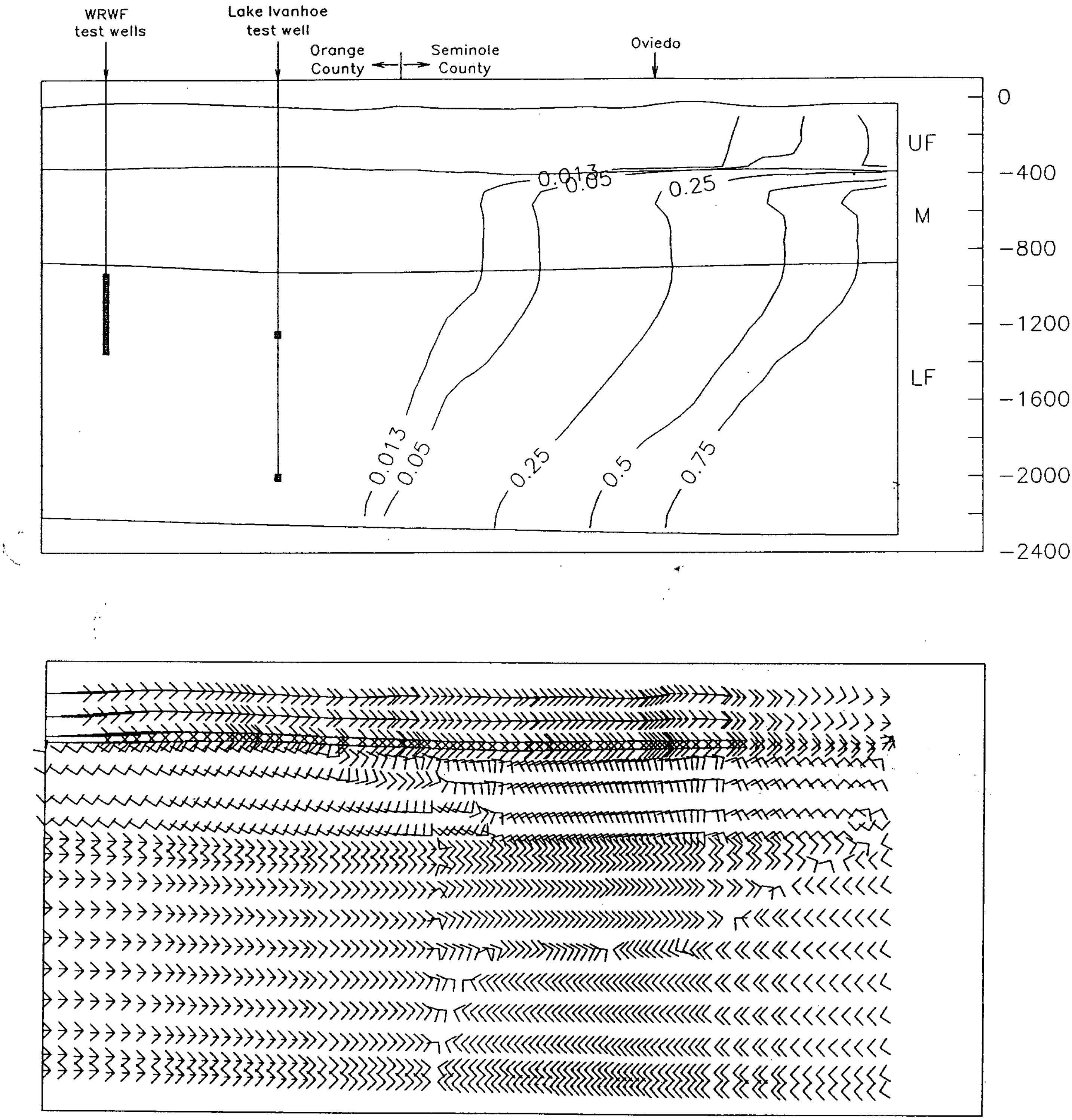


Figure 4.22 Simulated 1988 normalized chloride concentration and velocity vectors for cross-section 1.

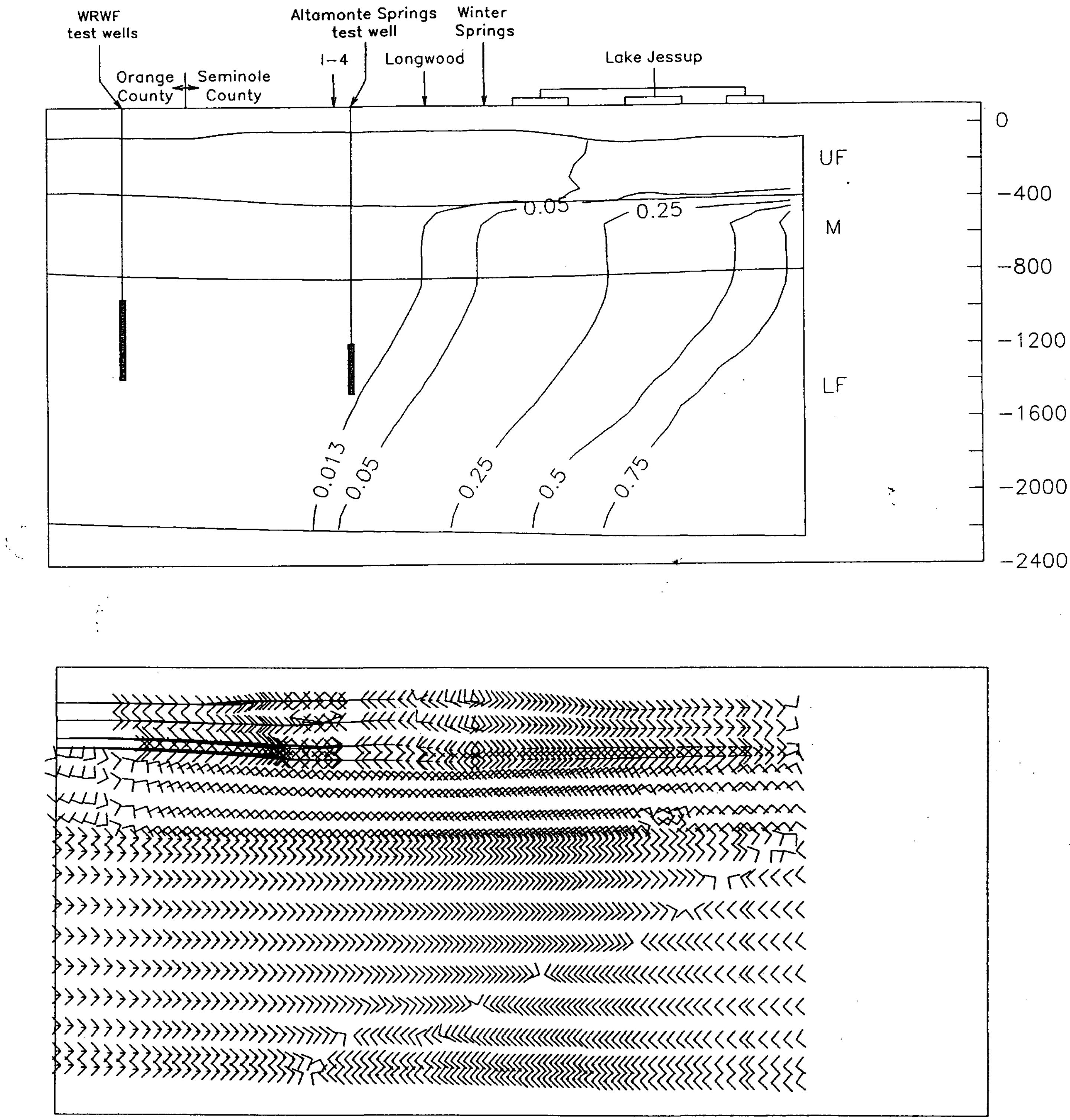
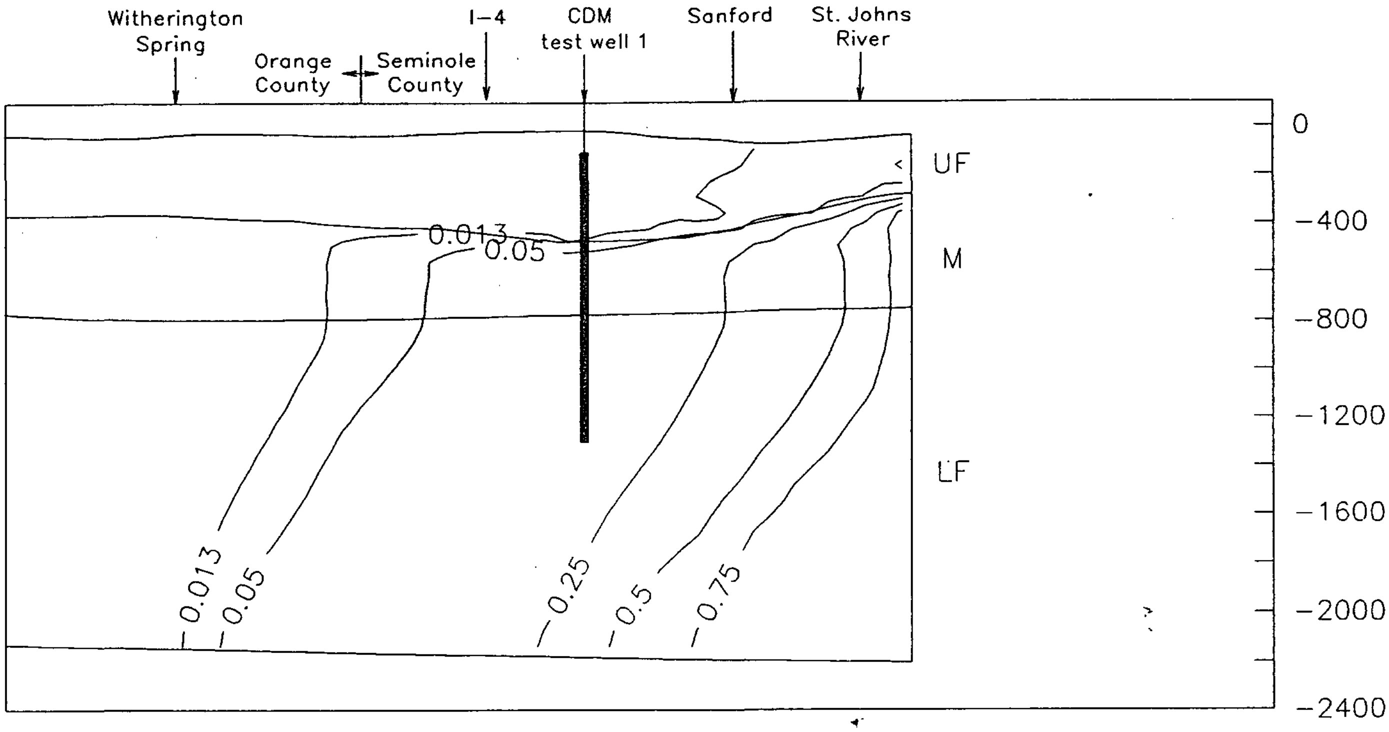


Figure 4.23 Simulated 1988 normalized chloride concentration and velocity vectors for cross-section 2.



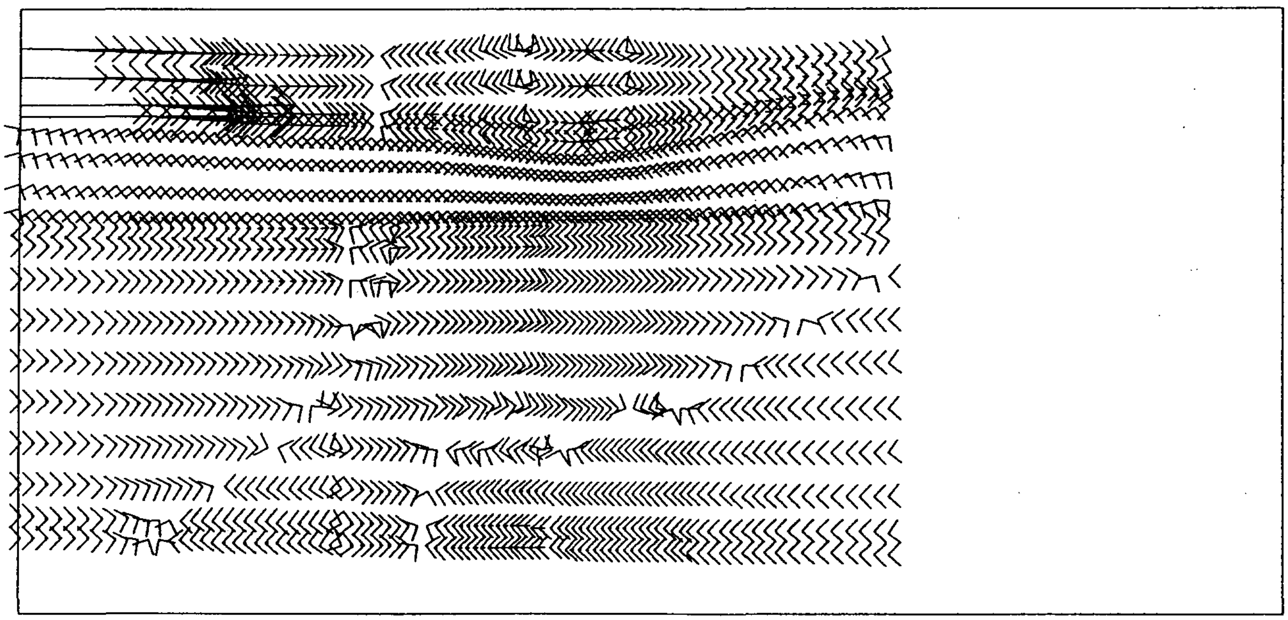


Figure 4.24 Simulated 1988 normalized chloride concentration and velocity vectors for cross-section 3.

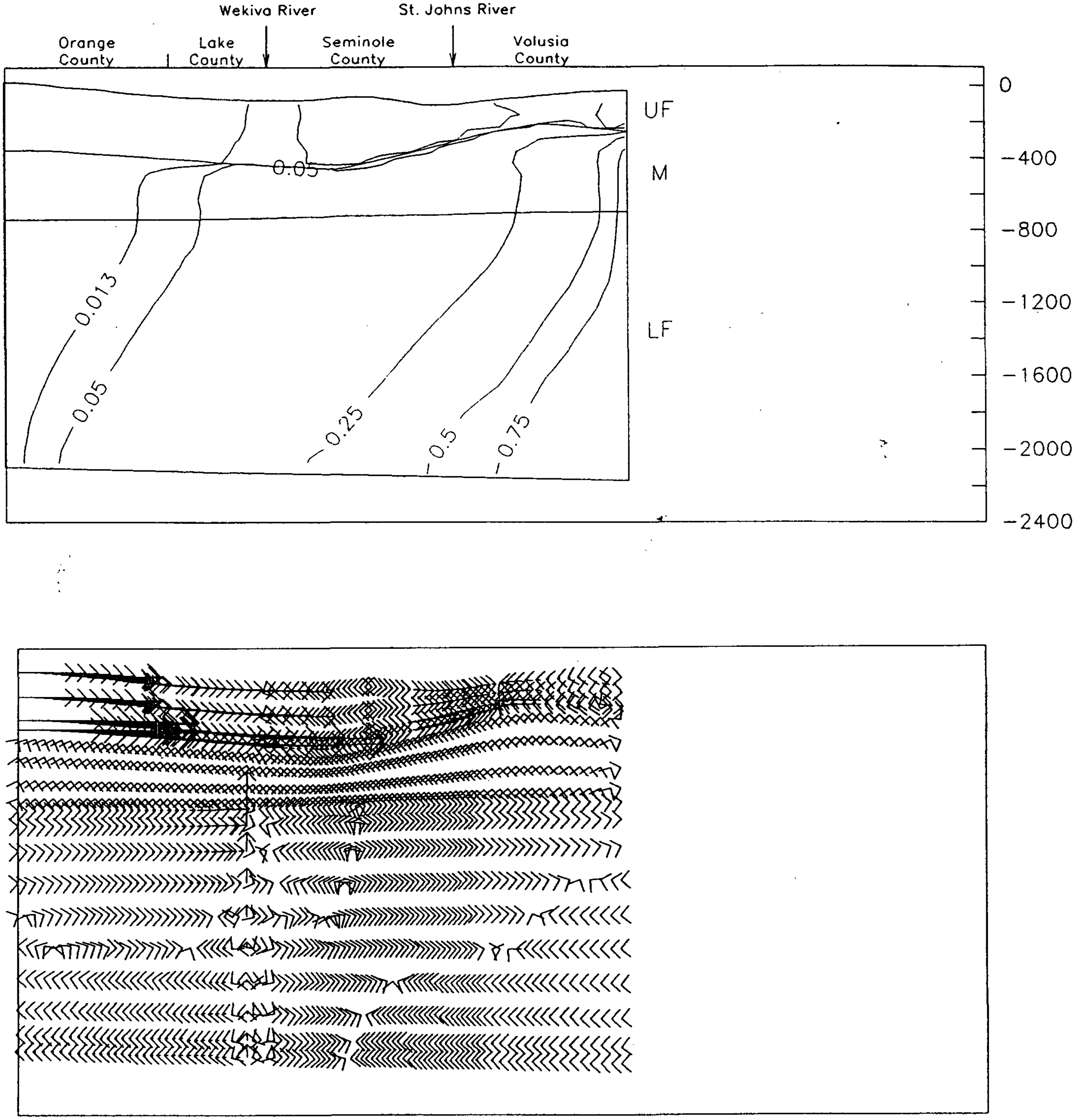


Figure 4.25 Simulated 1988 normalized chloride concentration and velocity vectors for cross-section 4.

There is a local zone along the north-central boundary of the model domain where the simulated heads are up to 10 ft higher than those observed. This zone corresponds to a pronounced trough in the 15 ft potentiometric surface contour in the vicinity of the confluence of the Wekiva and St. Johns Rivers (Blandford and Birdie, 1992b). The simulated head in this region is about 25 ft. The major cause of the large head differences in this area are due to the high leakance values applied in the middle semiconfining unit along the Wekiva River; this zone of increased leakances reduces drawdown (increases head) in the Upper Floridan aquifer in this region.

As mentioned previously, the zone of high leakance in the middle semiconfining unit along the Wekiva River is closely linked to the prescribed postdevelopment discharge of 12.75 million gallons per day (MGD) at the Wekiva Falls Resort. Initially, high chloride concentrations were simulated in the vicinity of the Wekiva River for the predevelopment calibration, and when the postdevelopment simulation was conducted chloride concentrations in this region reduced substantially due to the new efflux prescribed. In order to maintain simulated chloride concentrations along the Wekiva River from predevelopment to average 1988 conditions, it was necessary to increase the leakance of the middle semiconfining unit.

The observed and simulated average 1988 spring flows are presented in the bottom portion of Table 4.1. For the major springs, there is generally less than a 5 percent error, which is an excellent calibration match. There is about 3 percent error in total spring flow within the model domain.

As expected, the simulated postdevelopment isochlors (Figures 4.17, 4.20 and 4.22-4.25) are very similar, and in many places identical to the simulated predevelopment isochlors. This result is consistent with previous investigations (e.g., Blandford and Birdie, 1992a), and is due primarily to the fact that large time scales (generally much larger than 30 years) are required for solutes in the aquifer to equilibrate, or move, in response to imposed stresses. An unexpected result was obtained, however, in that at several locations in the Upper Floridan, specifically south and southeast of Sanford and east of Oviedo, the simulated postdevelopment 250 mg/ℓ isochlor moved east, rather than remaining stationary or moving west towards regions of pumping. This result is due primarily to changes in recharge to the Upper Floridan aquifer between predevelopment and postdevelopment simulation conditions, and is discussed in detail in the following section.

In the Lower Floridan aquifer, the simulated postdevelopment isochlors are generally identical to the predevelopment isochlors. There is a local region in southern Seminole County, about 1-2 miles northeast of Winter Park, in which the simulated 1,000 mg/ℓ isochlor moved slightly west from predevelopment to postdevelopment conditions. The movement occurred in response to pumping in the Lower Floridan aquifer in this region, which is due primarily to Casselberry Lower Floridan public supply wells. This result should be interpreted only as a warning that movement potentially could occur, since the Casselberry wells do not currently extract water of high chloride concentration, and because simulation results in the Lower Floridan aquifer can not be rigorously calibrated due to insufficient data. The same general region was also indicated by Blandford and Birdie (1992a) to be one of potential saltwater intrusion in the Lower Floridan aquifer.

The 1988 areal velocity vector plots (Figure 4.21) are quite similar to the predevelopment simulation results, with the exception that in the Lower Floridan aquifer in the northwest portion of the model domain, ground-water flow is primarily north to northeast, and the small northwestern component of flow observed for the predevelopment simulation nearly vanishes (compare Figure 4.21 with Figure 4.9). This result is also illustrated by the number 3 and 4 cross-sectional velocity vector plots, in which the direction of ground-water flow along the western model boundary is to the east for average 1988 conditions (Figures 4.24 and 4.25) rather than to the west as was observed for predevelopment conditions (Figures 4.12 and 4.13). Finally, the velocity vector plots for cross sections 1 and 2 (Figures 4.22 and 4.23) indicate that the Upper Floridan aquifer recharges the Lower Floridan aquifer along the southern portion of the western model boundary. This result is consistent with observations conducted at Orange County's Western Regional wellfield, situated near the western model domain (see Figure 3.12).

4.7.5 Change in Recharge from Predevelopment to Postdevelopment Conditions and the Effect on the Saltwater-Freshwater Interface

In the previous section, the observation was made that in several areas of Seminole County the simulated postdevelopment 250 mg/ℓ isochlor moved slightly east, rather than west, relative to the simulated predevelopment position. This result is attributed to two factors. First, many regions in the vicinity of the 250 mg/ℓ isochlor changed from Upper Floridan discharge to recharge from predevelopment to postdevelopment conditions (Figure 4.26), and secondly there is a substantial increase in recharge to the Upper Floridan aquifer from predevelopment to postdevelopment conditions throughout the high recharge areas in Seminole County (Figure 4.27). The net result of these two factors is that where the 250 mg/ℓ isochlor exists in close proximity to good recharge areas in Seminole County (particularly south of Sanford and east and southeast of Oviedo, see Figure 3.9), the simulated postdevelopment 250 mg/ℓ isochlor moves slightly east due to the increased influx of freshwater from the surficial aquifer.

This result indicates that in order to accurately simulate movement of the 250 mg/ℓ isochlor in Seminole County it is important that increases in recharge to the Upper Floridan aquifer be appropriately accounted for. In the Phase IV modeling study (Blandford and Birdie, 1992b), simulated increases in recharge in Seminole County from predevelopment to average 1988 conditions were found to be reasonable and in accordance with other studies (e.g. Tibbals, 1990). However, the potential exists for increases in recharge to be overestimated because prescribed heads in the surficial aquifer are not altered between the predevelopment and postdevelopment simulation periods, when in actuality it might be expected that the water table in the surficial aquifer may have declined somewhat from predevelopment conditions. The effects of reducing the simulated increase in recharge from predevelopment to postdevelopment conditions in the vicinity of the 250 mg/ℓ isochlor are evaluated in a sensitivity analysis run presented in the next section. To summarize the simulation results here, locally the 250 mg/ℓ isochlor can be simulated to move west or east, depending upon the imposed increase in recharge to Upper Floridan aquifer.

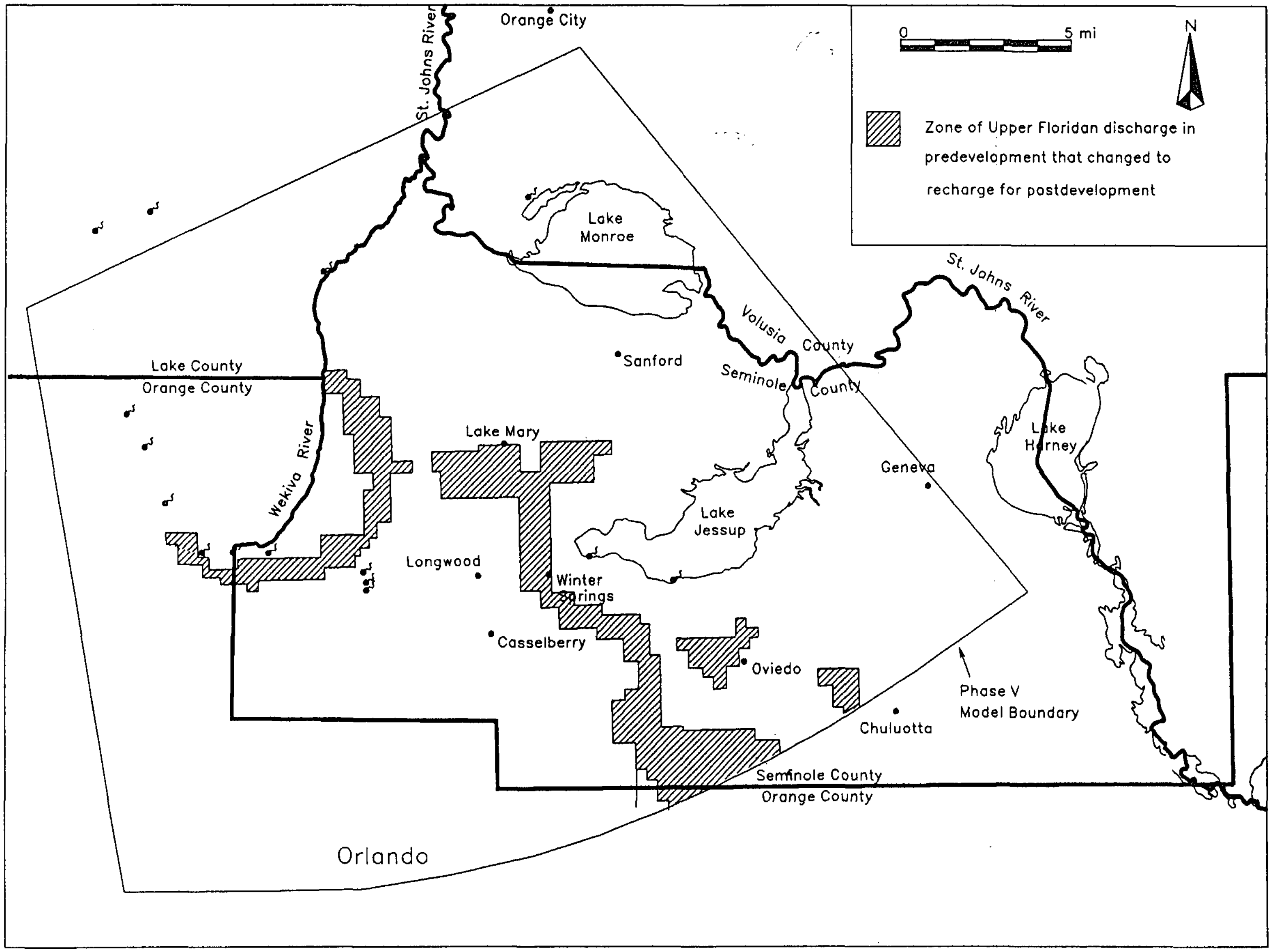


Figure 4.26 Portions of the Phase V model domain that changed from discharge from the Upper Floridan aquifer to recharge to the Upper Floridan aquifer from predevelopment to postdevelopment conditions.

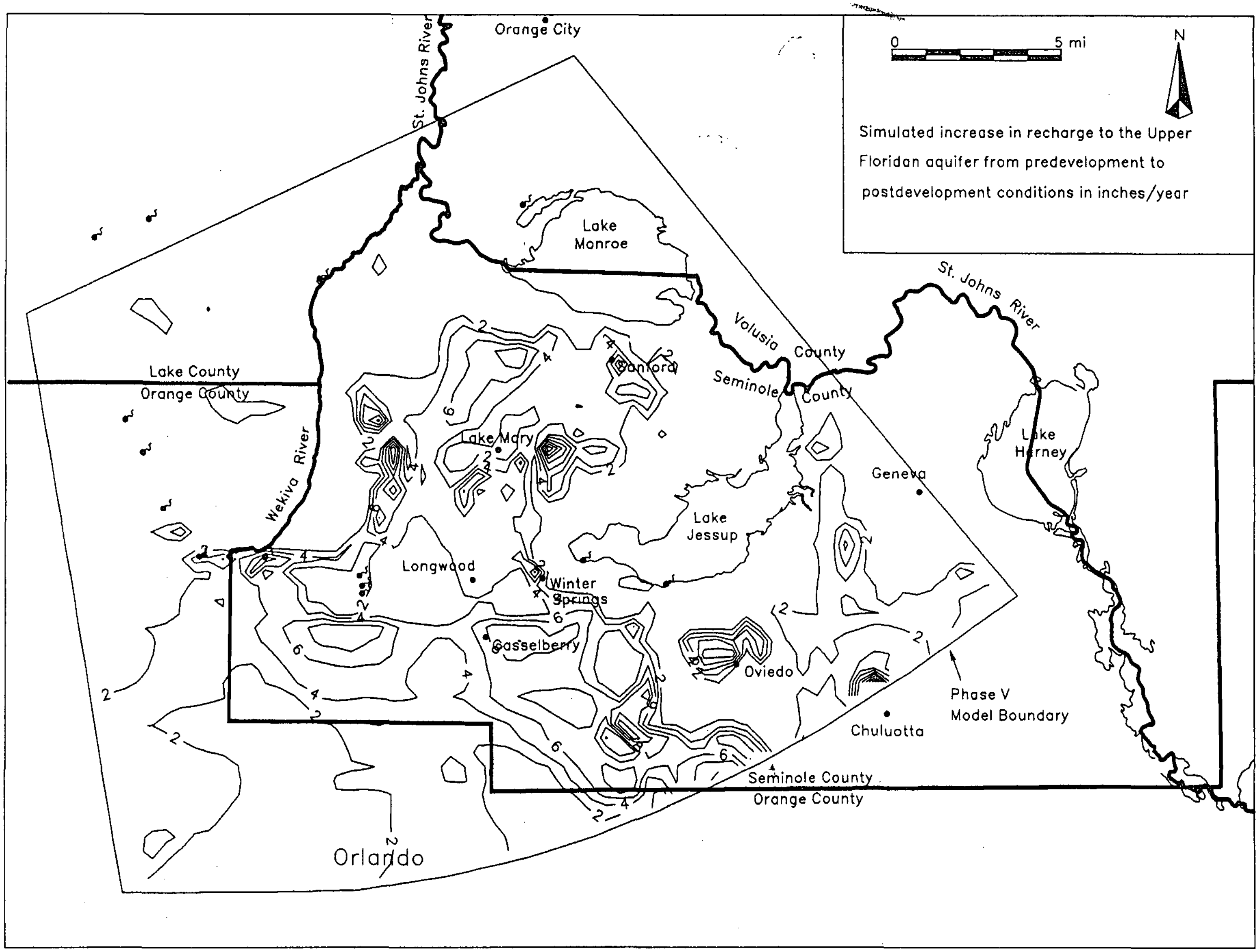


Figure 4.27 Increase in recharge to the Upper Floridan aquifer from predevelopment to post-development conditions in inches/year.

4.8 Model Sensitivity Analysis

A series of seven sensitivity runs were conducted to illustrate the effect that varying certain model input parameters has upon the simulated hydraulic heads and chloride concentrations. The model parameters investigated during the sensitivity analysis are the hydraulic conductivity in the Upper Floridan aquifer; the longitudinal and transverse dispersion coefficients; the leakance of the middle semiconfining unit; and the effective porosity of the Upper Floridan aquifer. Two sensitivity runs were conducted for the northeastern model boundary by assuming both increased and decreased values of equivalent freshwater head in the Lower Floridan aquifer. The final sensitivity run involved a reduction in the simulated increase in recharge to the Upper Floridan aquifer from predevelopment to postdevelopment conditions in the vicinity of the 250 mg/ℓ isochlor. Except for the effective porosity and reduced recharge sensitivity runs, all sensitivity runs were conducted for predevelopment, steady-state conditions. Furthermore, due to the intensive labor and computational demands required to conduct and evaluate each steady-state simulation, the sensitivity parameters listed above were only adjusted one time. For example, the Upper Floridan hydraulic conductivity was increased for a sensitivity run, but an additional run was not conducted in which the Upper Floridan hydraulic conductivity was decreased. In general, the model will respond in an opposite, although not necessarily equal, manner to opposite changes (increases and decreases) in model parameters. The steady-state sensitivity model runs should be compared against the figures in Section 4.7.3, and the transient sensitivity model runs should be compared against the figures in Section 4.7.4. A summary overview of each sensitivity analysis is provided in Table 4.3.

In addition to the formal sensitivity runs outlined above, a large number of model runs were conducted during the model calibration portion of this project to identify sensitive model parameters. A summary of model sensitivity with respect to some additional input parameters, specifically Lower Floridan aquifer hydraulic conductivity, anisotropy ratios in the various hydrogeological units, and the bottom boundary condition, is provided in Section 4.8.7. Due to the limited effects and/or relative insensitivity of simulation results to these parameters, formal sensitivity runs (runs based on the final calibrated model results) were not conducted for

Table 4.3 Summary of Phase V model sensitivity analysis.

Sensitivity Run No.	Description of Change	Summary of Results[a]
1	Upper Floridan hydraulic conductivity increased 2 times	Concentrations in the Upper Floridan substantially decreased. Concentrations in the Lower Floridan essentially unchanged.
2	Longitudinal dispersivity increased from 50 to 100 ft, and transverse dispersivity increased from 5 to 10 ft.	Minor changes in Upper and Lower Floridan isochlors. Higher chloride concentrations near Wekiva Falls Resort.
3[b]	Upper Floridan effective porosity decreased from 0.25 to 0.1	Simulated 250 mg/ℓ isochlor moved slightly to the east southeast of Oviedo and southeast of Sanford.
4	Middle semiconfining unit leakance increased by a factor of two	Simulated 250 mg/ℓ isochlor intruded toward freshwater regions throughout Seminole County approximately 1-2 miles.
5	Lower Floridan aquifer equivalent freshwater heads increased by 2 ft along the northeastern boundary to simulate higher chloride concentrations in the vertical profile	Substantial increase in Upper Floridan chloride concentrations in central Seminole County and in the vicinity of the Wekiva River.
6	Lower Floridan aquifer equivalent freshwater heads decreased by 2 ft along the northeastern boundary to simulate lower chloride concentrations in the vertical profile	Concentrations in the Upper Floridan decreased slightly in northern and central Seminole County.
7[b]	Increased recharge from predevelopment to postdevelopment conditions reduced by half in the vicinity of the 250 mg/ℓ isochlor	Simulated 250 mg/ℓ isochlor moved to the west, rather than the east, southeast of Sanford and east of Oviedo.

[a] Sensitivity run results summarized in terms of changes in simulated chloride distributions (isochlor locations)

[b] Sensitivity run conducted for transient, postdevelopment conditions rather than steady-state conditions

these parameters.

4.8.1 Hydraulic Conductivity

In the first sensitivity run, the hydraulic conductivity in the Upper Floridan was increased by a factor of two. This change had only a minimal effect on the equivalent freshwater heads and the chloride concentrations in the Lower Floridan; changes were more substantial, however, in the Upper Floridan (Figure 4.28). Heads in the Upper Floridan increased about 5 ft throughout most of the model domain relative to the calibrated model results. The 250 mg/ℓ isochlor migrated to the far eastern margin of the study area; the chlorides in the Upper Floridan were essentially flushed out by ground water moving at higher velocity.

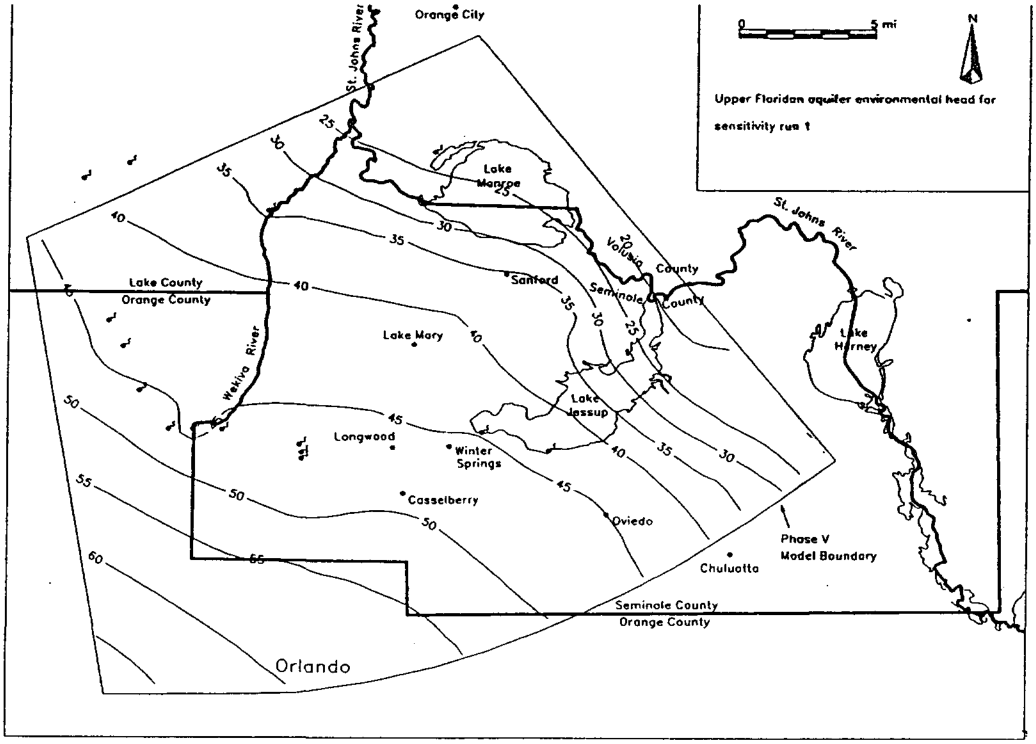
4.8.2 Longitudinal Dispersivity

In the second sensitivity run, the longitudinal dispersivity was increased from 50 ft to 100 ft, and the transverse dispersivity was increased from 5 ft to 10 ft. For this run, the environmental heads at the middle of the Upper Floridan are very similar to the predevelopment calibration. In the Upper Floridan aquifer, the 250 mg/ℓ isochlor moved slightly to the west and north in the northern half of the model domain, and remained relatively stationary in the southern half of the model domain (Figure 4.29). In the Lower Floridan aquifer, the saltwater wedge moved a significant distance to the east in the northern portion of the model domain (cross section 4), and moved slightly to the west in the southern portion of the model domain (cross section 1).

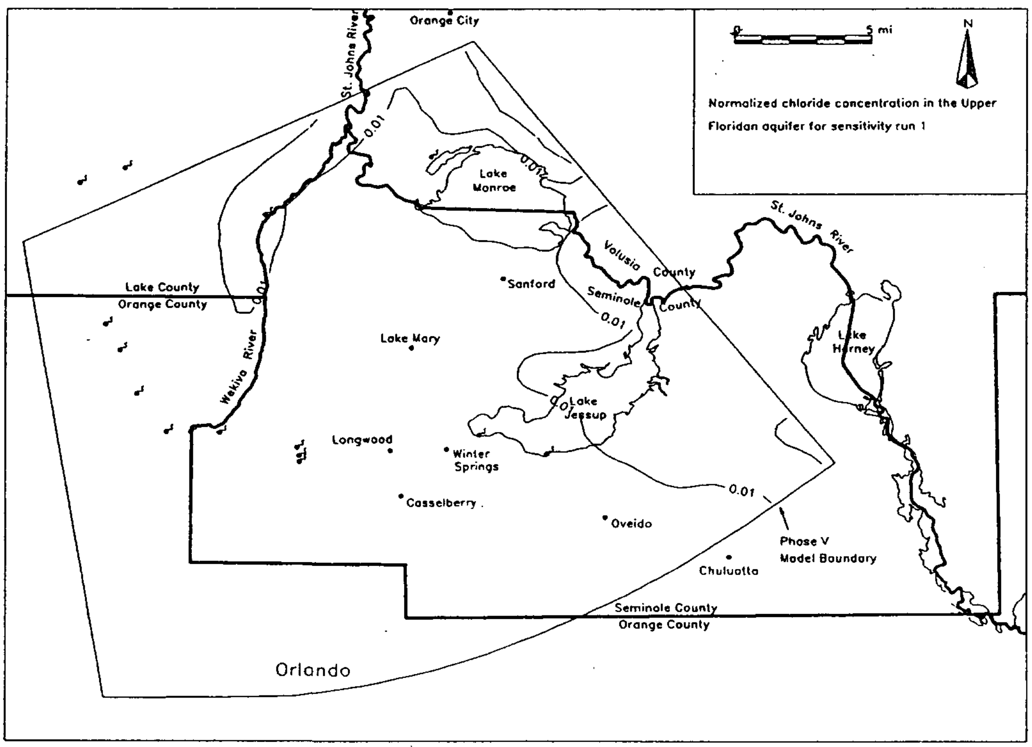
4.8.3 Effective Porosity

This sensitivity run (sensitivity run 3) involved a decrease in the effective porosity of the Upper Floridan aquifer from 0.25 to 0.1. A transient simulation (30 years) was conducted for this sensitivity run because effective porosity has only a minor influence on steady-state (predevelopment) simulation results.

The results of this sensitivity analysis indicate that reducing the effective porosity in the Upper Floridan aquifer leads to a simulated 250 mg/ℓ isochlor that is very similar to the calibrated

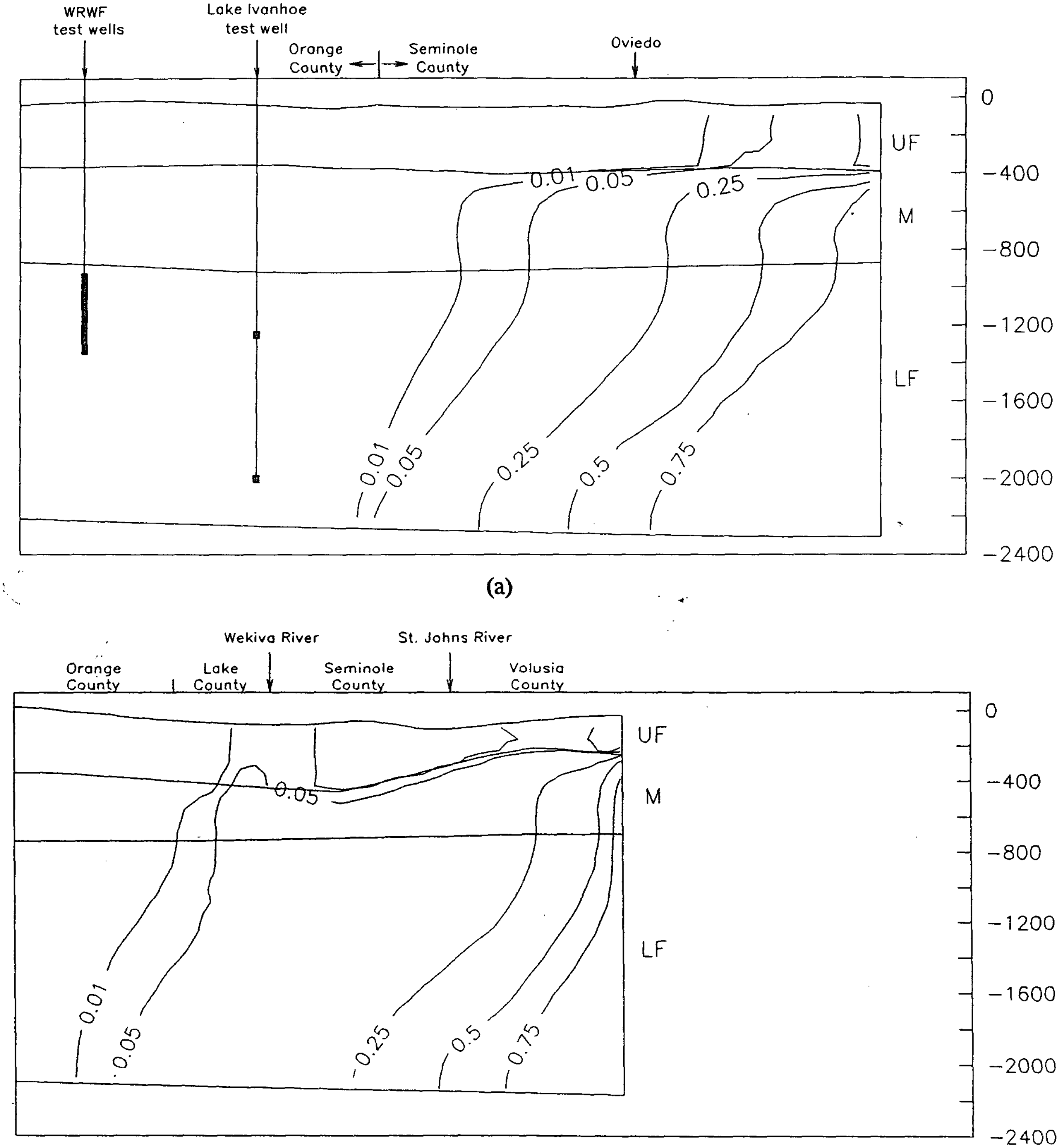


(a)



(b)

Figure 4.28 Environmental head (a) and normalized chloride concentrations (b) for the Upper Floridan aquifer for sensitivity run 1; hydraulic conductivity increased by 2 times in the Upper Floridan.



(a)

(b)

Figure 4.29 Normalized chloride concentrations for cross-section 1 (a) and cross-section 4 (b) for sensitivity run 2, longitudinal dispersivity of 100 ft.

model result. The only change is that in regions where the calibrated postdevelopment isochlor moved slightly east relative to the predevelopment isochlor, the simulated 250 mg/ℓ isochlor moved even farther east by approximately a quarter of a mile or less. This effect is due to the increased ground-water flow velocities caused by decreasing the effective porosity.

4.8.4 Middle Semiconfining Unit Leakance

In sensitivity run 4, the vertical and horizontal hydraulic conductivity of the middle semiconfining unit was increased by a factor of two. Increasing the middle semiconfining unit leakance facilitates the vertical movement of ground water and solutes, and would therefore be expected to increase chloride concentrations in the Upper Floridan aquifer. This effect was observed (Figure 4.30). In general, the simulated 250 mg/ℓ isochlor intruded into the freshwater regions of Seminole County by about 1-2 miles for this sensitivity run.

4.8.5 Northeastern Model Boundary Condition

Two sensitivity runs were conducted in which the prescribed northeastern model boundary condition was altered. In run 5, the equivalent freshwater head prescribed in the Lower Floridan aquifer was increased 2 ft to simulate increased chloride concentrations or an increase in vertical head gradient in the vertical profile through this boundary. Normalized chloride concentrations for the Upper Floridan aquifer for this run are presented in Figure 4.30. Increasing the equivalent freshwater head along this boundary is equivalent to increasing the driving force for the saltwater wedge in the Lower Floridan aquifer. Consequently, the simulated isochlors move substantially to the west in Seminole County, particularly in the vicinity of Sanford. Also, chloride concentrations along the Wekiva River increase substantially.

In sensitivity run 6, the equivalent freshwater head prescribed in the Lower Floridan aquifer was decreased 2 ft to simulate reduced chloride concentrations or a reduction in vertical head gradient in the vertical profile through this boundary. The simulated 250 mg/ℓ isochlor for this sensitivity run moved about 0.5-1.0 miles east of the calibrated isochlor position between Lake Jessup and Lake Monroe. The 250 mg/ℓ isochlor moved only slightly in the region east of

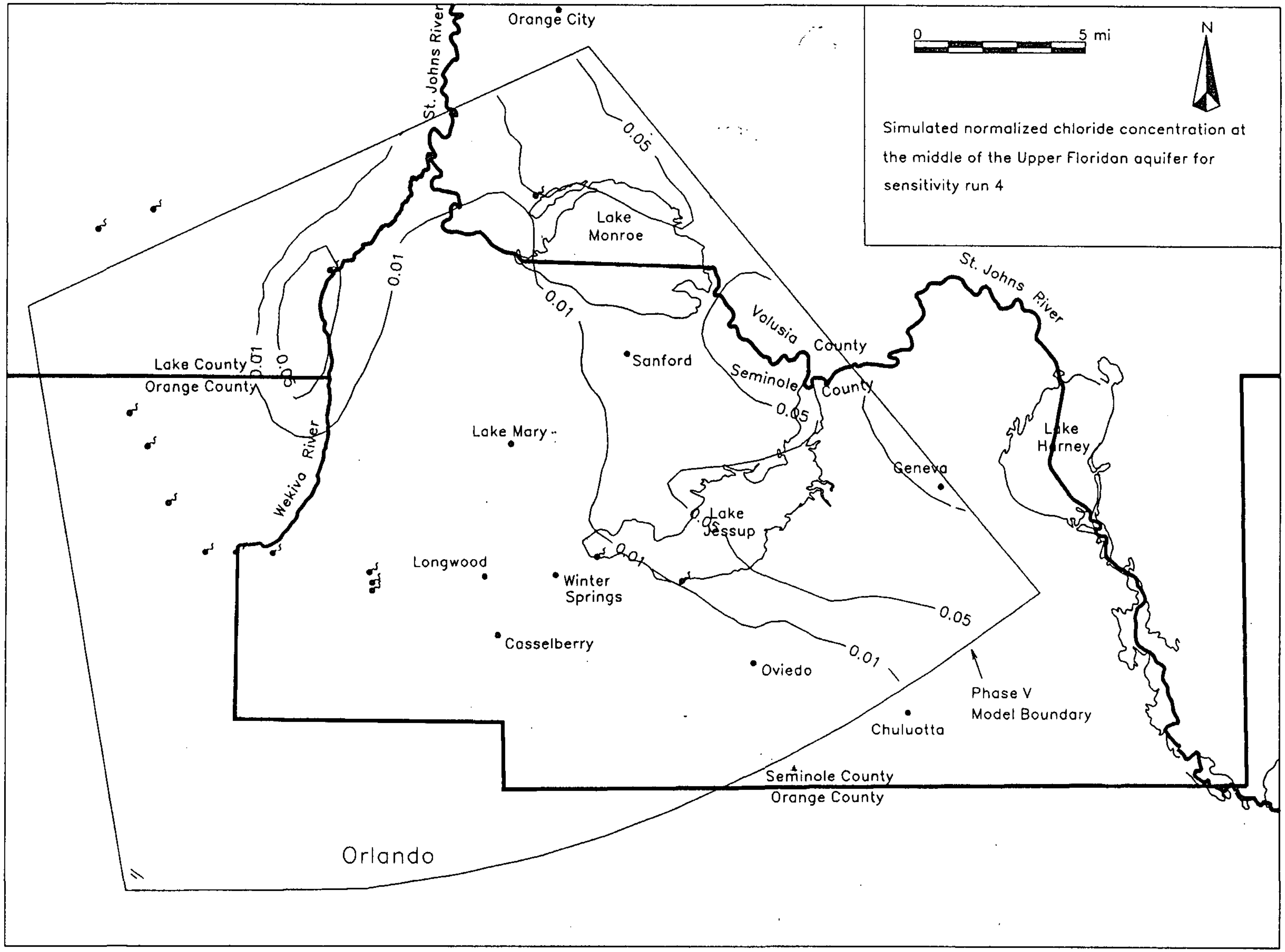
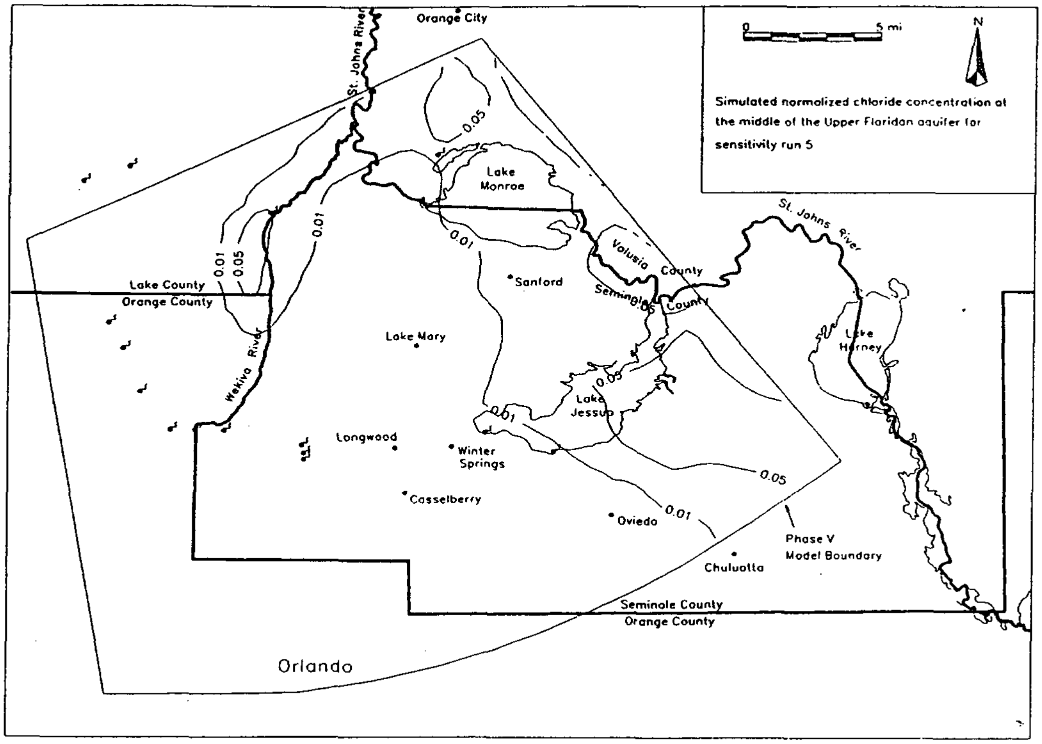
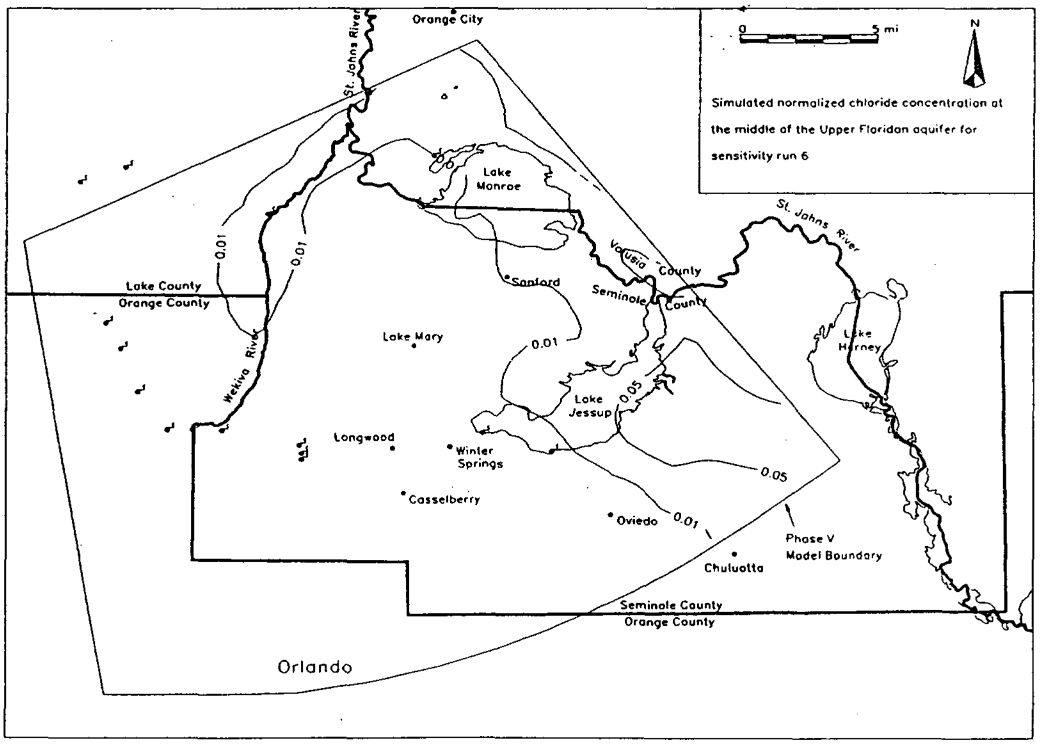


Figure 4.30 Simulated normalized chloride concentration in the Upper Floridan aquifer for sensitivity run 4, middle semiconfining unit leakance increased by a factor of two.



(a)



(b)

Figure 4.31 Simulated normalized chloride concentration in the Upper Floridan aquifer for sensitivity run 5 (a) and sensitivity run 6 (b).

Oviedo.

4.8.6 Decreased Areal Recharge

It was noted earlier that the simulated 250 mg/ℓ isochlor moves slightly to the east, particularly southeast of Sanford and east of Oviedo, from predevelopment to postdevelopment conditions. This simulation result is caused by increased recharge to the Upper Floridan aquifer from predevelopment to postdevelopment conditions. To evaluate the influence of recharge on the simulated 250 mg/ℓ isochlor, a sensitivity run was conducted in which the simulated postdevelopment areal recharge was reduced by one-half in the vicinity of the 250 mg/ℓ isochlor. The region of reduced recharge, marked by the dashed line in Figure 4.32, was selected arbitrarily. The purpose of this sensitivity run was to illustrate that in certain locations in Seminole County, the location of the 250 mg/ℓ isochlor in the Upper Floridan aquifer is relatively sensitive to the magnitude of recharge applied to the Upper Floridan aquifer in the vicinity of the saltwater front.

The simulated 250 mg/ℓ isochlor in Figure 4.32 has indeed moved slightly to the west, rather than to the east, as was observed for the postdevelopment calibration run.

4.8.7 Additional Parameters

In this section, the sensitivity of the simulation results to Lower Floridan aquifer hydraulic conductivity, aquifer anisotropy (horizontal/vertical), and the prescribed influx through the bottom boundary is discussed. The information presented was obtained during the model calibration process, prior to the final sensitivity runs.

The Lower Floridan aquifer hydraulic conductivity has only a limited affect on chloride concentrations in the Upper Floridan aquifer. The primary affect of this parameter is to displace the saltwater wedge in the Lower Floridan aquifer; higher hydraulic conductivities cause the wedge to move to the east, and lower hydraulic conductivities cause the wedge to move to the west. In general, a change in Lower Floridan aquifer hydraulic conductivity of an order of

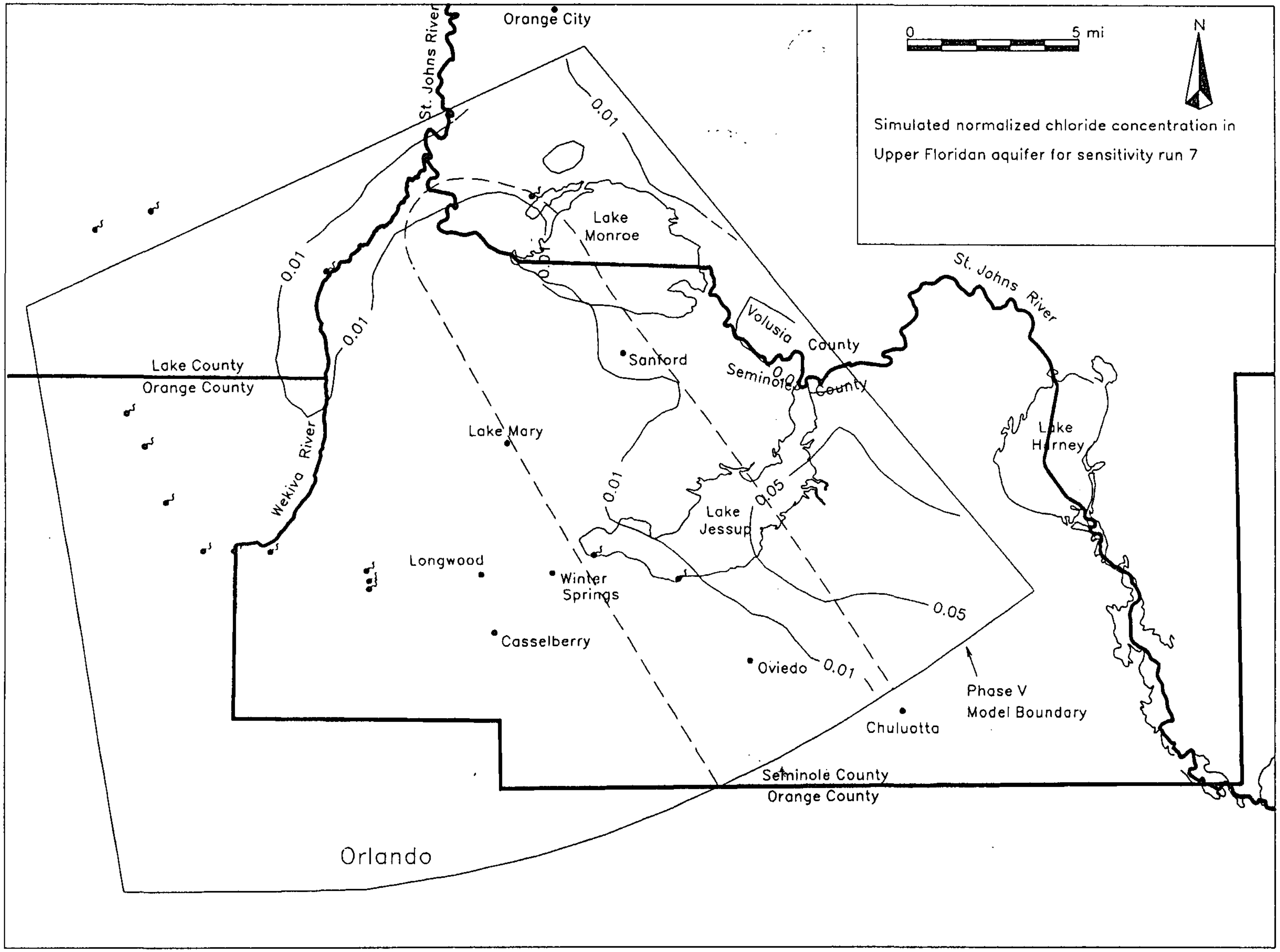


Figure 4.32 Simulated normalized chloride concentration in the Upper Floridan aquifer for sensitivity run 7. Zone of reduced recharge outlined by dashed line.

magnitude or more is required to cause significant movement in the simulated saltwater front location.

The anisotropy ratio of hydraulic conductivities (vertical hydraulic conductivity divided by horizontal hydraulic conductivity) in each hydrogeological unit is not a sensitive model input parameter. In the Upper Floridan aquifer, results are very insensitive to the anisotropy ratio used. In the middle semiconfining unit, simulation results are more a function of the vertical hydraulic conductivity, rather than the horizontal hydraulic conductivity. In the Lower Floridan aquifer, lower anisotropy ratios tend to "tilt" the saltwater wedge, or make the saltwater-freshwater interface more slanted. This affect, however, is relatively minor.

The simulation results are sensitive to the value of prescribed influx across the bottom boundary in the vicinity of the Wekiva River channel. However, this boundary condition only influences Upper Floridan aquifer chloride concentrations in the immediate vicinity of the Wekiva River, and it does not affect simulated chloride concentrations elsewhere in the model domain.

5 PREDICTIVE SIMULATIONS

5.1 Background

Using the calibrated Phase V model, a base-case predictive simulation was performed using estimated pumping rates for the year 2010. Estimates of pumping rates as of the year 2010 were compiled for the Phase IV modeling effort (Blandford and Birdie, 1992b); refer to the Phase IV report for a detailed explanation of the methods and sources of information used. Projected pumping increases were derived only for municipal supplies obtained from the Upper and Lower Floridan aquifers; agricultural pumpage and recharge due to drainage wells was assumed to remain unchanged from the average 1988 values. The Phase IV 2010 withdrawal estimates were updated by the SJRWMD prior to this study to account for new withdrawal projections and corrected/revised withdrawal estimates and well locations obtained for Seminole and Orange Counties. Throughout the entire Phase IV study area, municipal pumping as of 2010 is projected to increase from average 1988 withdrawals by a factor of 1.65 in the Upper Floridan aquifer, and by a factor of 2.5 in the Lower Floridan aquifer.

As is mentioned in Chapter 4, the position of the 250 mg/ℓ isochlor in the Upper Floridan aquifer in Seminole County is dependent upon (sensitive to) the rate and distribution of recharge to, and discharge from, the aquifer. In order to obtain representative predictive simulation results, therefore, it is important to adequately address the potential for changes in recharge and discharge to the Upper Floridan aquifer, particularly in the vicinity of the 250 mg/ℓ isochlor. Since Seminole County contains several zones of high Upper Floridan aquifer recharge, the potential for changes (increases) in recharge due to increased withdrawals in the Floridan aquifer system is high. However, if increases in recharge are overestimated, the predictive simulation results could be misleading and nonconservative. For this reason, the SURFDOWN simulation procedure developed by the SJRWMD (Huang and Williams, 1993) was used to obtain boundary conditions, including recharge, for the predictive simulation. The SURFDOWN simulation procedure, described in the next section, accounts for potential drawdowns in the surficial aquifer. It is believed that application of the SURFDOWN procedure provides a better estimate of boundary conditions for the predictive simulation then does the head-dependent flux boundary condition used for the calibration runs, where the surficial aquifer water levels were maintained at constant values.

5.2 SURFDOWN Modeling Procedure

The SURFDOWN modeling procedure (Huang and Williams, 1993) was developed by the SJRWMD as a simulation tool for assessing the effects that drawdown in the surficial aquifer may have on simulated drawdowns in the Upper Floridan aquifer. Many of the regional ground-water flow and solute transport models applied by the SJRWMD treat the surficial aquifer as either a prescribed head boundary condition layer or as a head-dependent flux boundary, as was done in this study. These surficial aquifer simulation approaches are employed because they appear to be reasonable on the regional scale, and the time and effort involved in conducting a calibration of the surficial aquifer layer would be immense. One drawback of these modeling approaches, however, is that during predictive simulations drawdown in the Floridan aquifer could be underestimated because surficial aquifer water levels are maintained at constant values, where they might be expected to drop somewhat in reality as withdrawals from the Floridan aquifer system increase.

To avoid the time and expense required to activate the surficial aquifer layers of their regional models, yet obtain a more accurate estimate of drawdowns in the Upper Floridan aquifer, the SJRWMD developed the SURFDOWN modeling procedure using the MODFLOW code in conjunction with an analytical model (Motz, 1978) for drawdown in a confined aquifer with an overlying unconfined aquifer. Briefly, the analytical model permits drawdown in the confined aquifer due to pumping to be computed. The drawdown in the confined aquifer is dependent upon downward leakage through the confining unit, which depends upon the leakance and the hydraulic gradient across the unit. However, the solution allows for decreases in the surficial aquifer water level as well as hydraulic head declines in the confined aquifer. Water level declines in the aquifer system are dependent upon a reduction in evapotranspiration efflux from the unconfined aquifer.

The analytical drawdown model and the MODFLOW model are linked in the following manner in the SURFDOWN modeling procedure. First, the MODFLOW model is run for steady-state 2010 conditions using the 2010 pumping file and the other parameter files, including the head-dependent flux surficial aquifer boundary condition. Based on this run, nodal drawdowns from 1988 to 2010 conditions are calculated for the Upper Floridan aquifer. Next, the computed drawdowns are input into SURFDOWN to determine initial estimates of corresponding surficial aquifer drawdowns. These initial estimates of surficial aquifer drawdowns are then subtracted from the prescribed surficial aquifer head used in the MODFLOW model head-dependent flux boundary condition. The entire procedure is repeated iteratively until changes in simulated surficial aquifer drawdowns are less than a specified criterion.

5.3 Predictive Simulation Procedure

The simulation procedure for the predictive scenario was similar to that used for the postdevelopment (average 1988) calibration. The major steps involved are outlined below:

1) The Phase IV MODFLOW regional model was run to steady state using estimated 2010 pumping conditions. These results were then used as an initial condition for the SJRWMD SURFDOWN modeling procedure (Huang and Williams, 1993). The SURFDOWN modeling results were used in the steps that follow.

2) The predicted MODFLOW hydraulic heads obtained in step 1 were used in conjunction with the simulated 1988 chloride concentrations to derive the predictive simulation boundary conditions. For the predictive simulation, equivalent freshwater heads and normalized chloride concentrations were prescribed along <u>all</u> <u>lateral</u> Phase V model boundaries; this is in contrast with the average 1988 calibration where portions of the northern and southern boundaries are no-flow. Spring fluxes and areal recharge rates within the Phase V model domain were also obtained from the procedure conducted in step 1. Note that for the predictive simulation,

the head-dependent flux boundary used to represent the surficial aquifer layer was removed, and recharge fluxes determined through the SURFDOWN modeling procedure were applied directly to the top of the Upper Floridan aquifer.

3) The new set of 2010 boundary conditions developed in step 2 were implemented, and a Phase V model transient simulation was conducted using the appropriate 2010 pumping file and the simulated 1988 head field and chloride distribution as initial conditions. Simulation results were obtained for the years 2010, 2060 and 2110 (simulation times of 22, 72 and 122 years).

Global mass balances for the predictive simulations are provided in Appendix A.

The approach of using a step change in the predictive simulation boundary conditions from average 1988 conditions is both reasonable and conservative. The approach is reasonable due to the large response time of the chloride concentrations relative to changes in the hydrogeologic system. Since the simulated chloride concentrations within the model domain respond to the new configuration of the potentiometric surface slowly, differences in the simulated isochlors that would occur due to progressively stepping the boundary condition through time, rather than imposing the "ending" condition immediately, are believed to be minor. The approach is conservative in that the simulated increase in chloride concentrations for the predictive scenarios may be slightly larger than would be expected in reality, since that estimated 2010 boundary conditions and withdrawal rates are imposed directly upon the simulated average 1988 condition, rather than increasing the predicted withdrawals (and making the related adjustments to the boundary conditions) through time.

SJRWMD staff conducted the SURFDOWN modeling used as a basis for the Phase V model predictive simulation. Initially, the Phase IV MODFLOW input files, updated to incorporate changes made during the Phase V modeling, were used. However, for some unknown reason, the simulated drawdowns diverged during the SURFDOWN modeling procedure. Although the cause for the divergence could not be isolated, it was found that it was related in some manner to the updated MODFLOW river package constructed during the Phase V modeling. To circumvent the nonconvergence problem, the Phase III modeling river package was applied in conjunction with the updated Phase V MODFLOW input to obtain converged results. This approach is reasonable, since a comparison of 1988 Upper Floridan aquifer hydraulic heads obtained using each river package (Phase III and updated Phase V) indicated small differences in simulated values in the vicinity of the 250 mg/ℓ isochlor. Observed differences were on the order of 1-2 ft or less. A comparison of the regional (MODFLOW) simulation results obtained using each river package is provided in Appendix B.

As is the case with the postdevelopment calibration results, the predictive simulation results are dependent upon the value of effective porosity used. There is, in general, a direct correspondence between the effective porosity and the simulation time. For example, simulation results obtained for 2010 (22 year simulation) using an effective porosity of 0.2 would be very similar to simulation results obtained for 1999 (11 year simulation) using an effective porosity of 0.1.

5.4 Predictive Simulation Results

Figures 5.1 and 5.2 illustrate the simulated environmental head in the Upper and Lower Floridan aquifers, respectively, for 2010. Plots of environmental head for 2060 and 2110 are not presented because they are nearly identical to those for 2010. In the southern portion of the Phase V model domain, in the vicinity of Oviedo and south of Casselberry, over 10 ft of drawdown is simulated in the Upper Floridan aquifer. In other regions of the Upper Floridan aquifer, simulated drawdowns from average 1988 conditions are about 5 ft or less. In the vicinity of Wekiva Falls Resort (near the point where Orange, Lake and Seminole Counties meet), simulated heads increase about 2-3 ft from 1988 to 2010 due to the imposed reduction in discharge from 12.75 MGD to 0.223 MGD. In the Lower Floridan aquifer, simulated drawdowns are 10-15 ft throughout most of the Phase V model domain. The simulated

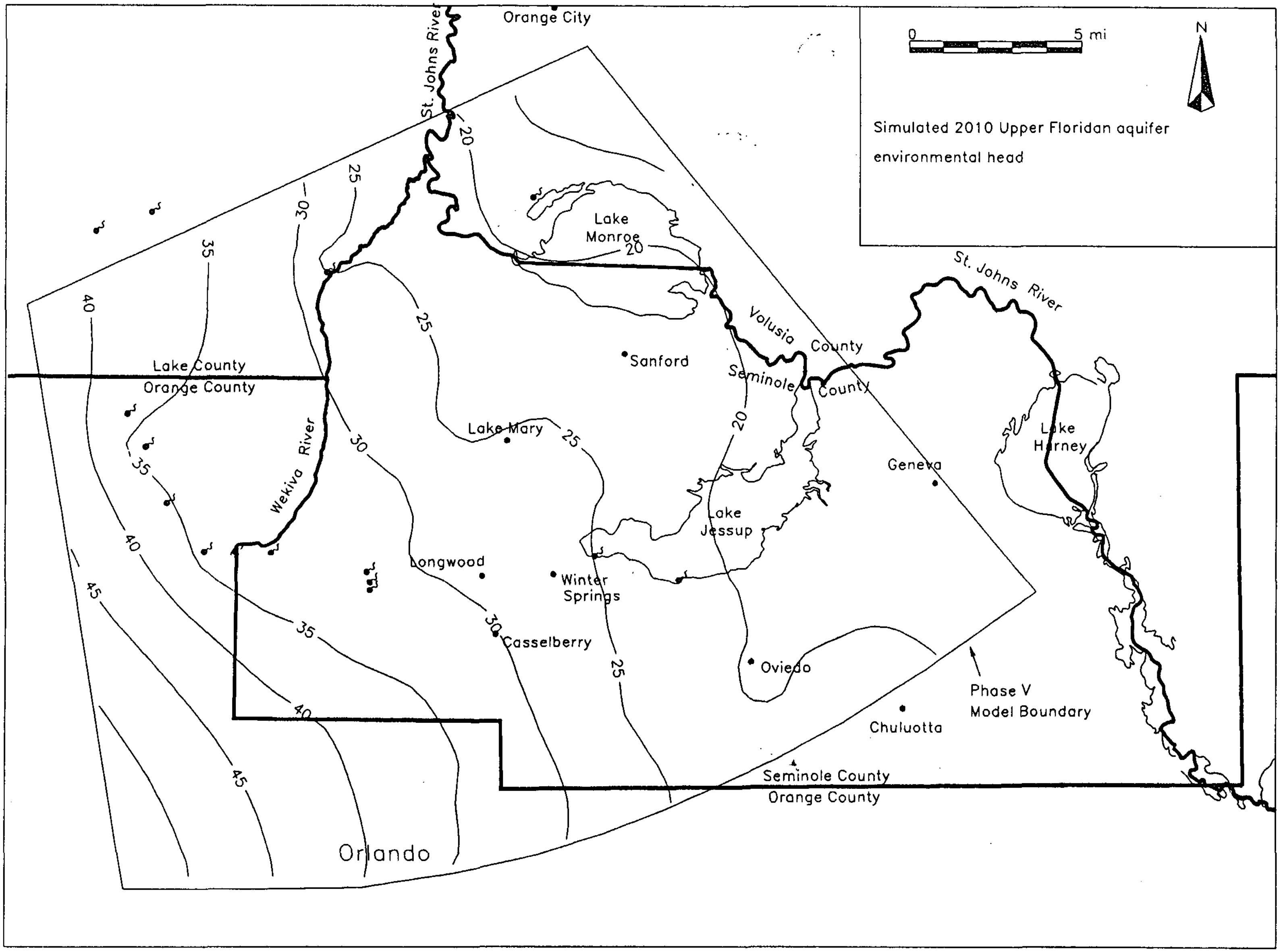


Figure 5.1 Simulated 2010 environmental head in the Upper Floridan aquifer in ft. Datum is mean sea level.

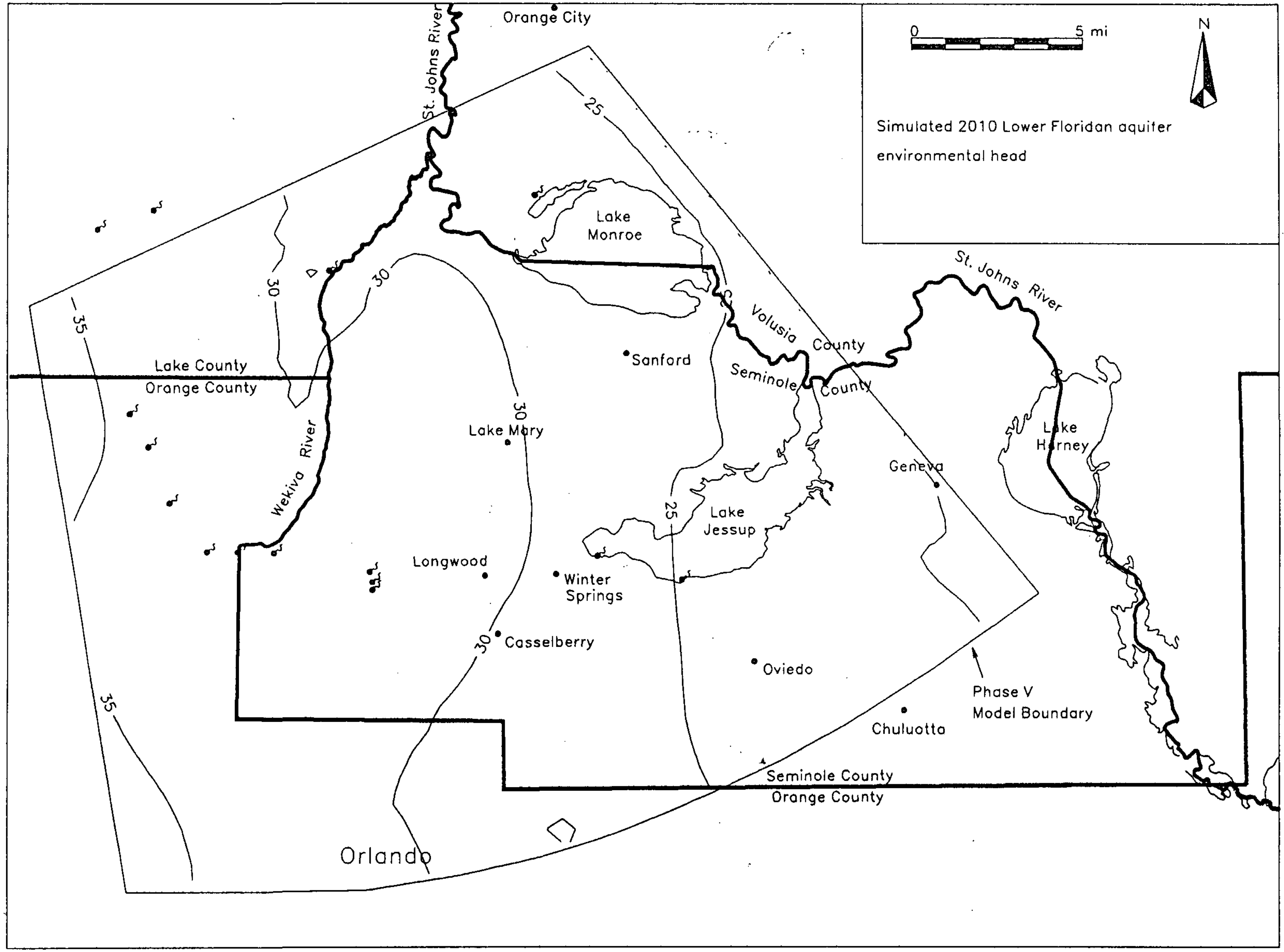


Figure 5.2 Simulated 2010 environmental head in the Lower Floridan aquifer in ft. Datum is mean sea level.

drawdowns cause nearly a 20 percent decrease in overall simulated spring flow from 1988 to 2010 conditions (Table 5.1).

Figures 5.3 and 5.4 are areal plots of simulated normalized chloride concentration at the middle of the Upper Floridan aquifer for 2010 and 2110, respectively. Results for 2060 are not shown because they lie between those of the 2010 and 2110 time periods. Over the 122 year simulation period, three major trends of movement in the 250 mg/ℓ isochlor may be observed. First of all, in the general region between Lake Jessup and Sanford, the isochlor regresses, or moves to the east, in a similar manner as observed for the average 1988 simulation. The largest lateral displacement of the 250 mg/ℓ isochlor in this area is less than one mile. As explained in Chapter 4, this result is due to increasing recharge to the Upper Floridan aquifer simulated as the potentiometric surface of the Upper Floridan aquifer decreases. Figure 5.5 is a contour plot of increased recharge to the Upper Floridan aquifer from 1988 to 2010 conditions. In general, simulated recharge increased from 2-8 inches/year in recharge areas; these magnitudes are similar to those observed from predevelopment to 1988 conditions.

A second trend is observed in the vicinity of Oviedo and Chuluotta south of Lake Jessup. In this area, the 250 mg/ℓ isochlor steadily intrudes the southwest during the predictive simulation period. There is very little movement of the isochlor in this region as of 2010, but by 2110 the 250 mg/ℓ isochlor has moved about 1.5 miles to a position just southeast of Oviedo. In fact, it seems that the movement of this isochlor may be somewhat constrained in the predictive simulation due to the prescribed chloride concentration used for the model boundary in the vicinity of Chuluotta. Although it is unlikely that substantial saltwater intrusion will occur in the vicinity of Oviedo over the next 20 years or so, the region west of Oviedo would seem to be an area where significant saltwater intrusion could occur over relatively long time frames (approximately 50-100 years). The simulated saltwater intrusion in the vicinity of Oviedo is a combination of the vertical and lateral movement of saltwater.

The third region of significant migration of the 250 mg/ℓ isochlor in the Upper Floridan aquifer is the Wekiva River valley which separates Lake and Seminole counties. In this area, the bulb

Table 5.1 Simulated 1988 and 2010 spring flows for springs within the Phase V model domain obtained using the regional MODFLOW model.

Spring	Simulated Discharge (ft^3/s)		Percent Reduction
	1988	2010	
Gemini	7.88	6.90	12.4
Island	7.61	7.34	3.5
Rock	55.30	45.43	17.8
Witherington	3.79	3.19	15.8
Wekiva	69.78	61.48	11.9
Miami	4.54	3.87	14.8
Lake Jessup	0.70	0.46	34.3
Clifton	1.38	0.83	39.9
Starbuck	14.06	8.77	37.6
Palm	6.08	3.83	37.0
Sanlando	15.89	9.48	40.3
Sulphur	1.00	.90	10.0
Total	188.01	152.48	18.9

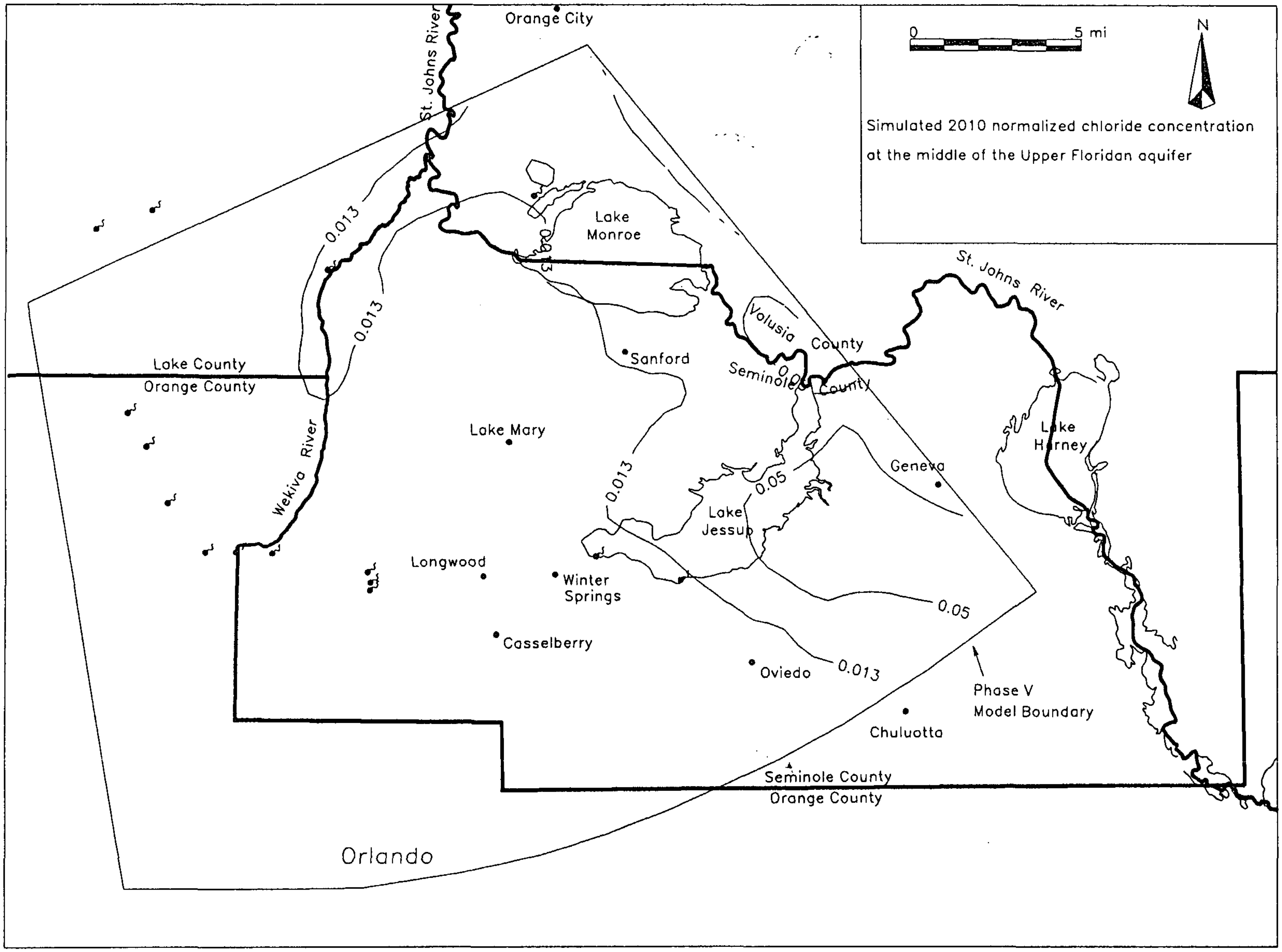


Figure 5.3 Simulated 2010 normalized chloride concentration in the Upper Floridan aquifer.

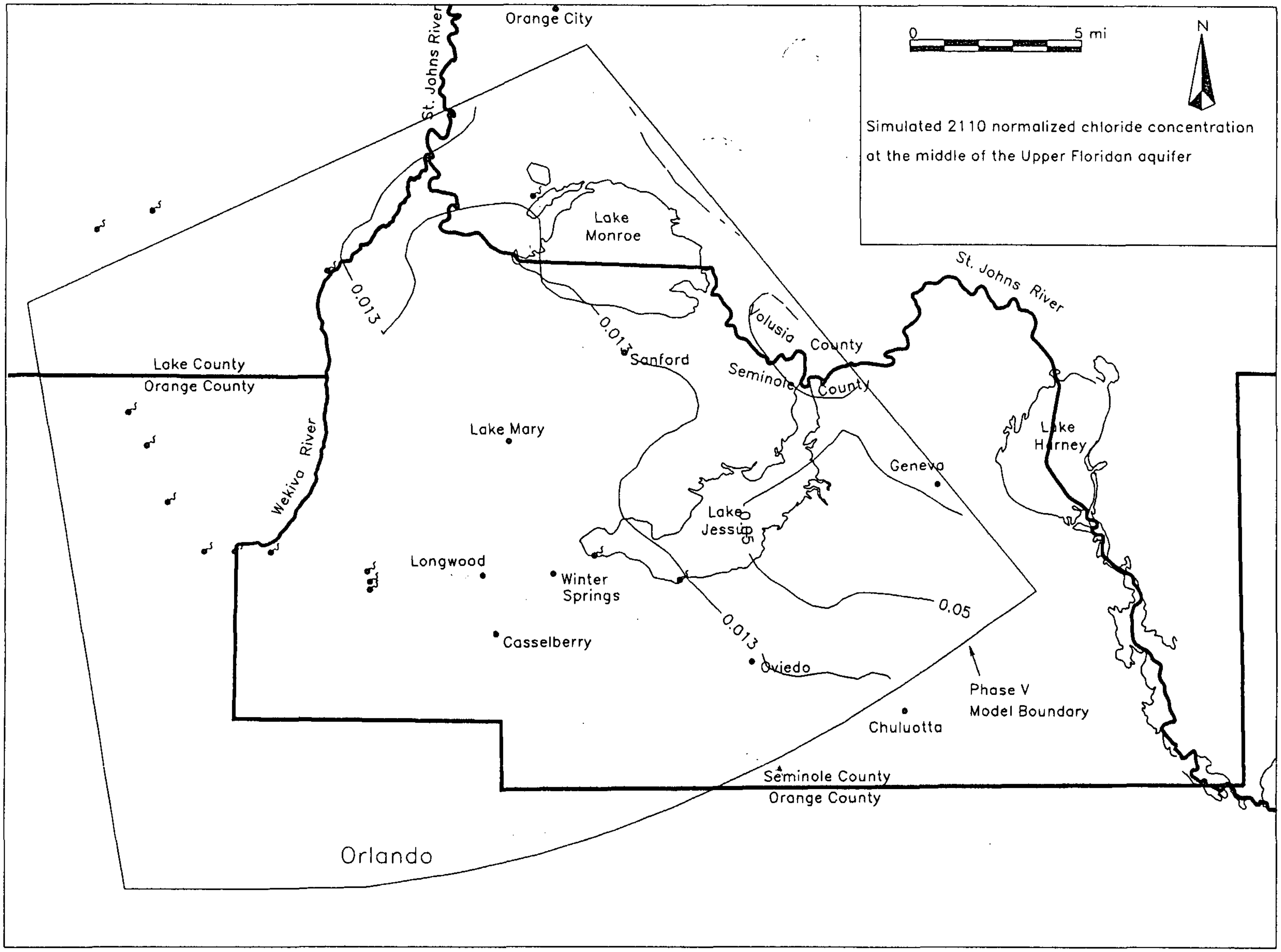


Figure 5.4 Simulated 2110 normalized chloride concentration in the Upper Floridan aquifer.

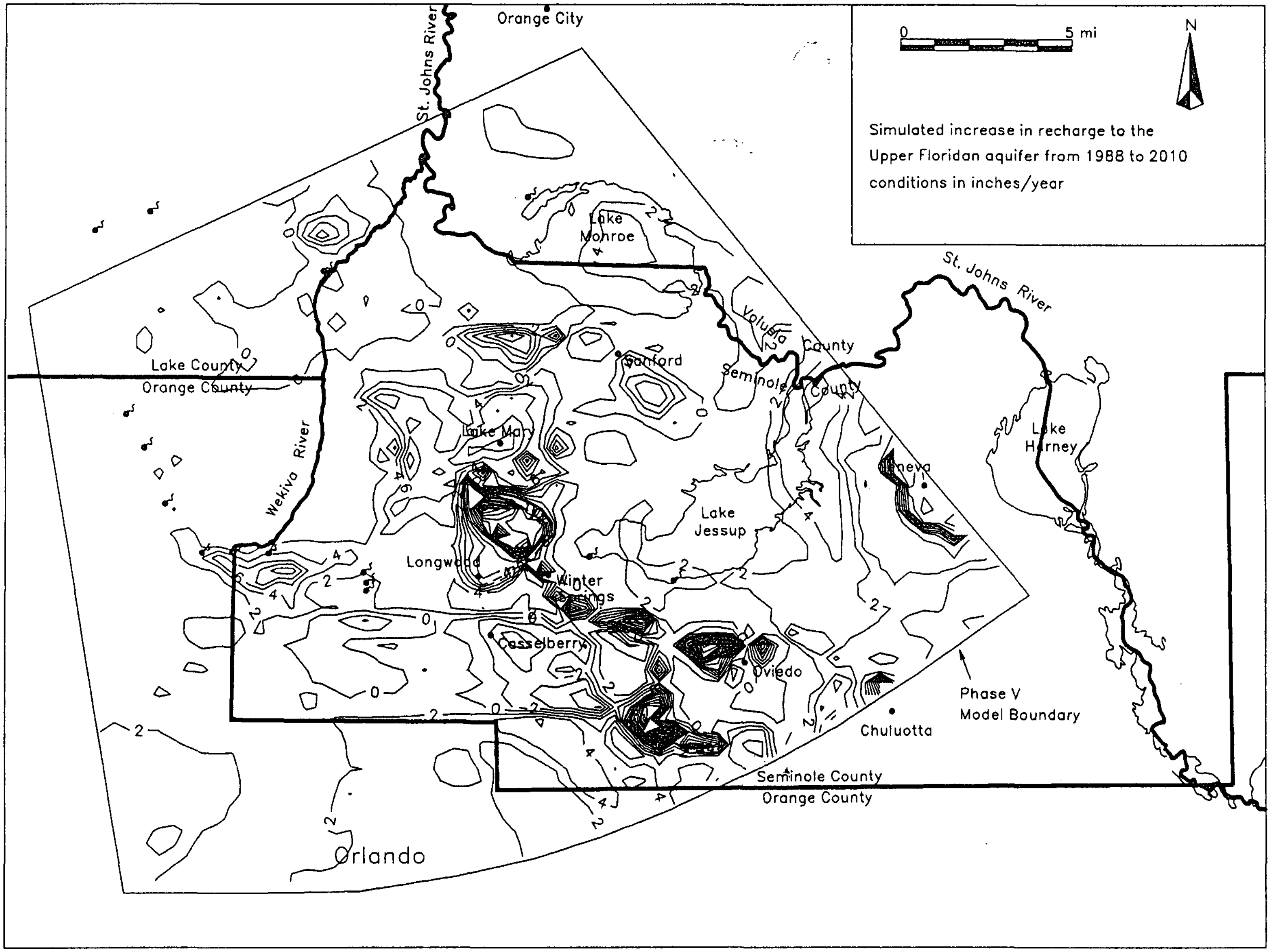


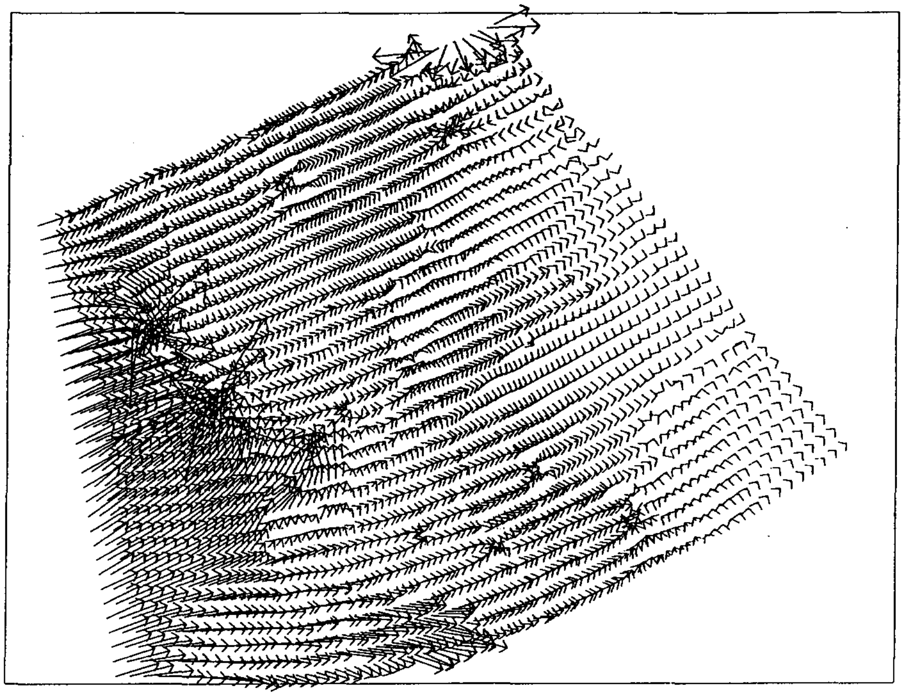
Figure 5.5 Simulated increase in recharge to the Upper Floridan aquifer from 1988 to 2010 conditions in inches/year.

of saltwater oriented north to south and centered along the river valley shifts to the east and diminishes in areal extent from 2010 to 2110 conditions. This result is not considered to be realistic, and it is attributed to a limited understanding and ability to simulate the highly complex subsurface flow system in this region. The exact reason for the movement of the 250 mg/ℓ isochlor in this region is not clear, but it is probably related to the significant variations in the ground-water flow field in the Upper and Lower Floridan aquifers from 1988 to 2010. This observation is best illustrated by the velocity vector plots presented in Figures 5.6-5.10. For example, Figure 5.6b indicates that, due to the simulated drawdowns in the Lower Floridan aquifer, ground-water flow directions in the Lower Floridan aquifer in the northwestern portion of the model domain are nearly reversed from 1988 conditions (compare Figure 5.6b with Figure 4.21b). Furthermore, a comparison of 2010 cross sections (Figures 5.7-5.10) with the 1988 cross sections (Figures 4.22-4.25) indicates that, in the western portion of the model domain, ground-water flow has changed from upward to downward in the middle semiconfining unit at many locations.

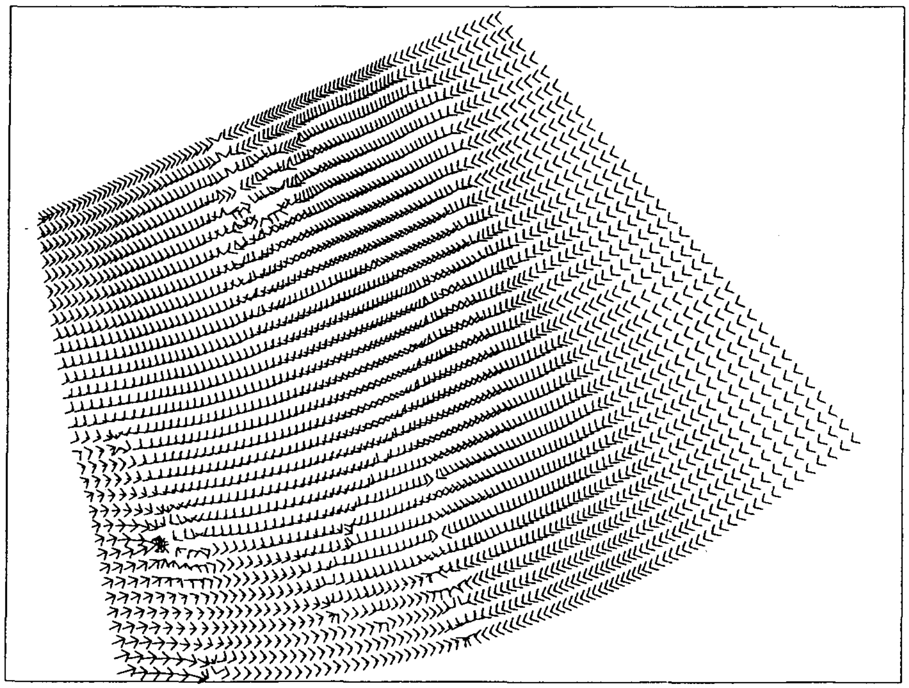
It should be emphasized once again that the cross sections presented in this report have a very high vertical exaggeration. If the cross-sectional figures were plotted to scale, they would be approximately 53 times as long as they are thick. Consequently, the simulated isochlors would form a true wedge shape, rather than appear vertical or nearly vertical as indicated by the figures in this report.

In summary, the model results indicate that significant changes in the ground-water flow system may occur in response to projected pumping withdrawals. In the immediate vicinity of the Wekiva River, the Phase V model is not capable of accurately predicting changes in chloride concentrations that may occur in response to these withdrawals.

Normalized chloride concentrations for 2010 in the Lower Floridan aquifer (Figure 5.11) are very similar to the simulated 1988 isochlors. In southern Seminole County, in the vicinity of the Casselberry Lower Floridan wells, the 1,000 mg/ℓ isochlor continued to move to the west from 1988 to 2010. In southwestern Seminole County and northern Orange County, the 250



(a)



(b)

Figure 5.6 Areal 2010 velocity vector plots for the Upper Floridan aquifer (a) and the Lower Floridan aquifer (b).

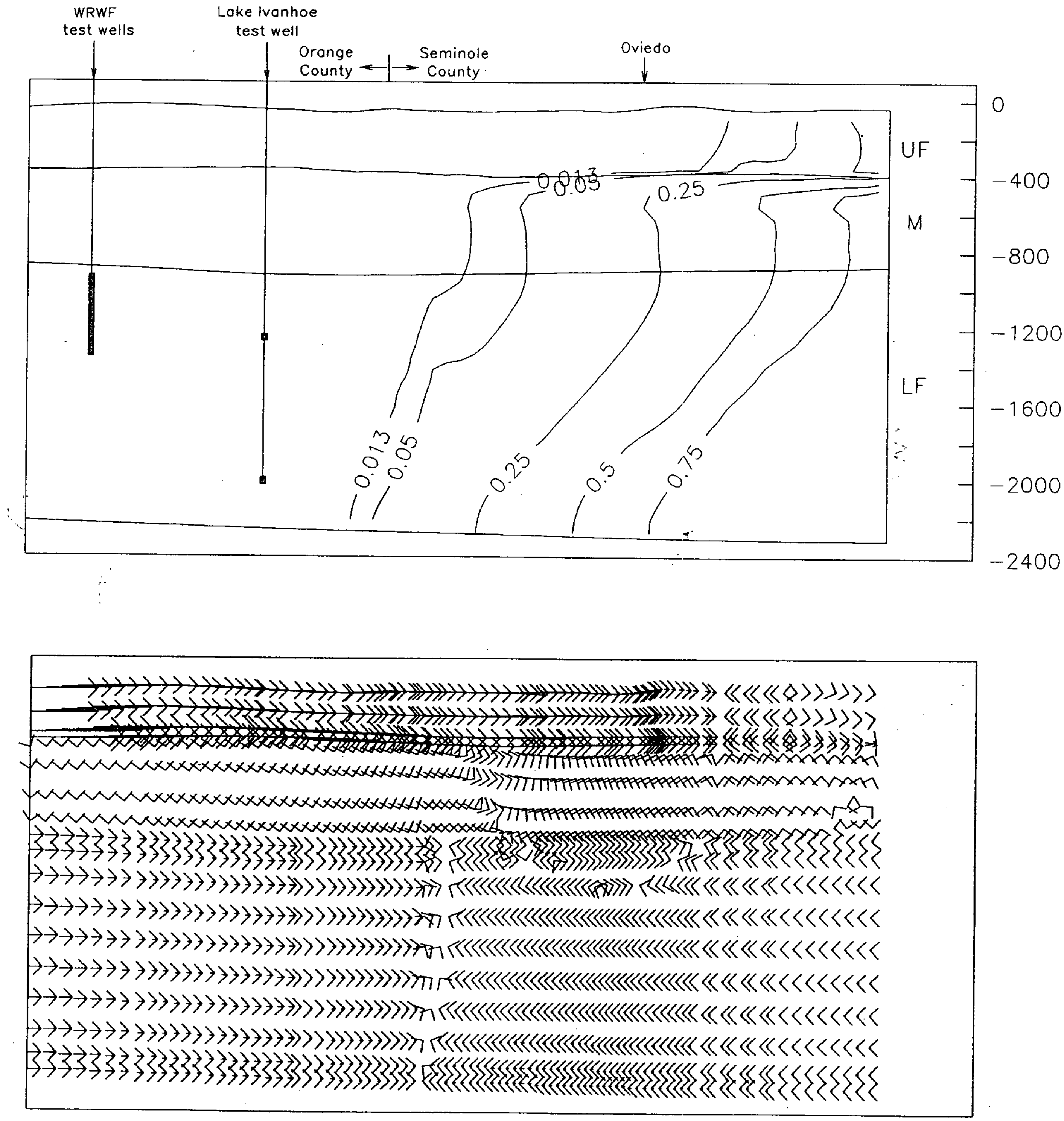


Figure 5.7 Simulated 2010 normalized chloride concentration and velocity vector plot for cross-section 1.

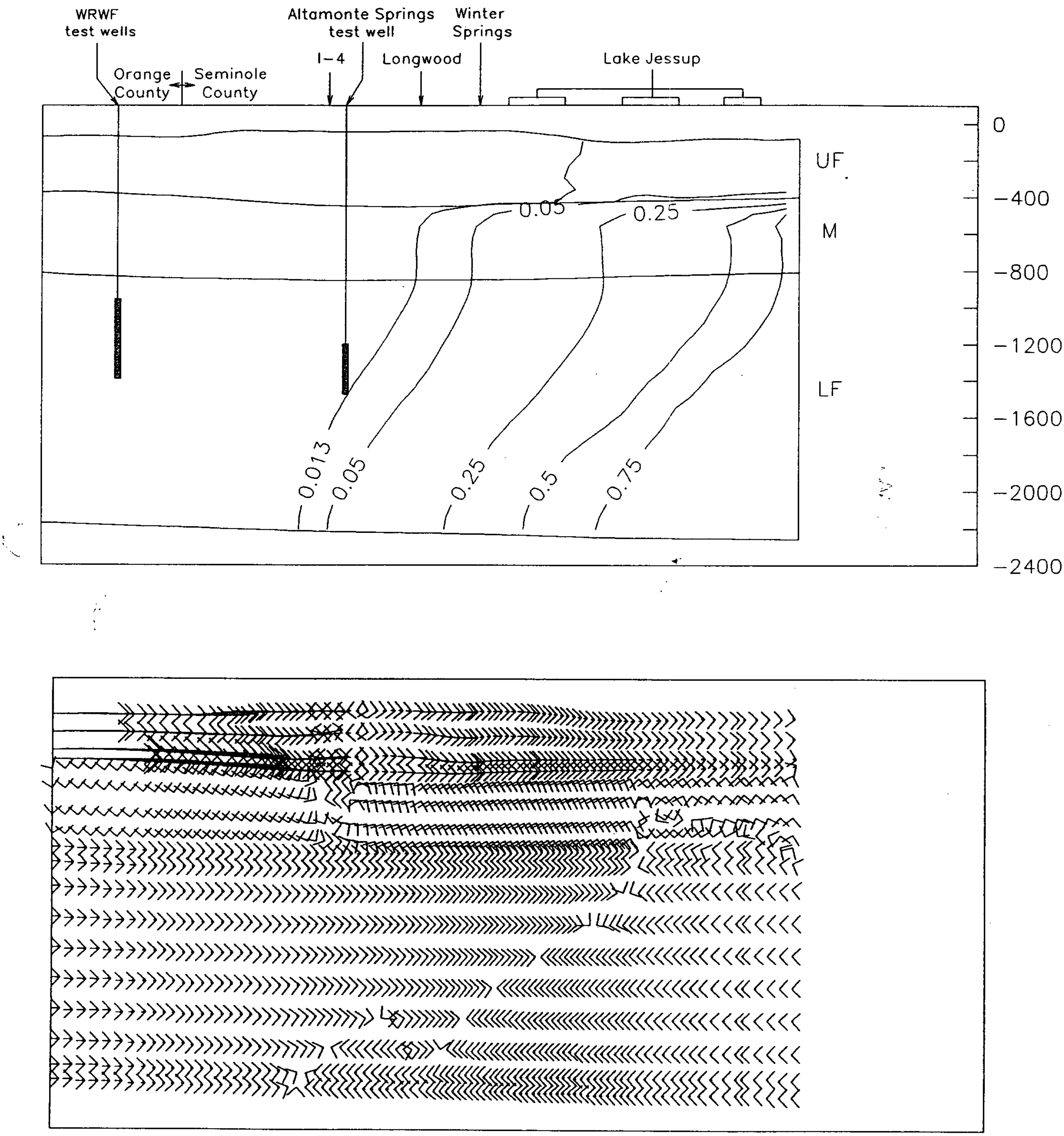
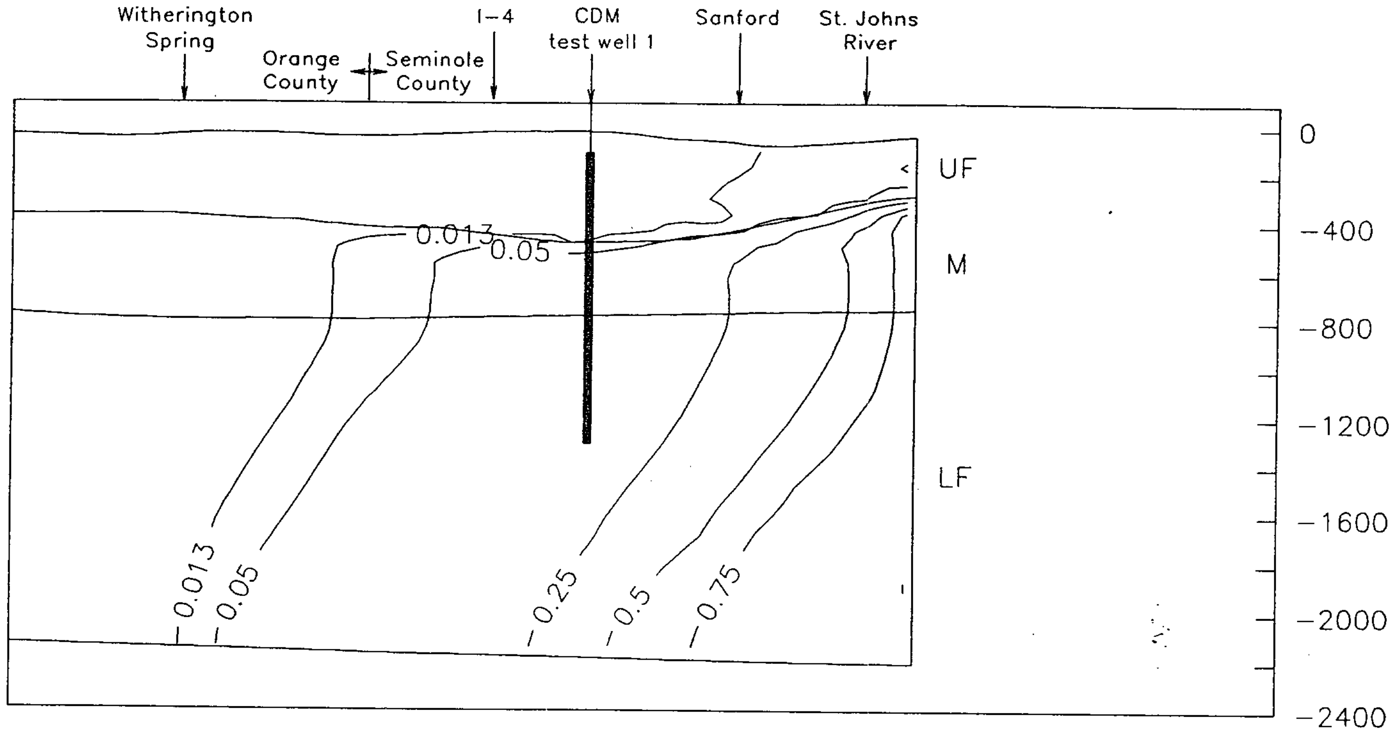


Figure 5.8 Simulated 2010 normalized chloride concentration and velocity vector plot for cross-section 2.



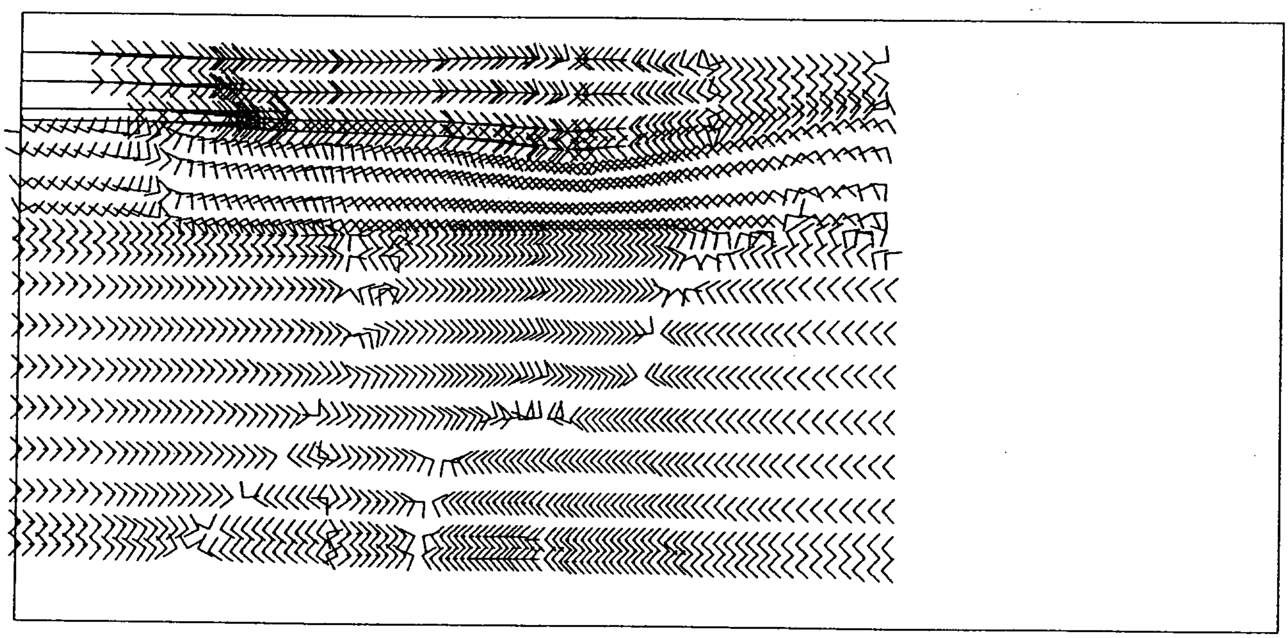


Figure 5.9 Simulated 2010 normalized chloride concentration and velocity vector plot for cross-section 3.

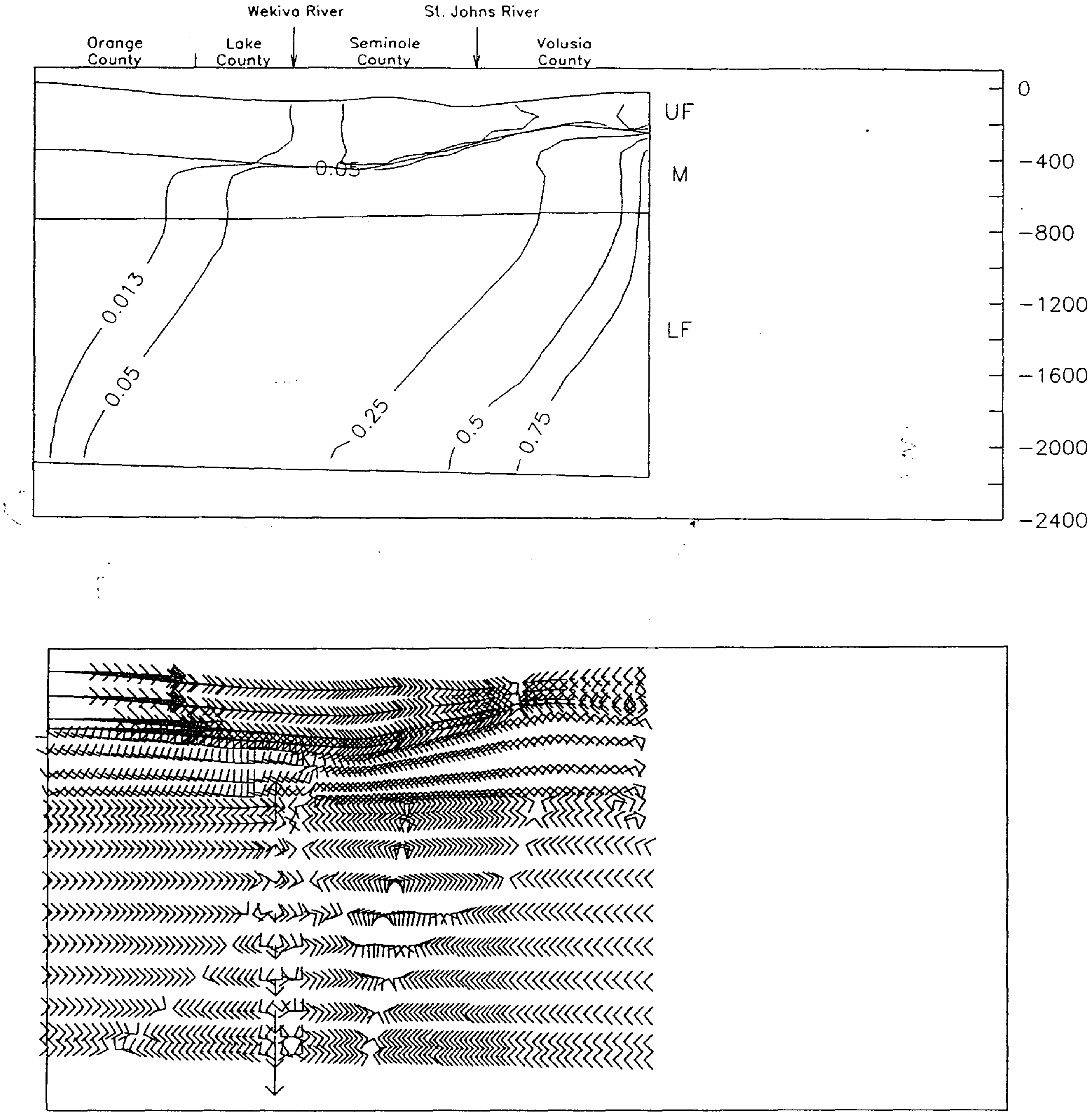


Figure 5.10 Simulated 2010 normalized chloride concentration and velocity vector plot for cross-section 4.

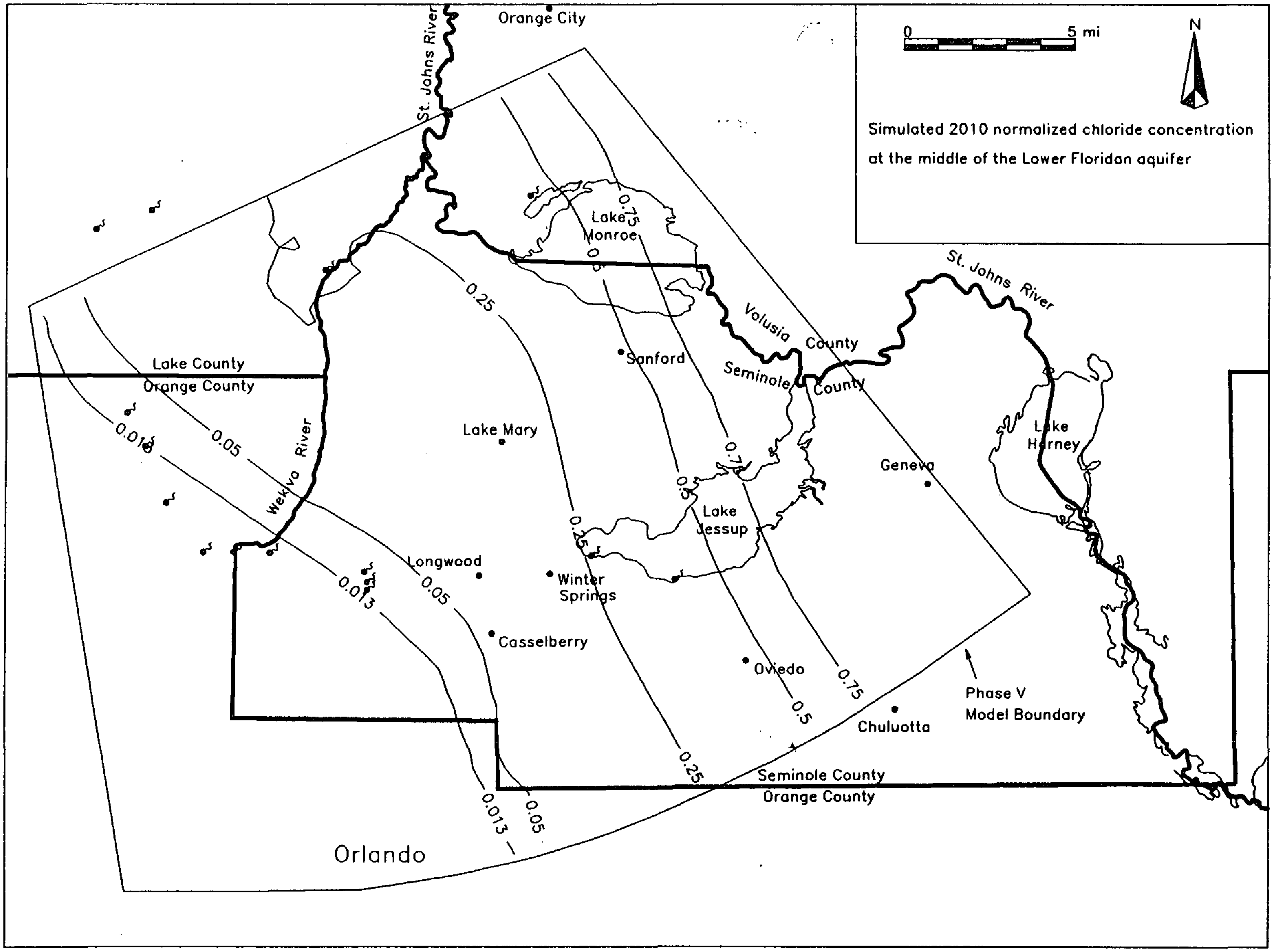


Figure 5.11 Simulated 2010 normalized chloride concentration in the Lower Floridan aquifer.

mg/ℓ and 1,000 mg/ℓ isochlors move slightly to the southwest from 1988 to 2010. These same general trends continue for the 2060 and 2110 (Figure 5.12) simulation periods.

Note that in the southern part of the model domain in Orange County, the simulated 250 mg/ℓ isochlor in the Lower Floridan aquifer remains stationary from 1988 to 2010 conditions, despite the fact that the simulated 1,000 mg/ℓ isochlor about 1 mile to the east moved west to the Seminole County-Orange County border. The movement of the 1000 mg/ℓ isochlor from 1988-2010 is a local (rather than regional) upconing effect in the Lower Floridan aquifer due to pumping from the Lower Floridan Casselberry wells.

This result should be viewed with caution as it is most likely due to simulation inaccuracies. The simulated predevelopment and 1988 isochlors in the vicinity of the Lower Floridan Casselberry wells probably lie too far west, since 1) to date, the Lower Floridan Casselberry wells produce good water quality which is not deteriorating with time, and 2) results from a deep test well at Orange County's proposed Eastern Regional wellfield site, approximately 7 miles southeast of the region in question, indicate that low-chloride water exists within about the upper one-sixth of the Lower Floridan aquifer. Therefore, since the chloride concentrations in the vicinity of the Casselberry wells are too high at the beginning of the predictive simulation, the simulation results that indicate an increase in concentrations are most likely not valid. This result does, however, underscore the general observation that wellfields in Seminole and Orange counties are generally vulnerable to local upconing of poor quality water, rather than regional, or large scale, saltwater intrusion. This observation is consistent with Blandford and Birdie (1992a).

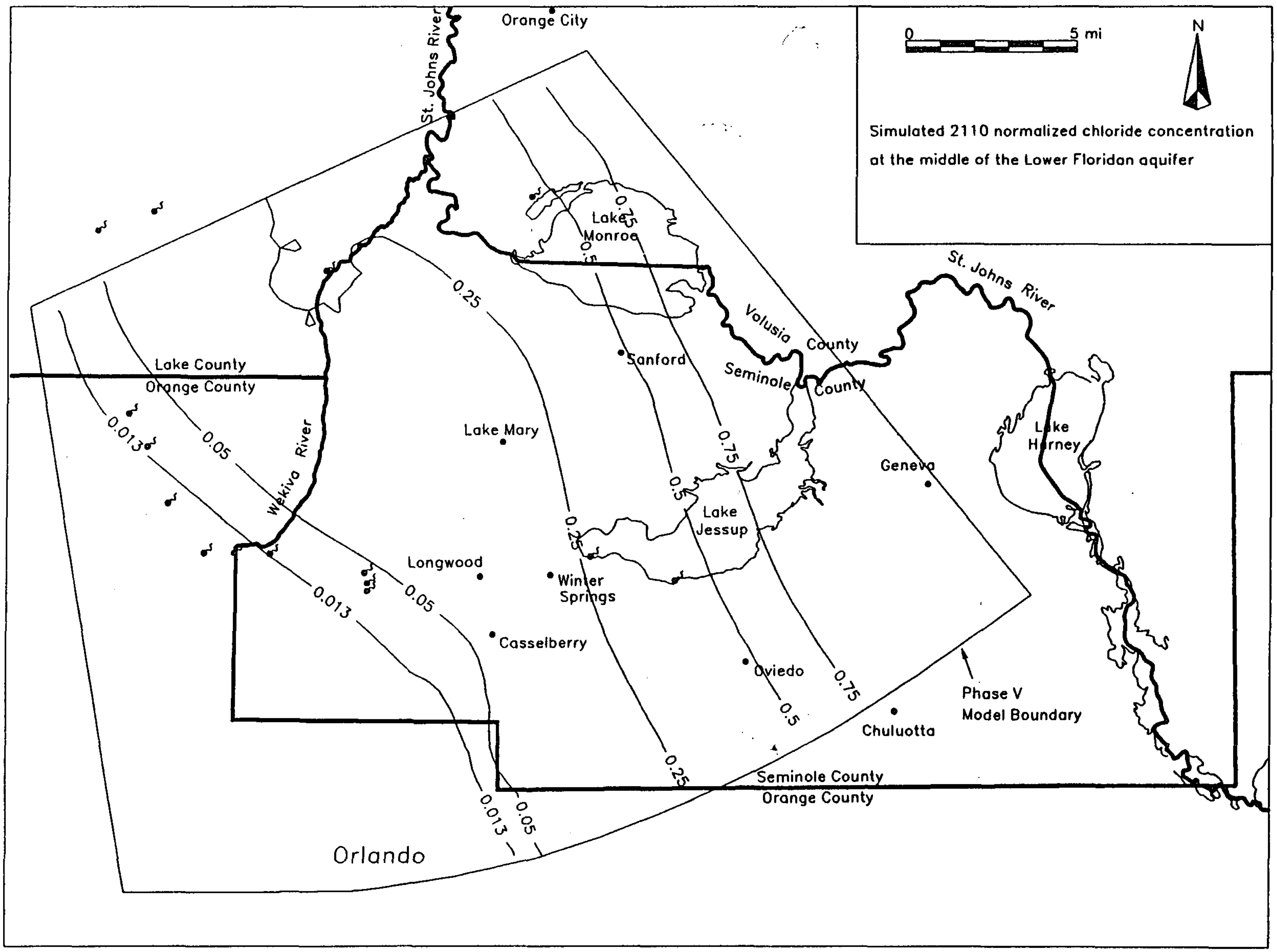


Figure 5.12 Simulated 2110 normalized chloride concentration in the Lower Floridan aquifer.

6 SUMMARY AND CONCLUSIONS

The primary purpose of this (Phase V) modeling effort was to develop a three-dimensional, density-dependent ground-water flow and solute transport model capable of simulating the complex, variable density ground-water flow system of the Floridan aquifer in central and western Seminole County and immediately adjoining regions. Of primary concern is the potential for the degradation of fresh ground-water resources in the vicinity of the major municipal wellfields in Seminole County. To accomplish this task, a model calibration was performed for average predevelopment and 1988 (postdevelopment) hydrologic conditions using the DSTRAM computer code. The Phase V model calibration was performed for a subregion of the Phase IV regional model domain (Blandford and Birdie, 1992b). The Phase IV modeling results formed the basis for many of the aquifer parameters and boundary conditions used in this study. A reasonable calibration was obtained for predevelopment and average 1988 conditions.

Although the Phase V model was successfully calibrated to known predevelopment and average 1988 conditions, it should be emphasized that the basic data available for use in constructing the model were quite limited in several significant areas:

1) Observed chloride concentrations (both areally and with depth) in the Lower Floridan aquifer

2) Observed potentiometric head in the Lower Floridan aquifer

3) Hydraulic properties of the Lower Floridan aquifer and the middle semiconfining unit

4) Solute transport parameters for both the Upper and Lower Floridan aquifers

Due to the above data constraints, the model could not be rigorously calibrated with respect to the Lower Floridan aquifer. This has potential implications for the simulation results within the Upper Floridan aquifer since the Lower Floridan aquifer is the major source of salt for this unit. At present, the simulated chloride concentrations in the Lower Floridan aquifer are in reasonable agreement with observed chloride concentrations at the Sand Lake Road test well, the Lake Ivanhoe test well, the Western Regional wellfield deep test wells, the results of a geophysical study and other nondirect observations or interpretations. However, taken as a whole with respect to the size of the modeled area, the available observation points are relatively sparse. To improve this, or another, model in the future and to add reliability to the simulation results, it is critical that additional hydrologic observations/data be collected for the Lower Floridan aquifer and the middle semiconfining unit.

Several important insights were obtained during the modeling process. First of all, the location and movement of the 250 mg/ℓ isochlor in Seminole County is highly sensitive to the location of the transition zone from Upper Floridan aquifer recharge to Upper Floridan aquifer discharge. Related to this point, the 250 mg/ℓ isochlor is influenced significantly by nearby zones of high recharge to the Upper Floridan aquifer. Of particular significance are the good recharge areas south of Sanford, in the vicinity of Oviedo, and in the vicinity of Chuluotta. In order to maintain fresh ground-water resources in Seminole County, it is very important that regions of high-moderate recharge are maintained as much as possible.

Secondly, the model simulations indicate that ground water with chloride concentrations equal to or exceeding 250 mg/ℓ underlies much of Seminole County in the middle semiconfining unit. This result is supported by the deep monitor well completed in Seminole County west of Sanford. It would seem that the most immediate threat to water quality at individual wellfields is not regional scale movement of the 250 mg/ℓ isochlor in the Upper Floridan, but rather local upconing of poor quality water from the middle semiconfining unit. Such upconing is a local scale phenomena highly dependant on local hydrogeologic conditions that are often unknown.

Along the western and northern borders of Seminole County, ground water with chloride concentrations exceeding 250 mg/ℓ exists in relatively narrow bands (several miles) centered along the Wekiva and St. Johns river channels. It is a particularly difficult task to simulate the movement of ground water and solutes in these regions, as there is a great deal of uncertainty with respect to the hydrogeologic conditions in the Lower Floridan aquifer, the existence and nature of preferential flow paths through the middle semiconfining unit due to geologic structure or other factors, and the ground-water budget (e.g. diffuse discharge rates). Fortunately, regional ground-water flow in the Upper Floridan aquifer (even for the 2010 predictive simulation) is to the north and northeast in this region, and hence these zones of high chloride concentration are not likely to pose a significant threat to the major municipal wellfields in Seminole County.

In the predictive simulation, the 250 mg/ℓ isochlor in the Upper Floridan aquifer regresses somewhat (less than a mile) in the general region between Lake Jessup and Sanford. This result, as explained in the text, is due to simulated increases in recharge to the Upper Floridan aquifer as drawdowns in the Upper Floridan aquifer increase. South of Lake Jessup, in the vicinity of Oviedo and Chuluotta, the predictive simulation indicates a western migration (intrusion) of the 250 mg/ℓ isochlor. The movement, however, is relatively limited (approximately 1-1.5 miles over a 100 year simulation period). The region of saltwater in the Upper Floridan aquifer along the Wekiva River where the river forms the boundary between Seminole and Lake counties is substantially reduced in areal extent and moves to the east in the predictive simulation. This result is not considered to be realistic, and is attributed to a limited understanding and ability to simulate the highly complex subsurface flow system in this region. This region is very complex hydrogeologically, and there is little direct information available with regard to aquifer parameters and geological controls. This result does not affect the isochlors in other regions of the model domain.

In the Lower Floridan aquifer, the 1988 and predictive simulation results indicate some upconing of saltwater due to pumping at the Casselberry Lower Floridan wells. This result is believed to be an artifact of the model, since the simulated saltwater wedge in the Lower Floridan aquifer is probably too far to the southwest. However, this region would be a good one in which to have at least one, and preferably a series, of deep monitor wells to record changes in chloride concentrations in the Lower Floridan aquifer, since it is centrally located within the simulated future cone of depression in the Lower Floridan aquifer.

The ground-water flow and solute transport model documented herein is appropriate and sufficiently accurate for the assessment of ground-water resources on a regional (county) scale. The model is not suitable for the short-term or seasonal prediction of chloride concentrations on the local scale at individual wells. As with all models used for predictive purposes, the modeling conceptualization and framework should be periodically updated and reevaluated to consider or incorporate new data and insites. For the purposes of future model calibration and validation efforts, it would be very useful, and indeed necessary if more accurate models are required, to obtain additional data on hydraulic parameters of the Lower Floridan aquifer and the middle semiconfining unit; chloride concentration observations in the Lower Floridan aquifer and the middle semiconfining unit; and potentiometric surface elevations in the Lower Floridan aquifer, particularly in northern and eastern Seminole County. The major sources of error in the Phase V model stem directly from a lack of data for the middle semiconfining unit and the Lower Floridan aquifer.

Lower Floridan aquifer and middle semiconfining unit data collection should be concentrated in central Seminole County in the vicinity of, or slightly east of, the major centers of pumping. Critical parameters that should be obtained are chloride concentrations with depth, vertical hydraulic conductivity or leakance of the middle semiconfining unit, and hydraulic gradients across the middle semiconfining unit. Obviously, the hydraulic gradients would be determined by collecting hydraulic head observations for the Upper Floridan and Lower Floridan aquifers, and if possible the middle semiconfining unit, at the same location.

In addition, it would be very useful to have at least one regional series of observation wells that intersect the saltwater front at approximately a right angle. Such an observation well network would run approximately parallel to the southern cross sections presented in this report. For each of the observation locations in this series, chloride concentrations with depth, preferably for the entire thickness of the Floridan aquifer system, should be collected. Such a network would permit a detailed picture of the saltwater wedge to be developed. If constructed, this network should be placed in the vicinity of the southern model boundary for two reasons. First of all, an observation network thus placed could act as a regional monitoring network for

Seminole County and eastern Orange County for the Floridan aquifer system. The network could be used to monitor long-term variations in chloride concentrations in both the Upper and Lower Floridan aquifers. Secondly, the northern portion of Seminole County is very complex hydrogeologically, and it is possible that numerous deep monitor wells would have to be constructed to obtain a detailed knowledge of the flow system in this area. Furthermore, the predictive simulation results indicate that substantial reductions in the Upper Floridan aquifer potentiometric surface will not occur in northern Seminole County in response to estimated 2010 withdrawal rates. Finally, due to the existence of various deep test wells completed in the vicinity of southwestern Seminole County (i.e., Altamonte Springs and regions west), this region is fairly well characterized hydrogeologically and additional test holes are not required.

For the immediate purpose of sustaining a good quality water supply for the major municipalities in Seminole County, one of the key unknowns that should, if possible, be addressed is the quality of ground water in the middle semiconfining unit which underlies the major wellfields. There is some uncertainty regarding this issue, since chloride sampling results and geophysical testing of the CDM deep test well west of Sanford seem to indicate conflicting results. Determining with reasonable accuracy the depth to 250 mg/ℓ water beneath the good recharge areas in central Seminole County is critical to predicting the potential for future degradation of ground-water resources within the county. Also, in order to accurately assess the potential for saltwater upconing on a local scale, it is necessary to obtain more accurate estimates of the vertical hydraulic conductivity in the middle semiconfining unit in the vicinity of individual well fields. The simulation results presented herein may be considered to be more on the conservative, or worse case, end of possibilities since significant chloride concentrations are simulated to exist within the middle semiconfining unit throughout much of Seminole County. If the depth to high chloride water is actually greater than the model simulations indicate, the potential for future water quality degradation is reduced, unless the calibrated values of middle semiconfining unit leakance are determined to be substantially underestimated.

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APPENDIX A

Simulation Global Mass Balance

Table A-1. Global DSTRAM simulation normalized mass balance for ground-water flow and solute transport for calibration and predictive simulations.

Simulation	Normalized Global Mass Balance (Percent)	
	Ground-Water Flow	Solute Transport
Predevelopment	0.008	1.1
Postdevelopment (1988)	0.064	2.7
Predictive	0.21	2.1

APPENDIX B

Comparison of Phase III and Phase V Regional MODFLOW Model River Packages

As documented in Chapter 5, converged SURFDOWN simulation results could not be obtained using the regional MODFLOW model river package as updated during the Phase V modeling effort. Since the cause of the nonconvergence could not be identified by SJRWMD staff, the decision was made to apply the existing Phase III model river package. Note that the Phase III river package referred to in this report is the Phase IV river package which was updated during the Phase III modeling effort (Blandford and Birdie, 1992a). It is believed that application of the Phase III river package produces reasonable predictive simulation results for Seminole County. The purpose of this Appendix is to document the differences in the regional MODFLOW model simulation results attributable to application of the Phase III, rather than the Phase V, river package.

The prescribed surficial head in the Phase III river package was updated during the Phase V model calibration process; the difference in surficial heads between the two river packages is presented in Figure B.1. The largest differences occur west of Lake Jessup (12 ft) and in the Geneva Hill area (-8 ft). The regions of large differences are very localized. Surficial aquifer heads were updated during the Phase V modeling to fine-tune the model input parameters in some regions of Seminole County. In both river package files, the river bed elevation is set such that a maximum recharge rate of 20 inches/year is enforced (Blandford and Birdie, 1992b).

The simulated 2010 Upper Floridan aquifer hydraulic heads obtained using the Phase III and Phase V regional MODFLOW model river packages are presented in Figures B.2 and B.3, respectively. The latest block-centered flow, drain and well packages updated during the Phase V modeling were used. A comparison of Figures B.2 and B.3 indicates that Upper Floridan aquifer hydraulic heads simulated using the Phase V river package are about 1-2 ft lower throughout much of Seminole County than those simulated using the Phase III river package. This difference is deemed to be sufficiently small for the purposes of the Phase V predictive simulation. Note that the 2010 simulation results presented in Figures B.2 and B.3 were obtained using MODFLOW only; they were not obtained using the SURFDOWN procedure.

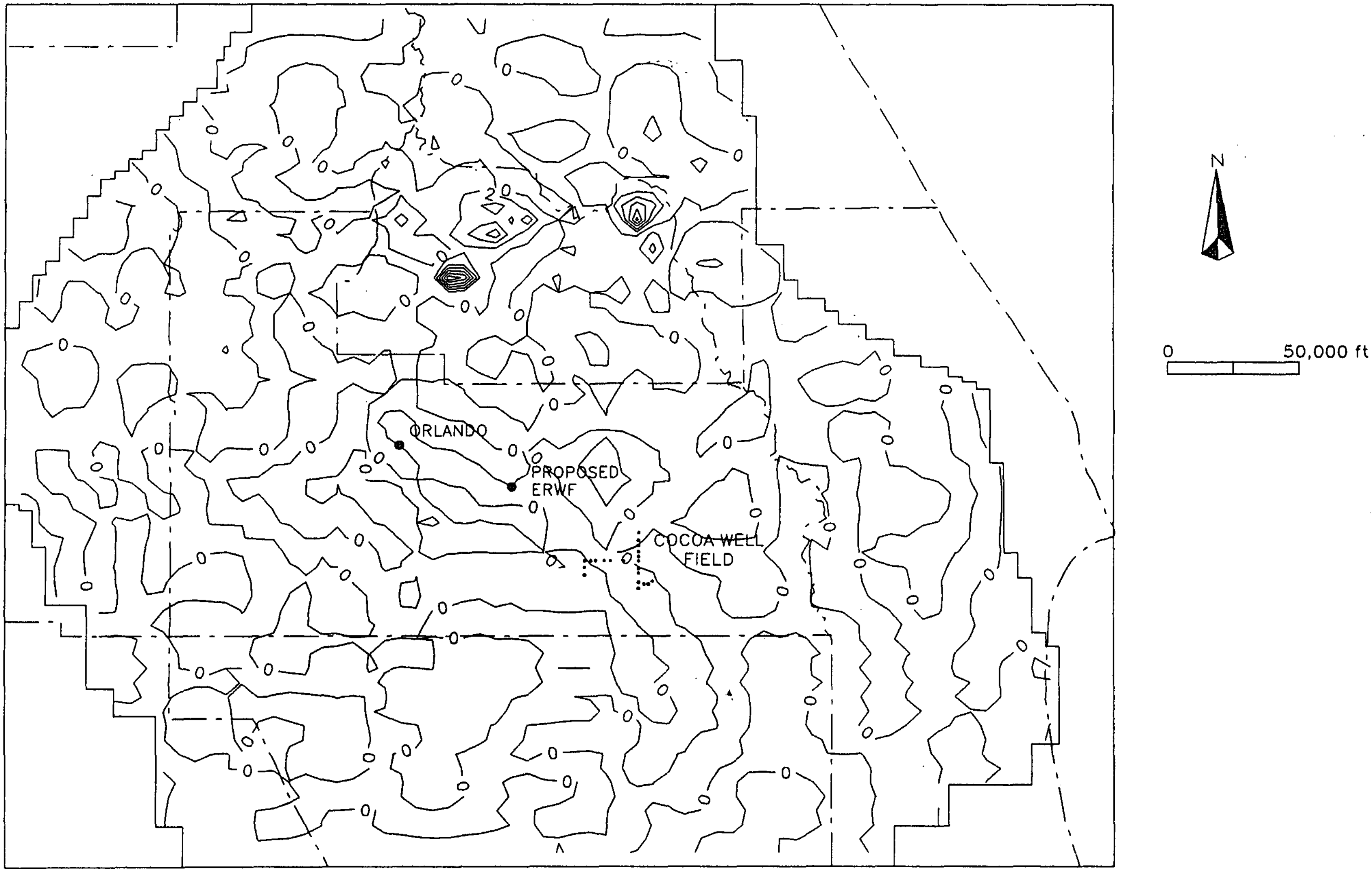

Figure B.1 Difference in prescribed surficial aquifer heads for the Phase III and Phase V regional MODFLOW river packages (Phase III subtracted from Phase V). Contour interval is 2 ft.

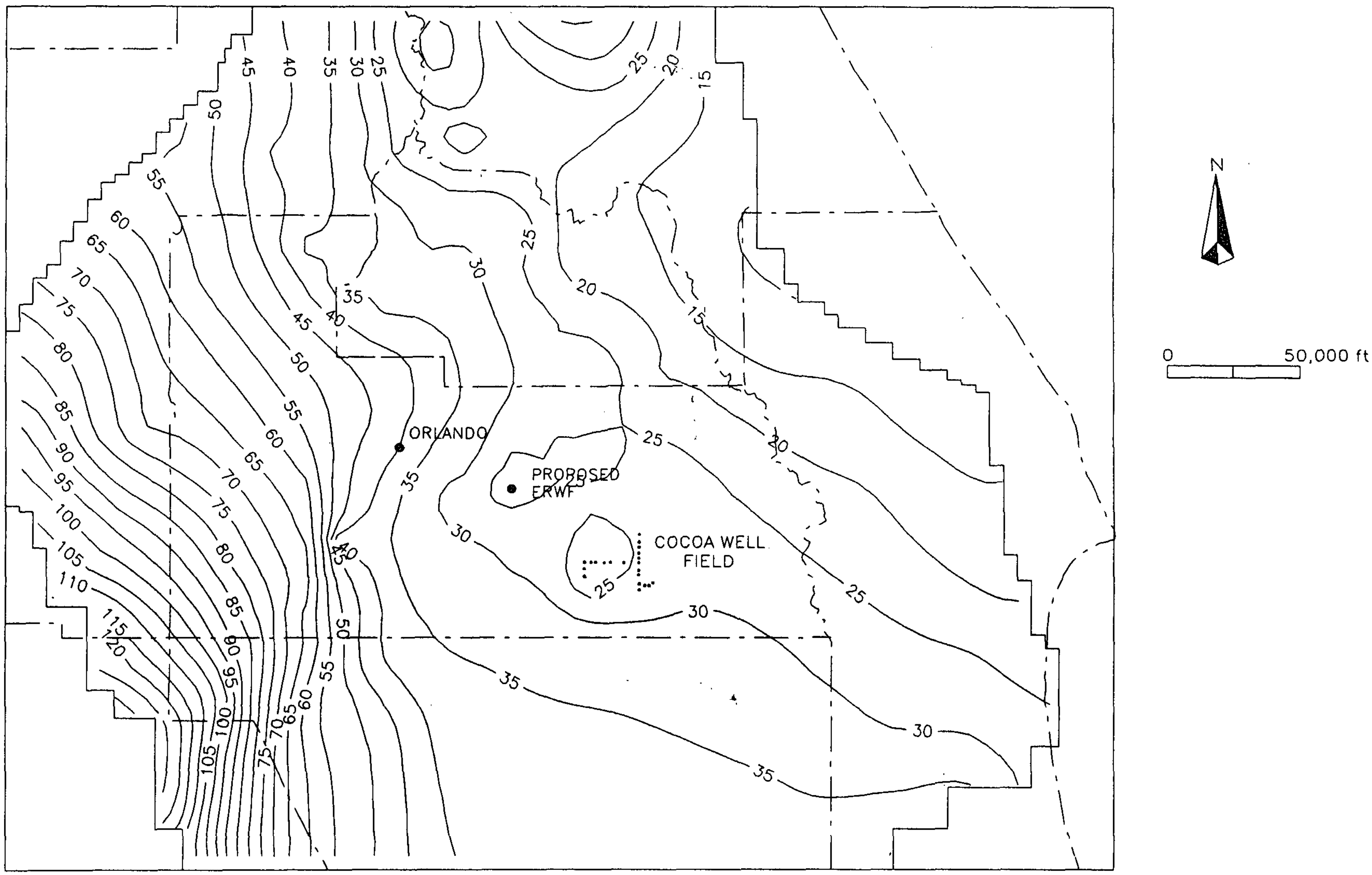

Figure B.2 Simulated 2010 Upper Floridan aquifer hydraulic head obtained using the Phase III river package.

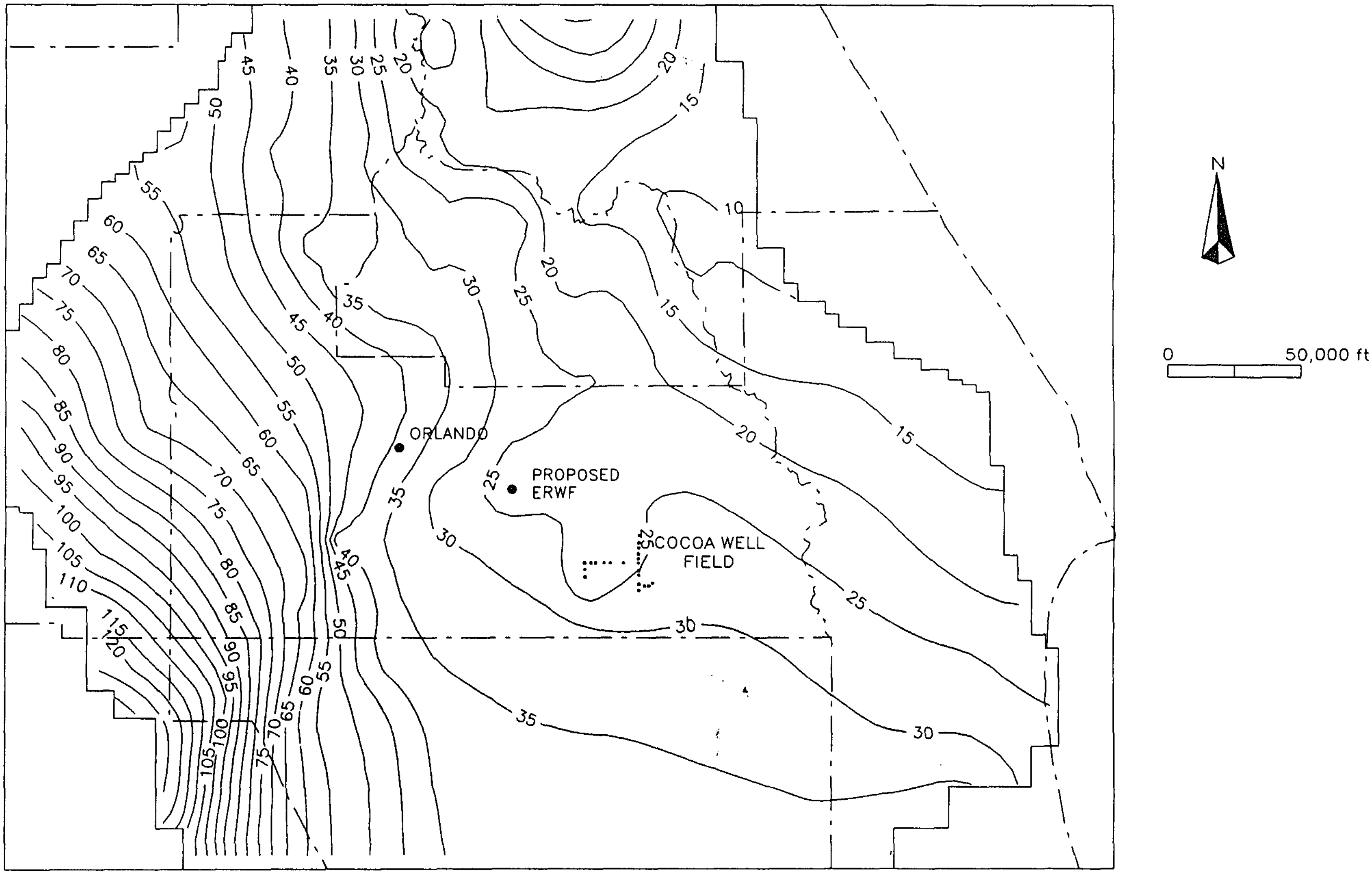

Figure B.3 Simulated 2010 Upper Floridan aquifer hydraulic head obtained using the Phase V river package.

Figure B.4 is a contour plot of the difference in simulated recharge and discharge to the Upper Floridan aquifer attributable to application of the Phase III and Phase V river packages. Throughout most of the regional model domain, the simulated differences are zero or very small (less than 1 inch/year). In Seminole County, there are some very localized zones where differences are as high as 8-10 inches/year. In eastern Seminole County north of Geneva, there is one zone of up to 20 inches/year difference. The majority of this zone lies outside the Phase V model domain, and has a minimal effect upon simulated chloride concentrations with the Phase V model.

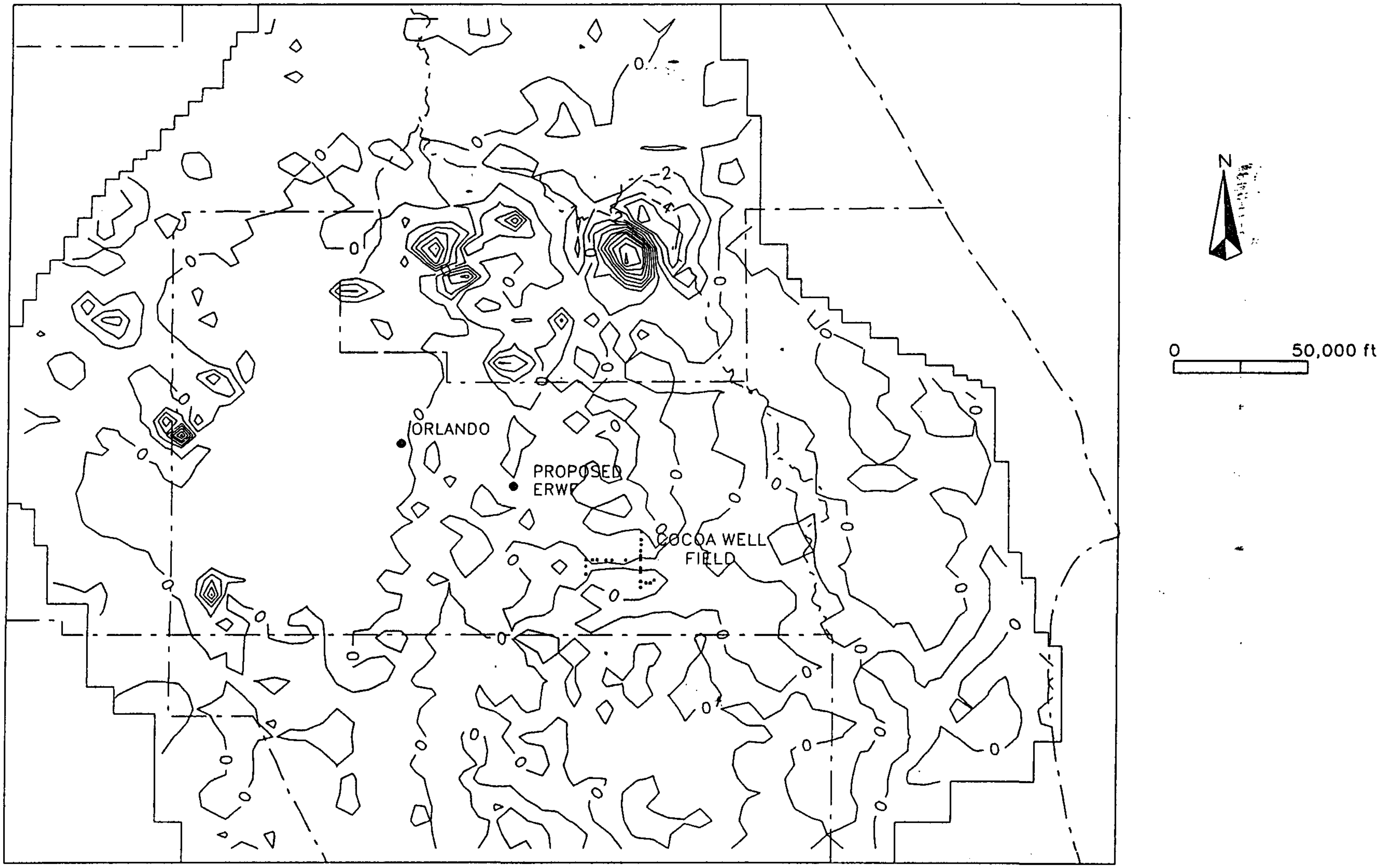

Figure B.4 Difference in simulated 2010 recharge to the Upper Floridan aquifer obtained using the Phase III and Phase V regional MODFLOW river packages (Phase V recharge subtracted from Phase III recharge). Contour interval is 2 inches/year.